TOWARDS AN INTEGRATED MODEL FOR ASSESSING THE EFFECTS OF CHANGES IN CLIMATE AND LAND USE PATTERNS ON THE QUANTITY AND VARIABILITY OF RIVER FLOWS IN INDONESIA

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ABSTRACT

The thesis examines this question: What are the relative effects of changes in land use and climate on the quantity and variability of river flows in Indonesia in relation to land use and water use planning and management for sustainable development? The contribution of this thesis is to provide a method and tool for shedding light on this important research question.

A new integrated model system INDOCLIM has been developed for policymakers and planners as a tool for examining the possible impacts of changes in land use patterns and climate on the river flows, as part of an effort to support environmentally sustainable development in a country such as Indonesia. This is a trial model that consists of three components (land use, climate and hydrology). The land use component is used to generate land use change patterns based on four policy-related scenarios: business-as-usual; ecological concern; pro-industrialisation; and pro-agriculture. These scenarios were constructed in a time-series between 2000 and 2100, with 1990 as the baseline. The land use change pattern is created by using a GIS, based on the cellular automata principal. The climate component is used to generate time dependent climate scenarios, based on the global temperature change under IPCC SRES GHG emission scenarios and downscaled GCM patterns. The land use patterns are translated into a set of hydrological parameters and, together with the climate variables, are used for calculating the monthly discharge on a cell-by-cell basis. The runoff is totalled from all cells in the basin area. The model is: very specific in purpose; user oriented; designed for sensitivity analysis to answer 'what if' questions; designed for a catchment scale; and transportable.

The model has been implemented in the Upper Citarum river system, Bandung basin, Indonesia for a preliminary assessment. The results from the model show that: both land use change and climate change have impacts on the annual yield, monthly discharge, and changes in seasonal variations of river flows; climate change has a greater possible impact on the change of the annual yield, and on monthly discharge variations, than the land use change; the superimposed effects of land use change and climate change can exacerbate or reduce the impacts; the land use change has a more significant impact on local scale variation than the climate change. The findings suggest that land use management as part of an integrated management programme for sustainable development is very relevant.

Characteristics of this integrated model and some feedbacks from potential users have been identified for further development and improvement of the model.

This thesis contributes to the need for an integrated assessment for examining the possible changes in the quantity and variability of river flows as the result of changes in land use and climate. It specifically contributes by: developing the integrated system for this specific purpose; developing the methodology for transferring land use information to monthly water consumption as required by the hydrological model; and developing procedures to create land use change scenarios. Overall, the integrated model framework, as developed, tested and applied in the Bandung basin of Indonesia, is potentially transferable to other basins and countries in Southeast Asia where similar issues of climate change, land use change and water resource management are key elements of sustainable development.

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[1] RCG-LIPI = Research Centre for Geotechnology, Indonesian Institute of Sciences

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On the final touch of this thesis, I looked back at what I had gained during my four years stay in New Zealand. So much knowledge that I have gained in this fascinating topic and it was all quite new to me. Moving from one section in the university library to another section, and moving again to a different section, and then getting stuck in front of the computer... these were 'enjoyable' experiences. The most pleasant of all was being surrounded by lovely, friendly and helpful people throughout my study.

This thesis is dedicated to my wife Fitri, and my daughter Rizkita. I feel greatly indebted for their understanding and support during some hard times that I encountered. Especially to Rizkita, I thank you for your 'maturity' in understanding all of this.

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Glossary of local terms and abbreviations

amsl.	above mean sea level
AOGCM	Atmosphere-Ocean coupled General Circulation Model
BMG	*Badan Meteorologi dan Geofisika* (Meteorological and Geophysical Agency), Indonesia
BOD	Biological Oxygen Demand
BPS	*Badan Pusat Statistik* (Central Bureau of Statistics), Indonesia
CIA	Central Intelligence of America
CSIRO	Commonwealth Scientific and Industrial Research Organisation, Australia
DEM	Digital Elevation Model
Direktorat Bina Produksi Tanaman Pangan	Food Crop Production Directorate
FAO	Food and Agriculture Organisation
GCM	General Circulation Model
GDP	Gross Domestic Product
GHG	Green-House Gas
GIS	Geographical Information System
GRDP	Gross Regional Domestic Product
GTL	*Geologi Tata Lingkungan* (Directorate of Environmental Geology), Indonesia
HadCM	Hadley Centre
HRU	Hydrological Response Unit
IDW	Inverse Distance Weighting
IPCC	Intergovernmental Panel for Climate Change
IPCC-TGCIA	Intergovernmental Panel for Climate Change - Task Group on Scenarios for Climate Change Impact Assessment
ITC	The International Institute for Aerospace Survey and Earth Sciences, Enschede, the Netherlands (*formerly known as:* International Training Centre).
kabupaten	regency or district
kebun	garden
kebun	garden, part of the dry agricultural land
kecamatan	subdistrict
kotamadya	municipality
LAM	Limited Area climate Model
palawija	secondary crop or seasonal crop

RegCM	Regional Climate Model (*see also* LAM)
Rupiah	Indonesian currency
SAR	Second Assessment Report
SCM	Simple Climate Model
SCS	Soil Conservation Service (*see also* US SCS)
SIS	Spatial Information System
SRES	Special Report on Emission Scenarios
SS	Solid Suspension
TAR	Third Assessment Report
tegalan	dryland or hill-side land, part of the dry agricultural land
TGHK	*Tata Guna Hutan Kesepakatan* (Forest Land Use by Consensus)
US SCS	United States Soil Conservation Service

Glossary of mathematical notations and parameters

ρ	coefficient of correlation between two sets of data, regardless of their unit
Acc Pot WL	accumulated potential water loss
BF	baseflow
DRO	direct runoff
E_a	accumulated water excess
I	infiltration coefficient
INBF	part of the water that infiltrates to the deep soil and becomes baseflow
k_c	a crop coefficient that determines the amount of water used by a crop relative to a reference crop
k_l	a land use coefficient that determines the amount of water used by a land use relative to a reference crop (see also: k_c)
L_a	accumulated potential water loss (see also: *Acc Pot WL*)
LRO	late runoff
M	monthly recession coefficient
MAX	maximum groundwater storage
OVFL	overflow water that cannot fill the groundwater storage
P	precipitation
P'	effective rainfall, which is the portion of rain (*P*) treated further in the water balance calculation after the other portion turns to become surface runoff

PET	potential evapotranspiration
PET_0	potential evapotranspiration of a reference crop
r^2	coefficient of determination, a statistical value which is commonly used to examine fitness of the computed graph against observed graph
Ref PET	potential evapotranspiration of a reference crop (see also: PET_0)
S	storm runoff coefficient
SM	soil moisture
SRO	storm runoff
STBF	part of the baseflow that comes from the groundwater storage
W	available water capacity of a root zone

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND AND PROBLEMS

This thesis is about the development of an integrated model for assessing the quantity and variability of river flow as the result of changes in land use patterns and climate.

The background of this thesis comes from some observations on the condition of many watersheds in Indonesia that have declined as the result of uncontrolled logging activities. Particularly in Java, the degradation is mainly caused by population pressure and unsuitable farming systems (Soeseno, 1998; Purwadirdja, 1982). People have moved onto higher and steeper slopes in their search for new agricultural land, and forested lands have been cleared and planted with food crops with little attention being paid to problems of erosion and water conservation. Irrigated paddy-fields, small lakes and other vegetation-covered lands have changed to become residential areas. The immediate impact of this land use change is in the form of flooding and deterioration of water sources. In the longer term this can increase the seasonal variability of river flow. The Brantas River basin in east Java, for example, suffers a shortage of water or very low flow during the dry season as well as very high flows during the rainy season.[1-1] Some river basins in the southern parts of central Java, such as the

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[1-1] This river basin has not suffered from flooding since flood prevention designs were built from the 1960s to 1980s, but flooding is still a threat. In fact, an early warning system to forecast flooding, FFWS (Flood Forecasting and Warning System), was set up in 1991. The recent high flows reached approximately 70 to 80% of the present design flood discharge in March 1984 and March 1992 (Nippon Koei and Nikken Consultants, 1997).

Wawar River basin, recently suffered from enhanced dryness or low runoff during the dry season and flooding during the rainy season. Furthermore, deterioration of many catchment areas has created disturbances in river basin development, silting up the riverbeds, increasing flood intensity, diminishing the effective capacity of reservoirs, and increasing the need to maintain the irrigation schemes (Muryadi, 1982).

In many parts of the world, this kind of phenomenon has also been observed. Some examples are: Peachtree Creek watershed in Atlanta, U.S. (Ferguson and Suckling, 1990); a watershed in Zimbabwe (Lørup *et al.,* 1998); in southwest Western Australia (Taniguchi and Bari, 1997); Carnation Creek, Canada (Hetherington, 1987); and in one catchment in Malaysia (Bruijnzeel, 1988).

A major issue concerns the causes of the apparent changes in the seasonal variability of river flow. In addition to land use conversion, a change in climate can also cause a change in the hydrology of a river basin as have been reported by many authors; for example, changes in river baseflow and groundwater storage in Central Africa (Orange *et al.*, 1997) and in North China (Chun-Zhen, 1991). A simple case of a change in climatic variation can have dramatic consequences. An increase in rainfall intensity, for example, can exacerbate flooding, while a prolonged dry season can reduce low flows.

The apparent increases in flooding and droughts observed in east and central Java during the rainy season and dry season, as mentioned above, raise the following questions:

- Is the increase in river flow variability the result of climate change (for example, causing prolonged dry season with increased precipitation intensity in the rainy season)?

  Or,
- Is it the result of land use changes?

These questions lie at the heart of this thesis.

1.2 STREAMFLOW VARIABILITY RELATED TO LAND USE CHANGE AND CLIMATE CHANGE

Land use change

Many researchers have studied the effects of land use changes on streamflow (or river flow). It is now widely accepted that changes in land use can cause hydrological variations, for example, an increase in urbanisation and a reduction in forested areas can cause an increase in major peak flows of a stream (Booth, 1990; Moscrip and Montgomery, 1997) and an increase in total runoff in wet years (Ferguson and Suckling, 1990). This is because cutting the trees reduces the interception of water by the forest canopy and reduces the evapotranspiration by the trees (Pereira, 1973; Pearce *et al.,* 1987; Calder *et al.,* 1986; Asdak *et al.,* 1998). It is also shown by Cheng *et al.* (1987) that a forest with lower vegetation density has lower evapotranspiration loss and therefore produces higher streamflows. Deforestation can shorten the time lag of hydrographical units (James *et al.,* 1987) and can cause an increase in the annual runoff (Lørup *et al.,* 1998; Johnson and Black, 1997). Conversely, reforestation can reduce annual runoff (Pearce *et al.,* 1987; Johnson and Black, 1997) by increasing the evapotranspiration and interception loss.

The hydrological processes involved are complex and sometimes produce effects that may appear contradictory. Ferguson and Suckling (1990) reported that a land use change from forested land to urbanised land decreased the low flows as the result of an increase in impervious areas, while Johnson and Black (1997) reported that a decrease in the low flows had been caused by reforestation and afforestation. Bruijnzeel (1988; 1993) demonstrated how these seemingly conflicting results could actually be resolved by taking into account the net effect of changes in infiltration opportunities and evapotranspiration associated with the respective land use types. In particular, soil characteristics, including textures, structures and degree of compaction that affect the infiltration capability, as well as vegetation types, should be considered in the system. An understanding of such mechanisms and parameters that drive the wet season and dry season flows and their correlation with the land uses is potentially important in *managing* streamflows through land use management.

There are several reasons for attempting to keep the magnitude and the performance of the dry season flows in a certain favourable condition. One reason is to maintain the quality of the river water. In the Brantas River of East Java, low dry season flows not only require restrictions in irrigation water use, but also cause pollutants to concentrate in the river. This pollution concentration in the river water, as measured by the values of SS (Solid in Suspension) and BOD (Biological Oxygen Demand), reaches its peak at the beginning of the rainy season (Nippon Koei and Nikken Consultants, 1997). This is what is called the washout effect. Other than improving the water quality, the benefits of keeping adequate dry season flows are; cleaner riparian areas, increased channel and bank stability, decreased erosion and sediment transport, enhanced fish and wildlife habitat, lower stream temperatures, and improved stream aesthetics (Ponce and Lindquist, 1990).

Floods are both beneficial and detrimental. Catastrophic floods cause loss of property and life and are obviously undesirable. However, floods are also necessary as part of natural processes that control biota. As reported by Goubersville (1997), the winter floods in Germany are important for the flora and the reproduction of birds and fish, while maintaining the high summer flows is necessary for preserving boggy soils. The ecology of the flood plain is commonly linked to, and forms an integrated ecology with, the river channel in a concept described as the flood pulse concept (Junk *et al.,* 1989). This link depends on the strength of the link between the channel and the flood plain. Without this flood pulse, animal biomass production within this hydrosystem is reduced which may change the community composition and energy pathways (Petts and Maddock, 1996). Bayley (1991) showed that annual yields from multi-species fish depended on the flood pulse and particularly on the rate of hydrograph rise. Nevertheless, extreme floods can have adverse effects on biota, and a quick rise of hydrographs is certainly unfavourable to fish yield.

In summary, controlling the peaks of high (flood) and low (drought) flows can have many advantages for both people and ecosystems.

Climate change

There have been numerous studies (Mimikou *et al.*, 1991; Murdiyarso, 1996; Orange *et al.*, 1997; Georgiadi, 1991; Arnell, 1997; Watts, 1997; Wilkie *et al.*, 1999; Arnell and Liu, 2001) that show how climate change and climate variability can affect the hydrology of a river basin. One example, is that reported by Chun-Zen (1991) who noted a significant change in hydrology by the reduction of rainfall and the inflow runoff in North China from the 1950s to 1980s and concluded that this was jointly contributed by drier climate (climate change) and by human activities involving an over-exploitation of groundwater. A prolonged drought can significantly lower water-tables and can therefore reduce baseflows that contribute to lower dry season flows (Orange *et al.,* 1997).

A trend of increasing global-mean surface temperatures has been revealed in the global climate data, part of which is likely to be due to increasing atmospheric concentrations of greenhouse gases particularly since 1950 (Houghton *et al.*, 2001). This phenomenon is expected to have significant effects on hydrological regimes. Global warming is likely to change precipitation and evapotranspiration in many tropical island areas, resulting in a change in the water resource base (Watts, 1997). Change in precipitation and evaporation regimes may cause changes in the magnitude of runoff and its seasonal distribution (Georgiadi, 1991). Murdiyarso (1996) simulated the impact of a scenario of climate change on water resources and found that the water yield potential for irrigation in West Java, Indonesia, could increase but there could be concurrent problems of erosion and sedimentation as well.

In summary, climate change and variability could work hand-in-hand with changes in land use to affect streamflows.

1.3 LAND USE MANAGEMENT FOR ENVIRONMENTALLY SUSTAINABLE DEVELOPMENT

Land use management

It is apparent that both land use changes and climate changes can contribute to the hydrological change of a watershed. Many changes in land use can decrease low season flows and increase the occurrence of flooding. Lørup *et al.* (1998) note:

> Furthermore, land mismanagement may have inadvertent negative effects on the hydrological regime, such as increasing occurrence of floods and decreasing dry season flows (p.147).

This also implies that land management can potentially improve the performance of streamflows. Essentially, the objective of management is the ability to produce an orderly flow rather than a raging torrent and to minimise losses by evaporation (Pereira, 1973). In contrast to management through structural measures, such as reservoirs and flood protection works that commonly have specific objectives, management through land use can often be more cost effective (Krecmer and Perina, 1987).

In managing land, land use managers or planners must also consider the interests of all land users or people that live in the area. More importantly, with the increasing human pressure, such as increasing population or demand for agricultural land, the sustainability of the land use has to be taken into account. Therefore, it is important to raise the issue of sustainable land use management. Merkel (1998) defined sustainable land use as permanently preserving the natural fertility of soil in the production of food stuffs and regenerative raw materials, including attention to protective natural functions of the soil for other areas of environment, waters, atmosphere and biological diversity whenever human beings use or transform terrestrial ecosystems. However, as human beings seek to improve the quality of life through development, this should be included in the concept of sustainable land use management.

Fleischhauer and Eger (1998) put forward a concept of environmentally sustainable development, which is defined as an interdependent triangle framework that demonstrates the close ecological, economic and social interactions as prerequisites for sustainable development. This framework is dynamic, and ideally its equilibrium is maintained. However, from those three major groups of prerequisites, only a small number of ecological prerequisites have been formulated precisely enough for them to be used as an operational tool for implementing sustainable development. There is, therefore, a need to be able to formulate precisely a sufficient number of prerequisites within the framework for them to be used as an operational tool for implementing sustainable development. Naturally, this framework cannot be formulated easily as advances in technology such as cropping technology, mechanised farming, etc. can quickly shift the intensity or use capacity of the land.

Better streamflows through land use management

The concept of environmentally sustainable development forwarded by Fleischhauer and Eger (1998) is a general framework within which land use management for better performance of streamflows can be applied. A derivative framework is diagrammatically shown in Figure 1.

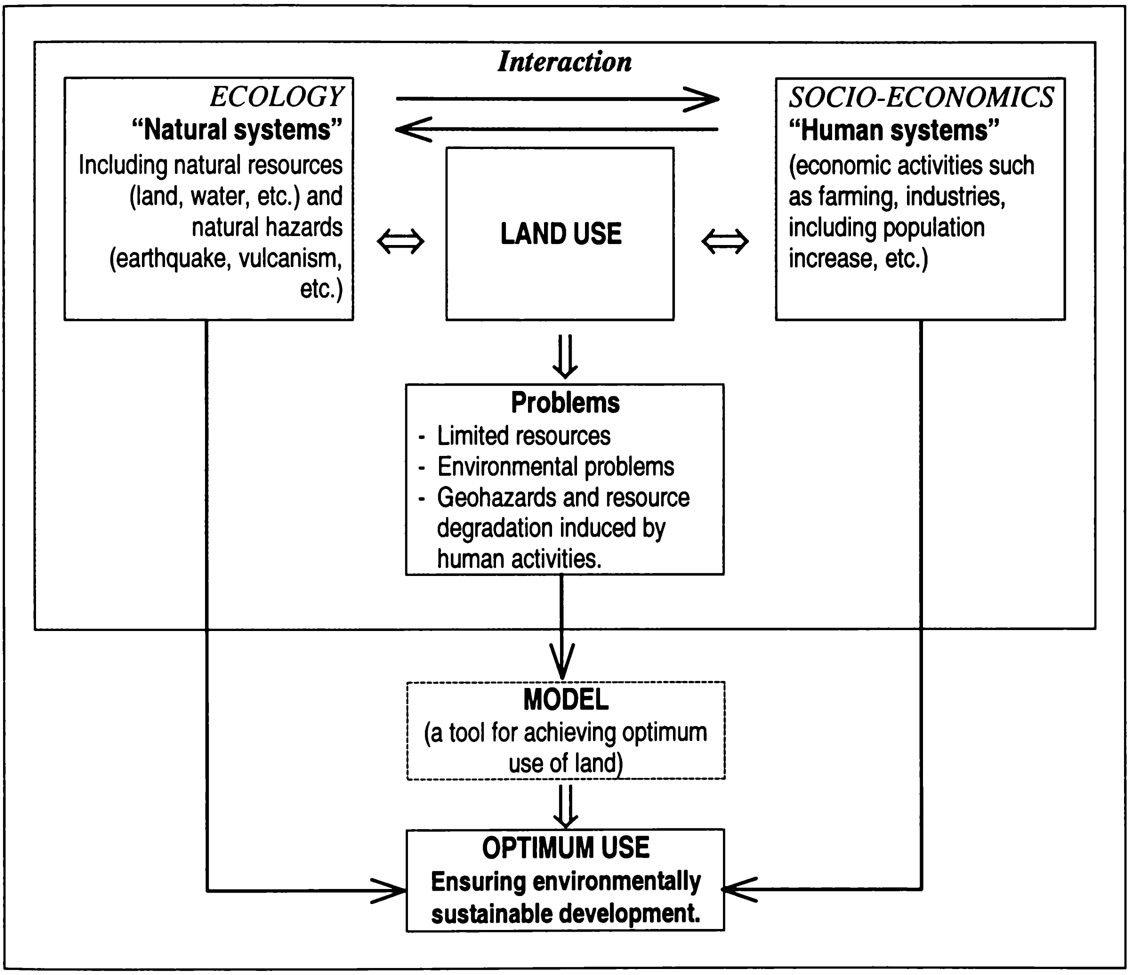

Figure 1.1: Concept of environmentally sustainable development.

Outlined in Figure 1.1 is a conceptual framework that shows the conditions in the field, including general problems, and how optimum use of land can be approached. Ecological aspects are part of natural systems that interact with socio-economic aspects, which are part of human systems, including economic activities such as, farming and industries, and pressures resulting from population growth. The shaded zone in Figure 1.1 shows interaction relationships between these socio-economic aspects and ecological aspects in the forms of various kinds of land uses. In turn, these interactions create problems, such as: limited natural resources to support people's requirements for living; environmental problems; and geohazards and resources degradation caused by human activities, such as flooding, dryness, soil erosion, and degradation of soil fertility and water resources. Optimum use of the land can be achieved if potential conflicting interests can be resolved or traded-off. Resolving conflicts can include, for example, preservation of the environment from economic activities, such as enhancing food production using intensive inputs while also controlling soil degradation and water pollution. However, in dealing with land use management, there is a need to specify an objective as the main priority that needs to be achieved. For this research, the main priority of land use management is to achieve the optimum quantity and quality (in terms of seasonal variability) of river flows.

To achieve this objective requires holistic and integrated management for one catchment as a whole that should cover the land use management and water use. The land use management includes forest management, control on agricultural activities, and management of urban areas (including control on urbanisation). Water use management should include river water use management, control on the river water quality and quantity, and control on groundwater use.

1.4 A POLICY-RELEVANT MODEL FOR SUPPORTING SUSTAINABLE DEVELOPMENT

As a decision support tool, a model would be useful for land use planners to examine possible changes in land use and how these changes would affect the streamflows. This would lead to more awareness of the results of the changes on streamflows and better guidance in designing and managing the land use. It would also be useful tool for better co-ordination of all government bodies and stakeholders dealing with the development in the river basin area.

This research, therefore, focuses on the development of an integrated model for catchment management that incorporates land use, climate, and hydrological system components. The proposed model should fit with, and support, the concept of environmentally sustainable development as described earlier. It has a specific target, that is, to assess the relative changes in the quantity and seasonal variability of streamflows (i.e. sensitivity analysis) as a consequence of changes in land use and climate. Therefore, the model must have the capability to demonstrate a strong link between land use patterns and hydrology, particularly runoff.

The model should generally be; simple, accommodative and transportable, and the outcome easily visualised. **Simple** means that the model should not be data demanding and computationally demanding, and can be used by decision-makers and policymakers. **Accommodative** means that it can accept a broad range of inputs from various stakeholders or other users (participants) and therefore, can provide a means for co-ordination among multi-agencies. This is especially useful when considering the resolution of conflicting interests in land management. **Transportable** means that the model can also be applied in other catchments. Accommodative and transportable characteristics are required since every catchment has its own specific problems and solutions.

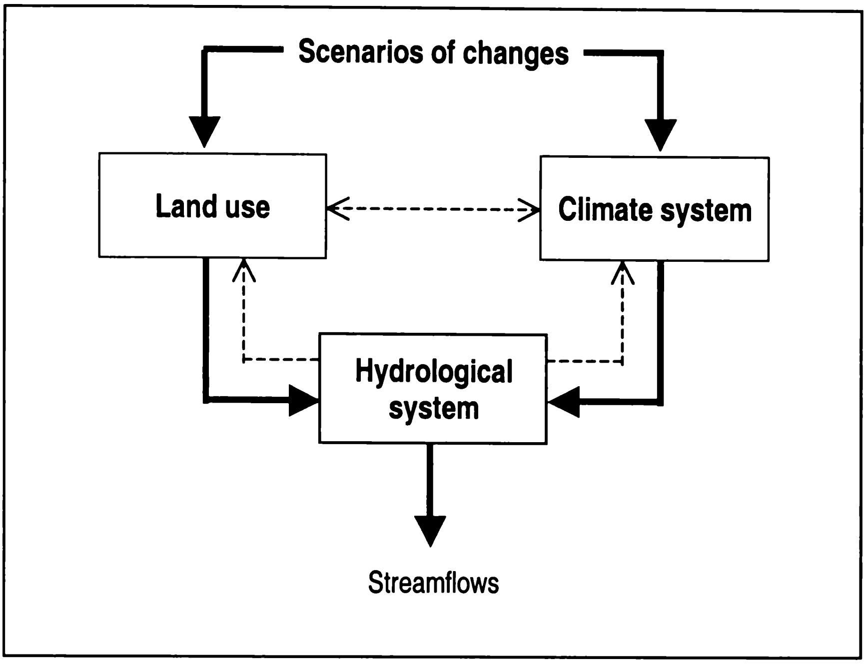

Figure 1.2: The structure of the integrated model system.

The conceptual structure of the proposed model is shown in Figure 1.2. The input to the model is a set of scenarios of changes in land use patterns and climate driven by human factors such as population, choices of economic activities, green-house gas emissions, etc. The land use and climate component act as separate processors that transfer the given input for each component into a series of hydrological variable and parameters that will be used by the hydrological component in producing the streamflow as output. The links between the land use component and the hydrological component and between the climate component and the hydrological component are in the form of cause and effect relationships as indicated in Figure 1.2 by solid arrows. Dynamic feedback relationships between those components are recognised as indicated by dashed arrows (e.g. Bonan, 1997; Scharpenseel and Pfeiffer, 1998; and Wasson, 1996), but to model this integrated interactive-dynamic relationship is beyond the scope of this thesis.

1.5 RESEARCH GOAL, OBJECTIVES AND TASKS

The ultimate **goal** that this thesis hopes is to promote **better management of land use patterns for optimum quantity and variability of river flow in order to support environmentally sustainable development.** This goal means developing an integrated conceptual framework of land use management that aims at ensuring environmentally sustainable development as described earlier. The thesis intends to make a contribution towards some part of this framework, that is, through water resources management. Its particular **aim** is: **to produce a policy-relevant, integrated model system for examining the effects of changes in land use patterns, as well as climate, on the quantity and variability of streamflow.** This model will be implemented on an Indonesian catchment as an example test for this thesis.

In order to achieve the goal of the thesis, three research objectives have been identified. These are to produce an integrated model; to implement the integrated model for an Indonesian river basin; and to evaluate the use of the model.

Objective 1: To **produce an integrated model** for the purpose of assessing the possible effects of possible future changes in the spatial patterns of land use, as well as climate change, on streamflow, in order to improve water resource management in Indonesia through land use planning and policy, by:

Task 1: Developing the **structure of a model system**, employing a spatial information system at a relevant scale and resolution, for the purpose of integrating land use, climate and hydrological components.

Task 2: Developing and incorporating the **land use component** of the integrated model system, including:

- identifying and developing an appropriate approach and methods for creating scenarios of future changes in land use patterns;

- identifying current land use types and grouping them based on their hydrological characteristics;
- collecting land use data and constructing the baseline in the form of spatial information;
- developing the functional relationships between the various land uses and hydrological parameters.

Task 3: Developing and incorporating the **climate component** of the integrated model system, including:

- reviewing the various methods for generating climate change scenarios and evaluating them in relation to the Indonesian context;
- adapting an existing climate change scenario generator from an existing integrated assessment model;
- identifying and collecting the climate data required as input to the hydrological component.

Task 4: Developing and incorporating the **hydrological component** of the integrated model system, including:

- reviewing existing hydrological models and evaluating them in relation to the Indonesian context;
- developing an appropriate hydrological model as part of the integrated model system taking into account the scale, objective and simplicity required for its practical use as a tool for development of policy;
- constructing the baseline streamflow quantity and variability from river discharge and runoff data.

Objective 2: To **implement the integrated model for an Indonesian river catchment**, in order to test the behaviour of the model for applications to real world conditions, by:

Task 5: Identifying a **suitable catchment** for modelling based on available data, size, spatial representation or other criteria.

Task 6: Incorporating the current **baseline data** for the catchment area, such as land use and hydrological data, at the required spatial and temporal resolutions using appropriate methods of interpolation where necessary.

Task 7: Conducting a range of **sensitivity analyses** to test whether the model behaves in a sensible manner in relation to observational data.

Objective 3: To **evaluate the use of the model in making a preliminary assessment** of the effects of future scenarios of changes in land use and climate on streamflow quantity and variability, by:

Task 8: Conducting an **evaluation** of the integrated model based on its use in the preliminary assessment.

In meeting Objective 1, that is, producing the integrated model, there is a need to keep in mind the requirements for the model: it should be simple, accommodative and transportable. The form of the model, including its structure and complexity, should also be guided by the aim of the research and the end-users of the model. The characteristics of catchments in Indonesia, as well as data availability, should also be considered. These requirements and considerations should be taken into account in developing each component of the model.

A spatial information system (SIS) is needed in order to handle and process spatial information and integrate land use, climate and hydrological components as one system. The link between this system and hydrological models can be made in several ways (Brilly *et al.,* 1993). One way is to use a SIS to derive required hydrological parameters or to develop hydrological parameters from basic data sets for existing hydrological models such as the US Soil Conservation

Service's model (U.S. Soil Conservation Service, 1975; Stuebe and Johnston, 1990) and the PRMS (Precipitation-Runoff Modelling System) (Leavesley *et al.*, 1983; Colby, 1996). Another way is by embedding the hydrological model into a SIS, so that it becomes an integrated part of the SIS. The latter requires the hydrological model to use the computing language of the host SIS to perform hydrological analysis. Such methodological issues will be carefully assessed later.

The land use component is a major part of the integrated model. Two different aspects need to be developed. One aspect is assessing and grouping land use types in terms of their hydrological characteristics, and relating them to hydrological parameters through functions as required by the hydrological component. Where land use - hydrological functions are not available from the scientific literature, notional relationships will be developed from local expertise. The other aspect is developing a method for generating scenarios of land use pattern changes. This will entail the identification of key drivers of land use change in Indonesia (e.g. population growth, urban-rural migration) as well as the specification of the effects of such drivers on land use decisions.

For the climate component, a model is required for generating scenarios of climate change and variability. The thesis will adapt existing components that have been developed for integrated assessment models for New Zealand (e.g. Kenny *et al.*, 1995; Warrick *et al.*, 1996), based on methods commonly used in other parts of the world (e.g. Hulme *et al.*, 1995; Carter *et al.*, 1994). For this component, climate data, as dictated by the required inputs to the hydrological model will also need to be collected and interpolated over the catchment selected for the study.

The hydrological component serves as a tool to produce output (streamflow). It needs to be developed by selecting and adapting the appropriate hydrological model in order to meet the requirements of the integrated model. Simplicity and practicality of use are important requirements. There are many hydrological models already published and used by researchers that attempt to analyse the impacts of land use change and climate change on hydrology. (A review of hydrological models is given in Chapter 4, Section 4.5 of this thesis.) The appropriate model for this research is the one that can simulate the relative changes in streamflow (output) from scenarios of changes in land use patterns and climate (inputs) on the decade to century time scale. By developing model components that produce such scenarios, the users can ask 'what if' questions in regard to the drivers of land use and climate change and their consequences for streamflow. Understanding the influence of land covers on the hydrology and how they affect streamflow is, therefore, crucial in developing the overall model.

The purpose of **Objective 2** is to implement the model and to test its behaviour. In meeting this objective, a suitable catchment that represents catchments in Indonesia needs to be identified, taking into account the availability of data, size and spatial representation of the area. Physical characteristics of the catchment, such as soil type, slopes, land use, climate, and other baseline data will be collected and incorporated, and sensitivity analyses will be conducted in order to examine the behaviour of the model.

In **Objective 3**, the use of the model as a preliminary assessment for the modelled catchment is evaluated. The evaluation is made on the potential effectiveness of the model in helping the users in conducting analysis of the impacts of 'what if' question based scenarios.

1.6 OUTPUTS AND POSSIBLE APPLICATIONS OF THE RESEARCH

The main output of the research will be an integrated trial model for examining the effects of changes in land use patterns and climate on the quantity and variability of river flow, as part of the concept of integrated land use management in support of sustainable development. The focus is on the sustainable use of water resources and improved variability of river flow that will reduce seasonal flooding and drought occurrences.

The proposed model is designed to be simple and policy-relevant. The model will be a tool to help policymakers and decision-makers in long-term planning and designing land use patterns. The model may also open possibilities for participation of land users and stakeholders in managing the land and it may also provide a means of co-ordination among them. It may also provide an opportunity to include environmental aspects (such as aesthetic aspects of the river, pollution management and flora / fauna habitat conservation) as part of land management.

1.7 ORIGINALITY

This thesis promises to be an original contribution to knowledge for a combination of the following reasons:

- The model is an **integration** of a land use component, climate component and hydrological component. There are many existing models that integrate a hydrological model with a land use component in order to assess the effect of land use change on the hydrological regime (e.g. Ott *et al.*, 1991; Eeles and Blackie, 1993; He *et al.*, 1997; etc.), and models that integrate a hydrological model with a climate change component (e.g. Bárdossy and Caspary, 1991; Dunn and MacKay, 1995; Boysen, 2000; etc.). Vörösmarty *et al.* (1991) produced a model that integrates a land use and a climate component with a hydrological model. However, the change in land use is arbitrary and not in a time-series, nor is it policy-oriented.

- The integrated model is applicable to a **mesoscale catchment**[1-2]. In many hydrological studies that integrate the climate change component, the catchment is very large (macroscale) (e.g. Bárdossy and Caspary, 1991; Ott *et al.*, 1991; Vörösmarty *et al.*, 1991). This was because the spatial resolution of the global climate models (GCM), which are commonly used to generate climate change scenarios, are very coarse (Mimikou *et al.*, 1991). Since early 1990s, methods used to downscale the GCM outputs have become available which allow these downscaled climate scenarios to be used for impact assessment application (Hewitson and Crane, 1996). A model that integrates the three hydrological models with the land use change and climate change components for a mesoscale catchment is not yet available.

- The proposed integrated model is specifically **user-oriented.** It is designed for policymakers and planners.

- The integrated model is developed for an Indonesian catchment. It takes into account conditions which are commonly found in Indonesia, in particular, the availability of climate and socio-economic data, the physiographical conditions, as well as the socio-economic conditions. Therefore, this model would be **appropriate to any countries with similar conditions to Indonesia, such as the southeast Asian countries.**

- This integrated model is the **first of its kind to be applied to an Indonesian catchment.** There have been no such studies using similar integrated systems in Indonesia.

[1-2] Schultz *et al.*, (1995) classify the catchment size as follows: macroscale, a catchment with an area > 10^4 km^2; mesoscale (upper transition) 10^3 - 10^4 km^2; mesoscale10 - 10^3 km^2; mesoscale (lower transition) 10^{-4} - 10 km^2; and microscale < 10^{-2} km^2.

1.8 THESIS OUTLINE

The remaining chapters of this thesis are briefly reviewed as follows:

- **Chapter 2:** This chapter describes the ***general conditions of Indonesian catchments***. It includes physical conditions, socio-economics, land use, etc., and general trend of conversion in land use;

- **Chapter 3:** It describes in more detail the conditions of the ***selected catchment***, including physical and socio-economic conditions, availability of data, agricultural practices, etc.;

- **Chapter 4:** This chapter describes the ***structures of the model***. It includes a detailed description of each component of the model, and how every component is linked into the model system and how each component is developed. It also contains ***literature reviews*** of the existing methods and models, and selection of methods and models to be adapted;

- **Chapter 5:** This chapter specifically describes the nature of the ***hydrological component***, and how this component is developed, including the calibration and validation of the model;

- **Chapter 6:** This chapter specifically describes the nature of the ***land use component***, and how it is developed including the assumptions used;

- **Chapter 7:** This chapter specifically describes the nature of the ***climate component***, and how it is developed and includes the assumptions used;

- **Chapter 8:** This chapter describes the ***implementation of the model*** on a catchment in Indonesia, and how ***sensitivity analyses*** are performed based on various inputs of climate change and land use change scenarios. It also includes ***discussion of results*** and ***an assessment on the model***;

- **Chapter 9:** This chapter contains a ***summary*** and ***conclusions*** of the study.

REFERENCES

Arnell, N. 1997. The impact of climate change on water resources. *The Globe.* Issue 40, December 1997, 8-10.

Arnell, N. and Liu, C. 2001. Hydrology and water resources. In: J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken and K.S. White (eds.) *Climate Change 2001: Impacts, Adaptation, and Vulnerability.* Contribution of Working Group II to the Third Assessment Report of the IPCC, Cambridge University Press, Cambridge, U.K.

Asdak, C., Jarvis, P.G., Van Gardingen, P. and Fraser, A. 1998. Rainfall interception loss in unlogged and logged forest areas of Central Kalimantan, Indonesia. *Journal of Hydrology* 206, 237-244.

Bárdossy, A. and Caspary, H.J. 1991. Conceptual model for the calculation of the regional hydrologic effects of climate change. In: F.H.M. van de Ven, D. Gutknecht, D.P. Loucks and K.A. Salewicz (eds.), *Hydrology for the Water Management of Large River Basins.* IAHS Publ. No. 201, 73-82.

Bayley, P.B. 1991. The floodpulse advantage and the restoration of river-floodplain systems. *Regulated Rivers* 6, 75-86.

Bonan, G.B. 1997. Effects of land use on the climate of the United States. *Climatic Change* 37, 449-486.

Booth, D. 1990. Stream channel incision following drainage basin urbanization. *Water Resources Bulletin* 26 (3), 407-417.

Boysen, M. (ed.) 2000. *Biennial Report 1998 & 1999.* Potsdam Institute for Climate Impact Research, Potsdam, Germany.

Brilly, M., Smith, M. and Vidmar, A. 1993. Spatially oriented surface water hydrological modelling and GIS. In: K. Kovar and H.P. Nachtnebel (eds.), *Application of Geographic Information Systems in Hydrology and Water Resource Management.* IAHS Publ. No. 211, 547-557.

Bruijnzeel, L.A. 1988. (De)forestation and dry season flow in the tropics: A closer look. *Journal of Tropical Forest Science* 1 (3), 229-243.

Bruijnzeel, L.A. 1993. Land-use and hydrology in warm humid regions: where do we stand? In: J.S. Gladwell (ed.), *Hydrology of Warm Humid Regions.* IAHS Publ. No. 216, 3-34.

Calder, I.R., Wright, I.R. and Murdiyarso, D. 1986. A study of evaporation from tropical rainforest West Java. *Journal of Hydrology* 89, 13-31.

Carter, T.R., Parry, M.L., Harasawa, H., and Nishioka, S. 1994. *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations.* Dept. of Geography, University College London, and Center for Global Environmental Research, National Institute for Environmental Studies, Japan.

Cheng, J.D., Hsia, Y.J., Lu, H.S., Liu, V.C. and Koh, C.C. 1987. Streamflow characteristics of two small, steep and forested watersheds in high elevation areas of central Taiwan. In: R.H. Swanson, P.Y. Bernier and P.D. Woodard (eds.), *Forest Hydrology and Watershed Management.* IAHS Publ. No. 167, 499-508.

Chun-Zhen, L. 1991. The impact of climate change and human activity on the hydrological cycle in North China. In: F.H.M. van de Ven, D. Gutknecht, D.P. Loucks and K.A. Salewicz (eds.), *Hydrology for the Water Management of Large River Basins.* IAHS Publ. No. 201, 149-151.

Colby, J.D. 1996. Physical characterization of the Navarro Watershed for hydrologic simulation. *AWRA Symposium on GIS and Water Resources* Sept. 22-26, 1996, Ft. Lauderdale, Fl.

Dunn, S.M. and MacKay, R. 1995. Spatial variation in evapotranspiration and the influence of land use on catchment hydrology. *Journal of Hydrology* 171, 49-73.

Eeles, C.W.O. and Blackie, J.R. 1993. Land-use changes in the Balquhider catchments simulated by a daily streamflow model. *Journal of Hydrology* 145, 315-336.

Ferguson, B.K. and Suckling, P.W. 1990. Changing rainfall-runoff relationships in the urbanizing Peachtree Creek watershed, Atlanta, Georgia. *Water Resources Bulletin* 26 (2), 313-322.

Fleischhauer, E. and Eger, H. 1998. Can Sutainable Land Use be Achieved? - An Introductory View on Scientific and Political Issues. In: H.-P. Blume, H. Eger, E. Fleischhauer, A. Hebel, C. Reij, K.G. Steiner (eds.), *Towards Sustainable Land Use, Furthering Cooperation Between People and Institutions - Vol. 1.* Advances in GeoEcology 31: XIX-XXXII.

Georgiadi, A.G. 1991. The change of the hydrological cycle under the influence of global warming. In: F.H.M. van de Ven, D. Gutknecht, D.P. Loucks and K.A. Salewicz (eds.), *Hydrology for the Water Management of Large River Basins.* IAHS Publ. No. 201, 119-128.

Goubersville, P. 1997. Assessment of the balance between environmental demands and water resources. In: D. Rosbjerg, N-E. Boutayeb, A. Gustard, Z.W. Kundzewicz and P.F. Rasmussen (eds.), *Sustainability of Water Resources under Increasing Uncertainty.* IAHS Publ. No. 240, 487-494.

He, M., Douglas, I. and Chen, Z. 1997. Hydrological effects of forests in northwestern Sichuan, China. In: D. Rosbjerg, N-E. Boutayeb, A. Gustard, Z.W. Kundzewicz and P.F. Rasmussen (eds.), *Sustainability of Water Resources under Increasing Uncertainty.* IAHS Publ. No. 240, 201-210.

Hetherington, E.D. 1987. Carnation Creek, Canada - review of West Coast fish/forestry watershed impact project. In: R.H. Swanson, P.Y. Bernier and P.D. Woodard (eds.), *Forest Hydrology and Watershed Management.* IAHS Publ. No. 167, 531-538.

Hewitson, B.C. and Crane, R.G. 1996. Climate downscaling: techniques and application. *Climate Research* 7, 85-95.

Houghton, J.T., Ding, Y. Griggs, D.J. Noguer , M., Van der Linden, P.J., Da, X. Maskell, K. and Johnson, C.A. (eds.) 2001. *Climate Change 2001: The Scientific Basis.* Contribution of Working Group I to the Third Assessment Report of the IPCC, Cambridge University Press, Cambridge, U.K.

Hulme, M. et al. 1995. An integrated framework to address climate change (ECAPE) and further developments of the global and regional climate modules (MAGICC). *Energy Policy* 23, 347-355.

James, E.J., Pradeepkumar, P.K., Rangana, G., Nayak, I.V. and Ravi, T.B. 1987. Studies on the hydrological processes in the forest drainage basins of the Western Ghats of India. In: R.H. Swanson, P.Y. Bernier and P.D. Woodard (eds.), *Forest Hydrology and Watershed Management.* IAHS Publ. No. 167, 223-229.

Johnson, R. and Black, A. 1997. The effects of forestry on low flows in Scotland and Northern Ireland. In: D. Rosbjerg, N-E. Boutayeb, A. Gustard, Z.W. Kundzewicz and P.F. Rasmussen (eds.), *Sustainability of Water Resources under Increasing Uncertainty.* IAHS Publ. No. 240, 125-132.

Junk, W.J., Bayley, P.B. and Sparks, R.E. 1989. The flood-pulse concept in river-floodplain systems. *Special Publication of the Canadian Journal of Fisheries and Aquatic Sciences* 106, 110-127.

Kenny, G.J., Warrick, R.A., Mitchell, N.D., Mullan, A.B. and Salinger, M.J. 1995. CLIMPACTS: an integrated model for assessment of the effects of climate change on the New Zealand environment. *Journal of Biogeography* 22, 883-895.

Krecmer, V. and Perina, V. 1987. Management of forests with water conservation function. In: R.H. Swanson, P.Y. Bernier and P.D. Woodard (eds.), *Forest Hydrology and Watershed Management.* IAHS Publ. No. 167, 475-480.

Leavesley, G.H., Lichty, R.W., Troutman, B.M. and Saindon, L.G. 1983. Precipitation-Runoff Modeling System: User's Manual. *Water-Resources Investigations Report* No. 83-4238.

Lørup, J.K., Refsgaard, J.C. and Mazvimavi, D. 1998. Assessing the effect of land use change on catchment runoff by combined use of statistical tests and hydrological modelling: Case studies from Zimbabwe. *Journal of Hydrology* 205, 147-163.

Merkel, A. 1998. Striving for Suistanable Land Use - A Challenge for All Countries. In: H.-P. Blume, H. Eger, E. Fleischhauer, A. Hebel, C. Reij, K.G. Steiner (eds.), *Towards Sustainable Land Use, Furthering Cooperation Between People and Institutions - Vol. 1.* Advances in GeoEcology 31: III-VII.

Mimikou, M.A., Hadjisavva, P.S. and Kouvopoulos, Y.S. 1991. Regional effects of climate change on water resources systems. In: F.H.M. van de Ven, D. Gutknecht, D.P. Loucks and K.A. Salewicz (eds.), *Hydrology for the Water Management of Large River Basins.* IAHS Publ. No. 201, 173-182.

Moscrip, A.L. and Motgomery, D.R. 1997. Urbanization, flood frequency and salmon abundance in Puget Lowland streams. *Journal of American Water Resources Association* 33 (6), 1289-1297.

Murdiyarso, D. 1996. Climate change impacts on water resource management. Paper presented in: Workshop on Living with Global Change – Linking Science and Policy in Southeast Asia, Bogor, Indonesia, 13-15 August 1996. Sponsored by START and IC-SEA.

Muryadi, A 1982. Catchment management and its role in water resources development in Indonesia. In: D.J. Moore (ed.) *Catchment management for optimum use of land and water resources: Documents from and ESCAP seminar.* Water and Soil Division, Ministry of Works and Development for the National Water and Soil Conservation Organisation, Wellington, N.Z. Water and Soil Miscellaneous Publication No. 45, 123-138.

Nippon Koei and Nikken Consultants 1997. *The Study on Comprehensive Management Plan for the Water Resources of the Brantas River Basin in the Republic of Indonesia - Interim Report.* Japan International Cooperation Agency, Directorate General of Water Resources Development, Ministry of Public Works, R.I. October 1997.

Orange, D., Wesselink, A.J., Mahe, G. and Feizoure, C.T. 1997. The effects of climate changes on river baseflow and aquifer storage in Central Africa. In: D. Rosbjerg, N-E. Boutayeb, A. Gustard, Z.W. Kundzewicz and P.F. Rasmussen (eds.), *Sustainability of Water Resources under Increasing Uncertainty.* IAHS Publ. No. 240, 113-123.

Ott, M., Su, Z., Schumann, A.H. and Schultz, G.A. 1991. Development of a disturbed hydrological model for flood forecasting and impact assessment of land-use change in the international Mosel river basin. In: F.H.M. van de Ven, D. Gutknecht, D.P. Loucks and K.A. Salewicz (eds.), *Hydrology for the Water Management of Large River Basins.* IAHS Publ. No. 201, 183-194.

Pearce, A.J., O'Loughlin, C.L., Jackson, R.J. and Zhang, X.B. 1987. Reforestation: on-site effetcs on hydrology and erosion, eastern Raukumara Range, New Zealand. In: R.H. Swanson, P.Y. Bernier and P.D. Woodard (eds.), *Forest Hydrology and Watershed Management.* IAHS Publ. No. 167, 489-497.

Pereira, H.C. 1973. *Land Use and Water Resources – In Temperate and Tropical Climates.* Cambridge Univ. Press, London.

Petts, G.E. and Maddock, I. 1996. Flow allocation for in-river needs. In: G.E. Petts and P. Calow (eds.), *River Restoration: selected extracts from the river handbook.* Blackwell Science, Oxford, 60-79.

Ponce, V.M. and Lindquist, D.N. 1990. Management of baseflow augmentation: A review. *Water Resources Bulletin* 26 (2), 259-268.

Purwadirdja, M. 1982. Some aspects of upper watershed management on the Jragung River, Central Java, Indonesia. In: D.J. Moore (ed.) *Catchment management for optimum use of land and water resources: Documents from and ESCAP seminar.* Water and Soil Division, Ministry of Works and Developmentfor the National Water and Soil Conservation Organisation, Wellington, N.Z. Water and Soil Miscellaneous Publication No. 45, 139-155.

Scharpenseel, H.-W. and Pfeiffer, E.M. 1998. Impacts of possible climate change upon soils; some regional consequences. *Advances in GeoEcology* 31, 193-208.

Schultz, G.A., Hornbogen, M., Viterbo, P., and Noilhan, J. 1995. *Coupling Large-Scale Hydrological and Atmospheric Models.* IAHS Special Publication No. 3.

Soeseno, I. 1998. IAEH Environmental Hydrology Activities Indonesia [online] available URL http:/www.hydroweb.com/indones.html

Stuebe, M.M. and Jhonston, D.M. 1990. Runoff volume estimation using GIS techniques. *Water Resources Bulletin* 26 (4), 611-620.

Taniguchi, M. and Bari, M.A. 1997. Hydrological impacts of forest clearing and reforestation in southwest Western Australia. In: D. Rosbjerg, N-E. Boutayeb, A. Gustard, Z.W. Kundzewicz and P.F. Rasmussen (eds.), *Sustainability of Water Resources under Increasing Uncertainty.* IAHS Publ. No. 240, 211-216.

U.S. Soil Conservation Service 1975. *Urban Hydrology for Small Watershed.* Technical Release No. 55, Engineering Division, Soil Conservation Service, United States Department of Agriculture (USDA).

Vörösmarty, C.J., Moore III, B., Grace, A., Peterson, B.J., Rastetter, E.B. and Melillo, J. 1991. Distributed parameter models to analyze the impact of human disturbance of the surface hydrology of a large tropical drainage basin in Southern Africa. In: F.H.M. van de Ven, D. Gutknecht, D.P. Loucks and K.A. Salewicz (eds.), *Hydrology for the Water Management of Large River Basins.* IAHS Publ. No. 201, 233-244.

Warrick, R.A., Kenny, G.J., Sims, G.C., Ericksen, N.J., Ahmad, A.K. and Mirza, M.Q. 1996. Integrated model systems for national assessments of the effects of climate change: applications in New Zealand and Bangladesh. *Water, Air, and Soil Pollution* 92, 215-227.

Wasson, R.J. (ed.) 1996. Land use and climate impacts on fluvial systems during the period of agriculture: Recommendations for a research project and its implementation. PAGES Workshop Report, Series 96-2.

Watts, D. 1997. Human dimensions of global change impacts on water resources in tropical islands. *The Globe.* Issue 40, December 1997, 13-14.

Wilkie, D., Morelli, G., Rotberg, F. and Shaw, E. 1999. Wetter isn't better: global warming and food security in the Congo Basin. *Global Environmental Change* 9 (4), 323-328.

CHAPTER 2

GENERAL CONDITIONS OF INDONESIAN RIVER BASINS

2.1 INTRODUCTION

Indonesia is a large archipelago country consisting of more than 17,000 islands. It extends some 4,800 kms from Aceh, on the northern tip of the island of Sumatra in the west, to the border of West Papua with Papua New Guinea on the island of New Guinea in the east (Figure 2.1). Its land area covers some 1.9 million square kms, together with sea area and its exclusive economic zone covers a total area of approximately 9.8 million square kms (Department of Information, 1995)[2-1].

This country has the fourth largest population in the world after China, India and the United States. The 2000 census showed that the total population was 203.5 million, with a growth rate of 1.35% for the 1990-2000 period (Kompas, 2001). However, the distribution of this large population throughout the country is uneven as it is influenced by topography, terrain, climate and natural resources (Cobban, 1996). About 60% of the population live in Java, which make this island one of the most densely populated islands in the world.

[2-1] Indonesia adopted the International Convention of the Law of the Sea in 1983 that includes a 12-mile territorial sea and 200-mile exclusive economic zone. The international boundary is determined based on this convention.

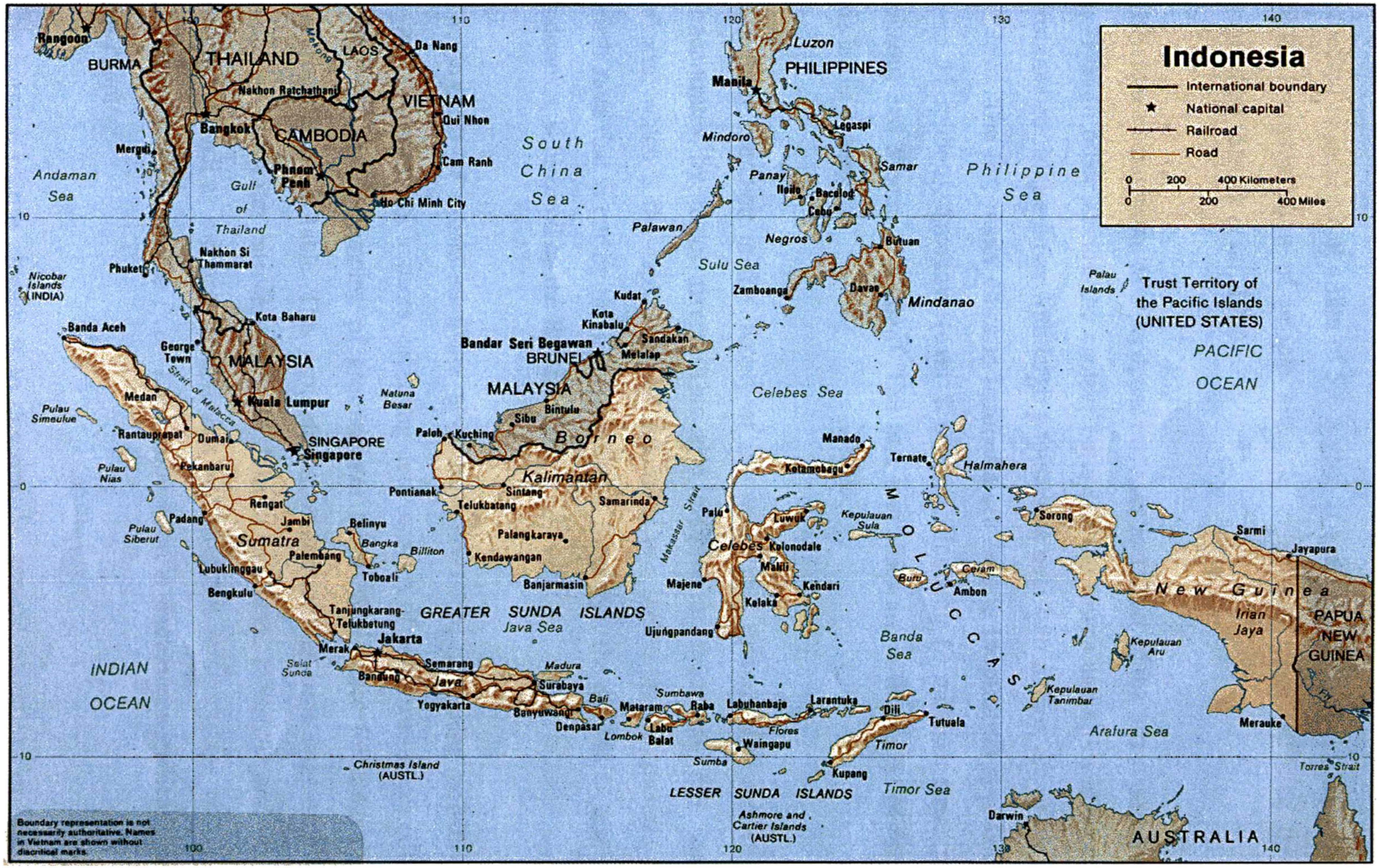

Figure 2.1: Map of Indonesia. (Source: On-line at http://www.lib.utexas.edu/maps/middle_east_and_asia/indonesia.gif.)

In general, the country is still predominantly rural. In 1993, the rural residents comprised about 75% of the total population of the country, but urbanisation was expected to increase at a rate of 5% a year. It had been estimated that in the year 2000, the population of people living in cities was about 40% of the total population (Struyk *et al.*, 1990).

The cities of Indonesia exist as dense enclaves and most of the urban population is in Java. In other islands, the enclave nature of the towns and cities is even more pronounced. Major cities with large populations over two million are in the island of Java. The five major cities in Indonesia are Jakarta (population approximately over 11 million), Surabaya (over 2 million), Bandung (2 million), Semarang (2 million) and Medan (2 million). The first four cities are in the island of Java and the last is in Sumatra.

It is very common in the history of the world that urbanisation develops and concentrates by major rivers. This also happens in Indonesia. For example, Jakarta, which is the capital city of Indonesia, is a region on the coastal plain of north Java that is cut by the Ciliwung River. Surabaya, the second largest city in Indonesia, is bisected by the Brantas River.

The impacts of urbanisation are land use conversion, increasing pollution and other environmental impacts, including deterioration of water resources (Cobban, 1996). Excessive pumping of groundwater to provide water for industries has lowered the water table. This groundwater extraction has been suggested as the cause of salt-water intrusion into the Jakarta mainland. Industrial and domestic wastes, as well as overuse of pesticides and fertilisers in agriculture have caused increased pollution in the river. Land conversion is discussed specifically later in this chapter.

The purpose of this chapter is to describe the general conditions of Indonesian river basins. However, some descriptions of the physical characteristic, demography and socio-economics of the country are also described as they contribute to the problems in Indonesian catchments.

2.2 GENERAL PHYSICAL CONDITIONS OF INDONESIA

Physiography

The Indonesian archipelago lies in a latitude between 6° north and 11° south, and between 95° and 141° eastern longitude. Hence, it is located in the equatorial zone. This archipelago forms the central part of the great archipelago, which extends between Southeast Asia and Australia, and between the Pacific and the Indian Oceans that includes the Philippine Islands, Malaysian Borneo, Brunei, and Papua New Guinea (van Bemmelen, 1949). Therefore, physiographically Indonesia is related to this great archipelago.

According to van Bemmelen (1949), this great archipelago is the most intricate part of the earth's surface because it contains very diverse forms and geological structures. It forms the border area where the continent of Asia of the northern hemisphere and the great Gondwanaland of the southern hemisphere meet. This border is the area where the active process of mountain building occurs. The more or less stable portion of the Sunda Platform area in the northwest and that of the Sahul Platform in the southeast are shown in Figure 2.2. Active structure lines are located between those stable parts of the platforms which represent the highly unstable portions of the earth's crust. The active portions geographically form a series of island arcs that extend from New Guinea and the Philippines through Indonesia and the Nicobar and the Andaman Islands groups in the Indian Ocean. The Sunda Mountain system, which is part of the Circum-Sunda System that has a length of about 700 kms, is traceable from the Banda Arcs, north of Timor island,

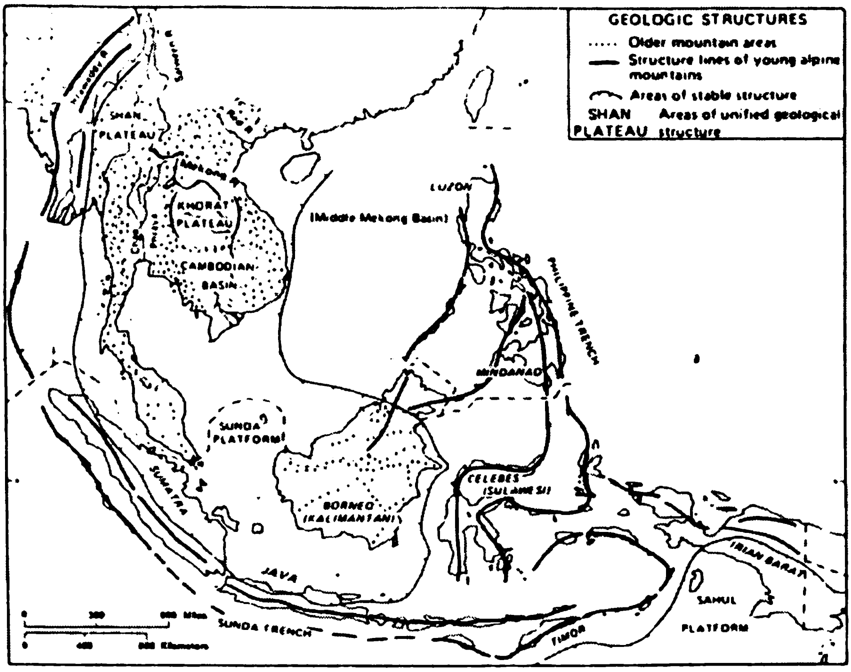

Figure 2.2: Geological structures of Indonesia (Source: van Bemmelen, 1949).

along the Lesser Sunda Islands, Java, Sumatra, Andaman, to Arakan in Burma where it meets the Himalayan System. This mountain belt consists of two parallel belts of mountain arcs, island-festoons and submarine ridges (van Bemmelen, 1949). The inner arc is volcanic in nature; the outer is non-volcanic. Another mountain arc, namely Circum-Australian System, extends along the central axis of New Guinea, and farther along the archipelagos situated east of Australia, to New Zealand. An indistinct branch of the median threshold in the Indian Ocean extends northeastward, via the Cocos Islands to Christmas Island, South of Java. The segment between the Christmas Island and New Guinea is overlapped by trendlines of the Sunda Mountain System. Another mountain system stretches from Halmahera group via the northern part of New Guinea to the New Britain group.

Volcanic activity is very strong along the inner arcs of the mountain building system and has been occurring in all stages of the geological evolution of this region. Major peaks in this country are in the form of volcanoes such as Mt.

Merapi in central Java (2,911m), Mt. Semeru in eastern Java (3,676m), and Mt. Marapi (2,891m) and Mt. Kerinci (3,800m) both in central Sumatra. The lowlands, such as in the northern coastal plain of Java, western Papua, and eastern Sumatra, are the products of alluvial deposits.

In conclusion, this region between Asia and Australia has undergone strong endogenic activities from its early evolution to the present time.

Climate

Because of its position on the earth's surface, which is in the tropics between two continents (Asia and Australia), and two oceans (Indian and Pacific), this archipelago country experiences a generally tropical climate of high temperatures and very high humidity. Based on data from CIA (1999) and BPS (2000), the average annual temperature at sea level is around 26-27°C. The average sunshine in the coastal plain is about 50-70% and the mean humidity is 80%. The temperature and the relative humidity are more or less constant and uniform throughout the year because this country is continually surrounded by warm ocean water. The variation in the temperature occurs mostly due to the influence of topography.

Indonesia is influenced by the monsoonal winds. These are reversal of wind regime that, in many parts of the world, cause most of precipitation to occur during a relatively small fraction of the year (Smith, 1993). The monsoonal winds cause Indonesia to experience two main seasons, namely dry season and rainy or wet season. The dry season generally occurs in the months of June to September and the rainy season occurs in the months of December to March, whilst the rest of the months in between the two seasons are known as transition months. The dry season is driven by winter anticyclone in the southern hemisphere that causes dry southeasterly wind from the Australian continent over the Indonesian region.

Oppositely, during winter in the northern hemisphere, the northwesterly wind brings the humid air from the South China Sea and the western Java Sea to a large part of Indonesia that causes the rainy season in Indonesia.

Despite having monsoon characteristics, no month has less than 51 mm (2 inches)[2-2] of rainfall in most parts of Indonesia. Therefore, the dry season does not exist, and the term dry season is only used as comparative term in the yearly balance (Noble, 1996). The annual precipitation of Indonesia is generally more than 2,000mm. The rain is generally torrential but short in duration. In the southern part of the country, in particular Nusa Tenggara, the climate is drier with an annual rainfall of ranging from about 700mm to 1000mm. During the dry season, this part of Indonesia, as well the adjacent areas such as southern Sulawesi, eastern Java, southern Papua and other islands between these three extremes experience drier months than the rest parts of Indonesia because of their proximity to the winter anticyclone in Australia (Noble, 1996).

Indonesia also experiences inter-annual climate variations of extreme events such as El Niño and La Niña that can have significant impacts on biological and hydrological processes. El Niño is a large scale oceanic warming that affects most of the tropical Pacific (e.g. Nicholls, 1993; Henson and Trenberth, 1998). Its meteorological effects may extend throughout the Pacific Rim and to eastern Africa. This event is normally accompanied by a change in atmospheric circulation called the Southern Oscillation, which is indicated by an inverse relationship between surface air pressure at Darwin, Australia and the island of Tahiti in South Pacific, and together they form a climatic phenomena called ENSO (El Niño-Southern Oscillation).

The ENSO has important implications for the climate of tropical regions including Indonesia because it causes severe drought in Indonesia, Australia, southern

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[2-2] The value of 2 inches (51 mm) is taken as the limit separating the dry months from wet as an environmental condition of importance for human utilisation (Noble, 1999).

Africa and northeastern Brazil, and heavy rainfall in the other parts the tropics (central Pacific, Peru, Ecuador, and the southern U.S.A.). The other extreme, La Niña (the opposite of El Niño), causes unusually heavy rainfall in Indonesia, Australia, southern Africa and northeastern Brazil and drought in the other parts of the tropics. In Indonesia, the El Niño has a potential impact in reducing food crops harvested area that disturbs the national food security (Irawan, 2002). The food crops harvested area dropped by about 1.25 million ha in 1982 and 1.18 million in 1997, or by 8.6% and 6.4% respectively, during the El Niño event. In the event of La Niña, severe flooding is expected that can also threaten the national food security and other flood risk disasters because many structural measures to protect from flood were designed to anticipate normal flood and not for an extreme of this kind. It is expected that about 31,600 ha of paddy fields to be inundated, and about 160,000 ha are at risk of inundation in 16 provinces of Indonesia (Caturhadi, 1998). Postponing the planting time may avoid this risk, but this could endanger the production of rice since after the La Niña, there is a possibility of El Niño (dryness) to occur (Republika, 1998).

More details on the predictability of the ENSO will be discussed in Chapter 7.

Demography

As has been mentioned earlier, Indonesia is the fourth largest country in the world in terms of population. The total population for the year in July 1999 was estimated at over 216 million with a growth rate of 1.46%. About 65% of the population are in their productive ages (15-64 years) (Table 2.1). The ratio of male to female is nearly 1 (99.6%), but there are more males than females at birth (Table 2.2). Based on the census data in 1990, about 35% of the population were below the age of twenty, which may indicate high population growth in the future. However, the estimated growth rates have fallen from 1.98% for years 1980–1990 to 1.46% for the year 1999.

Table 2.1: Population based on age structures, 1999 estimation.

Age	%-age of total population	Number of males	Number of females
0 – 14 years	30 %	33,367,287	32,411,786
15 – 64 years	65 %	70,541,893	70,866,972
65 years and over	5 %	3,936,415	4,983,992

Source: (CIA, 1999)

The distribution of the population is uneven. The islands of Java, Madura and Bali are very densely populated. The 1990 census shows that the population of Java and Madura constituted 58% of the total population even though their total land area is only 6.7% of the country. The population density in Java was 811 per sq. km and Bali was 500 per sq. km. These figures were much higher than for Sumatra, the second most densely populated island of the five largest islands in Indonesia, with a density of 77.1 per sq. km. They are also higher than the national figure, which was 93 per sq. km (BPS, 2000). As shown in Table 2.3, Sumatra with a population density of 77.1 per sq. km and West Papua, which was the lowest density of 3.9 per sq. km comprises 24.7% and 22% of the total area of the country respectively. In comparison, Java comprises 6.7% of the total area of the country.

Table 2.2: Sex ratio of male to female, 1999 estimation.

Age	Male/Female
at birth	1.05
under 15 years	1.03
15 – 64 years	1
65 years and over	0.79
Total population	1

Source: (CIA, 1999)

Table 2.3: Population statistics for the five major islands and smaller islands of the same provinces based on the 1990 census.

Island	Area (sq. km)	Population (x 1000)	Density (per sq. km)
Sumatra: including islands of Riau, Nias, Mentawai and other islands that belong to provinces in Sumatra.	473,481	36,507.1	77.1
Java: including Madura and other small islands that belong to provinces in Java.	129,017	104,668.1	811.3
Kalimantan (Borneo): including small islands that belong to provinces in Kalimantan.	548,005	9,099.7	16.61
Sulawesi (Celebes): including Butung, Baubau, Selayar, and other islands that belong to provinces in Sulawesi.	189,216	12,520.6	66.71
West Papua province: including Biak and other islands that belong to the West Papua province.	421,981	1,648.7	3.9

Source: (BPS, 2000)

Even though, in general, the country is still dominantly rural, it had been estimated that in the year 2000, 40% of the population would live in cities (Struyk *et al.*, 1990). In particular, in the island of Java with its very dense population, urbanisation has been expected to increase rapidly. The main force that drives urbanisation is the attractiveness of the towns or cities in providing opportunities for the people to gain better incomes. In addition, towns also provide better educational opportunities to attract young people and families with children to live there.

The increasing population in Java causes changes in land use. In particular, urbanisation is expected to invade most of agricultural area. In large cities, paddy fields provide places for houses, industries and road construction. In the rural area of some villages in Central Java, gardens have been used for house building. There have been few changes from paddy fields to become housing sites (Preston, 1989). The trend of land use change will be discussed in a greater depth later.

It can be seen that the island of Java is the area where demands on land are the highest due to its high population density. Hence resource problems are much more prominent in this island than in other islands and, in particular, the pressure for land use conversion is greatest. Water is one of the resources which is at risk as one result of these changes which can lead to reduced water to infiltration of the soil (Bruijnzeel, 1988).

Socio-economics

It has been known that socio-economics is also a driving force for the land use changes (Turner *et al.*, 1993; Skole and Tucker, 1993). Recently, Indonesia had undergone a set-back in its economy because of the collapse of its local currency (*rupiah*) in late 1997 and early 1998 that caused the GDP (Gross Domestic Product) to contract by 13.7% (CIA, 1999) and the inflation rate for 1999 reach 77%. In terms of the labour force, the agriculture is still the major sector in this country (see Table 2.4). The rate of open unemployment for the year 1998 was estimated about 15 – 20%.

However, even though agriculture is still a dominant occupation, the attitude of many households in Java towards this occupation has changed. There is a trend that agriculture is becoming a less important occupation, especially in areas close

Table 2.4: Labour force by occupation, 1997 estimates.

Occupation	Proportion to total labour forces
agriculture	41%
trade, restaurant, hotel	19.8%
manufacturing	14%
construction	4.8%
transport and communication	4.75%
other	15.65%

Source: (CIA, 1999)

to cities or towns where a wider range of jobs are available and access from rural areas to towns is easy (Preston, 1989). Young households prefer to be involved in business dealing directly with money (e.g. construction projects, services and helping with a carriage or delivery), office work and government employment. As a result of this trend of finding jobs in urban areas, the relative importance of rural-based activities has decreased. The increasing educational status of young people has also partly influenced this trend of change (Preston, 1988).

Land uses

Forests and woodlands are still a dominant land cover in Indonesia (over 60%, see Table 2.5). However, as stated by the Ministry of Forestry, the forests and woodlands in Java are much smaller in proportion (now only about 19%) to total land area (Republika, 1998). Based on 1993 estimates, arable land was only about 10% of the total area of the country and about 24% of this arable land was irrigated.

Below are brief descriptions of common land uses in Indonesia.

Forest and woodland

The forests of Indonesia grow in diverse ecological systems that can be classified into ten groups, based on their vegetation characteristics (Ministry of Forestry and Food and Agriculture Organisation of the United Nations, 1990, cited in Kartasubrata, 1993). They are: coastal forest, tidal forest, heath forest associated with sandy infertile soils, peat forest, swamp forests, evergreen forests, forests on basic rocks, mountain forest at elevation over 2,000 m, bamboo forest, and savannah forest. However, based on the designation of the forest land use by consensus (*Tata Guna Hutan Kesepakatan* (TGHK)/Forest Land Use by

Table 2.5: Land uses in Indonesia, based on 1993 estimation.

Land use type	Proportion to total area
Arable land	10%
Permanent crops	7%
Permanent pastures	7%
Forests and woodland	62%
Other	14%

Source: (CIA, 1999)

Consensus), it can be classified into four types (Kartasubrata, 1993; cited in: Ministry of Forestry and Food and Agriculture Organisation of the United Nations, 1990). They are:

- **Protection forests**, these are forests with slopes of more than 45% intended to maintain watersheds;
- **Nature reserve and conservation areas** in which all of the contents of the forest are protected;
- **Conversion forests**, these are forest lands that can be cleared for agriculture; and
- **Production forests** which can be exploited. These production forests are grouped further into limited production and full production. The limited production type of forest has a restriction on the logging, while the full production forest can be fully exploited and cleared for tree plantations.

Irrigated paddy-field

The Indonesian Department of Agriculture defines an irrigated paddy-field as a technically irrigated paddy-field and has classified it into two types based on the distribution of its water. One type is called a fully technical irrigated paddy-field and the other one is a semi-technical irrigated paddy-field (see for example, Directorate of Food Crop Production, 1994). An irrigated paddy-field is classified as fully technical if the paddy-field receives irrigated water in which the intake canal is separate from the outlet so that the supply and distribution of water can be easily controlled and measured. The irrigation of this type usually consists of a primary canal, and some secondary and tertiary canals. An irrigated paddy-field is considered semi-technical if the paddy-field receives irrigated water, but the government authorised body manages only the intake in order to control and measure the input supply of water. The government has no control over the rest of the irrigation network. Most irrigated rice fields enable farmers to plant paddy three times in a year.

Rainfed paddy-field

This paddy field gets water only from rain. A canal system to distribute water may exist, but during the dry season the canals may also become dry. This rainfed paddy-field can usually produce a rice crop once or twice in a year, depending on the amount of water normally available, and is followed by a dry season crop (secondary crop/*palawija*).

Gardens (*kebun*)

Gardens are used to produce a wide variety of food crops. In general, the crops are annual or perennial, but sometimes seasonal crops are also found in gardens. Usually, the households plant taro, cassava, pineapple, clove; and fruit trees such as bananas, mangoes, rambutans, coconuts, jackfruit, breadfruit, oranges, papayas, etc. in the gardens. Many geographers distinguish gardens from dry land (*tegalan*) by associating the location of this land with its environment (Supriyanto, personal communication, January 2000). Most of gardens are in villages or kampongs and among houses. (This in contrast to dryland which is usually located at high altitude, very often far from villages or groups of houses.)

Dryland or hillside land (*tegalan*)

This is basically dry land cultivated for seasonal crops such as dryland paddy, secondary crops such as maize, cassava, peanuts, soybeans, and sweet potatoes. This land is separate from the house garden and is usually in a relatively high altitude.

Horticulture or vegetable garden

Horticultural land is very similar to the dryland in its characteristics. The difference is mainly in the types of crops that grow on this dry land. Very often these crops are found planted next to each other. The horticultural crops consist mainly of vegetables such as cabbages, lettuces, carrots, onions, tomatoes, chillies, long beans.

Estate crops

Estate crops are agricultural commodities, which are usually exported. Many estates are owned by the government but some estates are privately owned. Common estate crops are tea, coffee, sugar, indigo, rubber, oil palm, cocoa, tobacco, cloves and cotton.

Urban areas

Urban areas are often shown on the basic topographic map as villages, towns or cities. An area is classified urbanised if human activity, in particular economic activity, is considerably high, or the density of houses is relatively high

(Supriyanto, personal communication, January 2000). Hence, an area of land with some isolated houses is not considered an urban area.

2.3 WATER USES AND CATCHMENT MANAGEMENT

The use of water varies depending on demand. In an area with an agricultural basis, such as a rural area or village, the demand for irrigation is highest. The domestic demand is normally low as villagers usually extract groundwater to fulfil their needs or get the water from a stream. In the urban areas, such as in a city, the industrial and domestic demand is higher.

The management of river basins in Indonesia has been conducted by the government since about 1974, as part of water resource management. However, the implementation of this management has not been satisfactory (Muryadi, 1982). This is particularly because components of the management programmes are conducted fragmentarily by various government bodies (see Table 2.6). The Department of Agriculture and Public Works, for example, is responsible for the management of surface water, while the Department of Mines and Energy is responsible for groundwater. On the other hand, land use which is considered an

Table 2.6: Government bodies responsible for management of water resources programme components.

Programme component	Responsible bodies
Water policies for agricultural uses and irrigation	Department of Agriculture
Forest management	Department of Forestry
Land use management and control	Department of Home Affairs, extended to local government offices.
River water quality and quantity	Department of Public Works
Groundwater uses / exploitation	Department of Mines and Energy

important aspect in water resources management, is managed by the Department of Home Affairs, while forests are managed by the Department of Forestry.

The total integrated management of one river basin or catchment has become difficult because each body has its own specific objective in managing the basin area and conflicting interests among these bodies often occur. The land use is also managed by various government bodies. In particular, the general land use is managed by the Department of Home Affairs, which is extended to local government offices, while the Department of Forestry is concerned specifically with conservation and exploitation management of forests. The management is more difficult particularly when a catchment area is shared administratively by two or more local governments, which are under the Department of Home Affairs, and each local government is responsible only for its working area. Therefore, there is a need for co-ordination among these government bodies in order to manage the water resources in Indonesia effectively.

2.4 GENERAL TREND OF LAND USE CHANGES AND POSSIBLE DRIVING FORCES

As mentioned earlier, changes in land uses are related to socio-economical factors and pressure from population growth. Purwadirdja (1982) argued that clear-cutting the forest in order to create land for food crop plantation was conducted as a result of an increasing demand for cultivation, and this therefore reduced the proportion of forest-land. This is also supported by Cobban (1996), Syam *et al.* (1997) and Imbernon (1999) who argued that conversion of forest to agricultural land should occur through a transition of shifting cultivation. Further, Cobban (1996) also argued that the permanent agricultural land may convert to paddy-fields in lowland areas and terraced slopes, and may convert to dry land farming uses such as vegetable gardens, if the land is too cold for growing paddy. Syam *et* *al.* (1997) and Imbernon (1999) reported that transmigration programmes and the development of agro-industries are the main causes of the rapid land use conversion in some parts of Indonesia. However, they also pointed out that these are local cases, and not a general case for Indonesia.

In many rural areas in Java, the expansion of house gardens onto dry hillside land is very prominent in a limited extent (Preston, 1989). The conversion of rice fields to house gardens is undesirable. The extension of house gardens is a logical consequence of increasing population and non-irrigated land should be the first choice for conversion to house gardens.

In more urbanised areas, the increasing socio-economic development of households has resulted in the decreasing relative importance of village-based activities. As a result, many house gardens that used to be used for cultivation of annual and perennial food crops as well as seasonal plants such as bananas, cassava, pineapple and vegetables, have become sites for of new houses or places of business.

However, in highly urbanised areas such as large cities, the function of cultivated land is converted in order to fulfil the needs of land for houses, industries and other constructions such as roads.

It is clear that the population growth and increasing socio-economics drive the changes in land use. These changes can be generalised into a pattern:

- In non-urbanised areas, forest changes to hillside dry cultivated land;
- In slightly urbanised areas with increasing population pressure, the dry non-irrigated land changes to become house gardens, while irrigated land where possible remains unchanged;
- In more urbanised areas, gardens become sites for housing or businesses;
- In highly urbanised areas, cultivated land and paddy fields are often used as places for housing, industries and other construction.

2.5 CONCLUSION

From the discussion above, the physical and socio-economic conditions of Indonesia in summary are as follows:

- It is geologically complex, rich with histories of mountain building and volcanic activity;
- The climate is typically tropical monsoon, high in humidity and annual precipitation. The dry season occurs in the months of June to September and the rainy season from December to March, whilst the rest of the months in between the two seasons are the transition months. The temperature is relatively high (an average of 27°C at the coastline) with variation due to elevation. Indonesia also experiences the ENSO phenomena that have significant impacts on the national food crops production and other flood risk disasters;
- The population is unevenly distributed, with the island of Java having the highest in density and therefore demanding the greatest area for settlement;
- Land use conversions are mainly due to increasing population and socio-economics, and they follow a general pattern.

REFERENCES

BPS 2000. *Indonesia's Quick Facts* [online] available URL http://www.bps.go.id/profile/indo.html.

Bruijnzeel, L.A. 1988. (De)forestation and dry season flow in the tropics: A closer look. *Journal of Tropical Forest Science* 1 (3), 229-243.

Caturhadi 1998. Local Head of Department of Public Works: Preparation for Flooding? Pray... *Surabaya Post* 24 Sept. 1998 (in Indonesian).

CIA 1999. *The World Factbook 1999* [online] available URL http://www.odci.gov/cia/publications/factbook/id.html.

Cobban, J.L. 1996. Indonesia: Insular contrasts of the Java core with other islands. In: A.K. Dutt (ed.) *Southeast Asia: A Ten Nation Region.* The Geojurnal Library, Kluwer Academic Press, 135-152.

Department of Information. 1995. *Indonesia, An Official Handbook.* Dept. of Information, Directorate of Foreign Information Service, Republic of Indonesia.

Directorate of Food Crop Production. 1994. *Synthesis of Main Crop Pattern Technology in Boosting the Cropping Index ≥ 300 on Intensive Paddy Land – West Java Province.* Directorate of Food Crop Production, Directorate General of Food Crops and Horticulture.

Henson, B. and Trenberth, K.E. 1998. Children of the Tropics: El Niño and La Niña. *Fact Sheet* [online] available URL http://www.ucar.edu/communications/factsheets/elnino [10 Apr. 2002]

Imbernon, J. 1999. Changes in agricultural practice and landscape over a 60-year period in North Lampung, Sumatra – Short communication. *Agriculture Ecosystems and Environment* 76, 61-66.

Irawan, B. 2000. *Stabilization of Upland Agriculture under El Nino Induced Climate Risk: Im Assessment and Mitigation Measures in Indonesia.* CGPRT Centre Working Paper No. 62, 78pp.

Kartasubrata, J. 1993. Indonesia. In: Committee on Sustainable Agriculture and the Environment in the Humid Tropics, *Sustainable Agriculture and the Environment in the Humid Tropics.* National Research Council, National Academy Press, Washington, D.C., 393-439.

Kompas 2001. Population increased, the rate of growth decreased. *Kompas* [online] available URL http://www.kompas.com/kompas-cetak/0101/04/utama/juml01.htm (in Indonesian), [4 Jan. 2001].

Ministry of Forestry and Food and Agricuture Organisation of the United Nations 1990. *Situation and Outlook of the Forestry Sector in Indonesia.* Government of Indonesia, Jakarta.

Muryadi, A 1982. Catchment management and its role in water resources development in Indonesia. In: D.J. Moore (ed.) *Catchment management for optimum use of land and water resources: Documents from and ESCAP seminar.* Water and Soil Division, Ministry of Works and Development for the National Water and Soil Conservation Organisation, Wellington, N.Z. Water and Soil Miscellaneous Publication No. 45, 123-138.

Nicholls, N. 1993. ENSO, drought and flooding rain in south-east Asia. In: H. Brookfield and Y. Byron (eds.), *South-East Asia's Environmental Future - the Search for Sustainability,* United Nations University Press - Oxford University Press, Kuala Lumpur, 154-175.

Noble, A.G. 1996. The physical environment. In: A.K. Dutt (ed.) *Southeast Asia: A Ten Nation Region.* The Geojurnal Library, Kluwer Academic Press, 41-56.

Preston, D. 1989. Getting by with little land: The evolution of household strategies in two hamlets in Central Java. Working Paper 520, School of Geography University of Leeds.

Preston, D. 1988. *Too busy to farm: Under-utilisation of farm land in central Java.* Working Paper 519, School of Geography University of Leeds.

Purwadirdja, M. 1982. Some aspects of upper watershed management on the Jragung River, Central Java, Indonesia. In: D.J. Moore (ed.) *Catchment management for optimum use of land and water resources: Documents from and ESCAP seminar.* Water and Soil Division, Ministry of Works and Developmentfor the National Water and Soil Conservation Organisation, Wellington, N.Z. Water and Soil Miscellaneous Publication No. 45, 139-155.

Republika. 1998. Clean water reservation continuously drops. *Republika* 20 Oct. 1998 (in Indonesian).

Skole, D. and Tucker, C. 1993. Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978 to 1988. *Science* 260, 1905-1910.

Smith, J.A. 1993. Precipitation. In: D.R. Maidment (ed.), *Handbook of Hydrology.* McGraw-Hill Inc., USA, Ch.3.

Struyk, R.J., Hoffman, M.L. and Katsura, H. 1990. *The Market of Shelter in Indonesian Cities.* The Urban Institute Press, Washington.

Syam, T., Nishide, H., Salam, A.K., Utomo, M., Mahi, A.K., Lumbanraja, J., Nugroho, S.G. and Kimura, M. 1997. Land use and cover changes in hilly area of South Sumatra, Indonesia (from 1970 to 1990). *Soil Science and Plant Nutrition* 43 (3), 587-599.

Turner II, B.L., Moss, R.H. and Skole, D.L. (eds.) 1993. *Relating Land Use and Global Land-Cover Change: A proposal for an IGBP-HDP Core Project.* IGBP Report No. 24, HDP Report No. 5, Stockholm.

Van Bemmelen, R.W. 1949. The Geology of Indonesia, Vol. 1A. General Geology of Indonesia and adjacent Archipelagoes Government Printing Office, The Hague.

CHAPTER 3

SELECTED STUDY AREA

3.1 INTRODUCTION

Several factors need to be taken into account in selecting the appropriate area. One main factor is that the study area should be physically a general representative of Indonesian catchments, which means that it includes some major and common land use types (as described in Chapter 2), has common physiography and common soil formation types. The second main factor is that the area must contain major actual problems that exist in some Indonesian catchments such as land use conversion, increasing population pressure, increasing urbanisation, etc. In addition, technical factors such as availability of data, size and spatial representation are also taken into account.

Bandung basin in west Java is one of several catchments in Indonesia which is well qualified to represent general catchments in Indonesia for this study. The area contains common land use types, is surrounded by volcanoes, and highly populated and therefore actual problems such as land use conversion, increasing population, and resource degradation (particularly of water resources), do exist. In fact, the changes in land use are quite observable within a short period of five years, particularly in the development of new residential areas in the east and west of Bandung City, and the industrial development as well as settlement in the south of the city. In terms of hydrology, this area has also been studied for many years. Citarum, the major river that flows across this basin, is the main source of water for three hydropower plants that exist along this river, namely Saguling, Cirata and Jatiluhur that produce power for Java, and particularly for the capital city, Jakarta. A relatively recent hydrological study was conducted by Iwaco-Waseco (Iwaco-Waseco, 1991).

This chapter describes in some detail the physical and socio-economic conditions of the selected catchment, the nature of the data collected from several government bodies[3-1] and information collected during a field observation conducted in January 2000. The specific purpose of the field observation was to observe land use variation.

3.2 PHYSICAL CONDITIONS OF THE AREA

General physiography and geology

Bandung basin is located in west Java, Indonesia with a geographical position of about 6°43' - 7°04' southern latitude and 107°15' - 107°55' eastern longitude. It covers an area of approximately 2,200 km^2 and is surrounded by volcanic mountains in the north and in the south, known as an intramontane depression area (van Bemmelen, 1949; Dam, 1994) (Figure 3.1, see also the 3-D view in Figure 3.2). Both the southern and northern mountains reach high peaks of over 2,000m above mean sea level (amsl).[3-2] The centre is relatively flat and consists of two flat plains, the large Bandung plain and small Batujajar plain, bordered by small hills of andesite intrusions. The elevation of the flat plains is approximately 650m – 675m amsl. The north border of the Bandung Zone is capped by a series of young volcanoes, including the Sunda Complex with peaks over 2,000m amsl.[3-3] The south border is marked by a series of volcanoes with peaks also over

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[3-1] Central Bureau of Statistics, BMG (Meteorological and Geophysical Agency), Research Institute for Water Resources, and Local Office of Agriculture Department.

[3-2] In the south; Malabar (2,321 m), Patuha (2,434 m), and in the north; Tangkuban Perahu (2,076m), Bukit Tunggul (2,209 m).

[3-3] Burangrang (2,064m amsl.) and Tangkuban Perahu (2,076m amsl.)

2,000m amsl.[3-4] The geological evolution that formed the Bandung basin is discussed in detail by Van Bemmelen (1949) and Dam (1994).[3-5]

The geology of the Bandung Zone is partly young volcanic, mainly at the upper mountain region, and alluvial deposits, partly at the lower part of the mountain slopes (alluvial fan) and at the centre of the basin (Figure 3.3). In particular, the Bandung plain is filled by alluvial lacustrine and swamp deposit. Tertiary rock of andesitic type can also be found occasionally in this area in the form of hills and ridges.

This geological variation has an important influence on the hydrology of the Bandung basin, which will be discussed in some detail later.

[3-4] Tilu (2,040m amsl.), Patuha (2,429m amsl.), Malabar (2,321m amsl.) and Papandayan (2,622m amsl.)

[3-5] The geological evolution of Bandung basin is as follows: The Bandung basin formation is part of the endogenic and volcanic processes that formed west Java. The basin is formed as a result of the uplift of Southern Mountains region in the Middle Miocene and a second uplift located at about 60km North of the Miocene geanticline. The break downs along the longitudinal slip faults and flexures caused the Bandung section subsided northward and formed a lake and swamp, in which black clays, tuffaceous sandstones and peat-layers were formed. Two major fault zones were formed between the Southern Mountains and the Bandung Zone. After this block faulting of the Bandung Zone, volcanic activity began along the fault lines, building up the basalto-andesitic and older structures in the south. The Bogor anticline, north of Bandung, was also pierced by basalto-andesitic magma, and the Sunda volcano-complex was formed. After the accumulation of volcanic deposit, this volcano-complex collapsed and formed the Lembang fault, just north of Bandung, and the arcuate Sunda rift.

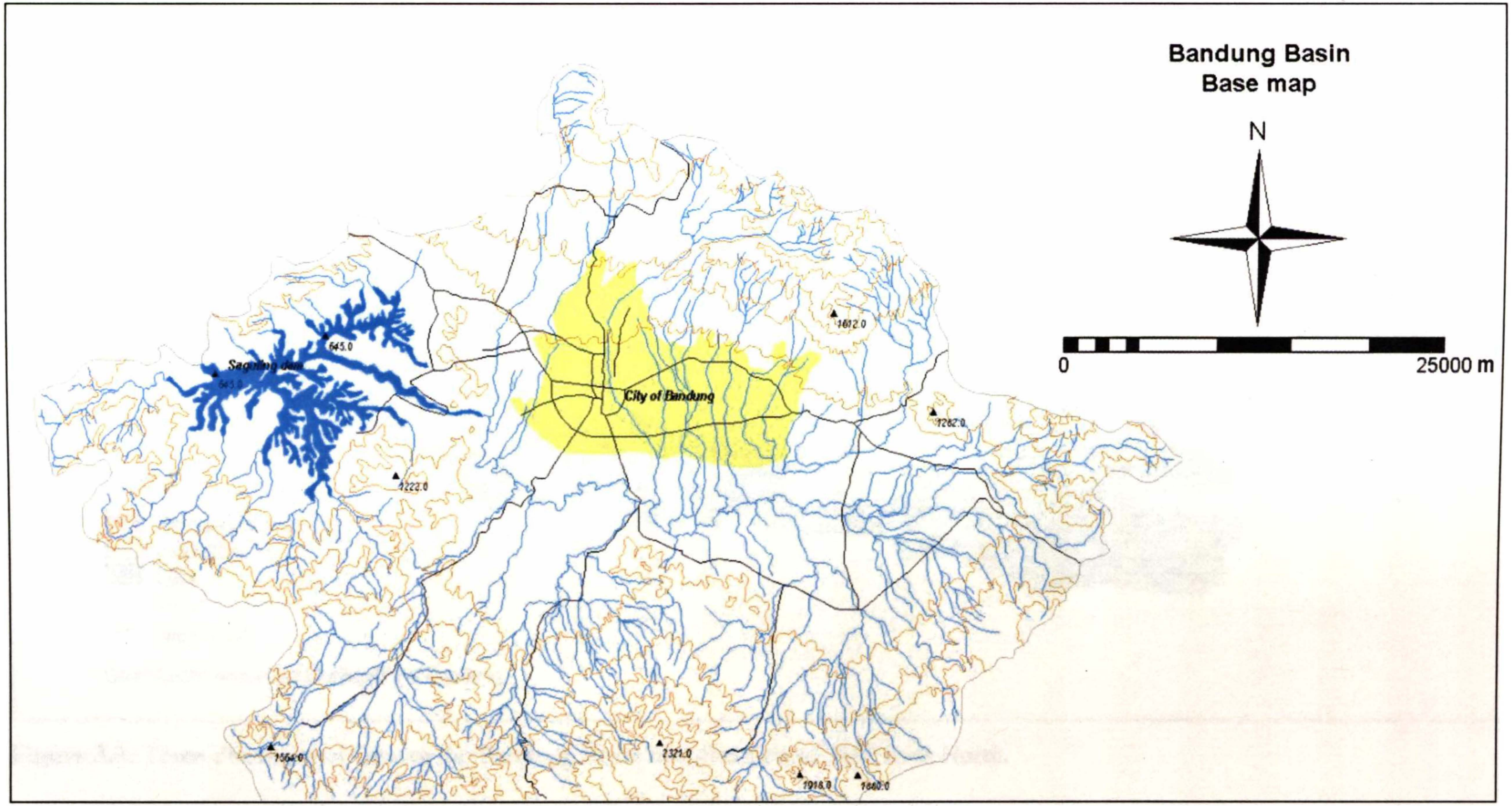

Figure 3.1: The base map of the Bandung Basin. Approximately less than 3% of the southern part of the basin is outside the map boundary.

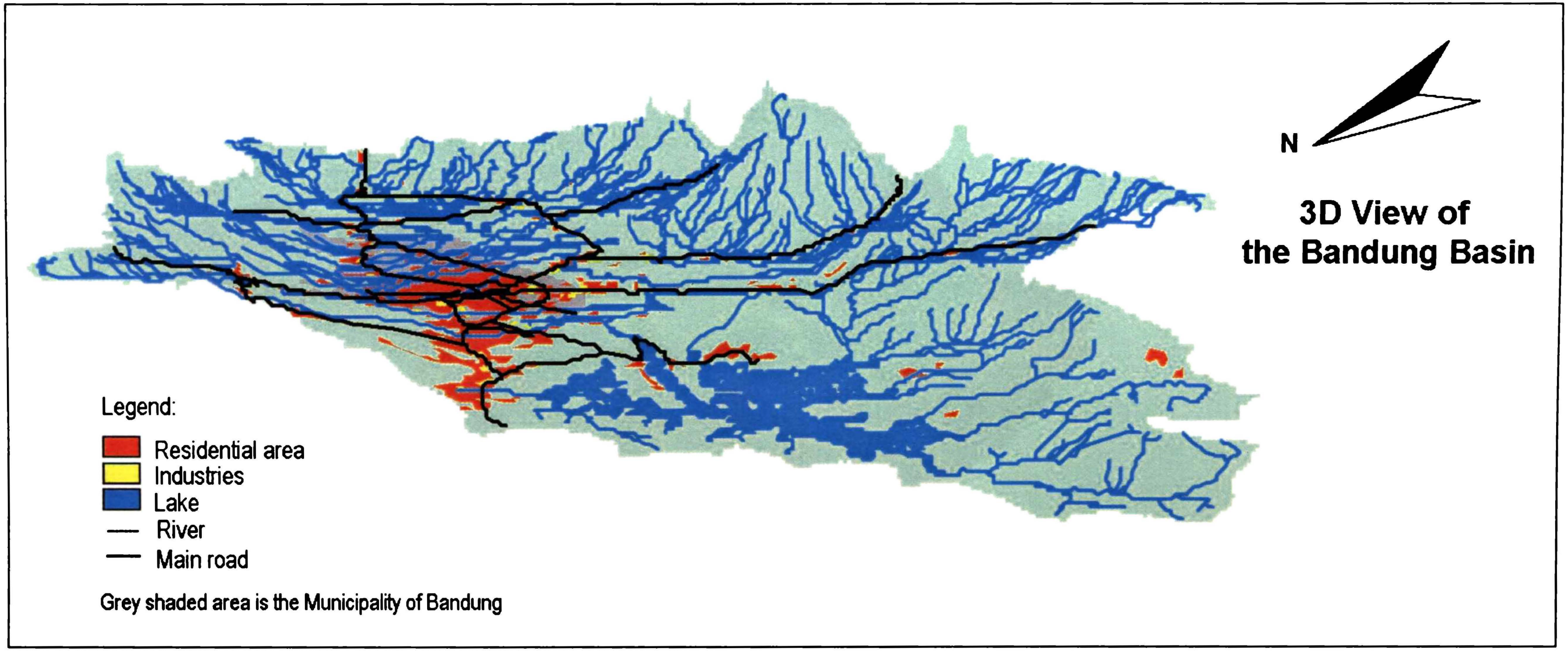

Figure 3.2: Three-dimensional view of the Bandung Basin in a direction of 310° from North.

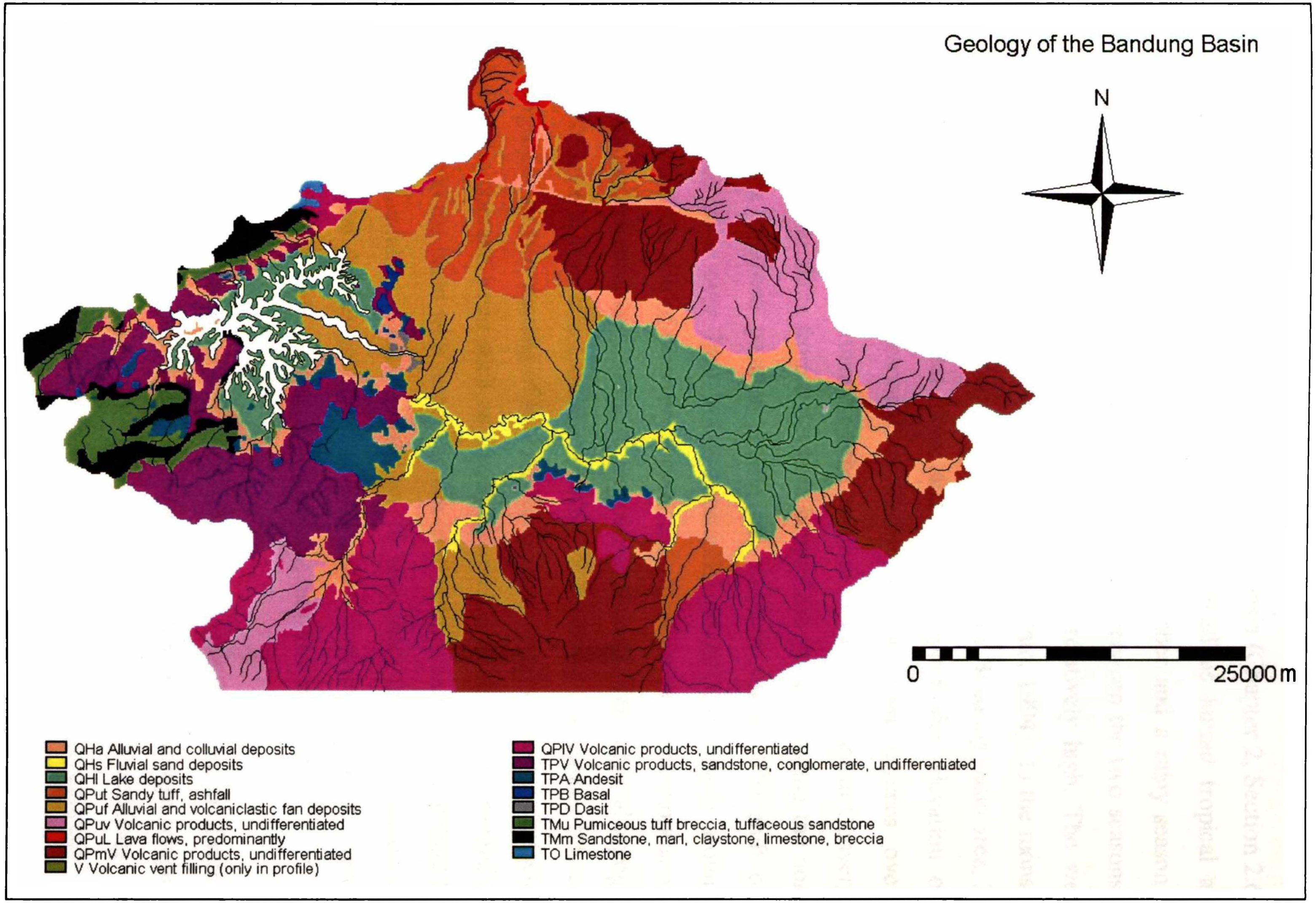

Figure 3.3: Geological map of the Bandung Basin (redrawn from Dam *et al.*, 1993).

Climatological setting

As commonly experienced by most parts of Indonesia (Chapter 2, Section 2.6), in general the climate of west Java can be classified as humid tropical and is characterised by a dry season from June to September and a rainy season from December to March, with the transition months in between the two seasons. The annual precipitation and the relative humidity are relatively high. The weather conditions are largely determined by three factors (Dam, 1994): 1) the monsoonal circulation that causes seasonal climate variation in the Bandung basin area; 2) the regional topography of west Java; and 3) the topographic elevation of the Bandung plain. The monsoonal circulation of the wind regimes over the Indonesian region is determined by the position of the Intertropical Convergence Zone (ITCZ) that shifts from a northern hemisphere position during the northern summer to a southern position during the northern winter. The shift of this convergence zone over Java brings substantial rainfall particularly around the beginning and the end of the rainy season, and therefore two peak-months of high precipitation are commonly found in the climate records. The regional topography of west Java has an effect on the weather in Bandung that causes this city to undergo one or two months of low rainfall under 60mm, which is a characteristic of an intramontane basin such as Bandung, and the relatively low rainfall in the dry season in the basin with respect to the continuously wet in the highland (Dam, 1994). The rainfall probability, based on 70 years data from the Meteorological and Geophysical Agency in Bandung, estimates a drop in the annual average of the precipitation by 25% in 1 out of 10 years (i.e. decadal variation).

The seasonal variation of sunshine is related to the monthly variation of rain-days, and so is the variation of evaporation. Monthly variations of average temperature and relative humidity are less pronounced than rainfall variations. Daily temperature variations in Bandung are quite high with a range between around 15°C in early morning and 29°C in the afternoon (Dam, 1994).

Altitude variation strongly affects the temperature. A temperature gradient of -0.6°C for every 100m increase in altitude is commonly adopted (Dam, 1994; Mock, 1973; Pulawski and Øbro, 1976).

Bandung basin is also affected by the inter-annual climate variations of extreme events such as El Niño and La Niña. These climate variations have significant impacts on the hydrology of the Bandung basin. The El Niño causes drought that affects water supply for domestic use, irrigation and the operation of the Saguling hydropower plant, and two other plants downstream of the Citarum river. The other extreme, La Niña, causes heavy rainfall that intensifies the flooding in the central Bandung basin.

Hydrological setting

The Citarum river system is the only one that flows over the Bandung basin. It is a large system of which the river originates at the eastern slope of Mt. Malabar and ends at the north coast of west Java, east of Jakarta. However, the Bandung basin forms the major part of the upper Citarum River system. Together with many tributaries, the river flows to the west and leaves the basin system at the Saguling hydropower plant. The river network showing the main river and its tributaries is diagrammatically shown in Figure 3.4.

Discharge varies considerably throughout the year. Dam (1994) reported that for all rivers a clear correlation between discharge and monthly rainfall exists and, in general, surface runoff could be determined primarily by rainfall. Deep groundwater outflow is considered negligible. For a sub-catchment, however, a study by Delinom and Suriadarma (1993) revealed a significant influence of geological structures on the discharge, in particular the Lembang fault north of Bandung city that acts as a barrier to the groundwater flow. This fault reduces the discharge of the Cikapundung River, which is one of tributaries of the Citarum River system.

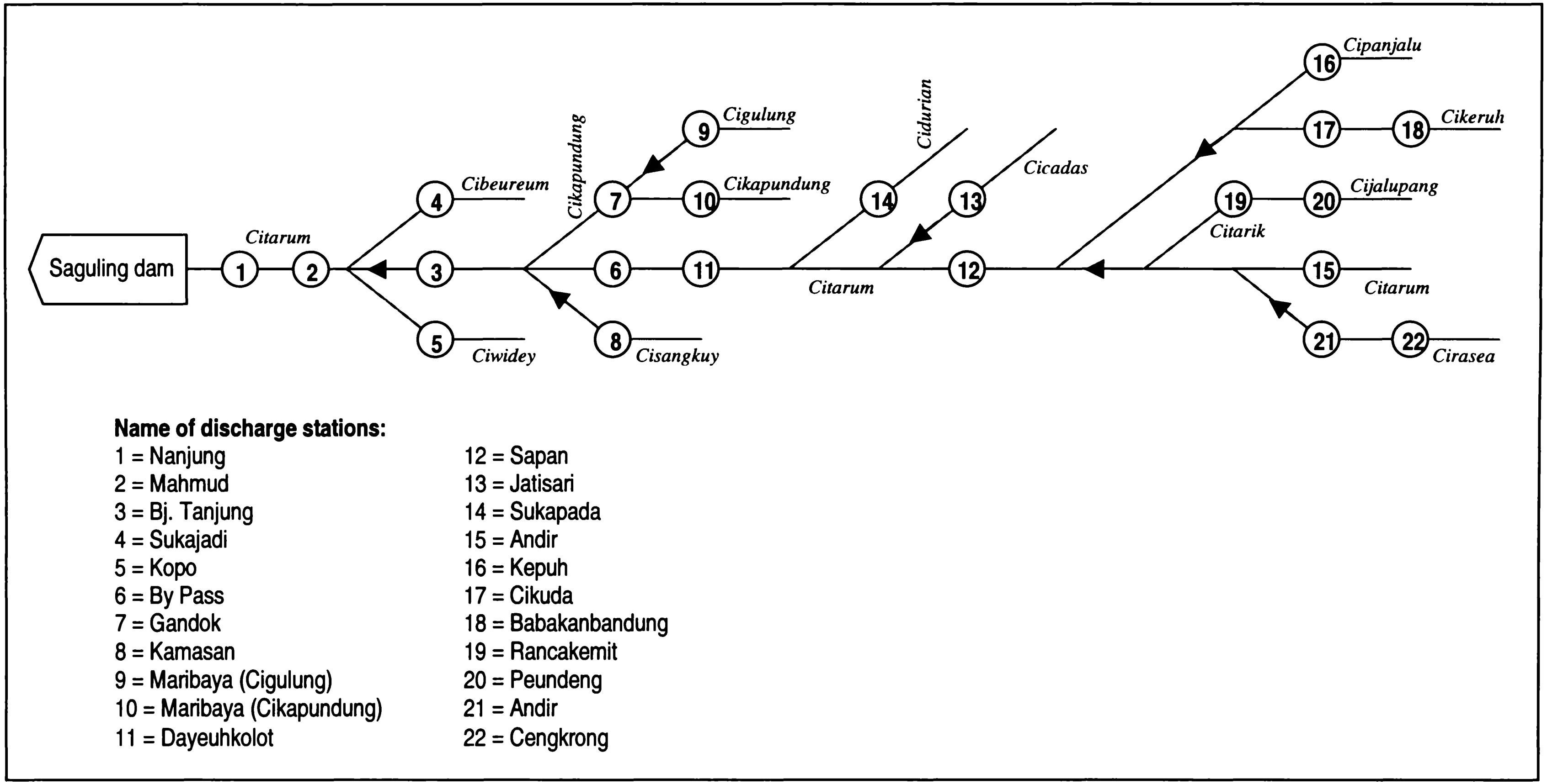

Figure 3.4: Diagram of Bandung basin river system. The arrows indicate the direction of flow.

A study showed that the foothills of the volcanoes along the margin of the plain contain important groundwater resources (Iwaco-Waseco, 1991), which is a common feature in volcanic terrain (e.g. Santoso *et al.*, 1992). The Bandung-Cimahi alluvial fan of volcani-clastic product in the northern foothills, slightly west of Bandung city, is an excellent source of groundwater where artesian wells with yields of up to 20 litres per second used to be common. The southern margin, however, is associated with undifferentiated volcanic products that have moderate to low transmissivity, and therefore the productivity is limited. Alluvial deposits in the Bandung plain are generally regarded as acquicludes or having low productivity (Dam, 1994), which also suggests that recharge by rainfall in the Bandung plain is very low, and therefore recharge mainly takes place in the uplands. About 30 – 50% of the net rainfall reaches shallow and deeper aquifers (Iwaco-Waseco, 1991; Pulawski and Øbro, 1976).

3.3 LAND USES

This section describes variation of land use types based on the land use map published by the Directorate of Environmental Geology (Suhendar, 1989) and as observed during a field visit in the months of January and February 2000. The land use map is given in Figure 3.5[3-6] and the description is classified into main groups that have distinct hydrological characteristics. The distribution characteristics of each land use will be discussed in detail in Chapter 6.

[3-6] Approximately less than 3% of the basin in the south is missing from the map. The field observation revealed that most of the missing area is covered with approximately equal proportions of tea plantation and forest.

Forest

This type of land cover is mainly located in the upland. It covers an area of approximately 419.24 km^2 (based on the 1989/1990 digitised map Figure 3.5). As seen on the map, the forest can be classified further into three types. The first type is a natural forest **(primary forest)** that contains a mix of tropical forest trees. The second type is a replanted forest **(reforested)** that contains single or limited types of trees such as pine. The other type is the **secondary forest**, which is mainly the regrowth forest containing bush and new trees. The reforested type of forest covers the largest in proportion (48%) and is located mainly in the southwest of the basin and fragmentarily in the north. The next largest in proportion is the primary forest (41.5%), and the remainder is the secondary forest.

Irrigated paddy-fields

This is a major land cover in the central part of Bandung basin, covering most low land area from south Bandung city to the gentle slopes in the southern upland, and from the east the Bandung basin to some parts of the Batujajar plain in the west. The irrigated paddy-fields usually can be identified by the presence of check dams or weirs (Supriyanto, personal communication, January 2000). The irrigated paddy-fields are found on flat plain (Plate 3.1) and on gentle slopes, forming terraces (Plate 3.2). In total, the irrigated-paddy fields cover an area of approximately 807.63 km^2 (1989 data).

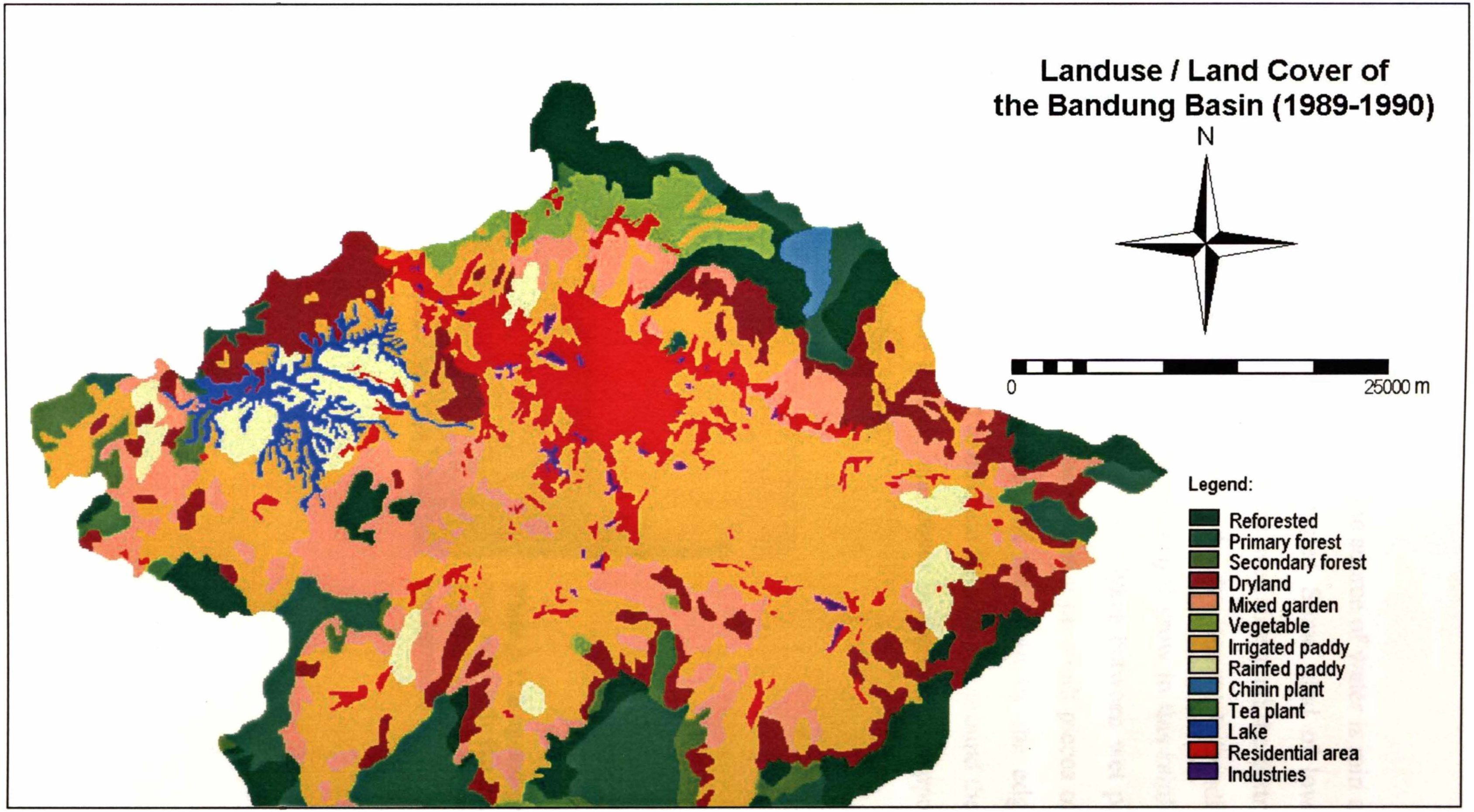

Figure 3.5: The land use map of the Bandung Basin (after: Suhendar, 1989).

Rainfed paddy-fields

Rainfed paddy fields are paddy-fields where the source of water is rain and during the dry season they normally receive less water. Some kind of low-technical irrigation method, such as small canals, may be used to extend the distribution of water, but these canals are mainly dry during the dry season. Depending on the availability of water, some seasonal crops (*palawija*) grow in this rainfed paddy-field (Plate 3.3). Sometimes they are planted on dykes between wet paddy-field (Plate 3.4). This kind of paddy-field is usually found on small pieces of land and scattered throughout the east and the west of the basin by the edges of the irrigated paddy fields. They are found to be quite large in size around the Saguling dam. The coverage area of this type of land cover in the basin is approximately 78.85 km^2 (1989 data; Suhendar, 1989).

Plate 3.1: Irrigated paddy-field on a relatively flat plain with residential area at the background.

Plate 3.2: Terraces of irrigated paddy-field on a slope.

Plate 3.3: Maize and cassava, on the topside of the paddy-field.

Plate 3.4: The *palawija* (seasonal crops) by the paddy-field, and on the dykes (background).

Plate 3.5: Inter-cropping of cassava and maize.

Dry agricultural land

In the Bandung area, there are three important groups of dry-agricultural land. They are dryland (*tegalan*), mixed garden and vegetable garden (horticulture). In the field, it is quite difficult to distinguish a mixed garden from dryland. In general, a house can be found by the garden while the dryland is situated on the hillside and quite far from the houses. There is also a tendency for maize, cassava, and bananas and fruit-trees to be grown in the garden, while the dryland is planted more dominantly by vegetables, even though main staple crops such as maize, cassava, ground-nut, etc. are not uncommon. Maize and cassava are often inter-cropped, i.e. they are grown on the same piece of land (Plate 3.5). Vegetable gardens (horticulture) are mainly found far north of Bandung City with an altitude around 1,000 to 1,500m amsl. Vegetables such as carrots, onions, cabbages, lettuces, tomatoes and chillies are the common crops. These types of dry-agricultural land cover an area of approximately 578.77 km^2 in the basin (1989 data; Suhendar, 1989).

Estate crops

Estate crops in the Bandung basin include tea and cinchona (quina). Tea estates (Plate 3.6) are mainly located in the far south part of the basin on the slopes of Mt. Malabar. The cinchona estates are located in the northeastern basin and in the south.

Plate 3.6: Tea plantation in the south of the Bandung basin.

Urban area

Urban areas are shown in the map as residential areas and industrial areas. The centre of the urban area is the City of Bandung (Plate 3.7). Other major urban areas are in Cimahi, which is on the main route from Bandung City to Padalarang in the west, Soreang, Banjaran and Majalaya in the south, Ujungberung, Rancaekek and Cicalengka in the east, and Lembang in the north. Industrial areas are located mainly south of Bandung City, along the main road from Bandung to the west through Cimahi and Padalarang, and to the east from Cicaheum to Ujungberung. In the basin, residential areas and industrial areas cover approximately 168.74 km^2 and 11.35 km^2 respectively (1989 data; Suhendar, 1989).

Plate 3.7: View of the Bandung basin from the north slope looking south with the city of Bandung in the centre and the southern mountain range at the background.

3.4 SOCIO-ECONOMIC CONDITIONS

Socio-economic information is important for the analysis of land use change drivers, because changes in land use are greatly controlled by human activities (Turner *et al.*, 1993). A detailed analysis is given in Chapter 6. This section, however, will describe the general socio-economic conditions of the study area.

The Bandung basin is administratively composed of two second-level regional administrations, namely the Municipality (*Kotamadya*) of Bandung and the District (*Kabupaten*) of Bandung. The Municipality of Bandung is also the Capital City of the province of West Java. The municipality and the district are divided further into smaller local administrations of Subdistrict level (*Kecamatan*). The municipality is located in the northern part of the central basin and surrounded by several sub-districts that belong to the District of Bandung. The municipality of Bandung consists of 26 subdistricts and the district consists of 42 subdistricts.

The City of Bandung is connected to other major urban areas by several main roads to the west, east, north and south (Figure 3.6). The east-west roads are the main economic and service routes that connect Bandung City with capitals of neighbouring provinces. A four-lane toll highway was opened in 1991 that connects Padalarang in the west and Cileunyi in the east, passes through the southern periphery of Bandung City with many branches towards the city.

Demography

Population growth is considered one of the main drivers for the land use change. The Bandung basin is a highly populated area with a total population in 1997 of nearly 6 million (Table 3.1). About 2.4 million of them live in the municipality. The population density for the municipality is 10,630 per sq. km and for the district is 1,247 per sq. km. The annual population rate of growth for Bandung City is averaged at 2.3% (Dam, 1994). However, the data from the Central Bureau of Statistics for the years 1989, 1992 and 1997 show a fluctuated rate of growth for the period of 1989 to 1997 with an average growth of 3.8% for the municipality, 3.0% for the district and 3.3% for the total area. The number of households is about 1.2 million, of which 31.6% are in the municipality. The average annual growth rate of the number of households is 0.75% for the municipality, 3.34% for the district, and 2.45% for both.

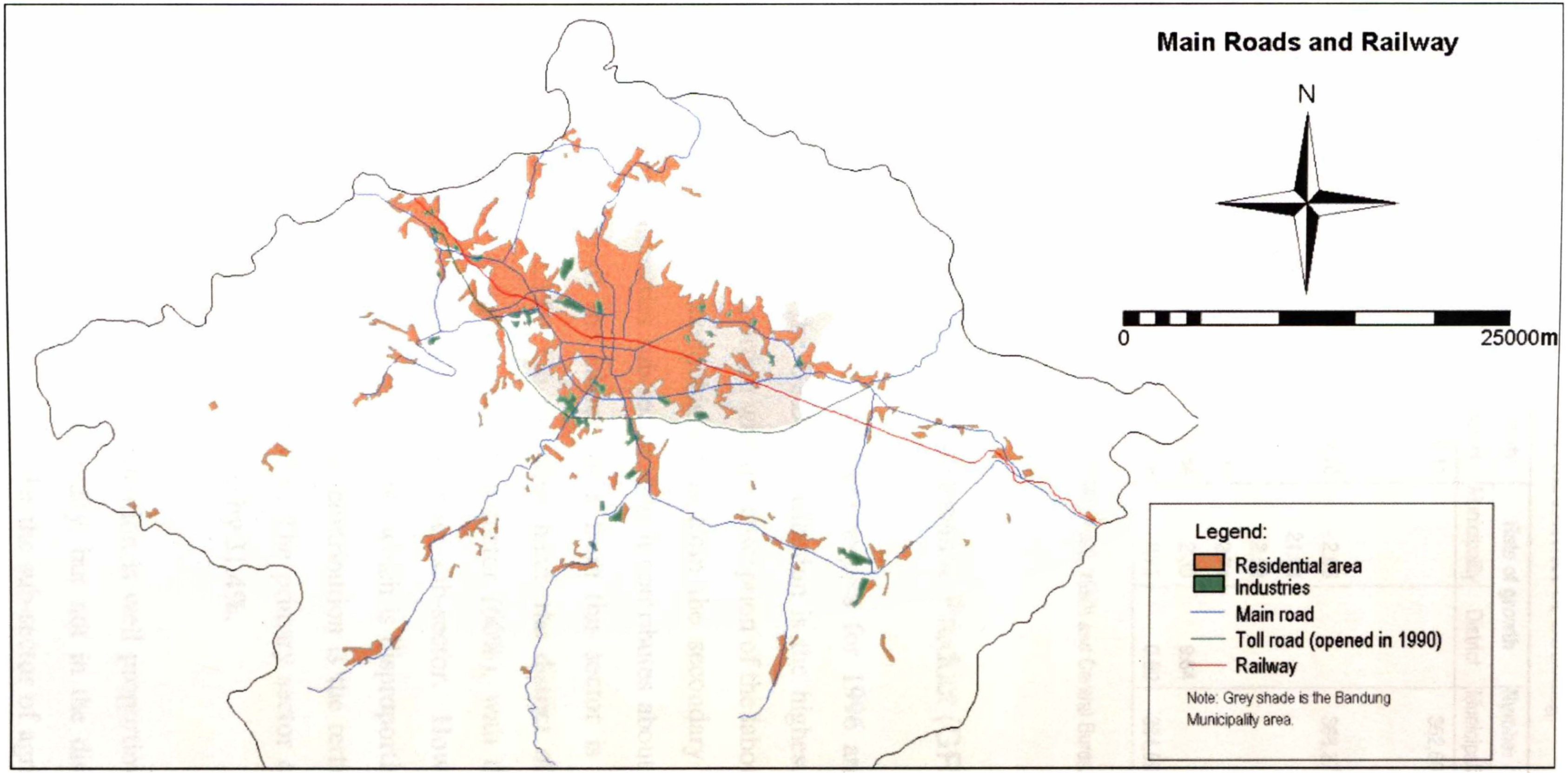

Figure 3.6: Main roads and railways in the Bandung Basin.

Table 3.1: Population data of the Municipality and the District of Bandung.

	Population			Population density		Rate of growth		Number of households	
	Municipality	District	Both (Sum)	Municipality	District	Municipality	District	Municipality	District
1989	1,801,999	2,806,942	4,608,941	10,971.74	919.11			362,601	639,842
1990									
1991	1,854,399			11,290.79					
1992	1,816,345	3,094,298	4,910,643	11,059.09	1,132.70	- 2.05		368,376	705,346
1993	2,197,820*			13,381.76		21.00			
1994	2,254,524			13,727.01		2.58			
1995	2,315,640	3,219,231	5,534,871	14,099.12	1,128.73	2.71			761,582
1996	2,371,008	3,529,584	5,900,592	14,436.24	1,237.54	2.39	9.64		819,143
1997	2,435,328	3,557,665	5,992,993	14,524.53	1,247.39	2.71	0.80	384,991	832,030

Note: * Estimated from the rate of growth.

Source: Central Bureau of Statistics for the Municipality of Bandung (1991, 1993, 1998) and Central Bureau of Statistics for the District of Bandung (1990, 1993, 1998).

Labour force and Gross Regional Domestic Product (GRDP)

GRDP and labour force distribution by business sectors for 1996 are listed in Table 3.2. For the municipality, the GRDP contribution is the highest from the tertiary sector (64.2%) and in proportion with the absorption of the labour force of the same sector (67%). The second highest is from the secondary sector, in particular the processing industries sub-sector, which contributes about 35.5% to the GRDP. The absorption of the labour force from this sector is equally in proportion to the GRDP (32.3%). On the other hand, the district of Bandung receives the highest GRDP from the secondary sector (60%), with the highest contribution coming from processing industries sub-sector. However, the absorption of labour in this sector is only 31.6%, which is disproportional to its contribution to the GRDP. The second highest contribution is the tertiary sector (27.2%) with a labour force absorption of 37%. The primary sector contributes 12.7% to the GRDP, but absorbs the labour force by 31.4%.

Table 3.2 clearly shows that the GRDP contribution is well proportioned to the absorption of the labour force in the municipality, but not in the district. This confirms that the primary sector, and in particular the sub-sector of agriculture, is

Table 3.2: Labour force and GRDP distributions by business sectors for 1996.

	Municipality				District			
	GRDP		Labour		GRDP		Labour	
Business sectors	Value*	(%)	People	(%)	Value*	(%)	People	(%)
I. Primary sector	**27.42**	**0.3**	**5,679**	**0.7**	**1,143**	**12.65**	**626,211**	**31.39**
1 Agriculture, forestry, husbandry and fishery	27.42	0.3	5,048	0.6	1,077	11.92	611,771	30.66
2 Mining and quarrying	-	-	631	0.1	66	0.73	14,440	0.72
II. Secondary sector	**2,864.39**	**35.5**	**281,200**	**32.3**	**5,432**	**60.13**	**630,881**	**31.62**
3 Processing industries	1,991.89	24.7	219,362	25.2	4,590	50.81	485,772	24.35
4 Electricity, gas and water	302.03	3.7	7,572	0.9	330	3.65	5,325	0.27
5 Building/construction	570.47	7.1	54,266	6.2	512	5.67	139,784	7.01
III. Tertiary sector	**5,174.70**	**64.2**	**583,179**	**67.0**	**2,458**	**27.21**	**738,048**	**36.99**
6 Retail, hotels and restaurants	2,606.49	32.3	270,686	31.1	1,234	13.66	387,762	19.44
7 Transportation and communication	648.52	8.0	43,848	5.0	384	4.25	117,817	5.91
8 Finance, rentals and business services	897.12	11.1	23,978	2.8	254	2.81	9,115	0.46
9 Services	1,022.57	12.7	244,667	28.1	586	6.49	213,805	10.72
10 Other	-	-	-	-	-		9,549	0.48
TOTAL	8,066.51	100.0	870,058	100.0	9,034	100.0	1,995,140	100.0

* = x 10^9 Rupiah (Indonesian currency)

Source: Central Bureau of Statistics the Municipality of Bandung through Komara (personal communication, October 1999).

not an interesting occupation because it contributes less to the GRDP in comparison to the absorption of the labour force.

3.5 AVAILABILITY OF DATA FOR THE DEVELOPMENT OF AN INTEGRATED MODEL

This section describes the availability of data for the purpose of modelling and the development of components of the proposed integrated model. Data that may be required are listed in Table 3.3. They are based on the commonly required data for running water balance calculation, land use analysis and modelling, and climate scenarios generation. Most of data were collected from government institutions, such as the Research Institute for Water Resources, Meteorological and Geophysical Agency, and some were collected from publications and reports, such as FAO Publications and the Department of Agriculture's Project Report.

Table 3.3: Required data and their availability.

Description of data	Purposes	Format	Time/period	Remarks
A. Basic data				
1. Topographic map	Basic data that can be used to derive slope, size of area, etc.	D+HC	NA	
B. Hydrological component				
1. Precipitation	Water balance	D	1983-1994	Partial
2. Climate, excluding precipitation	Water balance: Potential Evapotranspiration	D	1979-1994	From 2 stations, partial
3. Crop coefficients	Water balance: Water requirement for each crop type	HC	NA	FAO Publication
4. Crop patterns	Waterbalance: Seasonal variation in water requirement for each crop type	HC	NA	Dept. of Agriculture's Report
5. Discharge data	Model calibration and validation	HC	1953-1995	Partial
C. Land use component				
1. Land use/cover map	Land use model: Existing land use as a base for scenario generation	D+HC	1989	Published map by GTL (1991)
2. Demography and socio-economics	Identifying land use change drivers and modelling	HC	1989, 1992, 1997	Central Bureau of Statistics for the Municipality of Bandung (1991, 1993, 1998) and for the District of Bandung (1990, 1993, 1998)
3. Geomorphology: elevation, slope, river	Identifying land use change drivers and modelling	D	NA	Can be derived from topographic map
4. Supporting infrastructure such as main roads	Identifying land use change drivers and modelling	D	NA	Can be derived from topographic map
D. Climate component				
(Data available is as required for water balance calculation)	-	-	-	-

Note: The format of available data is classified into two: D = digitised, and HC = hardcopy
NA = Not Applicable

Basic data

Basic data is information that is commonly used or can be used for all components. For this study, the only required basic data is the topographic map. Usually, published topographic maps include natural features such rivers and their tributaries as well as human-made features such as roading networks, administrative boundaries, important buildings, airstrips, etc. Various information required for this study can be derived from this topographic map such as size of the selected area, distance from place to place, elevation, slopes, etc.

Hydrological component

The hydrological component requires various kinds of data as parameters for the model. The types of data collected are based on the parameters required for water balance calculation.

Precipitation

Precipitation is one of the main inputs to any hydrological model. Table 3.4 gives a summary of the nature of precipitation data after being converted from daily to monthly data, except for station number 27 (Bandung BMG) where the data is already in monthly format. These data came from 25 stations distributed in the catchment that are scattered unevenly throughout the study area (Figure 3.7). The distance from one station to the nearest station varies from less than 1km to about 15km. Most of the data were recorded between 1985 and 1993. Records earlier than 1985 are available for some stations, but many of them have missing records. In total, about 50% of the data are missing from the period 1983 - 1994.

Table 3.4: Availability of precipitation data from the study area. (Blank cells mean no records; shaded cells mean data are available.)

	Station	1983											
		J	F	M	A	M	J	J	A	S	O	N	D
1	Bandung												
2	Banjaran												
3	Bbk Siliwangi										▨	▨	▨
4	Bojongsalam												
5	Cibintinu							▨	▨		▨	▨	▨
6	Cicalengka												
7	Cililin												
8	Cinchona												
9	Ciparay	▨	▨	▨	▨	▨	▨	▨	▨		▨	▨	▨
10	Cisaranten Kidul												
11	Cisondari												
12	Derwati												
14	Jatihandap												
15	Lemburawi												
16	Mande												
17	Mkr-saluyu/Ciharalang												
18	Montaya												
19	Pangalengan												
20	Paseh												
21	Pasir Jampana						▨	▨	▨		▨	▨	▨
23	Saguling Dam												
24	Selacau												
25	Sukwana												
26	Ujungberung												
27	Bandung BMG												

	Station	1984											
		J	F	M	A	M	J	J	A	S	O	N	D
1	Bandung												
2	Banjaran					▨	▨	▨	▨	▨	▨	▨	▨
3	Bbk Siliwangi	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
4	Bojongsalam												
5	Cibintinu	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
6	Cicalengka												
7	Cililin												
8	Cinchona												
9	Ciparay	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
10	Cisaranten Kidul												
11	Cisondari												
12	Derwati												
14	Jatihandap												
15	Lemburawi												
16	Mande												
17	Mkr-saluyu/Ciharalang												
18	Montaya												
19	Pangalengan			▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
20	Paseh												
21	Pasir Jampana	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
23	Saguling Dam												
24	Selacau												
25	Sukwana												
26	Ujungberung												
27	Bandung BMG												

	Station	1985											
		J	F	M	A	M	J	J	A	S	O	N	D
1	Bandung							▨	▨	▨	▨	▨	▨
2	Banjaran	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
3	Bbk Siliwangi	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
4	Bojongsalam										▨	▨	▨
5	Cibintinu	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
6	Cicalengka							▨	▨	▨	▨	▨	▨
7	Cililin							▨	▨	▨	▨	▨	▨
8	Cinchona							▨	▨	▨	▨	▨	▨
9	Ciparay	▨	▨	▨	▨	▨				▨	▨		
10	Cisaranten Kidul										▨	▨	▨
11	Cisondari												
12	Derwati										▨	▨	▨
14	Jatihandap										▨	▨	▨
15	Lemburawi	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
16	Mande										▨	▨	▨
17	Mkr-saluyu/Ciharalang											▨	▨
18	Montaya							▨	▨	▨	▨	▨	▨
19	Pangalengan	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
20	Paseh	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
21	Pasir Jampana	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
23	Saguling Dam							▨	▨	▨	▨	▨	▨
24	Selacau										▨	▨	▨
25	Sukwana							▨	▨	▨	▨	▨	▨
26	Ujungberung							▨	▨	▨	▨	▨	▨
27	Bandung BMG	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

	Station	1986											
		J	F	M	A	M	J	J	A	S	O	N	D
1	Bandung	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
2	Banjaran	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
3	Bbk Siliwangi	▨	▨	▨									
4	Bojongsalam	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
5	Cibintinu	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
6	Cicalengka	▨	▨	▨	▨								
7	Cililin	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
8	Cinchona	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
9	Ciparay	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
10	Cisaranten Kidul	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
11	Cisondari												
12	Derwati	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
14	Jatihandap	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
15	Lemburawi	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
16	Mande	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
17	Mkr-saluyu/Ciharalang	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
18	Montaya	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
19	Pangalengan	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
20	Paseh	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
21	Pasir Jampana	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
23	Saguling Dam	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
24	Selacau							▨	▨	▨	▨	▨	▨
25	Sukwana	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
26	Ujungberung	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
27	Bandung BMG	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

	Station	1987											
		J	F	M	A	M	J	J	A	S	O	N	D
1	Bandung												
2	Banjaran	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
3	Bbk Siliwangi												
4	Bojongsalam	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
5	Cibintinu	▨			▨	▨	▨		▨		▨		
6	Cicalengka	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
7	Cililin												
8	Cinchona	▨											
9	Ciparay	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
10	Cisaranten Kidul	▨	▨	▨	▨	▨	▨	▨	▨			▨	▨
11	Cisondari	▨	▨	▨	▨				▨	▨		▨	
12	Derwati	▨	▨	▨	▨	▨	▨	▨			▨	▨	▨
14	Jatihandap	▨	▨	▨						▨			
15	Lemburawi	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
16	Mande	▨	▨	▨				▨	▨	▨	▨	▨	▨
17	Mkr-saluyu/Ciharalang	▨	▨	▨	▨	▨			▨			▨	▨
18	Montaya	▨											
19	Pangalengan	▨	▨	▨	▨	▨	▨				▨	▨	▨
20	Paseh												
21	Pasir Jampana	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
23	Saguling Dam	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
24	Selacau	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
25	Sukwana	▨											
26	Ujungberung												
27	Bandung BMG	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

	Station	1988											
		J	F	M	A	M	J	J	A	S	O	N	D
1	Bandung												
2	Banjaran	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
3	Bbk Siliwangi											▨	
4	Bojongsalam	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
5	Cibintinu											▨	▨
6	Cicalengka												
7	Cililin												
8	Cinchona												
9	Ciparay	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
10	Cisaranten Kidul	▨	▨	▨	▨	▨	▨			▨	▨	▨	▨
11	Cisondari	▨	▨	▨									
12	Derwati	▨	▨	▨	▨	▨	▨			▨	▨	▨	▨
14	Jatihandap			▨	▨	▨	▨		▨	▨	▨	▨	▨
15	Lemburawi	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
16	Mande	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
17	Mkr-saluyu/Ciharalang					▨	▨				▨	▨	▨
18	Montaya												
19	Pangalengan	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
20	Paseh												
21	Pasir Jampana	▨	▨	▨	▨	▨	▨		▨	▨	▨	▨	▨
23	Saguling Dam	▨	▨	▨									
24	Selacau	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
25	Sukwana												
26	Ujungberung												
27	Bandung BMG	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

	Station	1989											
		J	F	M	A	M	J	J	A	S	O	N	D
1	Bandung												
2	Banjaran	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
3	Bbk Siliwangi	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
4	Bojongsalam	▨	▨	▨	▨	▨	▨	▨	▨		▨	▨	▨
5	Cibintinu	▨	▨	▨	▨	▨		▨	▨	▨	▨	▨	▨
6	Cicalengka												
7	Cililin												
8	Cinchona												
9	Ciparay	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
10	Cisaranten Kidul	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
11	Cisondari						▨	▨	▨		▨	▨	▨
12	Derwati	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
14	Jatihandap	▨	▨	▨	▨	▨		▨	▨	▨	▨	▨	▨
15	Lemburawi	▨	▨	▨	▨	▨	▨				▨	▨	▨
16	Mande	▨	▨	▨							▨	▨	▨
17	Mkr-saluyu/Ciharalang	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
18	Montaya												
19	Pangalengan	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
20	Paseh												
21	Pasir Jampana		▨	▨	▨	▨				▨	▨	▨	▨
23	Saguling Dam			▨	▨	▨	▨	▨	▨	▨			
24	Selacau	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
25	Sukwana												
26	Ujungberung												
27	Bandung BMG	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

	Station	1990											
		J	F	M	A	M	J	J	A	S	O	N	D
1	Bandung												
2	Banjaran	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
3	Bbk Siliwangi	▨	▨	▨	▨	▨	▨			▨	▨	▨	▨
4	Bojongsalam	▨	▨	▨	▨	▨	▨	▨	▨				
5	Cibintinu	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
6	Cicalengka												
7	Cililin												
8	Cinchona												
9	Ciparay	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
10	Cisaranten Kidul	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
11	Cisondari	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	
12	Derwati	▨	▨	▨	▨	▨	▨	▨	▨	▨		▨	▨
14	Jatihandap	▨	▨	▨	▨	▨	▨	▨	▨		▨	▨	▨
15	Lemburawi	▨	▨										
16	Mande	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
17	Mkr-saluyu/Ciharalang	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
18	Montaya												
19	Pangalengan												
20	Paseh												
21	Pasir Jampana	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
23	Saguling Dam	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
24	Selacau	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
25	Sukwana												
26	Ujungberung												
27	Bandung BMG	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

	Station	1991											
		J	F	M	A	M	J	J	A	S	O	N	D
1	Bandung	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
2	Banjaran	▨	▨	▨	▨	▨	▨		▨	▨	▨	▨	▨
3	Bbk Siliwangi	▨								▨	▨	▨	▨
4	Bojongsalam	▨	▨	▨	▨	▨				▨		▨	▨
5	Cibintinu	▨	▨	▨	▨	▨	▨			▨	▨	▨	▨
6	Cicalengka	▨	▨	▨	▨	▨				▨		▨	▨
7	Cililin	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
8	Cinchona	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
9	Ciparay	▨	▨	▨	▨	▨				▨	▨	▨	▨
10	Cisaranten Kidul	▨	▨	▨	▨								
11	Cisondari								▨	▨	▨	▨	▨
12	Derwati	▨	▨	▨	▨					▨	▨	▨	▨
14	Jatihandap	▨	▨	▨	▨	▨				▨		▨	▨
15	Lemburawi				▨	▨				▨	▨	▨	▨
16	Mande	▨	▨	▨	▨	▨	▨			▨	▨	▨	▨
17	Mkr-saluyu/Ciharalang	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
18	Montaya	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
19	Pangalengan												
20	Paseh	▨	▨									▨	▨
21	Pasir Jampana	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
23	Saguling Dam	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
24	Selacau	▨	▨	▨	▨	▨					▨	▨	▨
25	Sukwana	▨	▨	▨	▨							▨	▨
26	Ujungberung	▨	▨	▨	▨	▨						▨	▨
27	Bandung BMG	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

	Station	1992											
		J	F	M	A	M	J	J	A	S	O	N	D
1	Bandung	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
2	Banjaran	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
3	Bbk Siliwangi	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
4	Bojongsalam	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
5	Cibintinu	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
6	Cicalengka	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
7	Cililin	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
8	Cinchona	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
9	Ciparay	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
10	Cisaranten Kidul										▨	▨	▨
11	Cisondari	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
12	Derwati	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
14	Jatihandap	▨	▨	▨	▨	▨		▨	▨	▨	▨		▨
15	Lemburawi	▨	▨	▨	▨				▨	▨	▨	▨	▨
16	Mande	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
17	Mkr-saluyu/Ciharalang	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
18	Montaya	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
19	Pangalengan												
20	Paseh	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
21	Pasir Jampana	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
23	Saguling Dam	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
24	Selacau	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
25	Sukwana												
26	Ujungberung	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
27	Bandung BMG	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

	Station	1993											
		J	F	M	A	M	J	J	A	S	O	N	D
1	Bandung	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
2	Banjaran	▨	▨										
3	Bbk Siliwangi	▨	▨										
4	Bojongsalam	▨	▨										
5	Cibintinu	▨	▨										
6	Cicalengka	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
7	Cililin	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
8	Cinchona	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
9	Ciparay		▨	▨	▨	▨	▨		▨		▨	▨	▨
10	Cisaranten Kidul	▨	▨	▨									
11	Cisondari	▨	▨	▨									
12	Derwati	▨											
14	Jatihandap	▨	▨										
15	Lemburawi	▨	▨										
16	Mande	▨	▨										
17	Mkr-saluyu/Ciharalang	▨	▨	▨									
18	Montaya	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
19	Pangalengan												
20	Paseh	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
21	Pasir Jampana	▨	▨	▨			▨	▨	▨	▨	▨	▨	▨
23	Saguling Dam	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
24	Selacau	▨	▨	▨									
25	Sukwana												
26	Ujungberung	▨	▨	▨	▨				▨	▨	▨	▨	▨
27	Bandung BMG	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

	Station	1994											
		J	F	M	A	M	J	J	A	S	O	N	D
1	Bandung	▨	▨	▨	▨								
2	Banjaran												
3	Bbk Siliwangi												
4	Bojongsalam												
5	Cibintinu												
6	Cicalengka	▨	▨	▨	▨								
7	Cililin	▨	▨	▨	▨								
8	Cinchona	▨	▨	▨	▨							▨	
9	Ciparay	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
10	Cisaranten Kidul												
11	Cisondari												
12	Derwati												
14	Jatihandap												
15	Lemburawi												
16	Mande												
17	Mkr-saluyu/Ciharalang												
18	Montaya	▨	▨	▨	▨								
19	Pangalengan												
20	Paseh	▨	▨	▨	▨								▨
21	Pasir Jampana												
23	Saguling Dam	▨	▨	▨	▨	▨	▨						
24	Selacau												
25	Sukwana	▨	▨	▨	▨								
26	Ujungberung	▨	▨	▨	▨								
27	Bandung BMG	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

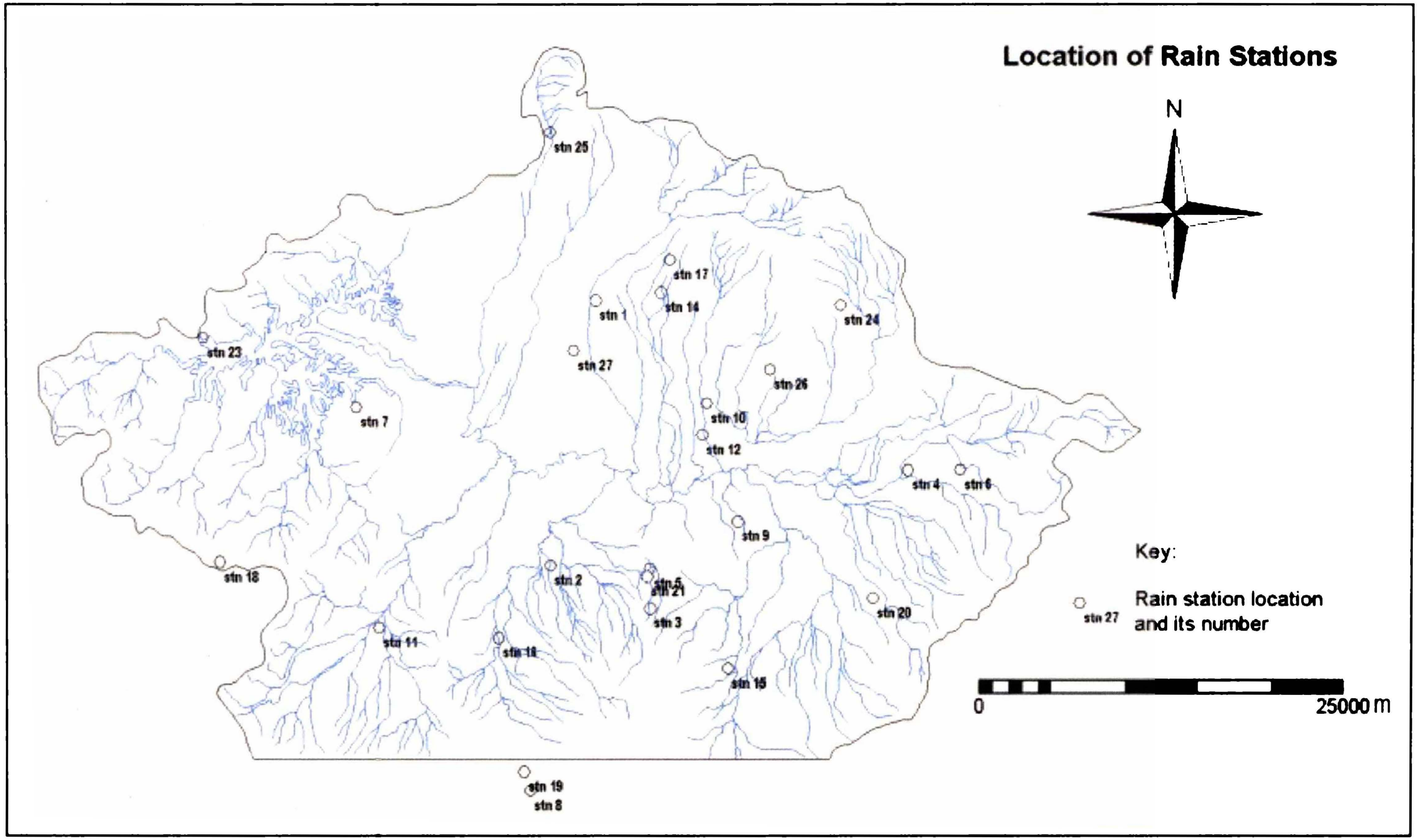

Figure 3.7: Locations of rain stations in the Bandung basin. Two stations are located outside the map boundary. In addition to rainfall, stations number 9 and 27 also record other climate data. (Basic map is modified from topographic map of Bandung Basin [GTL, 1992].)

Climate data

The term climate data in this hydrological component refers to required data for the calculation of potential evapotranspiration (i.e. excluding the precipitation). The types of data that have been collected are based on the parameters required for the potential evapotranspiration (PET) calculation using the Penman method. It is the method that demands the most types data but is considered the most accurate method in comparison to other methods such as Blaney–Criddle, radiation, and pan evaporation methods (Doorenbos and Pruitt, 1977). The required parameters for a PET calculation using the Penman method are: maximum temperature, minimum temperature and average temperature, humidity, wind speed and sunshine hours. Sun radiation data is preferable if available, but not essential.

The availability and nature of data are summarised in Table 3.5. The climate data come from two stations. Both stations provide monthly data. The Ciparay station represents the south-east part of the basin while Bandung station represents the north-west region (Taryana, personal communication, January 2000). The monthly data collected from the Bandung station are quite complete. (The selected time period was only 1985 – 1994.) The data from Ciparay station, however, were incomplete with some gaps in the temperature data, solar radiation, atmospheric pressure, and sunshine hours.

Crop coefficient (k_c)

Every crop has its own water requirement characteristics to allow it to grow properly. To calculate the amount of water consumption, a crop coefficient can be used which represents the relationship of the reference-crop evapotranspiration or any specific reference evaporation against the crop evapotranspiration. The crop coefficient also varies with the stage of growth of the crop, growing season and

Table 3.5: Summary of availability and condition of the climate data.

Type of data		1970										1980										1990									
		0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
Station Ciparay																															
1	Temperature									■	■	■		▥	▥	▥	▥		■			▥	■	■							
2	Relative Humidity									■	■	■		▥	▥	■	▥	▥	■			▥	■	■							
3	Wind speed									■	■	▥		▥	▥	■	▥	▥	■			▥	■	■							
4	Sunshine									■	▥	■		▥	▥		▥		▥			▥	■	■							
5	Radiation									■	■	■		▥			▥		■			■									
6	Pan Evaporation									■	■	■		▥	▥	■	▥	▥	■			▥	■	■							
7	Temperature on Pan									▥				▥	▥	■	▥	▥	■			▥	■	■							
Station Bandung																															
1	Temperature																■	■	■	■	■	■	■	■	■	■					
2	Relative Humidity																■	■	■	■	■	■	■	■	■	■					
3	Wind speed																■	■	■	■	■	■	■	■	■	■					
4	Sunshine																■	■	■	■	■	■	■	■	■	■					
5	Radiation																■	■	■	■	■	■	■	■	■	■					
6	Pan Evaporation																■	■	■	■	■	■	■	■	■	■					
7	Temperature on Pan																														

Notes:

■ *Complete set of data*

▥ *Incomplete set of data*

the weather conditions (e.g. Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979). The values of crop coefficient for each crop type in the humid tropical area are given in Table 3.6. Very often, in order to simplify the problem, a generalised value is taken. The Directorate of Food Crop Production (1994) use a value of 1.5 for paddy with respect to the evaporation of water on open surface, and 0.3 for seasonal crops (*palawija*) during the growing period, and 0.8 when already mature. Unfortunately, this generalisation is too vague as it eliminates variation as the result of crop maturity, in particular for the paddy field. In addition, it also eliminates the fallow condition between the cropping seasons. Furthermore, the given values are limited only to paddy and seasonal crops, disregarding the species of the crops. Calculation of the actual evapotranspiration and how to incorporate the crop coefficient into the water balance model is discussed in Chapter 5 (Hydrological Component).

Table 3.6: Value of k_c (Crop coefficient) for each plant in a humid tropical area (compiled mainly from Doorenbos and Pruitt, 1977; and Doorebos and Kassam, 1979).

	Plant type	**Length of Growing period (days)**					**Value of Kc**				**Approx. range$**		**Coverage area (Ha)**			
	(1)	Total (2)	Initial (3)	Developm. (4)	Mid-season (5)	Maturity (6)	Initial (7)	Developm. (8)	Mid-season (9)	Maturity (10)	Min (11)	Max (12)	Planting (13)	Harvest (14)	Difference** (15)	Difference % (16)
Rice	Paddy (wet land) *	105	15	20	50	20	1.10	1.10	1.05	0.95	500	950	116,701.0	110,825.0	5,876.0	5.0
	Paddy (dry land) *	105	15	20	50	20	0.90	1.10	1.05	0.95	500	950	11,008.0	13,021.0	-2,013.0	-15.5
'Palawija'	Corn/maize	80	20	20	30	10	0.30	0.70	1.05	0.55	400	750	20,957.0	22,079.0	-1,122.0	-5.1
	Cassava #	350					0.75						12,748.0	11,587.0	1,161.0	9.1
	Sweet potato *	105	20	25	35	25	0.40	0.70	1.05	0.70	400	675	5,468.0	5,242.0	226.0	4.1
	Soybean	85	15	15	40	15	0.30	0.70	1.00	0.45	450	825	6,791.0	6,197.0	594.0	8.7
	Groundnut *	85	15	25	30	15	0.40	0.70	0.95	0.55	?	?	3,491.0	3,334.0	157.0	4.5
	Mungbean *	85	15	15	40	15	0.30	0.70	1.00	0.45	?	?	149.0	110.0	39.0	26.2
	Onion	150	15	25	70	40	0.40	0.70	0.95	0.75	350	600	3,299.0	3,412.0	-113.0	-3.3
	Garlic *	150	15	25	70	40	0.40	0.70	0.95	0.75	*350*	*600*	650.0	607.0	43.0	6.6
	Cabbage	80	20	30	20	10	0.40	0.70	0.95	0.80	*250*	*500*	3,759.0	3,859.0	-100.0	-2.6
	Tomato	145	30	40	45	30	0.40	0.70	1.05	0.60	300	600	2,987.0	3,593.0	-606.0	-16.9 [3]
	Chili *	145	30	40	45	30	0.40	0.70	1.05	0.60	*300*	*600*	3,012.0	5,331.0	-2,319.0	-43.5 [3]
	Potato	130	25	30	45	30	0.40	0.70	1.05	0.70	350	625	3,839.0	4,039.0	-200.0	-5.0
	Chinese cabbage	80	20	30	20	10	0.40	0.70	0.95	0.80	*250*	*500*	2,305.0	2,274.0	31.0	1.3
Perennial	Banana [1]	0.7									700	1700	6,075.9	5,411.9	664.0	10.9
	Papaja &	NA					0.70				?	?	363.8	154.8	209.0	57.4 [4]
	Avocado #!	NA					0.95				650	1000	4,431.2	789.5	3,641.7	82.2 [4]
	Mango #!	NA					0.95				*650*	*1000*	453.3	187.6	265.7	58.6 [4]
	Rambutan #!	NA					0.95				*650*	*1000*	1,091.2	80.4	1,010.8	92.6 [4]
Estate crop	Tea	NA					1.00				?	?				
	Quinine #	NA					0.95				?	?				
Others	Grass [2]	NA					1.00				?	?				

[1] Banana: Months	1	2	3	4	5	6.00	7.00	8.00	9.00	10	11	12	13	14	15
Kc	0.40	0.40	0.45	0.50	0.60	0.70	0.85	1.00	1.10	1.10	0.90	0.80	0.80	0.95	1.05
			suckering	↑				shooting	↑			harvesting	↑		

Kc for total growing period = 0.7

Continued on the next page!

Continuation of Table 3.6 from the previous page.

[2] Grass for golf course, normally kept short similar to the reference crop condition.

[3] Market influence; harvesting of previous cropping year not followed by the next generation in the current year

[4] Start of planting in the current year and harvesting in the following year

$ These are approximate ranges of seasonal ET crops that can be used for easy reference. The actual magnitudes change according to climate, crop characteristics, length of growing season and time of planting.

* Data length of growth are interpreted from the Horticulture and Food Plant Production (1994) and some Kc values are estimated.

Value of Kc is estimated based on comparison with: coffee Kc = 0.9 throughout the year, but if significant weed growth is allowed Kc = 1.05 ~ 1.1, cacao Kc = 0.9 ~ 1.0 without shade trees or 1.1 ~ 1.5 with shade trees.

#! Value of Kc is estimated based on comparison with fruite trees (peaches, apricots, pears, plums, almonds, pecans): average Kc in summer = 1.0 for humid, light to moderate wind speed and without ground cover crop, and 0.8 with ground cover crop.

& Value of Kc is estimated based on comparison with banana.

** Difference as:
a. overlaping
b. failure; disease, pests, etc.
c. market control

Crop pattern

A crop pattern in a simple way shows seasonal planting and harvesting patterns. This crop pattern is generally controlled by agroclimate (including soil type and rainfall) and watering technique. Data on recent crop patterns for Bandung basin are not yet available, but can be represented by other areas that have similar agroclimatic zones.

Land use component

The land use component requires various kinds of data for the identification of driving factors, statistical analysis, and land use allocation procedures. These data consist of land use maps, demographic and socio-economic data (Table 3.7), as well as the basic topographic data. When land use maps are not available, satellite images or aerial photographs may be used to replace the land use maps. However, they need to be interpreted and classified into land use groups before being used.

The demographic and socio-economic data have been gathered from the Bureau of Statistics for analysis of the causes of land use changes and how they may change, because changes in land use are influenced by socio-economic conditions (Turner *et al.*, 1993). The demographic data that have been collected consist of population data, including population density, number of households, and the number of school students, number of industries and Gross Regional Domestic Product (GRDP). Most of the data are at district level and they were collected as a multi temporal set of data in order to find trends of change that may correlate with the rate of change in land cover/uses. Analyses of these data are discussed in Chapter 6 (Land use component).

Table 3.7: Availability of data for the land use component.

Required parameters	What	Time series			Remark or alternative source
		1989	1992	1997	
Land use / covers	Paddy fields (irrigated and non-irrigated)	x	x	x	Land use map, 1990
	Dry agriculture	x	x	x	
	Housing and industrial area (settlement)	x	x	x	
	Estates: commercial crops	x	x	x	
	Forest	x	x	x	
	Other	x	x	x	
	Harvested/planted area: (paddy, seasonal crops, perennial crops, and estate crops)		✓		
Demography	Population Density	✓	✓	✓	
	Rural Population Density	✓	✓	✓	
	Fraction rural population	✓	✓	✓	
	Labour force density	x	x	x	
	Agricultural labour force density	x	x	x	
	Fraction agricultural labour force	x	x	x	
	Adults and Children	✓	✓	✓	
	No. of households / family	✓	✓	✓	
	No. of school students (Secondary)	✓	✓	✓	
	No. of people/households affected by natural disasters (flood, landslide, etc.)	x	✓	✓	
	Sex ratio	✓	✓	✓	
Socio-economic	GRDP at current price	✓	✓	✓	
	No. of industries	✓	✓	✓	
	Direct distance to nearest major river (m)				Derived from topographic map
	Direct distance to nearest main road (m)				
Geomorphology	Elevation	n.a	n.a	n.a	Derived from topographic map
	Slope	n.a	n.a	n.a	
Climate*	Sunshine, % of time without clouds	n.a	n.a	n.a	✓
	Range in precipitation (mm)	n.a	n.a	n.a	✓
	Total precipitation (mm)	n.a	n.a	n.a	✓
	Average temperature	n.a	n.a	n.a	✓
	Number of wet months with more than 50 mm precipitation	n.a	n.a	n.a	✓
	Agro-climatic zone	n.a	n.a	n.a	✓
Soil*	Geological classification based on parent material	n.a	n.a	n.a	Geological map
	Soil fertility (low, moderate, high)	n.a	n.a	n.a	x
	Soil drainage class (well, moderate, poor)	n.a	n.a	n.a	x
	Soil permeability (rapid, moderate, slow)	n.a	n.a	n.a	x
	Soil texture (coarse, medium, fine)	n.a	n.a	n.a	x

* May Not be applicable (i.e. for very coarse scale analysis only).

Note: Types of data compiled on this Table are based on Verburg *et al.* (1999). Not all of these data may be necessary for this study.

Climate component

The data required for the development of the climate component for this integrated model are similar to the climate data required for the purpose of calculating the potential evaporation. They are: average monthly temperature, maximum temperature, and minimum temperature, average monthly precipitation data, and solar radiation. In addition, elevation data is also required which can be derived from a topographic map. These data, except the elevation data, are in the form of average data that comes from a long-term record. The data already available are from a 10-year record (1985-1994).

3.6 CONCLUSION

From discussion above, it can be concluded that the Bandung basin has been selected as the study area for the development of the proposed integrated model because:

- This basin has been experiencing a problem of rapid land use change, dominated by the increase in the residential area as the result of high population;
- Physically, the Bandung basin is quite representative of the Indonesian catchments. This medium size catchment (2,200 km^2) contains some common geological variations of volcanic products, some sedimentary rock and some intrusive rock that significantly varies in their hydrological characteristics. It also contains major land use groups commonly found in Indonesia, ranging from forest, to dry agricultural land, paddy-fields and urban areas (settlement and industrial area);
- The data availability from this catchment is among the best in Indonesia, even though some important data is missing. Nevertheless, this allows moderately good and comprehensive analyses that cover the hydrological

component, land use scenarios and climate change scenarios, for the development of the integrated model. In addition, there are a number of reports and published articles of hydrological studies and land use change analysis that have been conducted in this area, which can support the development of this thesis.

REFERENCES

Central Bureau of Statistics the District of Bandung 1998. *Kabupaten Bandung Dalam Angka - 1997 (The District of Bandung in Numbers - 1997).* Central Bureau of Statistics the District of Bandung (in Indonesian).

Central Bureau of Statistics the District of Bandung 1993. *Kabupaten Bandung Dalam Angka - 1997 (The District of Bandung in Numbers - 1997).* Central Bureau of Statistics the District of Bandung (in Indonesian).

Central Bureau of Statistics the District of Bandung 1990. *Kabupaten Bandung Dalam Angka - 1989 (The District of Bandung in Numbers - 1989).* Central Bureau of Statistics the District of Bandung (in Indonesian).

Central Bureau of Statistics the Municipality of Bandung 1998. *Kotamadya Bandung Dalam Angka - 1997 (The Municipality of Bandung in Numbers - 1997).* Central Bureau of Statistics the Municipality of Bandung (in Indonesian).

Central Bureau of Statistics the Municipality of Bandung 1993. *Kotamadya Bandung Dalam Angka - 1992 (The Municipality of Bandung in Numbers - 1992).* Central Bureau of Statistics the Municipality of Bandung (in Indonesian).

Central Bureau of Statistics the Municipality of Bandung 1991. *Kotamadya Bandung Dalam Angka - 1989 (The Municipality of Bandung in Numbers - 1989).* Central Bureau of Statistics the Municipality of Bandung (in Indonesian).

Dam, M.A.C. 1994. *The Late Quaternary Evolution of the Bandung Basin, West Java, Indonesia.* Thesis, Vrije Universiteit Amsterdam.

Dam, M.A.C., Suhirman, A. and Toloczyki, M. 1993. Geological map of the Bandung Basin. *Environmental Geology for Landuse and Regional Planning Bandung Basin.* Directorate of Environmental Geology.

Delinom, R. and Suriadarma, A. 1993. Influence of groundwater flow in the Upper Cikapundung catchment: A hydrology approach. *Proceedings of the*

22nd Annual Convention of the Indonesian Association of Geologists. Bandung 6-9 December 1993, 560-569.

Directorate of Food Crop Production 1994. *Synthesis of Main Crop Pattern Technology in Boosting the Cropping Index ≥ 300 on Intensive Paddy Land – West Java Province.* Directorate of Food Crop Production, Directorate General of Food Crops and Horticulture.

Doorenbos, J. and Kassam, A.H. 1979. *Yield Response to Water.* FAO Irrigation and Drainage Paper No. 33, FAO of the United nations, Rome, 193pp.

Doorenbos, J. and Pruitt, W.O. 1977. *Crop Water Requirements - Guidelines for predicting crop water requirements.* FAO Irrigation and Drainage Paper No. 24, FAO of the United Nations, Rome, Revised Edition, 144pp.

IWACO-WASECO 1991. *Bandung Hydrological Study, West Java Provincial Water Sources Master Plan for Water Supply, Jakarta.* Main Report, 111pp plus Appendices.

Mock, F.J. 1973. *Land Capability Appraisal Indonesia: Water Availabiility Appraisal.* Report prepared for the Land Capability Appraisal Project, Bogor - Indonesia, FAO of the United Nations.

Pulawski, B. and Øbro, H. 1976. Groundwater study of a volcanic area near Bandung, Java, Indonesia. *Journal of Hydrology* 28, 53-72.

Santoso, H., Suwijanto and Susilowati, Y. 1992. Land movement study in Majalengka, West Java based digitally processed LANDSAT images. *Proceedings of the IIPRS-92, Bandung 1992.* Indonesian Remote Sensing Society (MAPIN) (in Indonesian)

Suhendar, R. 1989. Present land use. *Environmental Geology for Landuse and Regional Planning Bandung Basin.* Directorate of Environmnetal Geology, Indonesia.

Turner II, B.L., Moss, R.H. and Skole, D.L. (eds.) 1993. *Relating Land Use and Global Land-Cover Change: A proposal for an IGBP-HDP Core Project.* IGBP Report No. 24, HDP Report No. 5, Stockholm.

Van Bemmelen, R.W. 1949. *The Geology of Indonesia, Vol. 1A. General Geology of Indonesia and adjacent Archipelagoes* Government Printing Office, The Hague.

Verburg, P.H., Veldkamp, T., and Bouma, J. 1999. Land use change under conditions of high populaiton pressure: the case of Java. *Global Environmental Change* 9, 303-312.

CHAPTER 4

A POLICY – RELEVANT INTEGRATED MODEL

4.1 INTRODUCTION

As described earlier in Chapter 1, a policy-relevant integrated model is being developed in order to perform sensitivity assessment on changes in the land use patterns and climate with regard to hydrological runoff. The model is intended to help the users in foreseeing the impacts of those changes on seasonal variability of river flows of a river basin. The model will provide guidance to better planning for future environmental conditions, and therefore will help in reducing potential negative impacts from such changes. This method of planning is also known as active adaptation to future changes, that is, to use present knowledge to plan ahead and take timely action as needed (GCTE, 1996).

The target users of this integrated model are individuals or groups of people involve in policymaking or decision-making for land use management. The model is designed to be user-friendly, and will guide the users to answer 'what if' policy related questions under various predefined scenarios with regards to the streamflow variability. Although prior hydrological knowledge is not necessary to run this model, some basic knowledge of water balance and scenario modelling will be useful in understanding the outcomes of this model.

This chapter describes in more detail the structure of the integrated model and how the three model components are linked to each other, how the model is developed, and aspects under consideration in the model's development.

4.2 STRUCTURE OF THE MODEL

Components of the integrated model

The basic structure of the model has been shown in Chapter 1, and is shown again in this section for further discussion (Figure 4.1).

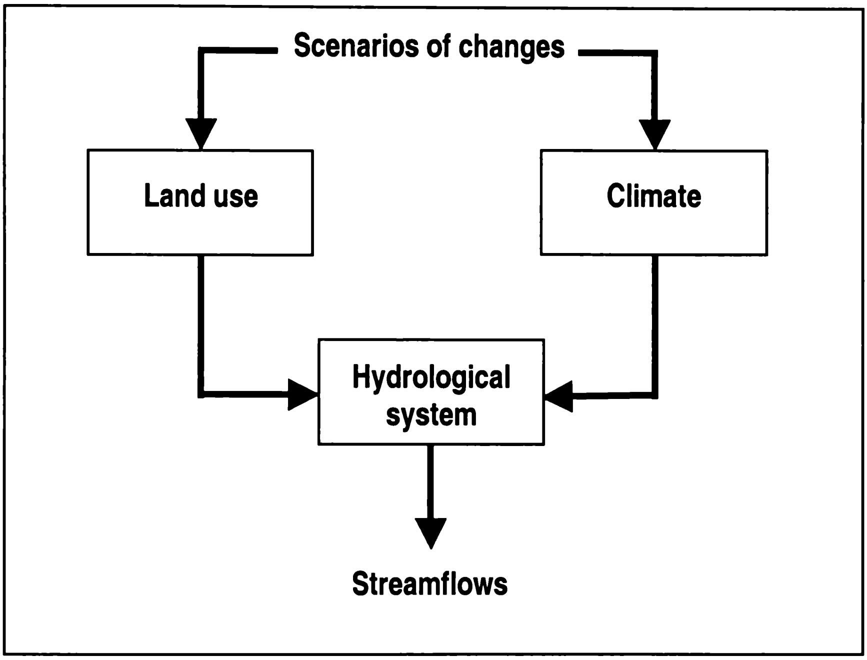

Figure 4.1: The basic structure of the integrated model system.

As outlined in Figure 4.1, the integrated model system has three main components. These are **land use**, **climate** and **hydrological components**. The input to the model is a set of scenarios of changes in land use patterns and climate. The land use scenarios are policy related. Both land use and climate components act as separate processors that transfer the given input for each component into a series of hydrological variables and parameters that will be used afterwards by the hydrological component. The hydrological component will process all the variables, incorporating basic characteristics of the catchment area and parameters derived from the land use and climate components, and produce the outcome in the form of seasonal streamflows.

The policy-related scenarios for land use change can be produced by at least two different approaches. The first is by using an already produced master plan, and considering this plan as one scenario pattern. Most local governments at district level have produced their own master plans for land use, at least in the short-term (between 5 and 20 years). This is particularly so in the areas where the government still has some control over land use. This is quite common in many parts of the country; for example, the government encourages a specific area for agriculture, other areas for industries, business, housing, etc. The other approach is through the use of a land use model. This is needed when master plans are not available or when future scenarios over the long term (more than 20 years ahead) are required. One advantage of this approach is that time dependent scenarios can be produced.

There is a large number of methods for generating scenarios of climate change (Carter and La Rovere, 2001). These methods can be incorporated into a climate scenario generators for facilitating applications. The results can then be passed on to the hydrological component in the form of climate-hydrological parameters as needed by the hydrological component. There are many climate scenario generators already available. Among them are models developed by Hulme *et al.* (2000), and Warrick *et al.* (2001). These are discussed in some detail later in a specific section of this chapter.

The hydrological component is the component that will produce hydrographs of streamflows as the output. In this component, all the parameters produced by land use and climate components are combined together with basin characteristics to produce average monthly streamflow hydrograph.

How the components are linked to each other

The land use component and climate component are linked to the hydrological component as a flow process, or a cause-and-effect relationship. This means that information derived from the land use and climate components become the input of the hydrological component. The model does not consider dynamic feedback relationship, nor does it show inter-relationship between the land use and climate components because those kinds of relationships are too complex to be included in the proposed integrated model. (In reality, such an inter-relationship between the land use and climate exists, see Bonan, 1997[4-1]; Scharpenseel and Pfeiffer, 1998[4-2]; and Wasson, 1996[4-3].)

Because land use information is basically spatial, the most common way to link land use information to a hydrological model is by means of a Spatial Information System (SIS). Another way to link the land use information to the hydrological model is by manually collecting and delineating the spatial information and all hydrological parameters from basic maps, and listing them all for further processing by the hydrological component. However, this method is time consuming and very tedious work, especially when the river basin is very complex. Thus, the use of SIS is preferable, particularly when basic data are already available in a digitised format.

This SIS can be linked into the model in several ways (Maidment, 1991). It may be used simply as a tool for determining hydrological parameters and the

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[4-1] Based on simulations with a land surface process model coupled to an atmospheric general circulation model, Bonan (1997) showed that the altered climate in the Eastern and Central U.S. was caused by a change in land use, and was particularly due to reduced surface roughness, reduced leaf and stem area index, reduced stomatal resistance, and increased surface albedo with modern vegetation compared to natural vegetation.

[4-2] Scharpenseel and Pfeiffer (1998) identified and assessed the effects of climate change on soil and land use of different ecosystems.

[4-3] Wasson (1996) reported a climate change interaction with land use on fluvial systems. Climate change might induce land use change by making agriculture either possible or impossible, and very likely that the climatic changes acting on societies that are economically marginal would be reflected in land use changes.

outcomes are fed into an existing hydrological model, or it may be combined with the hydrological model in which the SIS is used to develop hydrological parameters from basic data sets until the output. The SIS can also be embedded into the hydrological model as one integrated model. Moore *et al.* (1993) employed a Geographic Information System (GIS) together with a terrain analysis method to determine spatial distribution information and terrain attributes, including slope gradient which are often required in surface runoff modelling. Colby (1996) used a GIS to derive spatial characteristics of the watershed in order to provide thematic data layers that were used to delineate hydrologic response units (HRU) and other additional data layers, which were then used as parameters for the U.S. Geological Survey's Precipitation Runoff Modelling System (PRMS). Stuebe and Johnston (1990) used a GIS in combination with Soil Conservation Service runoff curve numbers (CN) to model runoff volume and the whole modelling process was conducted using GIS functions.

The climate component is also linked to the hydrological component as a flow process, in which the results of data processing from the climate component become the input of the hydrological component. The hydrological parameters to be derived from the climate component as required by the hydrological component, for example, are monthly precipitation, temperature, solar radiation, etc. In many cases, these parameters have to be spatially distributed, especially if the study area is quite large. This can also be managed easily by using a SIS.

Information to be derived from the land use and climate components

The land use component generates spatial information of land use patterns that will be mathematically translated into a set of hydrological parameters for runoff computation. Each land use type has its own potential evapotranspiration and runoff coefficient values. These are the main hydrological parameters that strongly link the land use with the hydrological component. The coverage of each land use type and its distribution is also required as this will influence the total amount evapotranspiration as well as runoff.

The climate component generates meteorological information that will be used as input parameters for the hydrological component. The main parameters, for example, are precipitation, temperature and radiation (Bárdossy and Caspary, 1991).

4.3 HOW THE MODEL IS DEVELOPED

Each component of the integrated model is developed separately, without forgetting how they are integrated as one model. There are two possible approaches in developing these components. The first is by selecting and adapting an existing model or method that has similar characteristics as required for the respective component. The second is by constructing the component from scratch. The first approach is less time consuming and requires less effort to develop the model than the second that requires special skill in computer programming. The advantage of this approach over the first approach is that the model to be produced can match the ideal model. However, producing a computer programme is not the main target of this thesis. Therefore constructing a new computer programme from the beginning will only be conducted when the appropriate model to be adapted for component development is not available.

4.4 ASPECTS TO CONSIDER IN SELECTING THE MODEL

There are many hydrological models, land use models and climate scenario generator models available nowadays. Existing hydrological models vary in their complexity from simple to very complicated as have been reviewed by several authors, e.g. Shaw (1988) and recently by Mirza (1997) and Arnold *et al.* (1998). Land use models also vary depending on their purposes (Lambin, 1997), as do climate models (Mimikou, 1995).

Any model has its own characteristics, and may possess both advantages and disadvantages. In general, new models are claimed to be more accurate than older models, but many new models are more complicated to use than the older ones. Because of their various characteristics, it is necessary to selectively choose the model based on the criteria required for the development of the integrated model in order to achieve the main aim of this thesis (i.e. the model is selected based on the purpose of this thesis).

Aspects to be considered in selecting the model and the basic requirements of the integrated models have been discussed in Chapter 1. They are; not highly data or computationally demanding, accommodative and transportable. There are also additional aspects to be considered in selecting the most suitable hydrological model to be adapted. These are important because they will influence how the model is to be developed. They include:

- Capability of the model to cope with the problem of land **heterogeneity**;
- At what **spatial scale** (or spatial resolution) the model may work;
- At what **time scale** (or time resolution) the model may work;
- **Accuracy** of the model; and
- Conceptual approach, 'Black box' or conceptual-process oriented model.

An additional need to consider for the hydrological model, is how it copes with the problem of **regulated streamflows in an area largely affected by human regulation**.

Each of these factors is discussed in turn below to show how these affect the selection of the methods and models for the development of the integrated model.

Heterogeneity

Heterogeneity of the land is one of the problems encountered in hydrological modelling. It includes the variation in the catchment slopes, soil types, geology, and land uses. Many researchers have tried to solve this heterogeneity problem by developing hydrological models that can include these variations in their models, and they have produced models using a distributed system or differential method (Leavesley *et al.*, 1983; Flügel, 1995). Models that have limitations in the model conceptualisation of the hydrological process involved, such as lumped parameter and empirical models, must be used carefully as they fail to predict the impact of land use change on catchment runoff (Kuczera *et al.*, 1993).

Land use (or land cover) classification can range from extremely detailed to simple depending on the purpose of the study. For a resource inventory, the classification can be very detailed and will include individual ecological types, forest types, vegetation, types of urban settlements, etc. (e.g. Spectranalysis Inc., 2001; Balsem and Buurman, 1989). A new concept of classification system proposed by FAO, using dichotomous and hierarchical phases, promises a system that is universally applicable and can be adapted into various spatial scales (Di Gregorio and Jansen, 1998). In general, the more class types, the more complicated the land use model is going to be. For the purpose of hydrological analyses, the land use classification is simplified by grouping land use types that have similar hydrological properties into one class, which results in four or five land use classes that are significantly different in their hydrological characteristics (e.g. Leavesley *et al.*, 1983; Bannert and Riyadi, 1989; Djuwansah, personal communication, May 1998).

Spatial scale

Studying the effect of land use changes by using real life catchment sizes (more than 100 km^2) is more difficult than using small catchments of less than 10 km^2 (Lørup *et al.*, 1998). Many catchment studies are conducted in small areas, as these are best for studying the basic physical processes of catchment hydrology (He *et al.*, 1997) including how each land use type and land use pattern change may affect the hydrology. The problem with large catchments is that they generally contain more heterogeneity than small catchments and therefore the number of parameters involved are far too many in comparison to those for small catchments. In addition, catchment parameters may also be scale dependent, particularly shape parameters such as slope and topography, which are highly scale dependent (Gustard, 1992; Moore *et al.*, 1993; Newson, 1994). If the aim of a study is about catchment resources, it will be more useful and appropriate to work on large-scale catchments than on small-scale catchments (He *et al.*, 1997). In this kind of study, details of physical processes in the catchments are not the point of interest. Rather it is the sensitivity, quantity and quality of the resources being questioned that are the main interest.

The size of coverage area also influences the land use models because driving forces for land use changes are highly scale dependent. The climate variable as a driving factor in land use change is more important than the terrain variable at a global scale, but less important in a regional scale (Hall *et al.*, 1995; Veldkamp and Fresco, 1996).

This spatial scale is also a concern in selecting climate simulation models. The most common models for evaluating climate changes are the General Circulation Models (GCMs) (Bárdossy and Caspary, 1991) because they are believed to be the most credible (Mimikou, 1995). However, GCMs have a coarse resolution and in general, they are unsuitable to be used directly for studies on a scale of one catchment (Mimikou *et al.*, 1991). Therefore, it is necessary to down-scale the result of the GCMs for more detailed spatial information (Hewitson and Crane, 1996).

Time scale (time resolution)

The purpose of the model can affect the methodological concept of the models. Models, which are developed for analysing short hydrological events such as floods, are different in their conceptual approach from models that are designed for monthly or annual water budget analysis. This is clearly differentiated in the Precipitation - Runoff Modelling Systems (PRMS) of the U.S. Geological Survey, where channel routing is the concept to be used for flood analysis, whereas for land use effect analysis, monthly or annual hydrographs, the water balance concept is used (Leavesley *et al.*, 1983). Yet, the channel routing concept can still be used for analysing the monthly or annual water budget, or land use effects to analyse hydrology, such as in TOPMODEL (Beven *et al.*, 1988) and Soil and Water Assessment Tool (SWAT) model (Arnold *et al.*, 1998). However, they require daily data for their analysis because they are actually designed for daily analysis, but the output can be extended to monthly or annual outputs. Therefore, even if the aim is a seasonal or monthly analysis, the amount of data to deal with will be too large and may demand significant mathematical computation.

Accuracy of the model

The purpose of this study is to produce sensitive analyses in order to study the relative changes in river resources, in particular streamflows, as the result of various scenarios of changes in land use and climate. Therefore, the model verification is directed in such a way as to ensure the accuracy of the model for these purposes. Accurate estimates of the absolute quantity of stream discharge are not necessarily required.

Accuracy is also related to spatial scale and justification of time scale. The integrated model is developed to deal with water resources analysis and therefore involves relatively large catchments. Thus, it is important to adjust the interpretation mechanism based on scale, which consequently may result in losing some details of processes (Hackett, 1988).

'Black box' model against conceptual model

Ideally, the model to be developed does not need to be calibrated and is readily transported onto different catchments when needed. With 'black box' type models, or models that have limitation in conceptualising the hydrological process, calibration (or model validation) is very necessary (Ewen and Parkin, 1996; and Parkin *et al.*, 1996). Among these models include the lumped models. The models that represent detailed physical processes, such as physically distributed based models, are naturally considered as having the ability to predict the hydrological response of ungauged catchments (Beven and O'Connell, 1982). However, this kind of model has the limitation of requiring a large number of parameters. Nandakumar and Mein (1997) showed the difficulty in avoiding errors when using physically based models, of which systematic errors in rainfall are the most serious effect on predicted flows. Estimated errors in model parameters also have significant effects.

In reality, all models regardless of type - 'black box', semi-conceptual or fully conceptual - require some amount of calibration or adjustment. The effort needed in conducting calibration is dependant on how accurate the model is expected to be, which is also related to the purpose of the model, spatial scale, and time scale.

Regulated streamflows

Another problem in catchment modelling that includes analysis of land use effects on streamflows is when the streamflows are not natural (Lørup *et al.*, 1998). This is particularly a problem if catchments have large reservoirs upstream of the gauging stations, which is very common for large catchments, and the streamflows are controlled by the operation of reservoirs. The data from those gauging stations cannot be used for this kind of study. If we assume that the streamflows are not regulated (i.e. natural flows) for a catchment (which in real life are significantly regulated), there is a need to select the model that does not require much calibration.

4.5 SELECTING SUITABLE METHODS AND MODELS

As mentioned in the previous section, selecting the methods and models depends on the purpose of the study, which is to produce an integrated system for examining the impact of changes in land use and climate on the seasonal streamflows. It will be used to assess the sensitivity of the streamflows in response to the changes in land use and climate. Based on this purpose, the selected methods and models for the integrated system should be able to handle heterogeneity of land use in the catchment area, and calculate the impact of changes in the land use. The integrated system should work on a catchment scale because the model is designed as a tool for policymakers and planners in managing a river basin. The integrated model is designed to work based on monthly data because the aim of this thesis is examining the sensitivity of seasonal streamflows. It reduces the amount of data to be handled and computational effort required compared to a model that uses daily data. Furthermore, daily data are more difficult to obtain than the average monthly data.

This section reviews in more detail available methods and models for each component of the integrated model. In addition to the purpose of the thesis, the appropriate methods are selected based on the ease of adapting the model and the considerations discussed earlier.

Hydrological component

Review

There are many hydrological models already published and used by researchers that try to analyse the impacts of land use changes and climate changes on a hydrological regime. Mirza (1997) has made a review of published hydrological models, specifically regarding their types, purposes, advantages and limitations. He classified the hydrological models into four types: empirical, water-balance, lumped-parameters and physically-distributed models. He found that all types of models could be used to analyse the hydrological impacts of land use changes. Each model is considered in the following discussion.

Empirical models

The empirical models are the simplest among all types of models in terms of data requirements and mathematical computational work. This is because empirical models do not explicitly consider the physical laws governing the process since they try to relate the input (precipitation) and the output (discharge) through an empirical relationship. Thus, these models cannot be directly applied to different catchments (i.e. are not transportable) as the relationship has to be heavily recalibrated when it is transferred from place to place. Moreover, these empirical models are generally used for specific purposes, such as estimating the impacts of tree cutting in a forest and forest regrowth, flood forecasting, assessing the effects of urbanisation on streamflows, or low flow management (Taniguchi and Bari, 1997; Ott *et al.,* 1991; Liu, 1987; Hornbeck *et al.,* 1987; Vogel and Kroll, 1990).

Lumped-parameter models

Conceptual lumped-parameter models also face the same limitation of not being able to be used on different catchments, though they embody a series of functions and approximations or simplification of physical laws such as hydraulic laws, topographic index, or empirical algebraic equations. Most of the catchment study areas using these models are small in size or less than 100 km^2. However, a combination of lumped-parameter models and statistical analyses may extend the analyses to medium size catchments of 100 to 2500 km^2 (Lørup *et al.,* 1998). Even though Mirza (1997) and Kuczera *et al.* (1993) stated that these lumped-parameter models were not suitable for predicting the effects of land use changes on the hydrological regime of a catchment, they have, been successfully used in some catchment studies (Lørup *et al.,* 1998; Lørup and Hansen, 1997; Bultot *et al.,* 1990; Eeles and Blackie, 1993).

Physically-distributed parameter models

Of all types of models, physically-based distributed models are considered as the most suitable models for studying the impacts of changes in land use on hydrological regimes. These are differential models based on conservation of mass, energy and momentum, and characterised by details of representation of physical processes and of the number of parameters that have to be evaluated (Arnold *et al.*, 1998). These are, however, perceived simultaneously as the main strength and weakness of these models (Parkin *et al.*, 1996; Mirza, 1997). These models require many more mathematical computations than other types of hydrologic models and therefore are difficult to use. These difficulties are mainly caused by the inability of the equations to represent actual field processes, the use of effective parameters to represent sub-grid scale processes, over-parameterisation, and calibration and validation methods. However, in spite of such difficulties, these models have been widely and successfully used (Bathurst, 1986; Storm *et al.*, 1987; Ott *et al.*, 1991; Vörösmarty *et al.*, 1991; Dunn and MacKay, 1995).

Water balance models

The water balance models use fundamental equations to estimate the balance between the inputs (precipitation) and loss of water by evapotranspiration, streamflow and infiltration to become groundwater (Thornthwaite and Mather, 1957; Sokolov and Chapman, 1974). They are a type of hydrological model that has very simple structures and is characterised by a limited number of parameters, which is in contrast to the physically distributed models that contain details of physical processes and large numbers of parameters. The models allow monthly and seasonal estimates of hydrologic parameters and they can be applied to reasonably large areas with sparse data. These models are good at predicting human impact on the hydrologic cycle, such as irrigation, predictions of streamflow and other impacts, including the impact of climate change and land cover change (Dunne and Leopold, 1978). Rowe (1998) is in favour of using these models for evaluating impacts of land use change through forestry on water resource (especially on low flows) - such as the impact of forest cutting and forest re-growth on streamflows. A limitation of these models is that they cannot be used to estimate the hydrologic parameters of an ungauged catchment.

One important issue is whether those models have been used to generate monthly runoff and have been successfully integrated or coupled with other components. Table 4.1 lists some examples of studies that have integrated the land use component and/or climate change component with the hydrological model, spatially explicit application or GIS. The catchment size of case studies and the purpose of studies are also included. It can be seen that the empirical model and lumped parameter model are not commonly used to generate mean monthly runoff. The list shows one model that can assess the impacts of land use and climate change together, and produce monthly runoff within a GIS (i.e. Vörösmarty *et al.*, 1991)[4-4].

Selected model and method for adaptation

To achieve the main objective of this thesis, in addition to its capability to generate mean monthly runoff for examinations of seasonal changes in streamflow, the hydrological model has to be able to integrate well with the land use and climate change components. Therefore it needs to be:

- spatially explicit, as the integrated model needs to spatially display changes in land use (i.e. distributed parameters);
- able to accommodate the changes in meteorological parameters, such as temperature changes, precipitation, sun radiation, etc.

[4-4] The model developed by Vörösmarty *et al.* (1991) calculates any changes in climate or land cover relative to a 'reference state', and the model is not time dependent.

Table 4.1: Examples of case studies with integrated application of hydrological models.

Type of model	Reference	Generating mean monthly runoff	Land use/ land cover change	Climate change	Explicitly spatial or GIS use	Catchment size	Main purpose of study
Empirical	He *et al.* (1997)		✓			small	p
	USCS (1975)		✓			small	p
Lumped parameter	Nandakumar and Mein (1997)		✓			large	a
	Bultot *et al.* (1990)		✓			medium	u
	Eeles and Blackie (1993)		✓				u
	Bárdossy and Caspary (1991)			✓		large	u
	Amold *et al.* (1998)					large	u
Physically distributed	Ott *et al.* (1991)	✓	✓		✓	large	p
	Vörösmarty *et al.* (1991)	✓	✓	✓	✓	large	a
	Dunn and MacKay (1995)		✓	✓			u
	Parkin *et al.* (1996)		✓	✓			p
	Ewen and Parkin (1996)		✓	✓			p
	Karvonen *et al.* (1999)		✓			large	u
Water balance	Rowe (1998)		✓				a
	Mimikou *et al.* (1991)	✓		✓		large	a
	Schaake *et al.* (1996)	✓		✓			u
	Boysen (2000)		✓	✓			u
	Emtsberger and Sokollek (1983)		✓			small	u
	Dvorak *et al.* (1997)			✓		large	a

Note:

Catchment size for this Table is classified as follow;

small approximately < 10 km²
medium approximately 10 – 100 km²
large approximately > 100 km²

Purpose of study;

p = prediction/estimation of the output, e.g. runoff, flood forecasting, including measured impact estimation
a = analysing impacts, sensitivity studies
u = understanding the processes, model development

Blank field; no (definitive) information.

By bringing together all considerations in selecting the model as described in section 4.4 and information in Table 4.1, it is clear that there is not any type of model that can be applied directly. The method to be adapted for this thesis is a kind of physically-distributed model with computation based on the water balance concept, that is by applying the water balance fundamental equation. The physically-distributed model is adapted to allow changes in land use, which is a spatially distributed parameter generated from the land use component, to be computed directly by the hydrological component (Choudry, 1998). With this method, the computation is conducted on a cell-by-cell basis. The changes in meteorological input parameters derived from the climate change component, as well as the changes in land use as derived from the land use component, can be computed directly in order to generate the streamflow.

Land use component

Review

Understanding what causes changes in land use, and how to model these changes have become major topics of inquiry by many geographers and natural scientists for over a decade (Irwin and Geoghegan, 2001). It is believed that the changes in land use can significantly influence local and regional weather and climate (Cotton and Pielke, 1995). At a basin scale, for example, as has been discussed before, the changes in land use can alter hydrological systems that may threaten the water resources or cause more frequent floods.

There are many causes of changes in land use or land cover. They can be classified as the **proximate causes** and **underlying causes** (Geist and Lambin, 2001). The proximate causes are the activities that directly cause the changes; for example, shifting cultivation that leads to deforestation. In terms of scale, the proximate causes work locally. The underlying causes are the fundamental forces that drive the proximate causes at a higher hierarchy, and normally they are associated with socio-economic factors such as population pressure, household income, government policies, etc. (Turner *et al.*, 1993; Skole and Tucker, 1993). In terms of scale, these underlying driving factors can work on a local, regional or national scale. Hence, these imply that the causes of the land use changes are scale dependent. More examples of scale dependency, for instance, are the biophysical factors such as environmental change and climate change which on a large regional scale have important roles in shaping environmental change in the landscape, while slope, elevation, soil fertility, etc. are more important on a more local scale (Hall *et al.*, 1995; Veldkamp and Fresco, 1996).

There are many methods for modelling land use that have been developed with various approaches such as remote sensing for monitoring and inventories (e.g. Karsidi, 1998; Kaufmann and Seto, 2001), probability models (e.g. Geoghegan *et al.*, 1997; Cropper, 1998), multiple regression models (e.g. Karsidi, 1998; SEA START RC, 1999), and economic approach models (e.g. About.com, 1997; Chomitz and Gray, 1995). They have been reviewed by Lambin (1997) and were classified based on the methodology and the questions that need to be answered, such as **when** and **where** the changes may occur in the future, and **what** drives the changes or **why** they change (Table 4.2). Irwin and Geoghegan (2001) have also reviewed the land use models, particularly the spatially explicit models.

Monitoring technique (remote sensing)

For the purpose of monitoring the changes, a remote sensing method is commonly used (Application Case 1: Table 4.2). This method detects the changes of land cover from a pre-defined reference state as a baseline. A common approach to monitoring the changes is by comparing sequential land cover maps derived commonly from remote sensing data. This method of analysis is readily available in many image processing software packages for earth resources studies such as IDRISI (Eastman, 1995) and ILWIS (ITC, 2001). Since the observation relies mostly on the interpretation of remote sensing data, only a drastic land cover conversion can be easily identified while the modification of land can be difficult to observe. This method allows the analysis of the temporal dimension of the changes (e.g. Karsidi, 1998; Sader, 1998; Kaufmann and Seto, 2001) to answer the questions of when and where in the past, but is unable to identify driving forces, i.e. what cause the changes.

Table 4.2: Research scenarios on land-cover change and general methodologies (modified after Lambin, 1997).

Example of application	What is already known about the change of process	What one needs to know about the change process	General methodology	Example of tools
1. Climate impact studies	Nothing	When and where	Monitoring techniques	Remote sensing
2. Projection of future surface - atmosphere interactions	When in the past	When in the future	Transition probability models; time-series analysis	Markov chain; logistic function-based models
3. Identification of driving forces	Where and when in the past	Why in the past	Multivariate statistical modelling	Multiple regression models
4. Habitat conservation	Where and when in the past	Where in the future	Empirical spatial models	Spatial statistical (GIS-based) models
5. Future wood resources availability	Where, when and why in the past	When in the future	Ecosystem models	Dynamic simulation models
6. National land-use planning	Where, when and why in the past	When and where in the future	Ecosystem models	Dynamic spatial simulation models
7. Corrective or preventive policy intervention	Where, when and why in the past	Why in the future	Economic models	Von Thünen-like models

Transition probability or time-series analysis

The transition probability method is a time-series analysis that can be done based on a Markov chain for projecting the land cover changes. Therefore, it can answer the question of when the changes take place (Application Case 2: Table 4.2, e.g. Thornton and Jones, 1998). The Markov chain transition probability method simulates the change process by using linear, stochastic techniques, based on a probability which refers to a likelihood of transition from one class of land use to another class in a given interval of time (Brown, 1970). The likelihood of transition is derived from statistical analysis of a sample of transitions occurring during that interval. One main disadvantage of this Markov transition probability method is that the projection uses a linear relationship and therefore assumes that the changes are stationary. In fact, the process of changes is not expected to be stationary because the underlying factors that drive the changes in land use (socio-economics) are unlikely to be stationary in the long-term (Turner *et al.*, 1993).

Hence, this transition probability method cannot be used for a long-term projection.

Similar to the previous types of models, this approach does not answer questions about why the changes take place.

Multivariate statistical modelling (multiple regression)

A multivariate statistical modelling method specifically explores the causes of the changes (Application Case 3: Table 4.2, e.g. Hansen, 1998; Serneels and Lambin, 2001) and therefore it focuses on identifying the causes of the changes, i.e. *why* the land use changes. These multivariate models generally use multiple regression techniques to derive empirical relationships for the rates of changes. The model explores a linear relationship between change of a land use type, as a dependent variable, and possible driving forces as independent variables. Population growth, population density and gross domestic product are commonly considered as the driving forces of the land use change. This method can be used at various scales (multi-scales), from regional to global scale, depending on the resolution of available data. However, it has been found that the relationships that perform well in one region do not necessarily perform well in a different region, i.e. the relationships are very site specific (Lambin, 1997).

Empirical spatial models

Empirical spatial or spatial statistical models are a combination of geographical information systems (GIS) and multivariate mathematical models (Application Case 4: Table 4.2). The goal of these models is to project future land use patterns and display these in the form of a map (to answer the question where the changes may occur). The process is based on an assumption that current management practices are still applied in the future. This method analyses the location of land use changes in relation to maps of natural and cultural landscape variables using a GIS that can describe relationships between the dependent variables, e.g. forestland, and the independent landscape variables. These are then used as the predictor of the likely location of changes. This method does not predict when the changes will occur and usually includes fewer socio-economic factors as independent variables in the processes than the multivariate statistical analysis method.

The cellular automata method is very similar to the empirical spatial method in the way that they aim to develop spatial patterns. This method uses connectionist techniques that allows the pattern to evolve in a self-organised manner (White and Engelen, 1993). It is a simple method, in which the state of an array of cells is dependent on the state of their neighbouring cells, and the change from one state (land use type) to another state is determined by a set of transition rules and their neighbourhood functions. White and Engelen (1993) were the first to successfully use this technique for estimating the growth of urban area. Hasan (1999) also used this technique for generating land use scenarios for the development of a scenario generation and evaluation system - QUEST (Quite Useful Ecosystem Scenario Tools).

Ecosystem models — Dynamic simulation

In contrast to the empirical spatial models, the dynamic simulation models predict temporal changes (when) and allow biophysical and socio-economic interaction to be included (Application Case 5: Table 4.2). The approach of these dynamic simulation models is to imitate the biophysical and socio-economic interaction processes in one system (Sklar and Costanza, 1991). They are considered as ecosystem models as they try to emphasise interaction of all components in one ecological system. The models try to formalise the key relationships between those factors by condensing and aggregating the complex systems into a smaller number of differential equations. They represent non-stationary conditions of land use changes since they are determined by the underlying processes in the system, and the transition probabilities are generated dynamically rather than empirically. Therefore, the models allow a long-term projection. These models also allow exploration of land use scenarios involving changes in parameters.

Ecosystem models — Dynamic spatial simulation

The dynamic spatial simulation models are ecosytem models that include spatial heterogeneity in their system, i.e. dynamic simulation model with additional spatial component (Application Case 6: Table 4.2, e.g. Verburg *et al.*, 1999). These models allow prediction of temporal and spatial changes in land use. The direction of changes is predicted by a process-based model integrating the flows between adjacent cells. A wide range of biophysical and socio-economic factors can be incorporated into the system (i.e. an ecosystem model). These models can only be developed after knowing what causes the changes and aims to generate scenarios of when and where the changes will take place in the future. An intervention, such as introducing a new policy by altering the parameters, can be incorporated into the system in order to explore the changes resulting from this intervention.

Economic models

An economic approach can also be used to explore the land use change (Application Case 7: Table 4.2, e.g. Chomitz and Gray, 1995). The common method is by using a Von Thünen like model. This method uses an economic assumption of a balance between the supply and demand functions of the land market based on the competitive free market. The original Von Thünen model was developed before industrialisation (About.com, 1997). It tries to model land use patterns based on a balance between the land costs and transportation costs for agricultural products, where the products of highest demand and that require quickest transportation are located near the market, i.e. centre of an urban area. This basic idea of the Von Thünen model is still in use and reflects how various land uses are distributed. In fact, the economic theory should be used to guide the model development because it is generally land-owners who make decisions to alter the land use, which is usually determined by the expected economic value to be gained from that land (Irwin and Geoghegan, 2001). Land conservation is also decided based on benefits and costs. By this method, the influence of policy measures on land allocation can be modelled.

All the methods described above that can be used to predict the land use changes can also be used to generate change scenarios by altering some parameters of the changes. Each method has advantages and disadvantages: some are simpler and less data demanding than others; some can only work on a specific area and are not transferable to different locations. As mentioned in Table 4.2, each method also has its own specific purpose depending on the research questions it seeks to address. Therefore, it is important to carefully select the appropriate method to be adapted for the development of the land use component of this integrated model, and this will be discussed in the next section. It is important to understand that all of the above methods are site-specific because the driving factors of the cause the changes are specific for each place.

Selecting and adapting the appropriate method/model

Ideally, the land use component for the integrated model can generate and display land use patterns at any time in the future, i.e. can answer questions of when and where in the future. In addition, the models need to be able to accommodate various policy interferences so that the impacts of such policy interference will be directly reflected in the land use pattern. Therefore, policy-relevant driving factors or the underlying causes of the changes also need to be understood. Based on these ideal requirements, the dynamic spatial simulation model seems to be the most suitable method to be adopted for this thesis. However, the dynamic spatial simulation model is very data demanding and requires complicated mathematical computation, making it unacceptable for the purpose of this thesis.

What the proposed integrated model requires from the land use components is the scenarios that can be linked easily with the hydrological component. For this reason, a simple cellular automata method is adopted. This method can be done with a GIS, which has an advantage of being capable of displaying the changes and directly processing the generated land use patterns as the output in the form of distributed parameters as required by the hydrological component. In addition, understanding the underlying driving factors and the proximate causes of the land use changes is required and can be provided by a GIS based spatial statistical analysis.

For simplicity reasons, the land use scenarios are pre-selected and are put off-line. The users will therefore have to choose one scenario from these pre-selected scenarios in order to run the model. The pre-selected scenarios are chosen with an aim to conduct sensitivity analysis of the impacts of land use changes on streamflows. Details of how to construct the land use scenarios are discussed in Chapter 6.

Climate component

Review

Climate is a complex system that forms a dynamic interaction of energy balance between the climate components such as atmosphere, ocean, land surface, cryosphere (ice sheets, snow, glaciers, etc.) and biomass (Figure 4.2) (GARP, 1975; Cotton and Pielke, 1995; Houghton *et al.*, 1995). The climate of the earth will remain constant as long as the contributions of each component to the global energy balance remain the same. Any change in the contribution of any component can cause an imbalance in the energy budget (a deficit or surplus of radiative forcing[4-5]) that may lead to warming or cooling of the average global temperature and, in response, will cause the climate to change in order to re-establish the radiative balance. The adjustment can include an increase in temperature, changes in cloud cover, wind patterns, etc. An increasing trend in the annual global mean-temperature has started (Figure 4.3)[4-6] and there is a strong belief among the science community that this global warming is associated with an increasing concentration of the greenhouse gases (GHGs) in the atmosphere[4-7] (Table 4.3).

Future climate patterns are difficult to predict. In particular, the future radiative forcing from the GHGs is difficult to quantify because the emissions of these gases depend upon many uncertain factors. Some of them are; population growth, the use of carbon fuel as an energy source, technological development, economic development, policy and attitudes towards environment, etc. For this reason,

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[4-5] A radiative forcing is defined as the change in average net radiation at the top of the atmosphere because of a change in either the solar or infrared radiation. A **positive** radiative forcing tends to warm the earth's surface, while a **negative** radiative forcing tends to cool it.

[4-6] As shown by measurement records, the global average temperature has been warming by 0.3°-0.6°C since 1860 (Jones *et al.*, 1999).

[4-7] The IPCC Working Group I Report indicates that the observed warming of the last 50 years is likely to have been caused by the increase in greenhouse gas concentration (National Research Council, 2001).

scenarios (estimates of plausible future patterns or conditions) of net GHGs in the long term (100 years or more) are required in order to support the sensitivity analyses on vulnerability and potential impacts of these gas emissions on the climate system.

There are a variety of ways to construct climate scenarios. The Intergovernmental Panel on Climate Change - Task Group on Scenarios for Climate Impact Assessment (IPCC-TGCIA) classified climatic scenarios into three main types (IPCC-TGCIA, 1999), based on how they are constructed. These are: synthetic

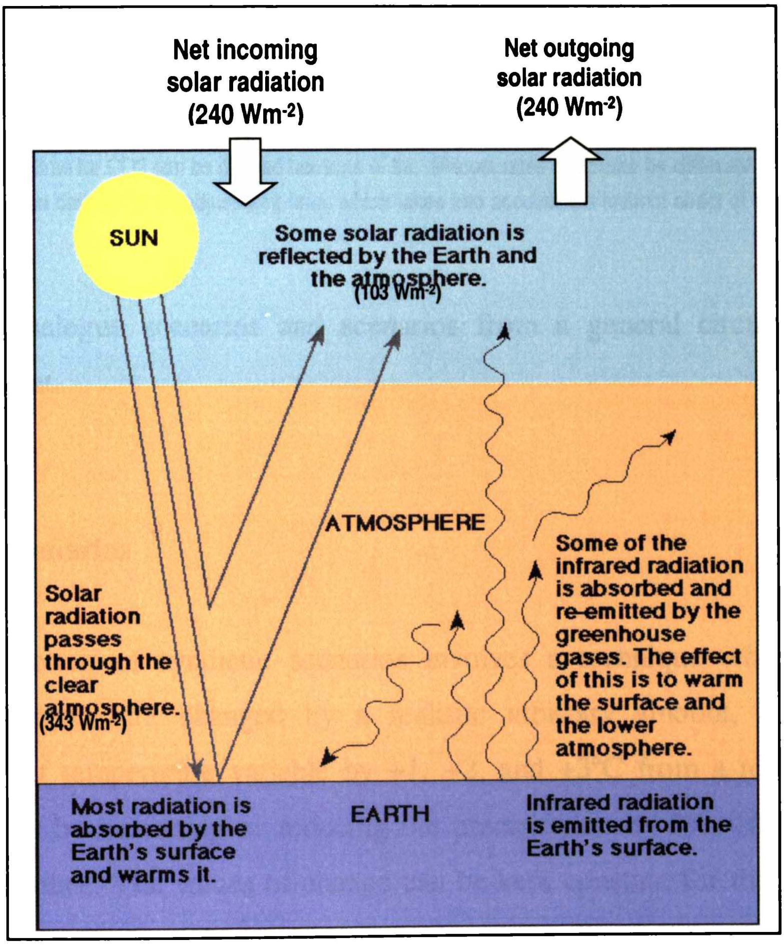

Figure 4.2: A simplified diagram illustrating the global long-term radiative balance. (Source of diagram: NASA (1998) [can also be found in http://www.puc.ohio.gov/Consumer/gcc/sciover.html]. The values in the brackets are cited from: Houghton *et al.* (1994, Figure 1, p.15).)

Table 4.3: A sample of greenhouse gases affected by human activities. (Source: IUC-UNEP, on-line http://www.unep.ch/iuc/submenu/infokit/fact30.htm, accessed on 21 March 2002.)

	CO_2 (carbon dioxide)	CH_4 (methane dioxide)	N_2O (nitrous oxide)	CFC11	HCFC22 (a CFC substitute)	CF_4 (a perfluoro carbon)
Preindustrial concentration (1)	~280 ppmv	~700ppbv	~275 ppbv	Nil	Nil	Nil
Concentration in 1994 (1)	358 ppmv	1720 ppbv	312 ppbv(2)	268 pptv(2)	110 pptv	72 pptv(2)
Rate of concentration change (3)	1.5 ppmv/yr	10 ppbv/yr	0.8 ppbv/yr	0 pptv/yr	5 pptv/yr	1.2 pptv/yr
	0.4 %/yr	0.6 %/yr	0.25 %/yr	0 %/yr	5 %/yr	2 %/yr
Atmospheric lifetime (years)	50200(4)	12 (5)	120	50	12	50,000

Note:

(1) Unit of concentration; ppmv = part per million by volume, ppbv = part per billion by volume, pptv = part per trillion (million million) by volume.

(2) Estimated from 1992 - 1993 data.

(3) The growth rates of CO_2, CH_4 and N_2O are averaged over the decade beginning 1984; halocarbon growth rates are based on recent years (1990s).

(4) No single lifetime for CO2 can be defined because of the different rates of **uptake by different sink processes.**

(5) This has been defined as an adjustment time, which takes into account the indirect effect of methane on its own lifetime.

scenarios, analogue scenarios and scenarios from a general circulation model (GCM) output.

Synthetic scenarios

The construction of synthetic scenarios involves a technique where particuar climatic elements are changed by a realistic arbitrary amount, for example, adjustment of temperature variable by +1, +2, and +3°C from a reference state (baseline), or by increasing or reducing the precipitation by 5%, 10%, and 15% from the baseline. The values of change can be kept constant for the whole year, or alternatively, they can be changed monthly, seasonally, or interannually (IPCC-TGCIA, 1999).

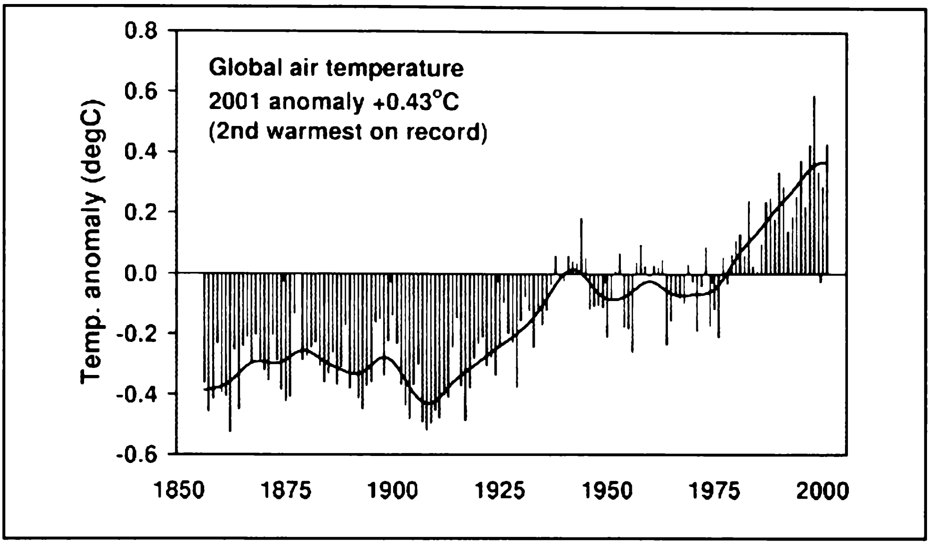

Figure 4.3: Average global air temperature. The warmest year in the entire series was 1998. [Source: Palutikof, (2001). The key reference for this series is: Jones *et al.* (1999). The record is continually updated and improved, and available on-line http://www.cru.uea.ac.uk/cru/info/warming.]

This method has some advantages and disadvantages for climate change impact analyses. The main advantage of this method is that the climatic scenarios are easy to create and the results can be quickly obtained. The relative sensitivity of the object of study to the changes in climate can be quickly explored. The disadvantge of this method is that it does not present a realistic future climate due to its arbitrary nature. However, for the purpose of exploring relative sensitivity, and taking into account its ease of application and straightforward results, the synthetic scenarios method is still useful.

Analogue scenarios

The analogue scenarios method involves an identification of climate record that may represent the future climate condition of the region of interest. This can be done by a **temporal analogue** method, which is a method that uses the past climate record as an analogue of possible future climate (e.g. Shabalova and Können, 1995; Budyko, 1989; Lough *et al.*, 1983; Warrick, 1984), or by a **spatial**

analogue method, which uses the present climate information from another region to represent the possible future climate as the analogue.

There are several drawbacks to this analogue method. For the temporal analogue method, the main disadvantage is using the past climate record, particularly the paleoclimatic reconstruction. Even when a systematic record already exists, the cause of climate change in the past is likely to be different from the cause future climate change (i.e. the past climate change was not caused by anthropogenic GHGs). The increase in the concentration of greenhouse gases is now considered an important influence in driving current climate change (Houghton *et al.*, 2001), and therefore scenarios do not correctly represent the future climate. The spatial analogue has a disadvantage for an obvious reason that the location is geographically different and therefore cannot correctly represent the future climate.

General circulation models (GCMs) based scenarios

The general circulation models (GCMs) are complex numerical climate models that try to represent physical processes that make up the climate system: atmosphere, ocean, land surface, cryosphere and biomass (GARP, 1975). There are many other climate models that are available as the result of a hierarchical evolution of the climate models, ranging from simple energy balance models to these complex GCMs[4-8], but the GCMs are considered as the only credible tool

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[4-8] Many types of climate models are available nowadays having evolved from simple to very complex, which have been reviewed by some authors (Schneider and Dickinson, 1974 and 1975; Cotton and Pielke, 1995). Cotton and Pielke (1995) classified the climate models based on their various approaches. They are: ***energy balance models*** (EBMs), ***radiative-convective models*** (RCMs), ***zonally-averaged models*** (ZAMs) and the ***general circulation models*** (GCMs). EBMs determine the effective radiative temperature of the earth, assuming there is a balance between the solar radiation absorbed by the earth and the longwave radiation emitted by the earth to space. RCMs are one-dimensional models that determine the vertical distribution of globally-averaged temperature for the atmosphere and the underlying surface (considered as the simplest models by Schneider and Dickinson (1974 and 1975)). ZAMs are two-dimensional models capable of simulating vertical and meridional variations in surface, and the atmospheric properties averaged around latitude circles. Their advantage over RCMs and EBMs is that they can respond to prescribed or modelled latitudinal variations in ice cover, land and ocean surface properties, and cloud distributions. GCMs are fully

currently available for simulating the response of the global climate system to increasing concentration of greenhouse gases (GHGs) (e.g. Schneider and Dickinson, 1975; Manabe, 1975; Cotton and Pielke, 1995; Goodess, 2000). However, because they involve very complex mathematical equations and require a high degree of computation, there are only very few centres that can perform experiments using these models. Some of the centres, together with their product models, are listed in Table 4.4. The results of these GCMs are commonly used as the basis for generating climate scenarios for the impact assessments studies (e.g. Amien *et al.*, 1996; Bårdossy and Caspary, 1991; Dvorak *et al.*, 1997; Jolley and Weather, 1997; Kite and Haberlandt, 1999; Kite *et al.*, 1994; Murdiyarso, 1996; Wilkie *et al.*, 1999), even though the models possess some limitations in their accuracy and uncertainties (Idso, 1998). [Results from some GCMs experiments are available on-line from the IPCC Distribution Data Centre (http://ipcc-ddc.cru.uea.ac.uk).[4-9]] Because of the importance of these GCM based types of scenarios, they are described in a greater depth than the two types of scenarios discussed earlier.

The GCMs can be classified into three main types (Viner, 2000). They are:

- **Atmospheric GCMs coupled with a simple slab ocean** (i.e. a single fixed layer representation of ocean) and simple land-surface parameterisation schemes. Examples of these models are UKMO, UKHI, CCC, GFDL, and GISS. These are an early generation of GCMs that perform future climate experiments based on an equilibrium response. With this method, the

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three-dimensional global models that attempt to simulate climate and climate change using numerical weather prediction techniques (i.e., finite-difference, or spectral, or hybrid spectral and finite-difference, or finite element techniques).

The general circulation models (GCMs) are considered as the most advanced climate models that explicitly simulate atmospheric circulations that contribute to meridional, zonal, and vertical transports of heat, water vapour, and other properties (Cotton and Pielke, 1995).

[4-9] The available data come from several models as indicated in Table 4.4. They have been derived based on the SRES (Special Report on Emissions Scenarios) (IPCC, 2000) and the IS92 (IPCC 1992 Scenarios) (Leggett *et al.*, 1992; and revised in Houghton *et al.*, 1996).

models evaluate the new stable state (equilibrium) of the global climate following an instantaneous increase of atmospheric gases, for example by doubling concentration of CO_2 or its radiative equivalent, including all greenhouse gases. That is why the equilibrium-response experiments are considered unrealistic because the change in the CO_2 concentration (or its radiative equivalent) in nature is gradual rather than sudden.

- **Atmospheric GCMs coupled to a three-dimensional representation of the ocean system**, in which ocean currents and heat transport are represented, and with simple land surface parameterisation schemes, e.g. UKTR, ECHAM1, and GISSTR. These models perform transient-response experiments and are conducted with coupled atmosphere-ocean models (AOGCMs), which link dynamically, detailed models of the ocean with those of the atmosphere. AOGCMs are able to simulate time lags between a given change in atmospheric composition (e.g. 1% change in CO_2 concentration per year) and the response of climate (Carter and La Rovere, 2001). The most recent evaluation of impacts, as reflected in the report, is based on scenarios formed from results of transient experiments as opposed to equilibrium experiments (see Table 4.4).[4-10]

[4-10] There are two types of transient response experiments. The 'cold start' transient-response and 'warm start' transient-response start experiments. The 'cold start' transient experiments do not take into account the historical forcing of rising greenhouse gases during the last century, but rather start the forcing from an assumed equilibrium at present. The 'warm start' experiments take account of the historical forcing of rising GHGs.

Table 4.4: List of GCM experiments that have been used to develop scenarios for impact studies (source: Carter and La Rovere, 2001).

Center	Model	Type	Forcing	ΔT_{2xCO_2} (ºC)	DDC
CCCma	CCC	EQ	2 x CO_2	3.5	-
	CGCM1	TRW	1% a^{-1}	3.6	✓
CCSR/NIES	CCSR	TRW	1% a^{-1}	3.5	✓
CSIRO	CSIRO	EQ	2 x CO_2	4.3	-
	CSIRO-Mk2	TRW	1% a^{-1}	3.7	✓
DKRZ	ECHAM1	TRC	IPCC90A	2.6	-
	ECHAM2	TRW	IPCC90A	2.2	✓
	ECHAM4	TRW	IPCC90A	2.6	✓
GFDL	GFDL	EQ	2 x CO_2	4.0	-
	GFDLTR	TRC	1% a^{-1}	4.0	-
	GFDL-R15	TRW	1% a^{-1}	4.2	✓
GISS	GISS	EQ	2 x CO_2	4.0	-
	GISSTR	TRS	1% a^{-1}	4.6	-
NCAR	NCAR	EQ	2 x CO_2	4.0	-
	NCAR1	TRW	1% a^{-1}	4.6	✓
OSU	OSU	EQ	2 x CO_2	2.8	-
UKMO	UKMO	EQ	2 x CO_2	5.2	-
	UKHI	EQ	2 x CO_2	3.5	-
	UKTR	TRC	1% a^{-1}	2.7	-
	HadCM2	TRW	1% a^{-1}	2.5	✓
	HadCM3	TRW	1% a^{-1}	3.0	✓

Centres / models

CCC : Canadian Centre for Climate
CGCM : Coupled general circulation model (Canadian Climate Centre)
CCSR : Centre for Climate System Research (Japan)
CSIRO : Commonwealth Scientific and Industrial Research Organisation (Australia)
ECHAM : European Centre/Hamburg Model (Germany)
GFDL : Geophysical Fluid Dynamic Laboratory (USA)
GISS : Goddard Institute for Space Studies (USA)
NCAR : National Center for Atmospheric Research (USA)
OSU : Oregon State University
UKMO : United Kingdom Meteorological Office
UKHI : United Kingdom Meteorological Office high resolution model
UKTR : United Kingdom Meteorological Office high transient output model (UK)
HadCM2 : Hadley Centre's second generation coupled ocean-atmospheric GCM (UK)
HadCM3 : Hadley Centre's third generation coupled ocean-atmospheric GCM (UK)

Type

EQ: equilibrium, TRS: transient with simple ocean, TRC: transient cold start with dynamic ocean, TRW: transient warm start with dynamic ocean.

Forcing: increase in CO_2 equivalent concentration.

ΔT_{2xCO_2} (ºC): effective climate sensitivity, equilibrium warming at CO_2-doubling from AOGCM experiments.

DDC: availability from IPCC Data Distribution Centre.

- **Atmospheric GCMs coupled to a three-dimensional representation of the ocean and a three-dimensional terrestrial biosphere model (aerosol experiments)**. Examples of the models are HadCM2 and HadCM3. The aerosols, which can be included in the model[4-11], may affect climate directly by scattering and absorbing solar radiation, and indirectly by altering the properties and lifetime of the clouds. The effect is to cool the surface temperature (i.e. a negative radiative forcing). At present, only the direct effect can be included in the model. Similar to AOGCMSs, these models perform transient-response experiments.

When creating GCM-based scenarios, there are a number of questions that need to be considered (Goodess, 2000). Some of important ones are briefly discussed as follows:

- **What underlying emissions scenarios should be used to predict atmospheric greenhouse gas and aerosol concentration?**
  The IPCC Special Report on Emissions Scenarios (SRES) in replacing the IS92 scenarios identifies 40 different scenarios in following four families of story-lines[4-12] with radiative forcing increases ranging from 0.4% to 1.2% per year (IPCC, 2000). Each of the scenarios is equally probable.

[4-11] The effect of aerosols is included in the models, usually under the assumptions of the IS92a scenario SO_2 emission profiles.

[4-12] SRES contains 40 scenarios that fall into four qualitative storylines (IPCC, 2000): A1, A2, B1and B2.

The **A1 storyline** describes a future world of very rapid economic growth, global population that peaks in the mid twenty-first century and declines thereafter. The A1 family develops into three groups that describe alternative directions of technological change in the energy system. These three: A1FI is fossil intensive (highest), A1T is non-fossil energy sources (mid), and A1B is a balance across all sources (lowest).

The **A2 storyline** describes a very heterogeneous world. The global population increases continuously and the economic development is primarily regionally oriented and per capita economic growth is more fragmented and slower than in other families.

The **B1 storyline** describes a convergent world with the same global population that peaks in the mid twenty-first century and declines thereafter, as in the A1 family, but with rapid changes in economic structures toward a service and information economy, with reduction in material intensity, and the introduction of clean and resource-efficient technologies.

The **B2 storyline** describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. The global population increase is at a lower rate than A2 family, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and

- **Which GCM or GCMs should be used?**

  GCMs are run by a number of centres. Some differences exist among the models, which result in various climate sensitivities[4-13] in a range between 1.5° and 4.5°C. Therefore, for sensitivity analyses, it is often useful to consider the results of several models when constructing the scenarios.

- **What method of downscaling should be used?**

  The current GCMs normally give a coarse resolution result in the order of 2.5° latitude and 3.75° longitude or about 400 km at 45° N or S latitude (see e.g. Kite and Haberlandt, 1999). Usually, a higher resolution (less than 50 km) is required for climate change impact studies. This requirement discourages the use of GCMs in climate change impact assessment studies (e.g. Mimikou *et al.*, 1991). In order to overcome this problem, there is a need to downscale the coarse grid size of GCM results to the grid size as required for the impact assessment studies (Hewitson and Crane, 1996) as illustrated in Figure 4.4. Nowadays, there are a number of methods that have been developed for downscaling the output of this GCM simulation into the required scale that allows the GCMs results to be projected at finer resolutions (Lins *et al.*, 1997). Thus, spatial scales should no longer be a problem.

Some authors (e.g. Houghton *et al.*, 2001; Carter and La Rovere, 2001; Wilby and Wigley, 1997) have reviewed the downscaling methods. In general, the downscaling methods can be classified into three main types: **regional climate modelling, statistical methods and variable- and high-resolution GCM experiments.** Of these three methods, the first two are the most commonly used

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A1 families. The scenario is oriented towards environmental protection but it focuses on local and regional levels.

[4-13] Climate sensitivity is defined as the temperature change in response to a doubling of the atmospheric CO_2 concentration (or its equivalent radiative gases).

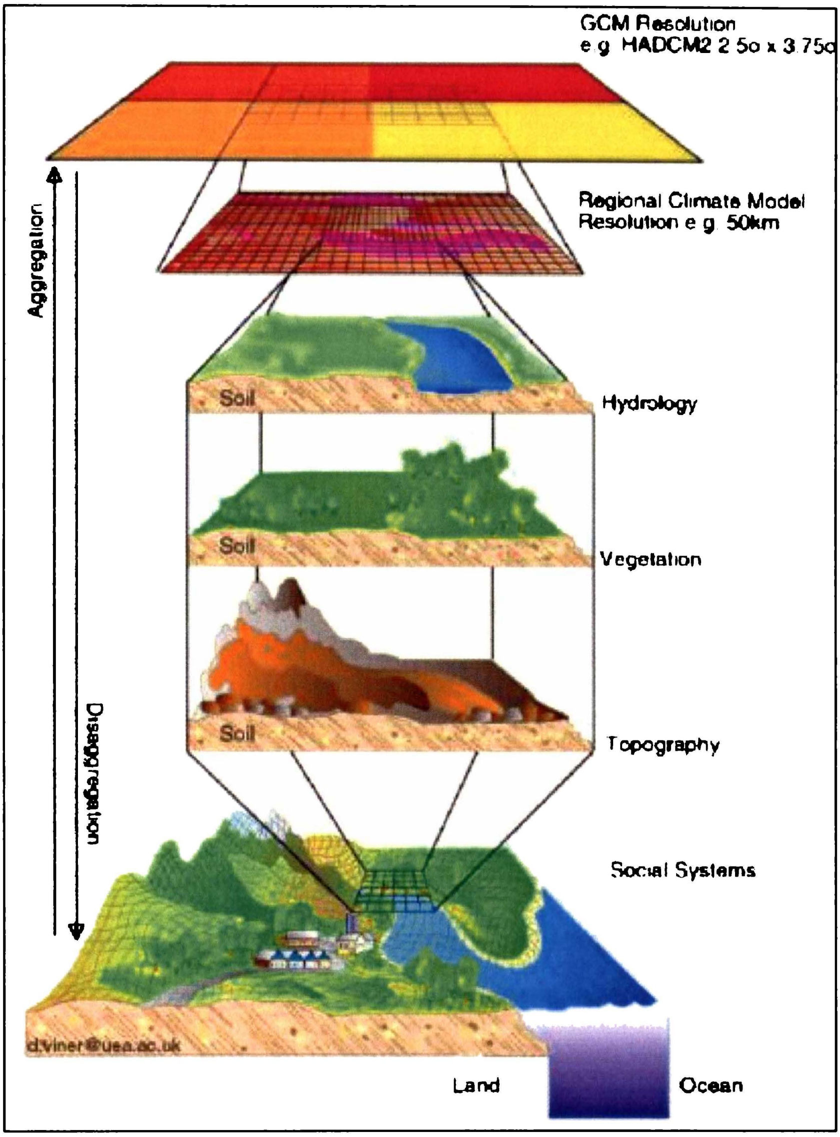


Figure 4.4: Scenario construction for impact assessment (source: Viner, 2000).

for impact assessments and will be discussed further in some detail. The third method, **variable- and high-resolution GCM experiments** (Fox-Rabinovitz *et al.*, 1997), is less commonly used. It allows integrated assessments and uncertainties to be explored, but the spatial resolution of the output is low and the temporal variability is poorly presented (Carter and La Rovere, 2001).

The regional climate modelling (RegCM), which is also known as **limited area climate model (LAM)**, uses output from GCM simulations to provide initial and driving lateral meteorological boundary conditions for high-resolution regional climate model (RegCM) simulations, with no feedback from the RegCM to the driving GCM (Giorgi *et al.*, 1990; Mearns *et al.*, 1995). Therefore, it involves nesting a finer-scale regional climate model (with a typical spatial horizontal grid resolution in a range between 20 and 50 km, and 100 to 1000 m vertical resolution) within the coarse-scale GCM. This method is considered to have good potential because some weather extremes can be well presented using this approach, including orographic influenced precipitations. Weather extremes are well presented using this approach. However, the use of this method is currently restricted by a number of technical problems and limitations, in particular its need for heavy and expensive computation and therefore limits the number of scenarios that can be performed (Goodess, 2000; Carter and La Rovere, 2001).

The statistical downscaling methods generally involve two main steps. The first step is the development of statistical relationships between local climate variables (e.g. surface air temperature and precipitation) and large-scale predictors. The next step is the application of such relationships to the output of the GCM experiments in order to simulate local climate characteristics, with an assumption that these statistical relationships remain the same in the future. The statistical downscaling methods can be approached by a regression technique (Hewitson and Crane, 1996; von Storch, 1993; Wigley *et al.*, 1990), a correlation with regional weather (circular) patterns (e.g. Bárdossy *et al.*, 1995; Hughes and Guttorp, 1994), and a stochastic weather generator (Markov's chain) approach (e.g. Wilks, 1992; Wilby *et al.*, 1994; Mearns *et al.*, 1996). Of all these statistical methods, Wilby *et al.* (1998) found that the weather generator approach with a stochastic method produced the best result.

The statistical methods have an advantage in requiring less expensive computation than the regional climate model-based approach, which allows quick application to multiple GCMs. However, they have a major disadvantage in that they do not represent physical processes, and the internal relationships are kept fixed in the future. In addition, developing a statistical downscaling method will always require very extensive observational data, and very often it cannot be transported easily from one region to another.

The simplest method of getting a finer resolution of climate change information is by interpolating the coarse GCM scale changes to a finer resolution, that is by perturbing the observed data by the GCM scale climate change scenario. This is called a **simple downscaling** because no additional meteorological information is added into the GCM based changes. This method is used in SCENGEN[4-14] (Hulme *et al.*, 2000) and CLIMPACTS[4-15] (Kenny *et al.*, 1995).

Simple climate models (SCMs)

Simple climate models (SCMs) are the early climate models in the hierarchy of complexity or the number of dimensions in the model (see Footnote 4-8 of this chapter for a brief review of the climate models). They represent the physical processes of climate components, but in simpler ways than the complex GCMs. Therefore, they can be used to construct scenarios in the same way as the GCMs. These models have been published in the IPCC Technical Paper II (Harvey *et al.*, 1997) and were widely used in the Secondary Assessment Report of Working Group I (SAR WGI). These models are discussed here because, even though they can be used to construct climate scenarios, they require some parameters to be derived from the complex climate models.

[4-14] SCENGEN is a global and regional SCENario GENerator database program that contains the results of a large number of GCM experiments, as well as observed global and regional climate data sets. SCENGEN manipulates the information about the rate and the magnitude of global warming and as directed by the user, can portray regional climate change.

[4-15] CLIMPACTS is an integrated computer-based system developed in the IGCI - the University of Waikato. This system will be discussed in the later section of this chapter, and in more detail in Chapter 7 (Climate component).

Normally, the SCMs consist of four modules for performing the calculation in steps that make it possible to produce changes of global mean temperature and mean sea level rise (Harvey *et al.*, 1997). The modules are: GHGs concentration emissions, radiative forcing, global mean temperature, and sea level rise. However, they are fundamentally different to the AOGCMs in several ways as follows.

- The SCMs belong to the one-dimensional energy balance models that cannot simulate the changes in the ocean, equilibrium response model, but time dependent scenarios can be deduced from the scenario of global mean radiative forcing. The complex GCMs (i.e. AOGCMs) are three-dimensional atmosphere and ocean GCMs, transient response (time dependent), and able to simulate changes in ocean circulation.
- The SCMs generally produce zonally- or globally-averaged results and therefore the simulation can only be performed on temperature change, and not for rainfall, etc. The AOGCMs are capable of simulating geographical variations of temperature, and other climate variables such as rainfall, evaporation, soil moisture, winds, etc.
- The SCMs require some basic information, such as climate sensitivity data, that must be derived from complex models. The AOGCMs compute such information based on physical laws.
- The SCMs can generate multi-scenarios quickly with a relatively low computational cost. The AOGCMs require a very high computational cost that limits the number of scenarios to be generated. In fact, this is the major disadvantage of complex GCMs.

Even though they are different in nature, both simple and complex climate models are useful in projecting future climate change. The SCMs are most useful for sensitivity studies as their results can be quickly generated. The complex climate models (AOGCMs) are useful for studies that emphasise the fundamental process, for which some parameters and properties of the SCMs need to be derived from the complex climate models.

Selecting the method for the climate component

The selected method for producing climate scenarios should follow the criteria as discussed in Section 4.1, which are simple (not highly data demanding and highly computationally demanding), and for the climate component, most important is the ability to generate scenarios quickly in order to conduct the sensitivity analyses, which is the aim of this thesis. The previous section has identified several methods to generate the scenarios.

From the discussion in the previous section, it can be decided that the GCM based patterns model fits well with the climate component of the proposed integrated model and a simple climate model is used for generating these global climate change patterns. A simple interpolation method can be applied in order to downscale the GCM climate change scenarios to a local scale for the study area. This downscaling method should be sufficient to meet the purpose of this study.

An integrated model that meets these selections has been developed, called CLIMPACTS (Warrick *et al.*, 1996; 2001; Kenny *et al.*, 1995). CLIMPACTS is a national and sub-national scale, integrated computer-based system that combines models and datasets, which is designed for assessing the impacts of climate change and variability on the New Zealand environment. It contains a model to produce time-dependent scenarios of regional changes in climate, which is accomplished by linking the time-dependent predictions of global temperature change from emissions of greenhouse gases (emission scenarios) with the output of GCM simulation results. Its variants have been developed for different regions such as Bangladesh (BDCLIM) and Australia (OZCLIM) (available interactive on http://www.dar.csiro.au/publications/ozclim.htm). One of the advantages of this model is its flexibility - it can be easily adapted to any region in the world, can be continuously upgraded to follow developments in climate change science, and can be designed to conduct sensitivity studies of any climate change related issue. This model can be adopted to fulfil the requirements for the proposed integrated model of this thesis.

In summary, the climate component, as well as the integrating core model framework, will be derived from the source code of the existing model (i.e. CLIMPACTS). The model uses the results of GCM experiments, together with the output of a SCM. The scenario generation, including scenario selection, will be discussed in more detail in Chapter 7.

4.6 CONCLUSION

The purpose of this integrated model is to help policy-makers and decision-makers to conduct sensitivity analysis on the impact of land use and climate changes on streamflows. This specific focus has influenced the structures and the way this integrated model is developed.

The integrated model consists of three main components, two of which produce scenarios of changes. These are the land use component and the climate component, which are linked to the hydrological component as a cause-effect process. The output of the model is seasonal streamflows in the form of hydrographs.

In developing each component of the integrated model, there is a choice to either adapt an existing model for the specified component, or construct the model component from the beginning. The first choice seems favourable because it reduces time and effort in computer programming. However, in selecting the appropriate model to be adapted, there are some aspects that need to be considered for all components. These are: capability of handling heterogeneity, at what spatial scale the model is appropriate, what time scale the model is designed for, the aspect of accuracy, and the problem of 'black box' or less conceptualised models as against conceptual models. In addition, how the model copes with the problem of regulated streamflows is also under consideration, particularly for the hydrological model. These aspects influence the selection of the appropriate model or method for the development of each model component.

There is no model and method that can be used directly for the hydrological component. This component will require a physically-distributed type of model (i.e. parameters are distributed on grid cell basis) and uses fundamental water balance equations for its computational procedure. With this approach of using grid-cells, the model can quickly compute the changes as the result of changes in land use patterns. The water balance concept has been chosen because it has simple structures and has a limited number of parameters in contrast to the complex physically-distributed parameter models that contain details of physical processes and a very large number of parameters.

The land use component adopts the simple cellular automata method for generating the pre-defined scenarios. All analytical processes and scenario generation are performed on, or with the help of, a computer based GIS. With this method, the changes in land use patterns are spatially explicit and they are readily linked into the hydrological component.

The climate component and integrating framework will adopt the method used in CLIMPACTS that has been successfully used for climate change impact assessments. This model can generate time-dependent scenarios of regional climate information based on the global temperature change from greenhouse gas emission scenarios and the GCM simulation, as required by the hydrological component.

The next three chapters will discuss the construction of each component of this integrated model.

REFERENCES

About.com 1997. The Von Thünen Model. [online] available URL http://geography.about.com/science/geography/library/weekly/aa060297.htm?rnk=r1&terms=land+use+model, (24 June 2000).

Amien, I., Rejekiningrum, P., Pramudia, A. and Susanti, E. 1996. Effects of interannual climate variability and climate change on rice yield in Java, Indonesia. *Water, Air and Soil Pollution* 92, 29-39.

Arnold, J.G., Srinivasan, R., Muttiah, R.S. and Williams, J.R. 1998. Large area hydrologic modelling and assessment. Part I: Model development. *Journal of the American Water Resources Association* 34 (1), 73-89.

Balsem, T. and Buurman, P. 1989. *Guidelines for Land Unit description.* Land Resource Evaluation and Planning Project, Technical report no. 13, Centre for Soil Research, Bogor.

Bannert, D. and Riyadi, D. 1989. *Results of SPOT Image Interpretation of the Bandung Basin, West Java.* Project Report No. 2 Project CTA 108 Environmental Geology for Land Use and Regional Planning. Directorate of Environmental Geology (DEG) – GEGATI, Bandung.

Bárdossy, A. and Caspary, H.J. 1991. Conceptual model for the calculation of the regional hydrologic effects of climate change. In: F.H.M. van de Ven, D. Gutknecht, D.P. Loucks and K.A. Salewicz (eds.), *Hydrology for the Water Management of Large River Basins.* IAHS Publ. No. 201, 73-82.

Bárdossy, A., Duckstein, L. and Bogardi, I. 1995. Fuzzy rule-based classification of atmospheric circulation patterns. *International Journal of Climatology* 15, 1087-1097.

Bathurst, J.C. 1986. Physically-based distributed modelling of an upland catchment using the Systeme Hydrologique Europeen. *Journal of Hydrology* 87, 79-102.

Beven, K.J. and O'Connell, P.E. 1982. *On the Role of Physically-Based Distributed Modelling in Hydrology.* Institute of Hydrology Report No. 81, Institute of Hydrology, Wallingford.

Beven, K.J., Wood, E.F. and Sivapalan, M. 1988. On hydrological heterogeneity – catchment morphology and catchment response. *Journal of Hydrology* 100, 353-375.

Bonan, G.B. 1997. Effects of land use on the climate of the United States. *Climatic Change* 37, 449-486.

Brown, L.A. 1970. On the use of Markov chains in movement research. *Economic Geography* 46, 393-403.

Budyko, M.I. 1989. Empirical estimates of imminent climatic changes. *Soviet Meteorology and Hydrology* 10, 1-8.

Bultot, F., Dupriez, G.L. and Gellens, D. 1990. Simulation of land-use changes and impacts on the water balance – a case study for Belgium. *Journal of Hydrology* 114, 327-348.

Carter, T.R. and La Rovere, E.L. 2001. Developing and applying scenarios. In: J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken and K.S. White (eds.) *Climate Change 2001: Impacts, Adaptation, and Vulnerability.* Contribution of Working Group II to the Third Assessment Report of the IPCC, Cambridge University Press, Cambridge, U.K.

Chomitz, K.M. and Gray, D.A. 1995. Roads, land, market and deforestation – A spatial model of land use in Belize. Environment, Infrastructure, and Agriculture Division, Policy Research Department, The World Bank

Choudhry, S.A. 1998. *Surface Hydrologic Modelling and GIS: A Case Study of the Kaimai Hydropower Project Catchment, New Zealand.* PhD Thesis, University of Waikato, New Zealand.

Colby, J.D. 1996. Physical characterization of the Navarro Watershed for hydrologic simulation. *AWRA Symposium on GIS and Water Resources* Sept. 22-26, 1996, Ft. Lauderdale, Fl.

Cotton, W.R. and Pielke, R.A. 1995. *Human Impacts on Weather and Climate* Cambridge University Press, 288pp.

Cropper, M. 1998. Regional land use modeling: past experience and future directions – Abstract. *Land Use/Cover Change-Data and Information System (LUCC-DIS) Workshop, 13-18 August 1998.* [online] available URL http://www.start.or.th/luccdis_98/socioeconomic_model.htm [20 April 2000].

Di Gregorio, A. and Jansen, L.J.M. 1998. A new concept for land cover classification system. *SDdimensions* Sustainable Development Department, FAO, (abstract) [online] available URL http://www.fao.org/WAICENT/FAOINFO/SUSTDEV/Eidirect/EIre0065.htm [29 Aug. 2001].

Dunn, S.M. and MacKay, R. 1995. Spatial variation in evapotranspiration and the influence of land use on catchment hydrology. *Journal of Hydrology* 171, 49-73.

Dunne, T. and Leopold, L.B. 1978. *Water in Environmental Planning* W.H. Freeman and Company, San Fransisco.

Dvorak, V., Hladny, J. and Kasparek, L. 1997. Climate change hydrology and water resources impact and adaptation for selected river basins in the Czech Republic. *Climate Change* 36, 93-106.

Eastman, J.R. 1995. *Idrisi for Windows - User's Guide Version 1.0* Clark Labs for Cartographic Technology and Geographic Analysis, Clark University, Worcester, U.S.A.

Eeles, C.W.O. and Blackie, J.R. 1993. Land-use changes in the Balquhider catchments simulated by a daily streamflow model. *Journal of Hydrology* 145, 315-336.

Ewen, J. and Parkin, G. 1996. Validation of catchment models for predicting land-use and climate change impacts – 1. Method. *Journal of Hydrology* 175, 583-594.

Flügel, W.-A. 1995. Hydrological response units (HRUs) to preserve basin heterogeneity in hydrological modelling using PRMS/MMS – case study in the Bröl basin, Germany. In: S.P. Simonovic, Z. Kundzewicz, D. Rosbjerg and K. Takeuchi (eds.) *Modelling and Management of Sustainable Basin-Scale Water Resource Systems.* IAHS Publ. No. 231, 79-87.

Fox-Rabinovitz, M.S., Stenchikov, G. and Takacs, L.L. 1997. A finite-difference GCM dynamical core with a variable resolution stretched grid. *Monthly Weather Review* 125, 2943-2961.

GARP 1975. *The Physical Basis of Climate and Climate Modelling: Report of the International Study Conference in Stockholm, 29 July - 10 August 1974.* GARP Publications Series No. 16.

GCTE 1996. *Workshop Summary and Synthesis – Living with Global Change: Linking Science and Policy in Southeast Asia, 13-15 August 1996, Bogor, Indonesia.* Global Change and Terrestrial Ecosystems Report No. 14 - BIOTROP-GCTE Southeast Asian Impacts Centre IC-SEA Report No. 2.

Geist, H.J. and Lambin, E.F. 2001. *What Drives Tropical Deforestation? A meta-analysis of proximate and underlying causes of deforestation based on subnational case study evidence.* LUCC Report Series No. 4, Ciaco, Louvain-la-Neuve.

Geoghegan, J., Ogneva-Himmelberger, Y. and Turner II, B.L. 1997. A spatially explicit Markov model of land cover change in Southern Mexico – Abstract. *American Journal of Agricultural Economics* 79 (5), 1714-1714.

Giorgi, F., Marinucci, M.R. and Visconti, G. 1990. Use of a limited-area model nested in a general circulation model for regional climate simulation over Europe. *Journal of Geophysics* 95 (D11), 18,413-18,431.

Goodess, C. 2000. Climate change scenarios. *CRU Information Sheet No. 9.* Climatic Research Unit, University of East Anglia, [online] available URL http://www.cru.uea.ac.uk/cru/info/scen/ [18 Mar 2002].

Gustard, A. 1992. Analysis of river regimes. In: P. Calow and G.E. Petts (eds.) *The River Handbook – Hydrological and ecological principles, Vol. 1.* Blackwell Scientific Publ., Oxford, 29-47.

Hackett, C. 1988. *Matching Plants and Land: Development of a general broadscale system from a crop project for Papua New Guinea.* Natural Resource Series No. 11, CSIRO Division of Water and Land Resources.

Hall, C.A.S., Tian, H., Qi, Y., Pontius, G. and Cornell, J. 1995. Modelling spatial and temporal patterns of tropical land use change. *Journal of Biogeography* 22, 753-757.

Hansen, A. 1998. Causes and consequences of land cover in a greater ecosystem: Trend assessment, monitoring and outreach - Abstract. [online] available URL http://lcluc.gsfc.nasa.gov/products/pdfs/Abstract-US-Hansen.pdf [13 Sept. 2000]

Harvey, D., Gregory, J., Hoffert, M., Jain, A., Lal, M., Leemans, R., Raper, S., Wigley, T. and de Wolde, J. 1997. *An Introduction to Simple Climate Models used in the IPCC Second Assessment Report.* IPCC Technical Paper II, IPCC, 51pp.

Hasan, N.M.H. 1999. A large scale ecosystem scenario development tool based on QUEST. *Information Paper For NETTLAP Regional Conference – Making A Difference: Progress in Environmental Education, Training and Research in Asia and the Pacific.* 30 September – 2 October 1999, Phuket, Thailand.

He, M., Douglas, I. and Chen, Z. 1997. Hydrological effects of forests in northwestern Sichuan, China. In: D. Rosbjerg, N-E. Boutayeb, A. Gustard, Z.W. Kundzewicz and P.F. Rasmussen (eds.), *Sustainability of Water Resources under Increasing Uncertainty.* IAHS Publ. No. 240, 201-210.

Hewitson, B.C. and Crane, R.G. 1996. Climate downscaling: techniques and application. *Climate Research* 7, 85-95.

Hornbeck, J.W., Federer, C.A. and Pierce, R.S. 1987. Effects of whole-tree clearcutting on streamflow can be adequately estimated by simulation. In: R.H. Swanson, P.Y. Bernier and P.D. Woodard (eds.), *Forest Hydrology and Watershed Management.* IAHS Publ. No. 167, 565-573.

Houghton, J.T., Ding, Y. Griggs, D.J. Noguer , M., Van der Linden, P.J., Da, X., Maskell, K. and Johnson, C.A. (eds.) 2001. *Climate Change 2001: The Scientific Basis.* Contribution of Working Group I to the Third Assessment Report of the IPCC, Cambridge University Press, Cambridge, U.K.

Houghton, J.T., Meira-Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. and Masekel, K. (eds.) 1996. *Climate Change 1995 - The Science of Climate Change.* Cambridge University Press, Cambridge, U.K.

Houghton, J.T., Meira-Filho, L.G., Bruce, J., Lee, H., Callander, B.A., Haites, E., Harris, N., and Maskell, K. (eds.) 1995. *Climate Change 1994: Radiative*

Forcing of Climate Change and An Evaluaion of the IPCC IS92 Emission Scenarios. Cambridge University Press, Cambridge, U.K.

Houghton, R.A. 1994. Emissions of carbon from land use change. In: T.M.L. Wigley and D. Schimel (eds.) *The Carbon Cycle.* Cambridge University Press, New York.

Hughes, J.P. and Guttorp, P. 1994. A class of stochastic models for relating synoptic atmospheric patterns to regional phenomena. *Water Resources Research* 30 (5), 1535-1546.

Hulme, M., Raper, S.C.B. and Wigley, T.M. 1995. An integrated framework to address climate change (ECAPE) and further developments of the global and regional climate modules (MAGICC). *Energy Policy* 23: 347-355.

Idso, S.B. 1998. CO_2-induces global warming: a skeptic's view of potential climate change (Review). *Climate Research* 10, 69-82.

IPCC 2000. *Emissions Scenarios.* A Special Report of Working Group III of the IPPC, Cambridge University Press, Cambridge, U.K.

IPCC-TGCIA 1999. *Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment.* Version 1. Prepared by T.R. Carter, M. Hulme and M. Lal, Intergovernmental Panel on Climate Change, Task Group on Scenarios for Climate Impact Assessment, 69pp.

Irwin, E.G. and Geoghegan, J. 2001. Theory, data, methods: developing spatially explicit economic models of land use change. *Agriculture, Ecosystems and Environment* 85, 7-23.

ITC 2001. *Ilwis 3.0 Academic User's Guide.* International Institute for Aerospace Survey and Earth's Scenarios.

IUC-UNEP 2002. *Climate Change Information Sheet 30.* Information Unit for Conventions (IUC), United Nations Environment Programme (UNEP), [online] available URL http://www.unep.ch/iuc/submenu/infokit/fact30.htm [21 March 2002]

Jolley, T.J. and Wheater, H.S. 1997. An investigation into the effect of spatial scale on the performance of a one-dimensional water balance model *Hydrological Process* 11, 1927-1944

Karsidi, A. 1998. Land use–land cover changes (Indonesia case study). *Land Use/Cover Change-Data and Information System (LUCC-DIS) Workshop, 13-18 August 1998.* [online] available URL http://www.start.or.th/luccdis_98/indonesia_case.htm [20 April 2000].

Kaufmann, R.K. and Seto, K.C. 2001. Change detection, accuracy, and bias in a sequential analysis of Landsat imagery in the Pearl River Delta, China: econometric techniques. *Agriculture, Ecosystems and Environment* 85, 95-105.

Kenny, G.J., Warrick, R.A., Mitchell, N.D., Mullan, A.B. and Salinger, M.J. 1995. CLIMPACTS: an integrated model for assessment of the effects of climate change on the New Zealand environment. *Journal of Biogeography* 22, 883-895.

Kite, G.W. and Haberlandt, U. 1999. Atmospheric model data for macrosclae hydrology. *Journal of Hydrology* 217, 303-313.

Kite, G.W., Dalton, A. and Dion, K. 1994. Simulation of streamflow in a macroscale watershed using general circulation model data. *Water Resource Research* 30 (5), 1547-1559.

Kuczera, G., Raper, G.P., Brah, N.S., Jayasuriya, M.D. 1993. Modelling of yield changes after strip thinning in a mountain catchment: an exercise in catchment model validation. *Journal of Hydrology* 150, 433-457.

Lambin, E.F. 1997. Modelling and monitoring land-cover change processes in tropical regions. *Progress in Physical Geography* 21 (3), 375-393.

Leavesley, G.H., Lichty, R.W., Troutman, B.M. and Saindon, L.G. 1983. Precipitation-Runoff Modeling System: User's Manual. *Water-Resources Investigations Report* No. 83-4238.

Leggett, J., Pepper, W.J. and Swart, R.J. 1992. Emissions scenarios for the IPCC: an update. In: J.T. Houghton, B.A. Callander and S.K. Varney (eds.) *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment.* Cambridge University Press, Camcridge, U.K.

Lins, H.F., Wolock, D.M., and McCabe, G.J. 1997. Scale and modeling issues in water resources planning. *Climatic Change* 37, 63-88.

Liu, C-M. 1987. Source of increased stormwaters after forest operations. In: R.H. Swanson, P.Y. Bernier and P.D. Woodard (eds.), *Forest Hydrology and Watershed Management.* IAHS Publ. No. 167, 539-544.

Lørup, J.K. and Hansen, E. 1997. Effects of land use on the streamflow in the southwestern highlands of Tanzania. In: D. Rosbjerg, N-E. Boutayeb, A. Gustard, Z.W. Kundzewicz and P.F. Rasmussen (eds.), *Sustainability of Water Resources under Increasing Uncertainty.* IAHS Publ. No. 240, 227-236.

Lørup, J.K., Refsgaard, J.C. and Mazvimavi, D. 1998. Assessing the effect of land use change on catchment runoff by combined use of statistical tests and hydrological modelling: Case studies from Zimbabwe. *Journal of Hydrology* 205, 147-163.

Lough, J.M., Wigley, T.M.L. and Palutikof, J.P. 1983. Climate and climate impact scenarios for Europe in a warmer world. *Journal of Climatology and Applied Meteorology* 22, 1673-1684.

Maidment, D.R. 1991. Hydrologic modelling. *Proc. 1st International Symp./Workshop on GIS and Environmental Modelling (15-19 Sept. 1991) in Boulder, Colorado.* Oxford University Press, NY.

Manabe, S. 1975. The use of comprehensive general circulation modelling for studies of the climate and climate variation. In: GARP, *The Physical Basis of Climate and Climate Modelling: Report of the International Study Conference in Stockholm, 29 July - 10 August 1974.* GARP Publications Series No. 16, Appendix 2.4.

Mearns, L.O., Giorgi, F., McDaniel, L. and Shields, C. 1995. Analysis of daily variability of precipitation in a nested regional climate model: comparison with observations and doubled CO2 results. *Global and Planetary Change* 10, 55-78.

Mearns, L.O., Rosenzweig, C. and Goldberg, R. 1996. The effect of changes in daily and interannual climatic variability on ceres-wheat: a sensitivity study. *Climatic Change* 32, 257-292.

Mimikou, M.A. 1995. Climatic change. In: V.P. Singh (ed.) *Environmental Hydrology.* Kluver Academic Publisher, Netherlands, 69-106.

Mimikou, M.A., Hadjisavva, P.S. and Kouvopoulos, Y.S. 1991. Regional effects of climate change on water resources systems. In: F.H.M. van de Ven, D. Gutknecht, D.P. Loucks and K.A. Salewicz (eds.), *Hydrology for the Water Management of Large River Basins.* IAHS Publ. No. 201, 173-182.

Mirza, M.M.Q. 1997. *Modelling the effects of climate change on flooding in Bangladesh.* D.Phil. Thesis. University of Waikato, New Zealand.

Moore, I.D., Lewis, A. and Gallant, J.C. 1993. Terrain attributes: Estimation methods and scale effects. In: A.J. Jakeman, M.B. Beck and M.J. McAleer (eds.), *Modelling change in environmental systems.* John Wiley and Sons Ltd., 189-214.

Murdiyarso, D. 1996. Climate change impacts on water resource management. Paper presented in: Workshop on Living with Global Change – Linking Science and Policy in Southeast Asia, Bogor, Indonesia, 13-15 August 1996. Sponsored by START and IC-SEA.

Nandakumar, N. and Mein, R.G. 1997. Uncertainty in rainfall – runoff model simulations and the implications for predicting the hydrologic effects of land-use change. *Journal of Hydrology* 192, 211-232.

NASA 1998. Global warming. *NASA Facts* NF-222, April.

Newson, M. 1994. *Hydrology and the River Environment.* Clarendon Press, Oxford.

Ott, M., Su, Z., Schumann, A.H. and Schultz, G.A. 1991. Development of a disturbed hydrological model for flood forecasting and impact assessment of land-use change in the international Mosel river basin. In: F.H.M. van de Ven, D. Gutknecht, D.P. Loucks and K.A. Salewicz (eds.), *Hydrology for the Water Management of Large River Basins.* IAHS Publ. No. 201, 183-194.

Palutikof, J. 2001. Global temperature record. *CRU Information Sheet No. 1.* Climatic Research Unit, University of East Anglia, [online] available URL http://www.cru.uea.ac.uk/cru/info/warming/ (18 Mar 2002).

Parkin, G., O'Donnell, G., Ewen, J., Bathurst, J.C., O'Connell, P.E., and Lavabre, J. 1996. Validation of catchment models for predicting land-use and climate change impacts – 2. Case study for a Mediterranean catchment. *Journal of Hydrology* 175, 595-613.

Rowe, L. 1998. Forestry and water resources. *Catchment Connections.* Issue 3, 7-8.

Sader, S.A. 1998. *Time-series forest change, land-cover/land-use conversion and socio-economic driving forces in the Peten District, Guatemala.* A Progress Repot to NASA - ESE - LCLUC Science Program, March 2000

Scharpenseel, H.-W. and Pfeiffer, E.M. 1998. Impacts of possible climate change upon soils; some regional consequences. *Advances in GeoEcology* 31, 193-208.

Schneider, S.H. and Dickinson, R.E. 1974. Climate modeling. *Reviews of Geophysics - Space Physics* 27, 447-493.

Schneider, S.H., and Dickinson, R.E. 1975. Climate modelling methodology. In: GARP, *The Physical Basis of Climate and Climate Modelling: Report of the International Study Conference in Stockholm, 29 July - 10 August 1974.* GARP Publications Series No. 16, Appendix 2.3.

SEA START RC 1999. *Indonesia: land use and land cover change case study.* [online] available URL http://www.start.or.th/LUCC/indonesia_lucc.htm [20 April 2000].

Serneels, S. and Lambin, E.F. 2001. Proximate causes of land-use change in Narok District, Kenya: a spatial statistical model. *Agriculture, Ecosystems and Environment* 85, 65-81.

Shabalova, M.V. and Können, G.P. 1995. Climate change scenarios: comparisons of Paleoreconstructions with recent temperature changes. *Climatic Change* 29, 409-428.

Shaw, E.M. 1988. *Hydrology in Practice.* 2nd edn. Van Nostrand Reinhold, London.

Sklar, F.H. and Costanza, R. 1991. The development of dynamic spatial models for landscape ecology: a review and prognosis. In: M.G. Turner and R.H. Gardner (eds.) *Quantitative Methods in Landscape Ecology. Ecological Studies* Vol. 82, Springer Verlag, New York, 239-288.

Skole, D. and Tucker, C. 1993. Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978 to 1988. *Science* 260, 1905-1910.

Sokolov, A.A. and Chapman, T.G. (eds.) 1974. *Methods for Water Balance Computations – An international guide for research and practice.* The Unesco Press, Paris.

Spectranalysis Inc. 2001. Ontario Land Cover Classification. *Spectranalysis Inc.* [online] available URL http://www.spectranet.ca/spectranalysis/htm/landcov.htm [29 Aug. 2001]

Storm, B., Jørgensen, G.H. and Styczen, M. 1987. Simulation of water flow and soil erosion processes with a distributed physically-based modelling system. In: R.H. Swanson, P.Y. Bernier and P.D. Woodard (eds.), *Forest Hydrology and Watershed Management.* IAHS Publ. No. 167, 595-608.

Stuebe, M.M. and Johnston, D.M. 1990. Runoff volume estimation using GIS techniques. *Water Resources Bulletin* 26 (4), 611-620.

Taniguchi, M. and Bari, M.A. 1997. Hydrological impacts of forest clearing and reforestation in southwest Western Australia. In: D. Rosbjerg, N-E. Boutayeb, A. Gustard, Z.W. Kundzewicz and P.F. Rasmussen (eds.), *Sustainability of Water Resources under Increasing Uncertainty.* IAHS Publ. No. 240, 211-216.

Thornthwaite, C.W. and Mather, J.R. 1957. *Instructions and Tables for Computing Potential Evapotranspiration and The Water Balance.* Publications in Climatology, Vol. X (3), Drexel Institute of Technology - Laboratory of Climatology, Centerton, New Jersey.

Thornton, P.K. and Jones, P.G. 1998. A conceptual approach to dynamic agricultural land-use modelling. *Agricultual Systems* 57 (4), 505-521.

Turner II, B.L., Moss, R.H. and Skole, D.L. (eds.) 1993. *Relating Land Use and Global Land-Cover Change: A proposal for an IGBP-HDP Core Project.* IGBP Report No. 24, HDP Report No. 5, Stockholm.

Veldkamp, A. and Fresco, L.O. 1996. CLUE-CR: an integrated multi-scale model to simulate land use change scenarios in Costa Rica. *Ecological Modelling* 91, 231-248.

Verburg, P.H., De Koning, G.H.J., Kok, K., Veldkamp, A. and Bouma, J. 1999. A spatially explicit allocation procedure for modelling the pattern of land use change based upon actual land use. *Ecological Modelling* 116, 45-61.

Viner, D. 2000. Modelling climate change. *CRU Information Sheet No. 8.* Climatic Research Unit, University of East Anglia, [online] available URL http://www.cru.uea.ac.uk/cru/info/warming/ [18 Mar 2002].

Vogel, R.M. and Kroll, C.N. 1990. Generalized low-flow frequency relationships for ungaged sites in Massachusetts. *Water Resources Bulletin* 26 (2), 241-253.

Von Storch, H. Zorita, E. and Cubasch, U. 1993. Downscaling of global climate change estimates to regional scales: an application to Iberian rainfall in wintertime. *Journal of Climate* 6 (6), 1161-1171.

Vörösmarty, C.J., Moore III, B., Grace, A., Peterson, B.J., Rastetter, E.B. and Melillo, J. 1991. Distributed parameter models to analyze the impact of human disturbance of the surface hydrology of a large tropical drainage basin in Southern Africa. In: F.H.M. van de Ven, D. Gutknecht, D.P. Loucks and K.A. Salewicz (eds.), *Hydrology for the Water Management of Large River Basins.* IAHS Publ. No. 201, 233-244.

Warrick, R.A. 1984. The possible impacts on wheat production of a recurrence of the 1930s drought in the U.S. Great Plains. *Climatic Change* 6, 5-26.

Warrick, R.A., Kenny, G.J. and Harman, J.J. (eds.) 2001. *The Effects of Climate Change and Variation in New Zealand, An Assessment Using the CLIMPACTS System.* International Global Change Institute, University of Waikato, Hamilton, New Zealand.

Warrick, R.A., Kenny, G.J., Sims, G.C., Ericksen, N.J., Ahmad, A.K. and Mirza, M.Q. 1996. Integrated model systems for national assessments of the effects of climate change: applications in New Zealand and Bangladesh. *Water, Air, and Soil Pollution* 92, 215-227.

Wasson, R.J. (ed.) 1996. *Land use and climate impacts on fluvial systems during the period of agriculture: Recommendations for a research project and its implementation.* PAGES Workshop Report, Series 96-2.

White, R. and Engelen, G. 1993. Cellular automata and fractal urban form: a cellular modelling approach to the evolution of urban land-use patterns. *Environment and Planning A* 25, 1175-1199.

Wigley, T.M.L., Jones, P.D., Briffa, K.R. and Smith, G. 1990. Obtaining sub-grid-scale information from coarse-resolution General Circulation Model output. *Journal of Geophysical Research* 95 (D2), 1943-1953.

Wilby, R., Greenfied, B. and Glenny, C. 1994. A coupled synoptic-hydrological model for climate change impact assessment. *Journal of Hydrology* 153, 265-290.

Wilby, R.L. and Wigley, T.M.L. 1997. Downscaling general circulation model output: a review methods and limitations. *Progress in Physical Geography* 21 (4), 530-548.

Wilby, R.L., Wigley, T.M.L., Conway, D., Jones, P.D., Hewitson, B.C., Main, J. and Wilks, D.S. 1998. Statistical downscaling of general circulation model output: A comparison of methods. *Water Resources Research* 34 (11), 2995-3008

Wilkie, D., Morelli, G., Rotberg, F. and Shaw, E. 1999. Wetter isn't better: global warming and food security in the Congo Basin. *Global Environmental Change* 9 (4), 323-328.

Wilks, D.S. 1992. Adapting stochastic weather generation algorithms for climate change studies. *Climatic Change* 22, 67-84.

CHAPTER 5

HYDROLOGICAL COMPONENT

5.1 INTRODUCTION

The hydrological component is the component that processes all information derived as required from the other two components (land use and climate) and, together with other hydrological parameters, produces seasonal streamflows as the output. As discussed earlier in Chapter 4 section 4.5, the hydrological component will use a water balance fundamental equation for its calculation, which will be conducted on cell-by-cell basis.

This chapter describes how this hydrological component is constructed. In general, it describes the approach in constructing this component, and the fundamental equation of the model. This chapter also discusses in some detail: the main components of water balance; the conceptual approach of water balance and how the calculation is conducted; how to translate land use information into meaningful hydrologic values; and how the model is calibrated and validated.

5.2 METHODOLOGY

The hydrological component is constructed using the distributed parameter approach on a grid system, by dividing the catchment area into a number of equal-size cells (Figure 5.1). The basic calculation is conducted on a cell-by-cell basis. Each cell represents one set of homogeneous hydrological characteristics

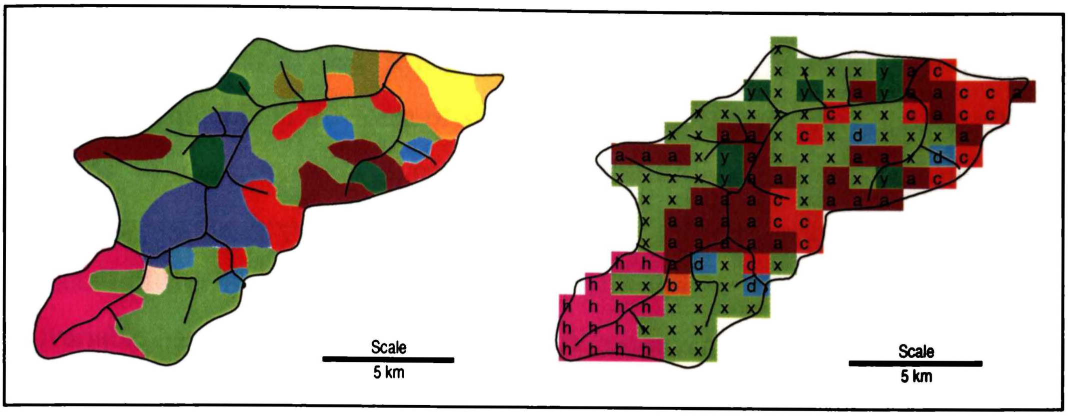


Figure 5.1: An illustration to convert a polygon type map (left) into a grid type map (right). Colours on the left map represent variation in land use, while on the right they represent variation in hydrological character (e.g. water consumption). Each cell is represented by the predominant character within that area of cell. Two or more types of land use may have similar characteristics of water consumption and therefore can merge into one class.

including land use that may differ from other cells. This method allows quick computation when the land use type of a cell changes. Thus, sensitivity analyses on the impacts of such changes can be performed quickly.

The appropriate size of the grid cell needs to be selected for the model to work effectively. For example, if the cell size is too large, depending on the rate of land use change, progressive spatial changes in the land use over a decade time scale may not be observable. In an extreme case, the cell may contain too much information so that a representative value may be difficult to pick. On the other hand, if the cell size is too small, the computation can be unnecessarily too much. Hence, it is important to choose the appropriate cell size that will allow noticeable changes in land use within a specific time-scale of observation and maintain the computation to a manageable amount.

To reduce the complexity of computation, the hydrological component for this study is based on some fundamental assumptions. It assumes that:

- The slope variable is already included into some coefficients within the mathematical functions such as the storm runoff and infiltration coefficients. In general, the slope variable can be significant in determining the runoff. The water from rainfall that reaches a land surface with a high slope tends to dissipate quickly in the form of storm runoff, but when it reaches a flat surface tends to dissipate slowly mainly through infiltration. However, this study focuses on the impact of land use change on the streamflows and not on the detail of the hydrological process. Thus, it is possible to assume that the slope variable has been included in some of the coefficients used by the model. Later on, all the coefficients that are used in the model will be adjusted in order to ensure that the model can perform well;

- The interconnected cell-to-cell flow is negligible.[5-1] The study area has a rough topography, in which every cell is positioned very close to a gully or stream. Therefore, it is acceptable to assume that the runoff (direct runoff and base flow) that comes out from each cell will join the main stream immediately. The monthly total runoff of the whole basin, therefore, can be defined as the total sum of monthly runoff from all cells in this basin.

5.3 FUNDAMENTAL EQUATION

The water balance of a water basin can be represented by Figure 5.2 and expressed in the following equation:

$$P = I + ET + \Delta SM + DRO + GWR \qquad (5\text{-}1)$$

where P is precipitation, I is interception, ET is evapotranspiration, ΔSM is the change in soil moisture, DRO is direct runoff (or overland flow), and GWR is groundwater runoff.

[5-1] A previous water balance study in Upper Cikapundung basin, a small catchment within the study area has also used such an assumption (Delinom and Suriadarma, 1993).

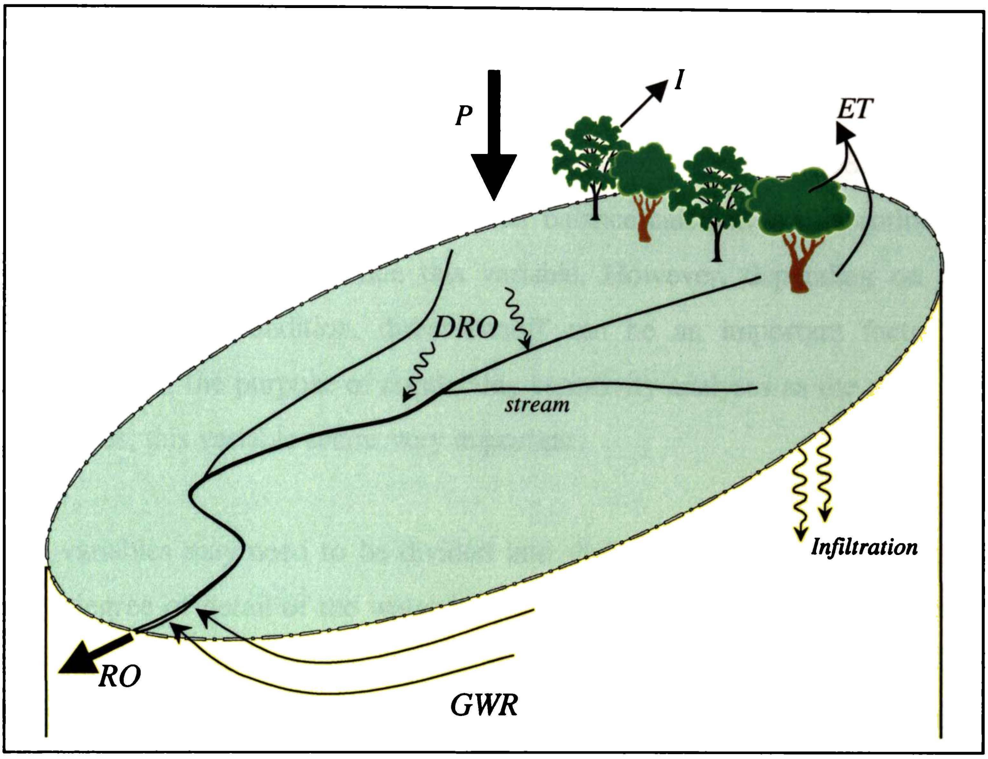


Figure 5.2: Components of water balance of a river basin.

Water balance uses the principle of mass conservation. It considers that one basin is one hydrological system. Therefore, the amount of water entering this basin system (total input) must be equal to the amount of water leaving the system (total output). For many studies, leakage from the system is assumed to be negligible (Dingman, 1994).[5-2] Water that enters the system is only from precipitation while water that leaves the system can be in the form of evaporation, plant transpiration, interception and runoff. Evaporation is usually combined with the transpiration and known as evapotranspiration (*ET*). Interception is often included in the evapotranspiration, which is considered as the total amount of water leaving the system from vegetation (*AET*). Hence, equation 5-1 can be simplified to become:

$$P = AET + \Delta SM + DRO + GWR \qquad (5\text{-}2)$$

[5-2] Depending on the geological condition of the catchment, leakage from the system can be high enough to be neglected. Especially in a karst dominated catchment, water may enter and leave the system through subsurface rivers (Katz *et al.*, 1997).

The runoff is the sum of direct runoff and the groundwater runoff (also known as baseflow). If the coefficient to estimate the amount of direct runoff is unavailable, the direct runoff may be left out of the equation (e.g. Donker, 1987; Dunne and Leopold, 1978). In fact, the original water balance calculation (Thornthwaite and Mather, 1957) does not include this variable. However, depending on the soil types and climate condition, direct runoff can be an important factor in the calculation. For the purpose of conducting sensitivity analyses as the result of land use changes, this variable seems very important.

Some variables may need to be divided into their smaller components depending on the degree of detail of the water balance computation and the objective of the computation. These will influence the conceptual approach of the computation. The conceptual approach to be used for this study will be discussed later in a specific section about water balance computation (Section 5.6).

5.4 PRECIPITATION

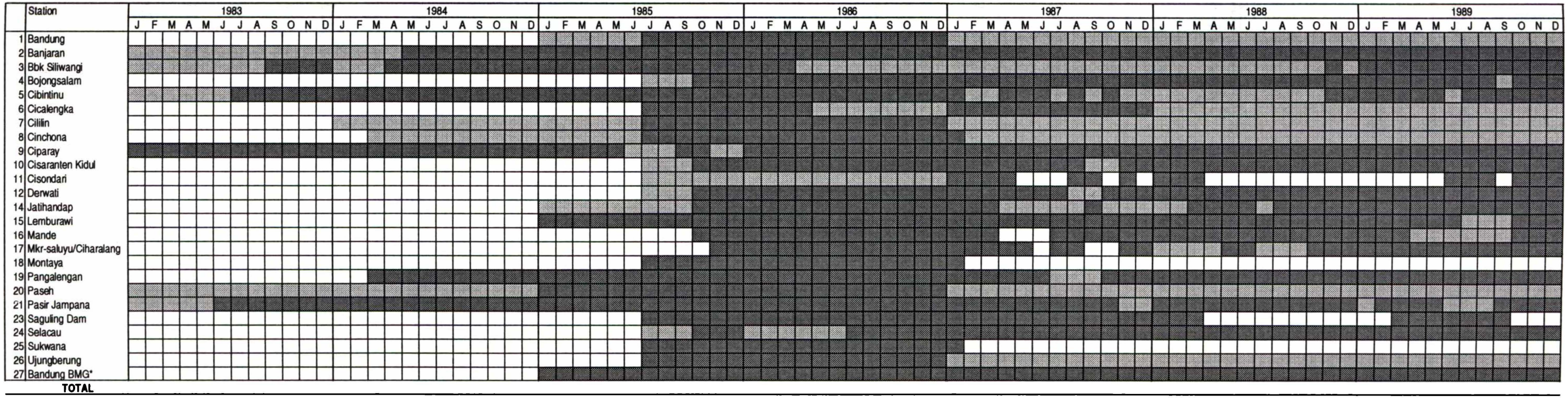
Data

Precipitation is one of the main inputs to the water balance system. The entire water balance calculation depends on the availability and quality of the precipitation data. For this study, the data come from 25 rainfall stations that are scattered unevenly throughout the study area. Most of the rain stations in this area started to operate in the early and mid 1980s, and only two stations have a record from 1974 (station 9) or earlier (station 27). A large amount of data is missing from almost every rain station since they began operation. In total, about 47% of monthly data is missing within the 1983 to 1994 period. Details of the periods with missing data in between these years can be seen in Table 5.1. Station 27, which is operated and maintained by the Agency of Meteorology Geophysics, is the only station without missing monthly records.

Estimating missing data

There is a need to estimate the missing monthly values and fill the gaps in the record in order to produce a continuous record for monthly water balance calculation. In particular, estimating the missing data is necessary for the area where the rain stations are sparsely distributed. This can be done by several methods ranging from a simple arithmetic average to a complex method that requires much mathematical computation. Some of the available methods, together with their requirements, are summarised in Table 5.2. All of the methods listed here are generally used to estimate the missing monthly data. They are discussed in some details below.

Table 5.1: The availability of precipitation data from the study area and their condition after conducting estimations of missing data.



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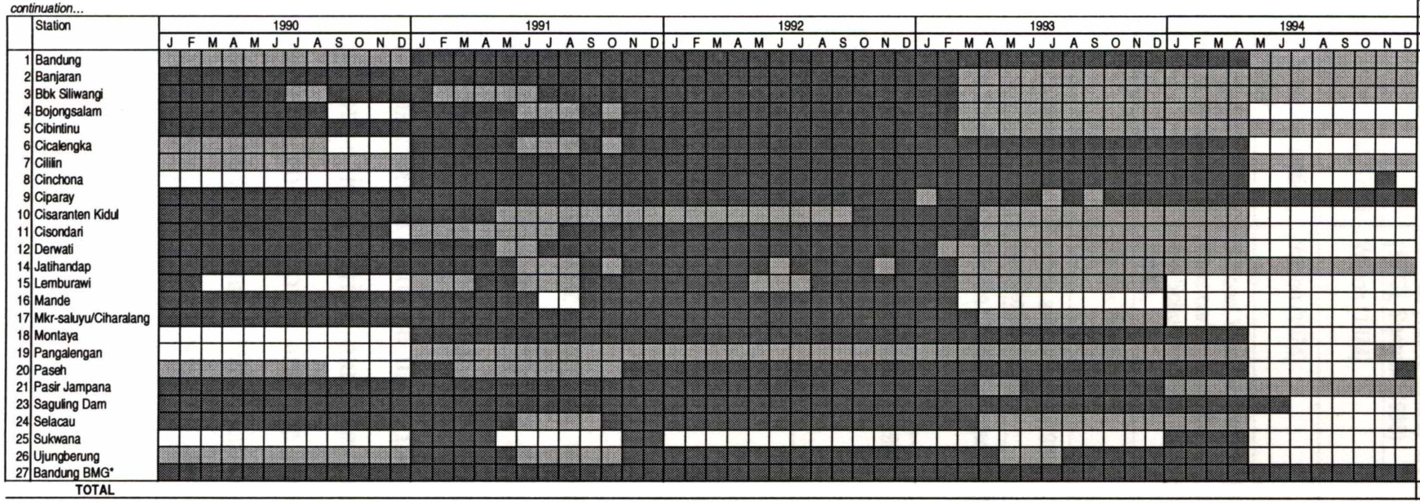

No.	Station	Original Available SUM	Original Available %	Original Missing SUM	Original Missing %	After gap filling Available+filled SUM	After gap filling Available+filled %	After gap filling Still missing SUM	After gap filling Still missing %
1	Bandung	58	40.3	86	59.7	120	83.3	24	16.7
2	Banjaran	106	73.6	38	26.4	144	100.0	0	0.0
3	Bbk Siliwangi	72	50.0	72	50.0	144	100.0	0	0.0
4	Bojongsalam	80	55.6	64	44.4	102	70.8	42	29.2
5	Cibintinu	99	68.8	45	31.3	144	100.0	0	0.0
6	Cicalengka	58	40.3	86	59.7	102	70.8	42	29.2
7	Cililin	58	40.3	86	59.7	132	91.7	12	8.3
8	Cinchona	60	41.7	84	58.3	111	77.1	33	22.9
9	Ciparay	136	94.4	8	5.6	144	100.0	0	0.0
10	Cisaranten Kidul	71	49.3	73	50.7	106	73.6	38	26.4
11	Cisondari	47	32.6	97	67.4	85	59.0	59	41.0
12	Derwati	84	58.3	60	41.7	106	73.6	38	26.4
14	Jatihandap	72	50.0	72	50.0	120	83.3	24	16.7
15	Lemburawi	76	52.8	68	47.2	98	68.1	46	31.9
16	Mande	78	54.2	66	45.8	84	58.3	60	41.7
17	Mkr-saluyu/Ciharalang	79	54.9	65	45.1	95	66.0	49	34.0
18	Montaya	59	41.0	85	59.0	59	41.0	85	59.0
19	Pangalengan	67	46.5	77	53.5	111	77.1	33	22.9
20	Paseh	57	39.6	87	60.4	133	92.4	11	7.6
21	Pasir Jampana	119	82.6	25	17.4	144	100.0	0	0.0
23	Saguling Dam	94	65.3	50	34.7	94	65.3	50	34.7
24	Selacau	80	55.6	64	44.4	106	73.6	38	26.4
25	Sukwana	29	20.1	115	79.9	29	20.1	115	79.9
26	Ujungberung	50	34.7	94	65.3	106	73.6	38	26.4
27	Bandung BMG*	120	83.3	24	16.7	120	83.3	24	16.7
	TOTAL	1909	53.0	1691	47.0	2739	76.1	861	23.9

Notes:

▓ = Available data

▒ = Filled data

* data were collected for the period of 1985-1994 only.

Table 5.2: Some methods for estimating missing rainfall data.

Method	Requirements	Reference
Arithmetic average	At least three nearby evenly spaced stations must exist. The U.S. Weather Bureau requires that normal annual precipitation variation of each nearby station to the station in question must be less than 10%. If the variation is more than 10%, then use the normal-ratio method instead.	Gilman (1964), Tran (1996), Linsley *et al.* (1975), Sumner (1988)
Adding anomaly to the mean monthly	At least one nearby station exists, and the mean monthly value of the station in question must be determined first	Salinger (1981)
Normal-ratio	Three nearby evenly spaced stations exist.	Gilman (1964), Linsley *et al.* (1975), Sumner (1988)
Mass-curve	A nearby station with a good record must exist. Total rainfall at station in question must be known.	Wilson (1974)
Simple proportion	Mean annual (or monthly) value of a nearby station, and the station in question must be known.	Wilson (1974)
Inversed distance weighting (IDW)	Some nearby stations must exist as control stations and the distance between the station in question and the control stations must be known.	National Weather Service (1972), Viessman *et al.*, (1989), Lynch and Schulze (1995), Reed *et al.* (1996),
Multiple successive correction (MSC)	(Not specified)	Barnes (1996)
Kriging	There is a need to select the appropriate variograms.	Lynch and Schulze (1995), Goovaerts (1999)
Isohyetal	Isohyetal map needs to be constructed for each time in question based on data from a number of rainfall stations.	Gilman (1964), Sumner (1988)
Shepard's weighted method	Values from at least five nearby stations are required. The distance between each nearby station and the station in question and the search radius that encloses the nearby stations need to be determined.	Lynch and Schulze (1995)

Unweighted methods

There are two unweighted methods available; the **arithmetic average method** and **adding to mean method**. The **arithmetic average method** is the simplest and most straight-forward to use. However, it has to be used carefully because it tends to average extreme local variations. If this method is to be used, the U.S. Weather Bureau puts a condition that the station in question must be evenly surrounded by at least three nearby stations with good records and the normal annual variation of each station must be less than 10% (Gilman, 1964; Linsley *et al.*, 1975 and Sumner, 1988). This method, therefore, is difficult to apply in a region where orographic influence in the precipitation is high. If normal annual variation is more than 10%, the use of the normal-ratio method is recommended.

Another unweighted method is by **adding the anomaly of a nearby station** for that particular time (month) in question **to the mean value of the station in question** (Salinger, 1981). The mean monthly value of the station in question has to be known first and both stations must be exposed to similar weather conditions.

Distance weighted methods

Another group of methods takes into account the distance between the station in question and the nearby stations (i.e. distance weighted methods). There are two different methods: the **inversed distance weighting (IDW) method** (also known as reciprocal-distance weighting method)[5-3] (National Weather Service, 1972; Dean and Snyder, 1977; Viessman *et al.*, 1989; Lynch and Schulze, 1995; Reed *et al.*, 1996) and the **Shepard's weighting method** (Lynch and Schulze, 1995). The difference between these two methods is in their weighting functions. The first type calculates the weights based on the distance between the position of the station in question and the reference stations only.[5-4] The other method includes a

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[5-3] Inversed distance weighting method can be expressed as (Lynch and Schulze, 1995):

$$Z_p = \frac{\sum_{i=1}^{n} Z_i W_i}{\sum_{i=1}^{n} W_i}$$

where Z_p = interpolated value at the grid node, Z_i = rainfall value at location (x_i, y_i), W_i = weighting function, and n = number of reference stations.

[5-4] Weighting function for inversed distance method is given by

$$W_i = \frac{1}{d_i^{\,b}}$$

where d_i = distance between Z_p and Z_i, and b = the exponent by which the distance are weighted.
The exponent value may be in the range between 1 to 3 as it does not significantly affect the accuracy of the estimation (Reed *et al.*, 1996), but Dean and Snyder (1977) found that for widely spaced stations, an exponent of 2 gave best results, and is favourable (e.g. Lynch and Schulze, 1995).

search radius in addition to the distance between the stations.[5-5] Lynch and Schulze (1995) pointed out that these methods could be programmed on any hardware. However, the inversed distance weighting method tends to produce a "bull's eye" pattern, which is concentric contours around the data points, while the Shepard's weighting method eliminates that kind of pattern.

Weighted by proportion or comparison methods

The group of weighted by proportion or comparison methods includes **simple proportion method**, **mass-curve method** (Wilson, 1974) and **normal-ratio method** (Gilman, 1964; Linsley *et al.*, 1975; Sumner, 1988).

The first two methods require a comparison between the station in question and a nearby reference station that has good records, and the two stations must be exposed to similar weather conditions. The **simple proportion method** calculates the proportion of long-term annual rainfall values between the two stations, and then uses this proportion in order to estimate the missing annual or monthly data from the corresponding reference station. The **mass-curve method** requires a mass-curve plot of monthly rainfall data against time for the reference station. Assuming that the station in question has a similar mass-curve pattern, then the missing value can be determined. These two methods are a kind of direct linear correlation between two stations so that extreme values from the reference station, which may be due to some error in reading or typing, will be interpolated to the station in question. The graphic plots of mass-curves have an advantage by

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[5-5] Weighting function for the Shepard's weighting method is given by

$$W_i = \frac{\left(1 - \frac{d_1}{R}\right)^2}{\left(\frac{d_i}{R}\right)^2} \quad \text{for} \quad \frac{d_i}{R} \langle 1 \quad \text{, and} \qquad W_i = 0 \quad \text{for} \quad \frac{d_i}{R} \geq 1$$

The choice of *R* (search Radius) depends on the density of the data points and should be chosen so that the sampling circle includes at least five sample points.

offering sight-examination of the seasonal characteristic of the data or suspicious errors in the data sets.

The **normal-ratio method** requires three nearby reference stations that are evenly spaced around the station in question and a determination of the normal-annual rainfall values for each station, including the station in question, as a weighting function.[5-6] This method is adaptable to regions where there is large orographic variation in the precipitation (Gilman, 1964).

Isohyetal method

The **isohyetal method** is another method that can be used to estimate the missing value (Gilman, 1964; Sumner, 1988), even though this method is more commonly used for average rainfall calculations over an area (e.g. Singh and Chowdury, 1986; Linsley *et al.*, 1949 and 1975; Shaw, 1994). The method involves plotting lines of equal precipitation value on a map. It can include the orographic variation in the precipitation and therefore is suitable for a region where large variation due to orographic effect occurs. However, when the work involves many time sets, many maps need to be drawn and therefore it is very time consuming and ineffective, unless a specific computer program for conducting this process is available.

[5-6] The estimation of missing rainfall value using normal-ratio method is expressed as:

$$P_x = \frac{1}{3}\left(\frac{N_x}{N_a}\cdot P_a + \frac{N_x}{N_b}\cdot P_b + \frac{N_x}{N_c}\cdot P_c\right)$$

where P = the precipitation value, N = the normal annual precipitation, x = the station in question, and a, b and c = the reference stations.

Complex mathematical methods

Complex mathematical methods such as the **kriging method** (Lynch and Schulze, 1995; Goovaerst, 1999; Mizzel, 1999) and **multiple successive-correction method** (Barnes, 1996) have also been used to estimate the missing data. The **kriging method** is used to determine the weight given to the surrounding station values by using popular geostatistical algorithms that incorporate a digital elevation model into the spatial prediction of rainfall. There are many kriging variograms available such as: spherical, circular, exponential, gaussian (Lynch and Schulze, 1995), simple kriging (Mizzell, 1999), universal kriging (Lynch and Schulze, 1995; Mizzell, 1999), kriging with varying local means, kriging with an external drift, and cocolated kriging (Goovaerst, 1999). Each variogram produces different results, and therefore when this method is to be used in a region, there is a need to determine which variogram produces the lowest errors (Lynch and Schulze, 1995). The **multiple successive-correction method** uses a matrix method to fill the gap in the record, or to estimate the values of selected locations where no observation stations exist (Barnes, 1996). It is quite new and therefore not as popular as the kriging method. Both kriging and multiple successive correction methods require sophisticated computer programs.

For this study, the method to be used should be easy to run on any spreadsheet program and should not be time-consuming. Various methods are used depending on local conditions, which include the distribution nature of the rain stations (in some parts of the area it is very dense and in others is sparse), the terrain condition and quality of data from neighbouring or reference stations. They are the **simple correlation method, inverse-distance weighting (IDW) method**, and the **normal ratio method**. If data from the station in question and a neighbouring station show a good correlation (coefficient of correlation, $\rho > 0.7$), the simple correlation method usually gives sufficiently good estimation of missing data. However, if the correlation with data from neighbouring stations is poor ($\rho < 0.7$),

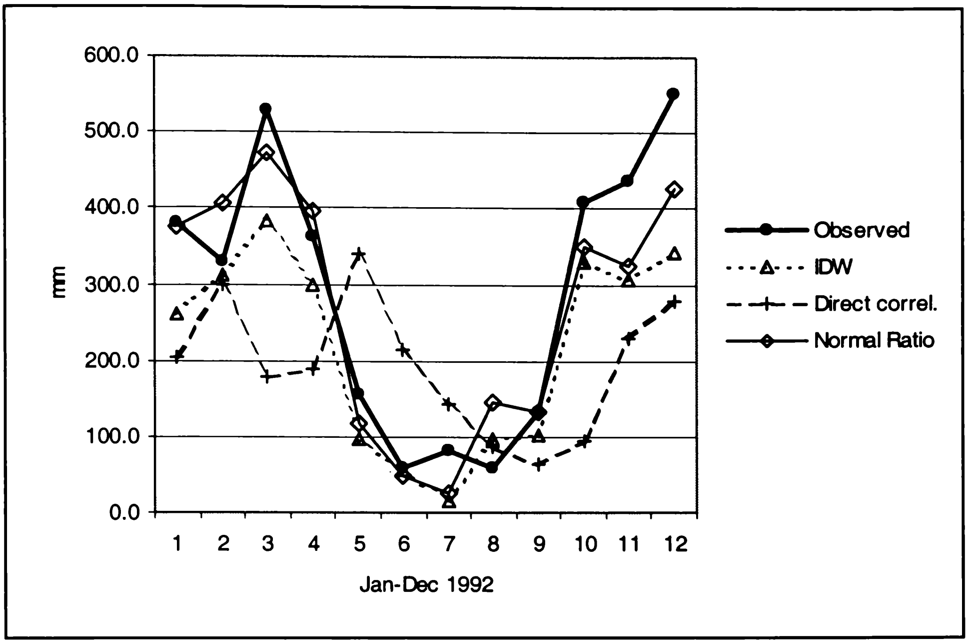

Figure 5.3: Performances of three methods for estimating the missing data in comparison to the observed data. The normal ratio method gives better results than the IDW (inverse-distance weighting) method and the direct correlation method (see also Table 5.3).

the IDW method or the normal ratio method can be used. At least three nearby stations are required when using this method which can be selected from the ones that show the best correlations with the station in question.

In general, the normal ratio method produces better results than the other methods (Figure 5.3, see also Table 5.3). The superiority of the normal ratio method is more pronounced in areas where orographic variation is high. When using this normal ratio method, the normal values must be estimated by taking the average annual precipitation values of each station.

By conducting the above methods, the gap in the precipitation records has been reduced from 47% to 23.9% (Table 5.1).

Table 5.3: Standard deviations of three methods for estimating missing precipitation data.

Year	IDW	D Correl.	N Ratio
1992*	***98.78***	***96.22***	***67.43***
1989	96.37	99.03	108.26
1988	80.88	85.30	83.73
1986	96.66	80.26	67.23
AVERAGE	**93.17**	**90.20**	**81.66**

Note:
* Selected as representative data for the chart on Figure 5.3.
IDW = Inverse-distance weighted method
D Correl. = Direct correlation
N Ratio = Normal ratio

Data projection to each cell

As the main computation is conducted on a cell-by-cell basis, it is therefore necessary to project precipitation data from stations to cells. This is conducted using an inverse distance weighted method (IDW) on a Geographical Information System computer program (ILWIS Version 3.0) (ITC, 2001). The IDW method is selected because of the nature of data that are unevenly distributed, and it requires the least number of stations for a certain radial-distance of a cluster in order to cover the whole study area. Other optional methods: Krigging method and a Least Squares Fit (LSF) method require more stations in order to cover the whole study area and therefore, these options are used, some parts of the study area are not covered. This method of projection from stations to cells is conducted for each month, so that 12 monthly precipitation maps with distributed an average precipitation value for every cell are produced for one calendar year.

5.5 EVAPOTRANSPIRATION

Calculation of potential evapotranspiration

Actual evapotranspiration depends on availability of water, which comes from rainfall and soil moisture, and the rate of potential evapotranspiration (PET). The PET is defined as the maximum amount of water that can be taken out from a piece of land in the form of evaporation and transpiration when the supply of water is unlimited. A different land use type causes a different PET because the consumption of water is different for each type of plant. This is an important factor in this thesis, which shows a direct link between the land use and hydrology.

The water consumption by plant is measured relative to a reference crop. Any method for calculating the PET usually calculates for a specific reference crop (PET_0). The reference crop can be alfalfa (Jensen, 1968) or coniferous forests in Germany (Dunne and Leopold, 1978), or short green grass (Doorenbos and Pruitt, 1977). This PET of the reference crop (PET_0) is used to calculate the PET of any crop (PET_{crop}) with a mathematical function,

$$PET_{crop} = k_c \cdot PET_0 \tag{5-3}$$

where k_c is the crop coefficient. This k_c value is specific for each method for calculating the PET, because each method may use a different reference crop. The k_c value of mature paddy given by PROSIDA (1976), for example, is different from the k_c value given by Doorenbos and Pruitt (1977) by about 14.5%. However, if the procedures to calculate the PET are followed by using their own respective k_c values, both methods produce the same amount of water consumption (Sir MacDonald and Partners, 1984).

The consumption of water by a crop is also determined by the growing stage of this crop. Therefore, it is controlled by the time of planting, time to reach maturity and time for harvesting. A crop pattern can be used to identify this growth stage of the crop, and usually the cropping pattern for one area is quite specific because it is determined by the agroclimate, in particular the number of wet months and dry months.

Selecting methods for PET_0 calculation

There are many available methods for calculating PET_0 from a simple method that requires few variables, such as the Thornthwaite method, to a complex one that requires many variables such as the Penman method. There are some aspects to consider in selecting the appropriate method as follows:

- ***List of k_c values***

  Before selecting any method, it is necessary to limit the choices by finding the methods that have ready k_c values that can relate the PET_0 to PET_{crop}. Doorenbos and Pruitt (1977) and Doorenbos and Kassam (1979) provide a list of k_c values for most crop types.[5-7] The accompanying methods for calculating PET_0 are: Blaney-Criddle, radiation, modified Penman, and pan evaporation (Doorenbos and Pruitt, 1977; and Doorenbos and Kassam, 1979). Based on this factor, therefore, the choice of methods is limited to those four methods.

- ***Accuracy***

  The most accurate method whenever possible is preferred. Figure 5.4 shows a comparison of results from several methods. The Thornthwaite method, which relies mainly on air temperature, can significantly underestimate the amplitude

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[5-7] Doorenbos and Kassam (1979) provides k_c values for many crop types commonly found in the study area, which range from main crops such as rice, maize, soybean and cassava to horticulture and fruit trees. Other studies (e.g. PROSIDA, 1976) provide a short list of k_c values limited for representative crops only such as rice, seasonal crops (*palawija*), and forest.

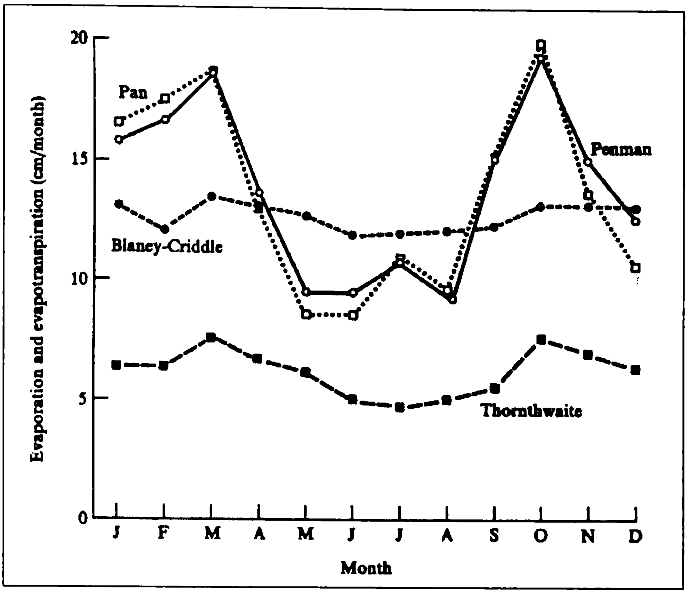


Figure 5.4: Comparison of results of PET calculations using several methods. (Source: Dagg and Blackie, 1970.)

of seasonal fluctuation whereas the Penman method, which is based on the energy-balance approach, can closely match the direct measurement from the pan evaporation method (Dagg and Blackie, 1970). The Penman method is considered good enough to serve the purpose of this thesis with a minimum possible error of ± 10% in summer and up to ± 20% under low evaporative conditions. The pan evaporation method is the other preferred choice with a possible error of ± 15%, depending on the location of the pan (Doorenbos and Pruitt, 1977).

- ***Availability of data***

Availability of climate data restricts the choice of methods to be used. The energy-balance approach such as the Penman method requires more types of climate data than other methods such as the Blaney-Criddle and radiation methods (Table 5.4). The climate data from the study area comes from two stations. The variation of climate data records from Bandung station is particularly good for calculating PET_0 using any method listed on Table 5.4. The climate data record from Majalaya station contains some gaps. Therefore, a full

Table 5.4: Climatic data required for different methods of PET_0 calculation. (Source: Doorenbos and Pruitt, 1977.)

Method	Temperature	Humidity	Wind	Sunshine	Radiation	Evaporation	Environment
Blaney-Criddle	♥	◊	◊	◊			◊
Radiation	♥	◊	◊	♥	(♥)		◊
Penman	♥	♥	♥	♥	(♥)		◊
Pan evaporation		◊	◊			♥	♥

♥ measured data; ◊ estimated data; (♥) if available, but not essential

set of PET_0 values cannot be calculated using a single method (i.e. Penman method only or pan method only), so they have to be calculated by using various methods. This may produce inconsistency in the results, for example, the calculation using the Penman method produces higher annual PET than the pan evaporation method for 1989 and 1994, but lower PET for 1990 (Figure 5.5). This kind of inconsistency needs to be avoided by using one method only.

Considering all the aspects discussed above (list of available accompanying k_c values, accuracy, and availability of data), this thesis will use the Penman method for calculating the PET. The PET is calculated on a monthly basis using the procedure given by Doorebos and Pruitt (1977). The calculation is based on the climate data from one station only, which is the Bandung station, in order to avoid inconsistencies in the results.

Variations of climate data with elevation

Some climate data change with elevation. Air temperature, in particular, shows a good correlation with elevation. In this study area, every 100m increase in elevation causes a drop in temperature by 0.6°C (Mock, 1973; and Dam, 1994), which is also a common general formula for most parts of Indonesia. Calculation of PET_0, which is on a cell basis, needs to consider such changes.

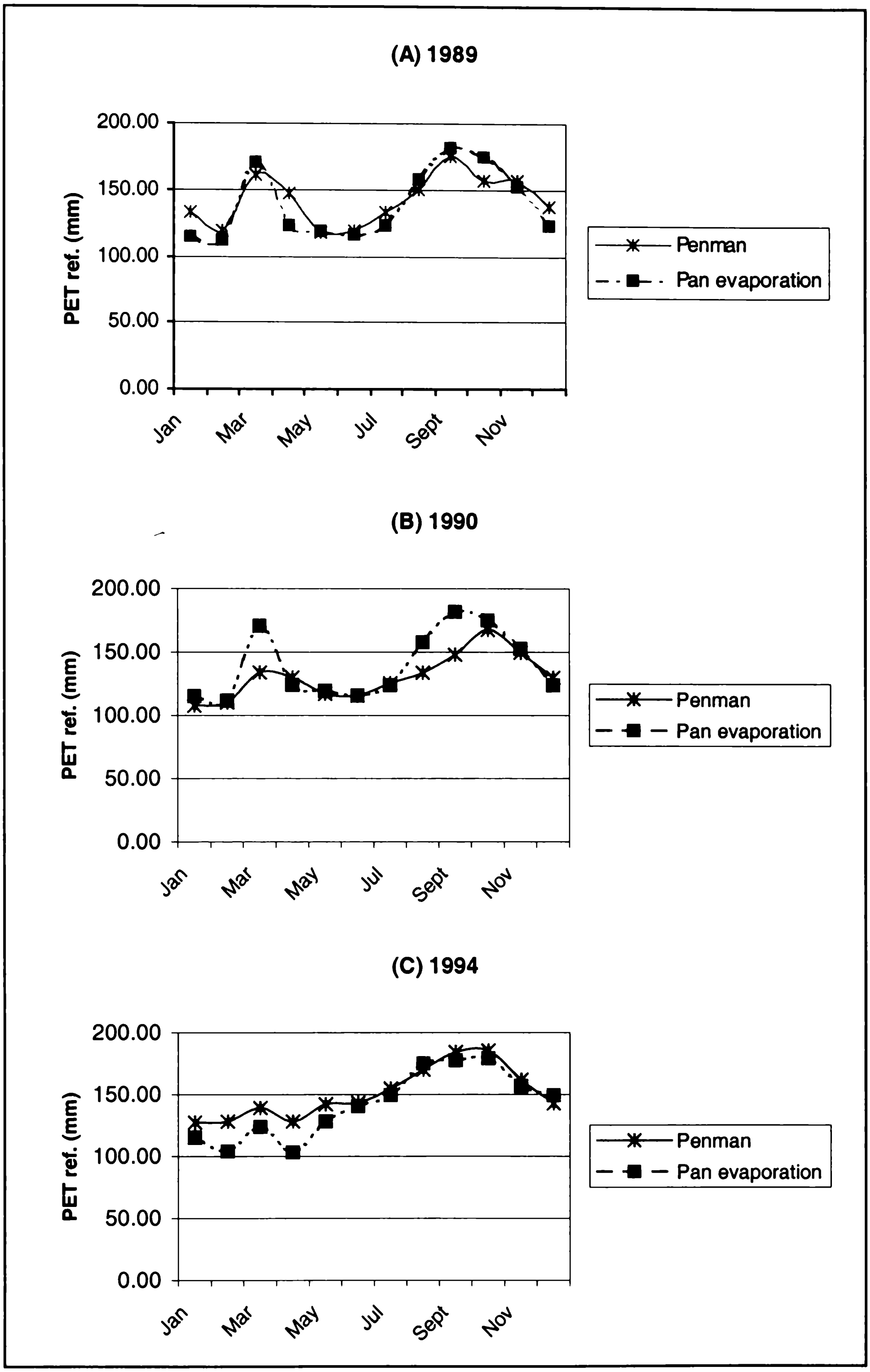


Figure 5.5: Comparison of PET calculated using the Penman and the pan evaporation methods from data of the same station.

The amount of sunshine hours also seems to have a correlation with the elevation (Mock, 1973; and Sir MacDonald and Partners, 1984). However, the degree of confidence in this correlation is quite low. An analysis on climate data from the Special Province of Yogyakarta (central Java) showed that the average annual sunshine hours dropped 1% for every 100m increase in elevation (coefficient of determination $r^2 = 0.45$). On a monthly basis, the average sunshine hours showed an increase in the months of January, February, and August to October, and a decrease in the other months, with r^2 values varying from 0.005 to 0.75 (very poor to good correlation) (Table 5.5). Because of this difficulty in making a good judgement on the relationship between elevation and sunshine hours, particularly on a monthly basis, this study assumes that the sunshine hours do not change with elevation.

The relative humidity, on both an annual and monthly basis, does not show a good correlation with elevation and is therefore considered unchanged.

Projecting PET over the whole study area

The PET needs to be calculated for each cell in the study area, because the water balance is computed on a cell-by-cell basis. As discussed earlier, there is only one station that provides reliable and consistent climate data. In order to calculate the PET for each cell, these climate data need to be projected to each cell. However, a common point-to-point interpolation cannot be done because only one station is available. In order to project these data to each cell, one important assumption is made. The data are projected based on their relationship with elevation only.

Of all the required data, temperature data are the only data that can be projected with confidence by using a known temperature gradient. As has been discussed in the previous section, other climate data such as; sunshine hours, relative humidity, and wind speed do not show any strong functional relationship with elevation.

These data, therefore, are considered unchanged with elevation, in other words they are assumed to have one value for the whole basin. Therefore, the spatial variation in the PET relies only on the temperature variation, which is controlled by the elevation.

The temperature can be easily projected to each cell in the study area by using a GIS (ITC, 2001). It requires the elevation data, usually from a topographic map, to be interpolated to every cell in the study area and the projected temperature for this cell is calculated based on its elevation. The projection is conducted for the average monthly maximum temperature, mean temperature, and minimum temperature, which are necessary to calculate the PET of each cell.

Monthly crop coefficient values for each land use type

The k_c values at various stages of growth for various kinds of crop types that have been given in Table 3.6 (Chapter 3) need to be transformed to monthly k_l values that represent the water use for various land use types. This is conducted by grouping the monthly individual k_c values according to their land use types from which the representative monthly values for each land use type (k_l) are determined. In doing this, cropping patterns from various agricultural lands such as irrigated paddy, rain-fed paddy, and dry-farm land are required.[5-8] The fallow agricultural land, which often shows up in the crop patterns, is given a k_c value of 0.44. This value is taken from the k_c value of fallow land given in PROSIDA (1976) after a comparative adjustment.

[5-8] The cropping patterns of the dry-farm land given here are specifically for ***tegalan*** type of agricultural land and represent the main food crops only. The cropping patterns for 'garden' are not known.

Table 5.5: Correlation between average sunshine hours and elevation for observation data from Yogyakarta Special Province (central Java). Number of stations is 17, with elevation in a range between 6 and 1,399m amsl.

	ΔS for every 100m (%)	**S_0 sunshine at 0 mean sea level (%)**	**r^2 (coefficient of determination)**
January	+0.23	80	0.0196
February	+0.63	82	0.0726
March	-0.37	88	0.0543
April	-0.24	105	0.0177
May	-2.33	108	0.7507
June	-0.62	113	0.0513
July	-0.35	116	0.0157
August	+1.04	114	0.2707
September	+1.34	107	0.2196
October	+0.36	103	0.0350
November	-0.12	94	0.0054
December	+0.58	85	0.1537
Annual	**-1.61**	**66**	**0.1537**

The main factor that controls the cropping patterns is agroclimate, which is determined by the length of wet and dry periods. The wet period is defined as the number of consecutive months in which monthly precipitation is over 200mm, and the dry period is the number of consecutive months in which monthly precipitation is less than 100mm (Directorate of Food Crop Production, 1994). An analysis of rainfall records from most rain stations within the Bandung basin for the period 1983 to 1994 shows that this basin has an average wet period of 3 to 4 months and a dry period of 2 to 3 months or a wet period of 3 to 4 months and dry period of 4 to 6 months, which fall under agroclimatic zone D2 and zone E respectively (Table 5.6). Only in the very southern part of the basin is the agroclimate in zone C2 where the wet period lasts for 5 to 6 months and the dry period for 2 to 3 months.

In order to obtain monthly values for applying coefficients, the crop patterns of each agricultural land type are converted into monthly k_c values (see Appendix 5-A). These monthly k_c values are collapsed into land use categories (k_l) by an area-weighting method using the area of each crop in order to produce the monthly k_l values.[5-9] However, month-to-month variation of the k_l values for the dry agricultural land, which includes *tegalan*, garden and horticultural land, is difficult to obtain because the planting time and sizes of area planted for each crop that grows on these types of agricultural land are always variable and they do not make specific crop patterns. Therefore, the averaged annual value is calculated and is then used as a single value for the entire year. However, calculating the

Table 5.6: Identification of agroclimatic zones based on wet period and dry period.

	Station	Elev. (m)	Zones*
1	Bandung	800	D2
2	Banjaran	675	D1 or D2
3	Bbk Siliwangi	1000	E
4	Bojongsalam	687	D2
5	Cibintinu	900	D2
6	Cicalengka	745	E
7	Cililin	775	D2
8	Cinchona	?	E
9	Ciparay	674	D2
10	Cisaranten Kidul	685	D2
11	Cisondari	1188	E
12	Derwati	673	E
14	Jatihandap	765	*unknown*
15	Lemburawi	963	D2 or E
16	Mande	812	E
17	Mkr-saluyu/Ciharalang	1020	E
18	Montaya	1195	C1 or D1
19	Pangalengan	1400	B2 or C2
20	Paseh	775	C2
21	Pasir Jampana	880	D2 or E
23	Saguling Dam	650	D2 or C2
24	Selacau	1000	E
25	Sukwana	1500	D1 or D2
26	Ujungberung	747	D2 or E
27	Bandung BMG	791	D1 or D2

* Zones:	*Wet period* (months)	*Dry period* (months)
B2	7 - 9	2 - 3
C1	5 - 6	2
C2	5 - 6	2 - 3
D1	3 - 4	2
D2	3 - 4	2 - 3
E	3 - 4	4 - 6

Notes:

- Wet period is a number of consecutive wet months, of which monthly precipitation is over 200 mm.
- Dry period is a number of consecutive dry months, of which monthly precipitation is less than 100 mm.

[5-9] Crop types for each land use are as follows. Full-technically irrigated paddy land consists of rice, soybean and mungbean. Semi-technically irrigated paddy land consists of rice, groundnut, soybean, sweet potato and maize. Rainfed paddy land consists of rice, maize, mungbean, soybean, groundnut and sweet potato. Dry agricultural land consists of 'palawija' crops (see Table 5.3, including vegetables), and fruit trees.

average value like this will eliminate the monthly fluctuation values, which cannot be avoided even though such variation can be significant for this study, unless detailed observations of crop patterns are available.

For forest, which is a significant land use type in hydrology but not listed in Table 3.6, the k_l value needs to be estimated. To determine an absolute k_l value for the forest is difficult mainly because of local variation in tree density (Cheng *et al.*, 1987). Thus, the water consumption of a degraded forest in comparison to an untouched forest differs significantly. The variation in the vegetation types has little effect on the water consumption of the forest (Rutter, 1968). The ratio of evapotranspiration from grassland with unlimited water supply to that from forest, as reviewed by Rutter (1968) is in a range between 0.8 and 1.0. Penman (1963) also suggested that the water consumption of forests is about 13% more than by grass. By knowing the average k_c values for grass, as given in Doorenbos and Kassam (1979), which is in a range between 0.95 and 1.05 depending on the grass type, it is possible to convert the ratio of evaporation as given by Rutter (1968) and Penman (1963) into k_c (or k_l) values for the forest in general. Based on the above information, the k_l value for forest is estimated at between 0.95 and 1.3, with an average of 1.1. These values are highly overestimated in comparison to the k_l values that have been used for forests in central Java (ranging from 0.61 to 0.98 with an average of 0.81[5-10] [Sir MacDonald and Partners, 1984]). The difference between these two may have been caused by at least two things: 1). the forest in central Java is relatively more degraded than the forest in general so that the k_l values for forests in central Java becomes very low relative to the estimated values from the literature; 2). the estimation of the k_l values is based on the information that comes from regions with relatively lower humidity than Java, where the k_l values of a region with low humidity are generally greater than the k_l values of a high humidity region.

[5-10] These values are already adjusted by a comparative method to fit the PET_0 calculation as suggested by Doorenbos and Kassam (1979). The actual values as given by PROSIDA range from 0.7 to 1.1 with an average of 0.93.

By considering all of the above information, i.e. by comparing the estimated values from previous studies, and with an assumption that the forest in Bandung basin is in a relatively better condition than the forest in central Java, this study assumes that the average k_l value for forest in the Bandung basin is 0.98 and uses this single value for the whole year. The variation in forest types in the Bandung basin (such as primary forest, secondary and reforested land) which not only differ in their vegetation types, but also in their tree density, and perhaps also in root-depth, may cause a significant variation in the k_l values. However, these apparently have not been studied. Therefore, unless there is new knowledge about the water consumption of various types of forests in the tropics, the model will use only one k_l value for all types of forest in the Bandung basin.

The monthly values for applying coefficients to specific land uses (k_l) are listed in Table 5.7. The proposed water balance model uses these values in its computational process. The k_l values for lakes, as given in this list are taken from PROSIDA (1976) after a comparative adjustment.

Of the various land uses, it can be seen, that for this study area, forest and irrigated paddy consume water annually at almost similar rates and they both consume the most water. The dry farm land and the rain-fed paddy are the least consuming water.

Table 5.7: Monthly water consumption for various land use types in Bandung basin area.

	K_l											
Land use	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Reforested Primary forest Secondary forest	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Dry-land (tegalan) Mix-garden Vegetable garden	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Irrigated paddy	0.96	1.01	1.04	1.04	0.96	0.99	1.00	0.95	0.84	1.10	1.07	1.05
Rainfed paddy	0.94	0.91	0.90	1.00	0.92	0.80	1.03	0.99	0.84	0.94	1.07	0.89
Urban area	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Cinchona (quina)	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Tea plantation	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Lake	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05

5.6 WATER BALANCE COMPUTATION

Conceptual approach

The water balance computation in principle follows a conceptual approach introduced by Thornthwaite and Mather (1957) that has been widely accepted (e.g. Dunne and Leopold, 1978; Donker, 1987). This concept has also been applied in a hydrological study in one part of the study area (Delinom and Suriadarma, 1993) and in another part of Indonesia (e.g. Hadi, 1988).[5-11] This conceptual approach is outlined in Figure 5.6a.

[5-11] Another water balance method, which is commonly accepted in Indonesia as it was developed for Indonesian conditions, was proposed by Mock (1973), but it was found to be far more complicated than the one introduced by Thornthwaite and Mathers (1957).

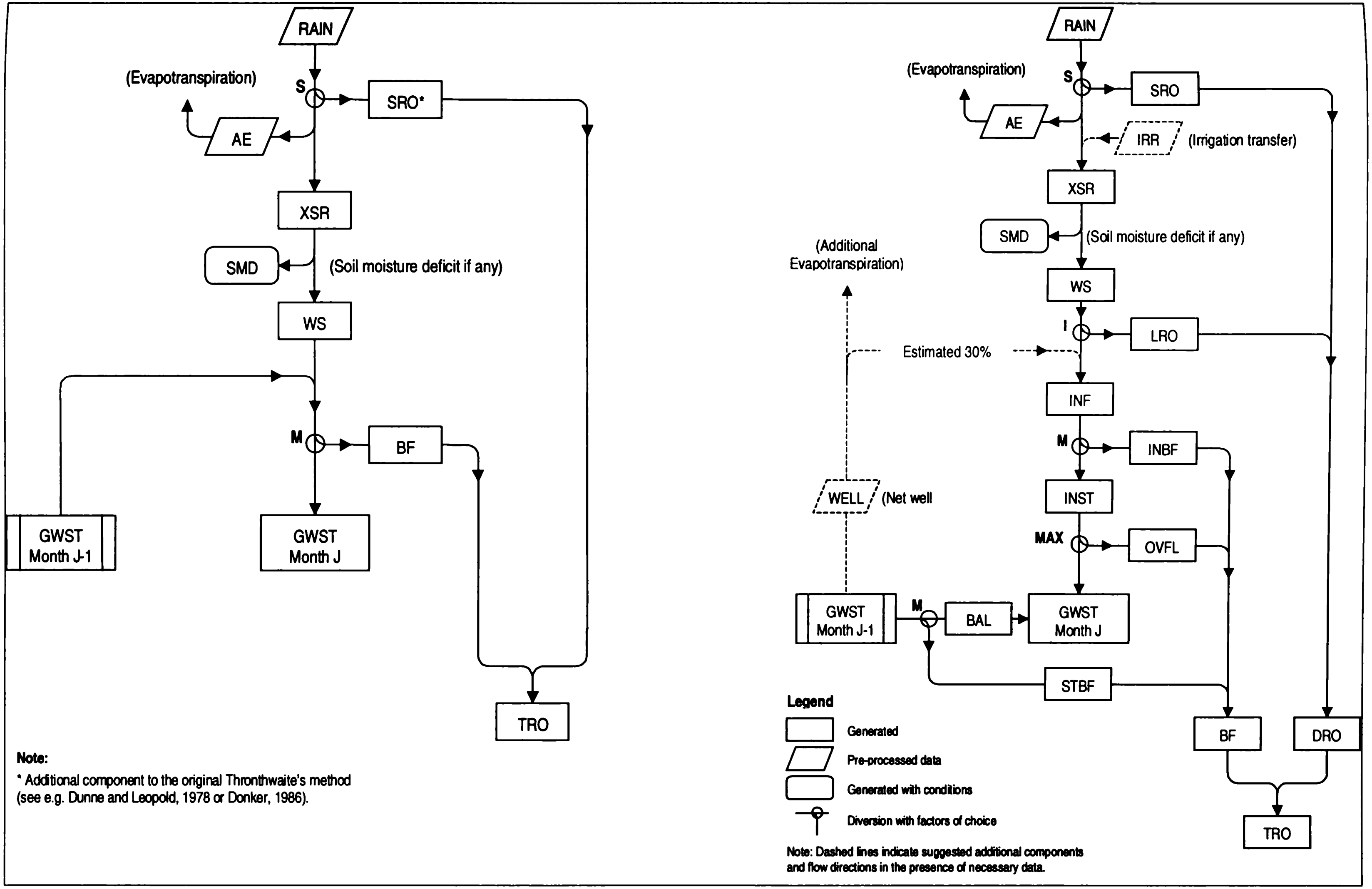


Figure 5.6: a). The original conceptual approach (*left*), and b). the expanded conceptual approach used in this thesis (*right*). See text for explanation. (Modified after Sir MacDonald and Partners, 1984.)

The hydrological component of this thesis also uses this conceptual approach for its cell-by-cell calculation. However, there is a need to expand this concept in order to accommodate additional components that are considered necessary (Figure 5.6b). This expanded conceptual approach is adopted from a study of a water cathment in Yogyakarta, central Java (Sir MacDonald and Partners, 1984). The advantage of the latter approach over the first is in the inclusion of several geological related parameters such as infiltration (*I*), and maximum groundwater storage (*MAX*), so that it allows the baseflow component (BF) and direct runoff (DRO) to be conceptualised in more detail. In addition, the storm runoff parameter (*S*) in this approach relates both the geology and the land use, and therefore can enhance the conceptual physical process of the total runoff. Both the BF and DRO are the two main components that may give significant seasonal variation in the streamflows. The whole process of the calculation together with some explanation of the concept behind it is discussed in more detail in the next section.

The expanded conceptual approach also allows for water transfer from neighbouring catchments in the form of irrigation and groundwater extraction to be included in the computational process whenever such data are available.[5-12]

[5-12] For this study, the irrigation and groundwater extraction data are not available, and therefore, are not included in the computation.

Line-by-line description of water balance computation

A water balance computation is usually a simple process that can be done on a line-by-line basis using any spreadsheet program.[5-13] The spreadsheet is especially good for testing the computational formula, which afterwards can be transferred into a computer program compiler. For this thesis, the water balance model has been created on a spreadsheet program. This spreadsheet is used for creating the calculation procedure, calibration and validation of the model.

The procedure used to calculate the water balance can be explained easily line-by-line using the model that has been created in a spreadsheet program (Table 5.8). The reference potential evapotranspiration (PET_O) has been calculated separately using a modified Penman method. For the calculation, all values are expressed in area-depth (mm). The following line-by-line description of the water balance computation refers to Table 5.8.

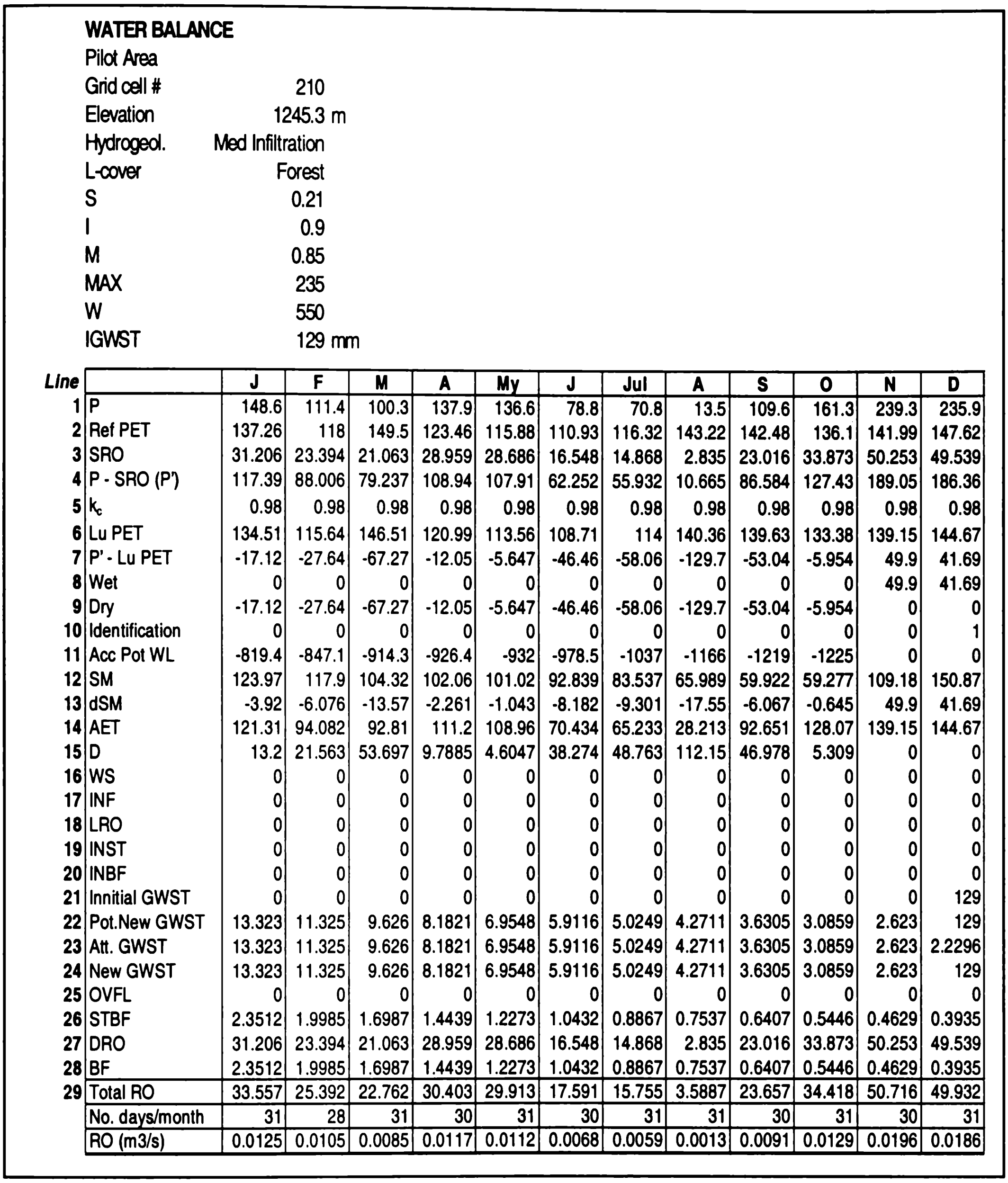
Line* 1:** ***P is the monthly precipitation. This is the average value of precipitation for this cell.

Line* 2:** ***Ref PET is the value of the reference crop potential evapotranspiration calculated separately by using the modified Penman equation.

Line* 3:** ***SRO is the amount of storm runoff, which is the proportion of rainwater that bypasses the water balance computation and is treated directly as runoff. It is equal to $P \times$ storm runoff coefficient S.

[5-13] A spreadsheet program is particularly good for testing the computation formulae. Modelling using a spreadsheet program has been done in the past (Dexter and Avery, 1991), and shows unique advantages over the compiled computer code program (Savenije, 1995). Some of advantages are: highly accessible, many people are now familiar with spreadsheets, they are transparent, easy to debug, easy to re-run, can give immediate error messages, give immediate output, cheap, and have a ready to use graphical interface, can easily import and export data to other software, have simple data base management facilities and built in statistical packages, can be programmed by using macro language, good data storage and retrieval. In addition, the spreadsheets are flexible, i.e. they are easy to adjust to a new situation such as economic changes, climate change, etc. The major disadvantage of the spreadsheet program over the compiled program is that it requires a large amount of memory (Savenije, 1995).

Table 5.8: Water balance calculation on a spreadsheet.



WATER BALANCE

Pilot Area

Grid cell #	210
Elevation	1245.3 m
Hydrogeol.	Med Infiltration
L-cover	Forest
S	0.21
I	0.9
M	0.85
MAX	235
W	550
IGWST	129 mm

Line		J	F	M	A	My	J	Jul	A	S	O	N	D
1	P	148.6	111.4	100.3	137.9	136.6	78.8	70.8	13.5	109.6	161.3	239.3	235.9
2	Ref PET	137.26	118	149.5	123.46	115.88	110.93	116.32	143.22	142.48	136.1	141.99	147.62
3	SRO	31.206	23.394	21.063	28.959	28.686	16.548	14.868	2.835	23.016	33.873	50.253	49.539
4	P - SRO (P')	117.39	88.006	79.237	108.94	107.91	62.252	55.932	10.665	86.584	127.43	189.05	186.36
5	k_c	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
6	Lu PET	134.51	115.64	146.51	120.99	113.56	108.71	114	140.36	139.63	133.38	139.15	144.67
7	P' - Lu PET	-17.12	-27.64	-67.27	-12.05	-5.647	-46.46	-58.06	-129.7	-53.04	-5.954	49.9	41.69
8	Wet	0	0	0	0	0	0	0	0	0	0	49.9	41.69
9	Dry	-17.12	-27.64	-67.27	-12.05	-5.647	-46.46	-58.06	-129.7	-53.04	-5.954	0	0
10	Identification	0	0	0	0	0	0	0	0	0	0	0	1
11	Acc Pot WL	-819.4	-847.1	-914.3	-926.4	-932	-978.5	-1037	-1166	-1219	-1225	0	0
12	SM	123.97	117.9	104.32	102.06	101.02	92.839	83.537	65.989	59.922	59.277	109.18	150.87
13	dSM	-3.92	-6.076	-13.57	-2.261	-1.043	-8.182	-9.301	-17.55	-6.067	-0.645	49.9	41.69
14	AET	121.31	94.082	92.81	111.2	108.96	70.434	65.233	28.213	92.651	128.07	139.15	144.67
15	D	13.2	21.563	53.697	9.7885	4.6047	38.274	48.763	112.15	46.978	5.309	0	0
16	WS	0	0	0	0	0	0	0	0	0	0	0	0
17	INF	0	0	0	0	0	0	0	0	0	0	0	0
18	LRO	0	0	0	0	0	0	0	0	0	0	0	0
19	INST	0	0	0	0	0	0	0	0	0	0	0	0
20	INBF	0	0	0	0	0	0	0	0	0	0	0	0
21	Innitial GWST	0	0	0	0	0	0	0	0	0	0	0	129
22	Pot.New GWST	13.323	11.325	9.626	8.1821	6.9548	5.9116	5.0249	4.2711	3.6305	3.0859	2.623	129
23	Att. GWST	13.323	11.325	9.626	8.1821	6.9548	5.9116	5.0249	4.2711	3.6305	3.0859	2.623	2.2296
24	New GWST	13.323	11.325	9.626	8.1821	6.9548	5.9116	5.0249	4.2711	3.6305	3.0859	2.623	129
25	OVFL	0	0	0	0	0	0	0	0	0	0	0	0
26	STBF	2.3512	1.9985	1.6987	1.4439	1.2273	1.0432	0.8867	0.7537	0.6407	0.5446	0.4629	0.3935
27	DRO	31.206	23.394	21.063	28.959	28.686	16.548	14.868	2.835	23.016	33.873	50.253	49.539
28	BF	2.3512	1.9985	1.6987	1.4439	1.2273	1.0432	0.8867	0.7537	0.6407	0.5446	0.4629	0.3935
29	Total RO	33.557	25.392	22.762	30.403	29.913	17.591	15.755	3.5887	23.657	34.418	50.716	49.932
	No. days/month	31	28	31	30	31	30	31	31	30	31	30	31
	RO (m3/s)	0.0125	0.0105	0.0085	0.0117	0.0112	0.0068	0.0059	0.0013	0.0091	0.0129	0.0196	0.0186

Line* 4: *P' is effective precipitation, which is the portion of precipitation that is going to be treated further in the computation and is equal to *P - SRO.*

***Line* 5:** k_l is the coefficient of specific land use as previously discussed.

Line* 6: *Lu PET is the potential evapotranspiration of the specific land use, which is equal to k_l times *Ref PET.*

***Line* 7:** is calculated by subtracting *Lu PET* from *P'*. Positive values mean that there is an excess of water from the precipitation and negative values mean that the amount of water from the precipitation is not enough to supply the evapotranspiration as needed. Hence, there is a need to obtain an additional supply from soil moisture.

***Line* 8: Wet** is used to identify wet months, i.e. months with excess precipitation. This is conducted by assigning a zero value to the dry months in line 7. The total of this value will be used in estimating the accumulated potential water loss.

***Line* 9: Dry** is used to identify dry months, and is the opposite of line 8.

Line* 10: Identification** is used to identify the last ***wet month before the dry month. The month in question is identified by the first column that has a value of 1 in a row. In the example (Table 5.8), the month in question is December.

Line* 11: *Acc Pot WL is the accumulated potential water loss, which is the successive increase in potential water loss starting from the last wet month, i.e. *P'* - *Ref PET* > 0.

Line* 12: *SM (soil moisture) can be calculated by Equation 5-4, which is an equation that substitutes published tables (Thornthwaite and Mather, 1957) and charts (e.g. Dunne and Leopold, 1978).

$$SM = W \cdot \exp\left(-\frac{L_a}{W} \right) \tag{5-4}$$

where SM is the soil moisture, W is available water capacity of root zone, and L_a is the accumulated potential water loss. All units are in mm. The use of this equation can be seen for example in Mock (1973), Donker (1987) and Hadi (1988).

Line* 13: *dSM is the change in soil moisture, which is calculated by subtracting the value of previous month from the current month, i.e. $dSM = SM_m - SM_{m-1}$. A positive value means that a recharge or an increase in soil moisture occurs.

Line* 14: *AET is the actual amount of evapotranspiration. If $P' \geq Lu\ PET$, then *AET* is equal to *Lu PET* (i.e. evapotranspiration is at maximum). However, if $P' < Lu\ PET$, some of the water required for evapotranspiration has to be supplied from soil moisture (i.e. $AET = P'$ plus change in soil moisture).

Line* 15: *D is the soil moisture deficit, which is the difference between *Lu PET* and *AET*.

Line* 16: *WS is water surplus and is equal to the difference between *P'* and *AET*, minus the change in soil moisture (i.e. $WS = P' - AET - dSM$).

Line* 17: *INF is the amount of water that gets into a deeper soil zone, which is equal to *I* (infiltration rate) × *WS*.

Line* 18: *LRO is part of the *WS* that does not get into a deeper soil zone, and it adds to the direct runoff component, i.e. *WS* - *INF*.

Line* 19: *INST is the amount of water that goes into the groundwater storage, and is calculated as $0.5\ INF(1+M)$ where *M* is the monthly recession constant (Mock, 1973).

Line* 20: *INBF is the remainder of the *INST* that contributes to baseflow, which is equal to *INF* - *INST*.

Line* 21: *Initial GWST is the initial volume of groundwater before a change in the volume as the result of hydrological change within the month in question takes place, i.e. *GWST* (*month J*-1) (see Figure 5.6b). The *Initial GWST* can be determined by a successive approximation method that will be described later.

Line* 22: *Pot. New GWST is the volume of the groundwater if there is no capacity limit in the storage capacity. It is equal to the *Initial GWST* or equal to the sum of *Att. GWST* (attenuated groundwater storage) and *INST* if the *Initial GWST* is zero.

Line* 23: *Att. GWST (attenuated groundwater storage) is the proportion of groundwater that is constantly discharged from the storage, and is equal to *M* × *New GWST* of the previous month.

Line* 24: *New GWST is the volume of groundwater, which is limited by the storage capacity, i.e. it equals to the *Pot. New GWST* but is limited by the maximum capacity *MAX*.

Line* 25: *OVFL is the amount of water that exceeds the storage capacity (overflow), which is equal to *Pot. GWST – New GWST*. It only exists if the *Pot. GWST* is greater than the maximum storage capacity. This overflow component adds to the baseflow component.

Line* 26: *STBF is the portion of groundwater in the storage that becomes baseflow, and is equal to *GWST of the previous month – Att. GWST*.

Line* 27: *DRO is the total amount of the direct runoff components, which is equal to the sum of *SRO* and *LRO*.

Line* 28: *BF is the total amount of the baseflow components, which is the total sum of *INBF, OVFL* and *STBF*.

Line* 29: *Total RO is the sum of both the direct runoff (*DR*) and the baseflow (*BF*). Sometimes the total runoff is expressed in cubic-meters per second (m^3s^{-1}), which is a common unit for streamflow. The converted values for this unit are given in the last row.

To produce a streamflow hydrograph of the basin, the calculated total runoff from each grid cell in the study area is summed up on a monthly basis in order to get the monthly runoff for the basin. An example of the hydrograph is shown in Figure 5.7.

Successive approximation method

The successive approximation method is used to determine a certain value and has to be conducted iteratively in such away that the estimated value will match the calculated value. In the above water balance computation, there are two lines that require this kind of method (*line* 11 and *line* 21).

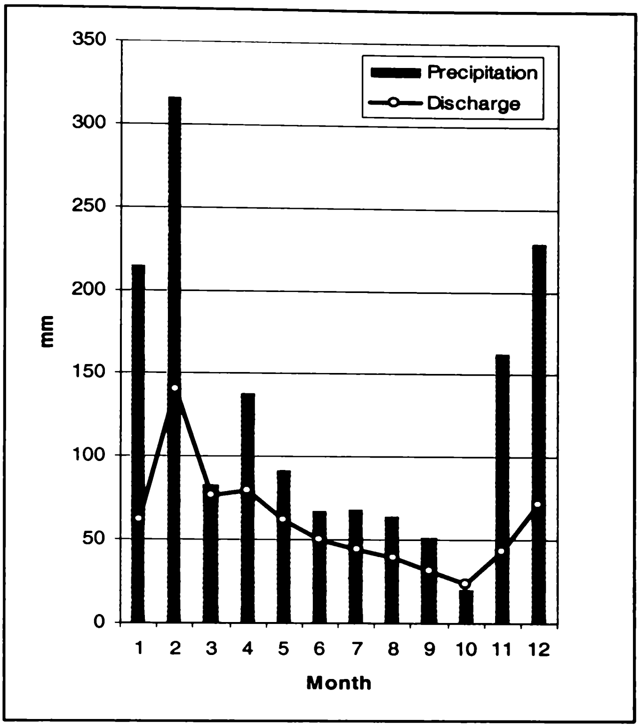


Figure 5.7: An example of hydrograph from a pilot area (Sukapada) for year 1990.

Estimating the soil moisture of the first wet month (line 11 in Table 5.8)

If the climate is so dry that the water capacity at root zone is not filled by the first wet month, then there is a need to estimate the soil moisture of this first wet month (month *m*+1) by taking into account the soil moisture value of the month before that (month *m*). The following procedures need to be conducted in order to get the value of soil moisture for month *m* ($L_{a(m)}$).

(1) Sum all the ***wet*** months on *line* 8 to obtain the accumulated water excess (E_a). Sum also all the ***dry*** months on *line* 9 to obtain the accumulated potential water loss (L_a).

(2) Apply equation 5-4 using the introduced value of L_a, and this will give the estimate value of soil moisture (*SM*) for month *m*.

(3) Add the calculated E_a from step (1) to the value of *SM* from step (2) to produce the new value of E_a.

(4) Calculate the value of accumulated potential water loss for month m ($L_{a(m)}$) using the following equation:

$$L_{a(m)} = -W.\ln\left(\frac{E_a}{W}\right) \qquad (5\text{-}5)$$

(5) The new value of L_a is given by $L_a = L_a - L_{a(m)}$.

Repeat these procedures from step (2) with the newly introduced value of L_a from step (5), until the value of $L_{a(m)}$ in step (4) remains unchanged.

Estimating the initial groundwater storage (line 21 in Table 5.8)

The iterative successive approximation method is required in order to estimate the initial groundwater storage in the last wet month so that this value will match the amount of groundwater in storage during the specified time. Hence, a full one-circular year of monthly groundwater storage values can be obtained. The method is basically to compare successively the estimated value and the calculated value, until they both reach the same value. It allows the *Initial GWST* to be determined automatically.

This process involves several steps that can be conducted on a spreadsheet. They are as follows:

(1) Create similar rows to *line* 21 to *line* 23 in Table 5.8, namely *line* 21a, *line* 22a, and *line* 23a;

(2) Identify the month that has the first value of 1 in a row from *line* 10 in Table 5.8. Set the initial value for this particular month on *line* 21a equal to the estimated value based on its geology (or any number > 0);

(3) Conduct the calculation on lines 22a and 23a in a similar way to lines 22 and 23 in Table 5.8;

(4) Obtain values of *Initial GWST* and the *Possible New Initial GWST.* These are the values that are greater than zero on *line* 21a for the *Initial GWST*, and obtain from the same column on *line* 23a for the *Possible New Initial GWST*;

(5) Compare the *Initial GWST* and the *Possible New Initial GWST* obtained in step (4). If they are similar, i.e. the difference between these values is less than 0.1, then the *New Initial GWST* equals *the Possible New Initial GWST.* This is the value that should be placed on line 21 in Table 5.8. However, if they are not similar (i.e. the condition is not met), repeat step 2 to 5 until the condition set in step 5 is met.

5.7 MODEL CALIBRATION AND VALIDATION

A model needs to be calibrated and validated before it can be used for a simulation. A calibration is a process to adjust or fine-tune some of the parameters or coefficients used in the model in order to achieve the optimum values for those parameters. Validation is a process to examine the model, to assess whether the model works in a correct way, or whether it produces an acceptable output.

For this thesis, the hydrological component is created by using the Cidurian subcatchment, Sukapada, as the pilot area. This subcatchment is about 18km^2 in size. It is selected as the pilot area for the development of the water balance model simply because the availability of data for input and observed discharge data is among the best in comparison to other subcatchments in the study area. It is surrounded by many rain stations within a relatively short radial distance. There are six rain stations within a distance of less than 12km from any point in the subcatchment that have reasonably good precipitation records for a period of 1983 to 1994. (Some of them contain missing data that have to be estimated). The observed discharge data from this subcatchmnet for the same period is limited to three years only (1986, 1990 and 1991). Actually, the Cikapundung and Ciguling subcatchments have longer observed discharge data than the Cidurian subcatchment (Table 5.9), but these data cannot be used for calibration and validation because they do not represent the true discharge. The presence of the

Table 5.9: Availability of discharge data for some subcatchments in the Bandung basin.

		1980							1990				
	Stations	3	4	5	6	7	8	9	0	1	2	3	4
1	Citarum, Nanjung												
2	Citarum, Mahmud										■	■	
3	Citarum, Bojong Tanjung												
4	Cibeureum, Sukajadi				■	■	■				■		
5	Ciwidey, Kopo												
6	Citarum, By pass												
7	Cikapundung, Gandok	■	▤		■	■	■			■	■	■	■
8	Cisangkuy, Kamasan											■	■
9	Ciguling, Maribaya	▤	■		■	■	■	■		■	■	■	■
10	Cikapundung, Maribaya	■		▤	■	■	■	■		■	■	■	■
11	Citarum, Dayeuhkolot	▤	▤									■	■
12	Citarum, Sapan												
13	Cibodas, Jatisari		▤	■									
14	Cidurian, Sukapada				■				■	■			
15	Citarum, Majalaya		▤	■	■	■			■		■		
16	Cipanjalu, Kepuh					■	■		■	■			
17	Cikeruh, Cikuda		▤			■	■		■	■			
18	Cikeruh, Babakan Bandung								■		■	■	■
19	Citarik, Rancakemit					■				■			
20	Cijalupang, Peundeuy					■			■				
21	Cirasea, Andir				■					■	■		
22	Cirasea, Cengkrong		▤			■					■	■	■

▤ Partial, available for only some months

■ Complete set of data for 1 year is available large Lembang fault in these subcatchments affects the actual discharge and the data would underestimate the actual total runoff (Delinom and Suriadarma, 1993). Therefore, model calibration and validation can only be done based on the available data for the years 1986, 1990 and 1991.

Calibration

The calibration is conducted by assessing the computed output discharge data against the observed discharge data. The r^2 value is used to identify how good the calculated output is in comparison to the observed data, i.e. it gives an indication of how well the calculated output match with the observed data. It is calculated by using the following equation (see e.g. Schwager, 1995)[5-14]:

$$r^2 = 1 - \frac{\sum_{i=1}^{n} \left(y_{obs\,i} - \hat{y}_{comp_i} \right)^2}{\sum_{i=1}^{n} \left(y_{obs\,i} - \bar{y}_{obs} \right)^2} \qquad (5\text{-}6)$$

where y_{obs} is the observed value,

$\hat{y}_{comp}$ is the computed output value, and

$\bar{y}_{obs}$ is the mean observed value.

A perfect match between the computed output and the observed data returns a value of 1 for r^2, whereas a poor match gives a value close to zero or a negative value.

Because of the availability of observed data, the calibration is conducted on a yearly basis. This will produce three calibrated models; Model 1986, Model 1990

[5-14] This statistical equation given in Schwager (1995) is used for identifying goodness of fit for comparing the regressed values (computed) and the observed values. This equation is commonly used for analysing the regression equation (or simulated values) with a focus on the unexplained variation (residuals). If the residual is much larger than the total variation, i.e. the total difference between the observed value and the simulated value is larger than the total difference between the observed value and the average observed value, a negative value is obtained. (This equation is also named Nash and Sutcliffe Coefficient [NSC] by Mohseni and Stefan [1998] after Nash and Sutcliffe [1970].)

and Model 1991. Hence, each model will have its own set of calibrated parameters.

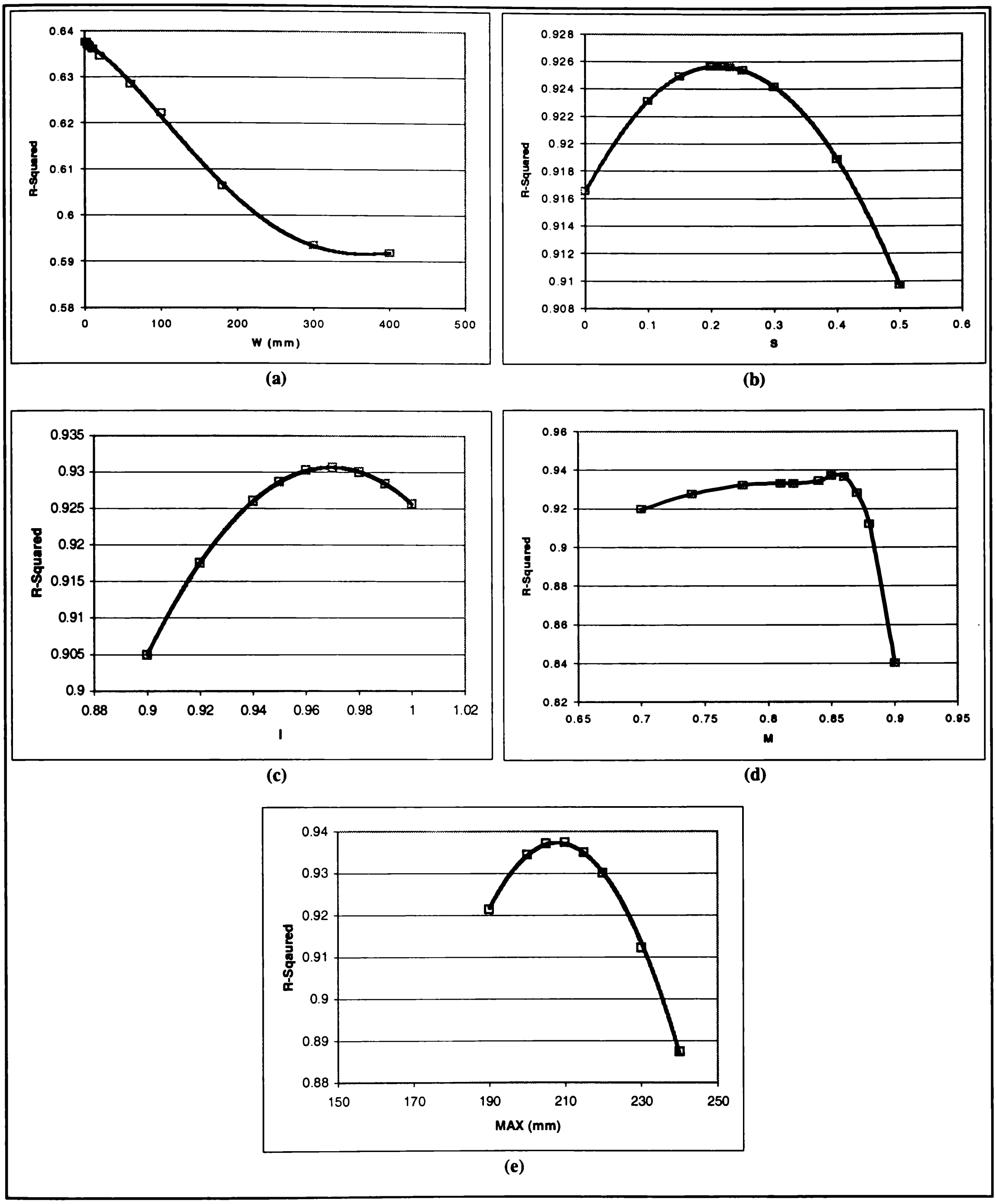
The parameters that need to be calibrated are the coefficients used in the water balance calculation. They are: *W* (available water capacity), *S* (storm runoff coefficient), *I* (infiltration factor), *M* (monthly recession constant) and *MAX* (maximum groundwater storage). All of them depend either on land use, or geology, or on both land use and geology. Specifically for *W*, the calibration aims at finding the best set of values from the three models to give the best r^2 value because annual climate variation can influence the apparent value of this parameter.

Each parameter is calibrated one-by-one by determining the value that gives the maximum r^2 from an optimum curve (Figure 5.8). However, in some cases, the optimum curve does not show. In this case, the possible value that can give the maximum r^2 value is taken.

Results of calibrations for the three models are listed in Table 5.10. It clearly shows that the Model 1990 is the best with $r^2 = 0.9395$.

Table 5.10: Results of model calibrations.

	r^2
Model 1986	0.7582
Model 1990	0.9395
Model 1991	0.4175



(a) (b) (c) (d) (e)

Figure 5.8: Some examples of optimum graphs from Model 1990: (a) Forest, no optimum value. For this, W = 0.5mm; (b) Forest, geology type 2, S = 0.21; (c) Geology type 1, I = 0.97; (d) Geology type 2, M = 0.85; (e) Geology type 1, MAX = 210mm.

Validation

The calibrated models need to be tested on different set of input data, and their computed outputs are compared with the observed data. For Model 1986, the input is the 1990 and 1991 data; for Model 1990, the input is the 1986 and 1991 data; whereas for Model 1990, the input is the 1986 and 1991 data. During this validation process, the three sets of available water capacity values (*W*) that have been obtained from the calibration processes are tested on each model in order to find the best set of these three sets. This process is conducted because the model was calibrated using data from a very short period. Therefore, they may not represent the condition of the catchment in general because this particular parameter is sensitive to the variation in soil moisture.[5-15]

The results of these model validation processes are given in Table 5.11. In general, the set of *W* values calibrated from Model 1991 produced the best results. In particular, Model 1990 in combination with this set of *W* values gives the best result with the $r^2 = 0.718$. This set of *W* values obtained from Model 1991 is, in fact, quite comparable with the suggested values by Thornthwaite and Mathers (1957), which range from an average of 75mm for paddy to an average of 400mm for mature forest. Based on the results of this validation process, Model 1990 with the calibrated *W* values from Model 1991 is selected for this study. Graphical comparison between the model output and observed discharge data is given in Figure 5.9.

[5-15] Available water capacity is defined as the difference between the field capacity and the permanent wilting point times the rooting depth of vegetation (Dunne and Leopold, 1978). If the soil is saturated, water will drain quickly from the large pores due to gravitational force, until it reaches a certain water content where the water cannot drain because the gravitational force is countered by a capillary force exerted by the soil's pores. The water content at this balance state is called the field capacity. For water to be removed from the soil, the plants must exert a suction force on the soil moisture. However, there is a limit in the amount of water that can be drawn from the soil by the plants. When the plants cannot withdraw water at a sufficient rate to fill the demand for transpiration, the plants wilt. When this condition occurs the soil moisture is called the permanent wilting point. The available water capacity, therefore, depends on the soil type and vegetation type. When the soil is always filled with water, the wilting point is never met. Therefore, the optimum available water capacity cannot show up in the calibration processes.

Table 5.11: Results of model validations, given in r^2 values.

	Set of available water capacity		
	1986	1990	1991
Model 1986	-3.974	-4.398	0.499
Model 1990	-0.775	-0.879	0.718
Model 1991	0.380	0.481	-0.546

Shaded cells mean using their own set of calibrated *W* values.

Significance analysis

All the values of parameters obtained from the calibration process, excluding *W*, are assessed in terms of their significance to the model. This analysis will examine how much the error in determining the parameters can change the performance of the model. The significance of each parameter in affecting the output can also be assessed, which can help in determining the parameters that have to be treated carefully.

The analysis is conducted by using all the available observed data. Each parameter is assessed by examining the percentage change in r^2 when the value of each parameter is increased or decreased by 10%. The results are shown in Table 5.12.

In general, an increase or a decrease in the storm runoff coefficient for any environment does not significantly change the overall performance of the model. The most significant change in this land use and geology dependent parameter is shown for a combination of environment of geology type 1 and urban area. In this type of environment, an increase in the storm runoff parameter value by 10% produces a change in r^2 by 1.23%. Other environments give a change in r^2 of less than 0.25%.

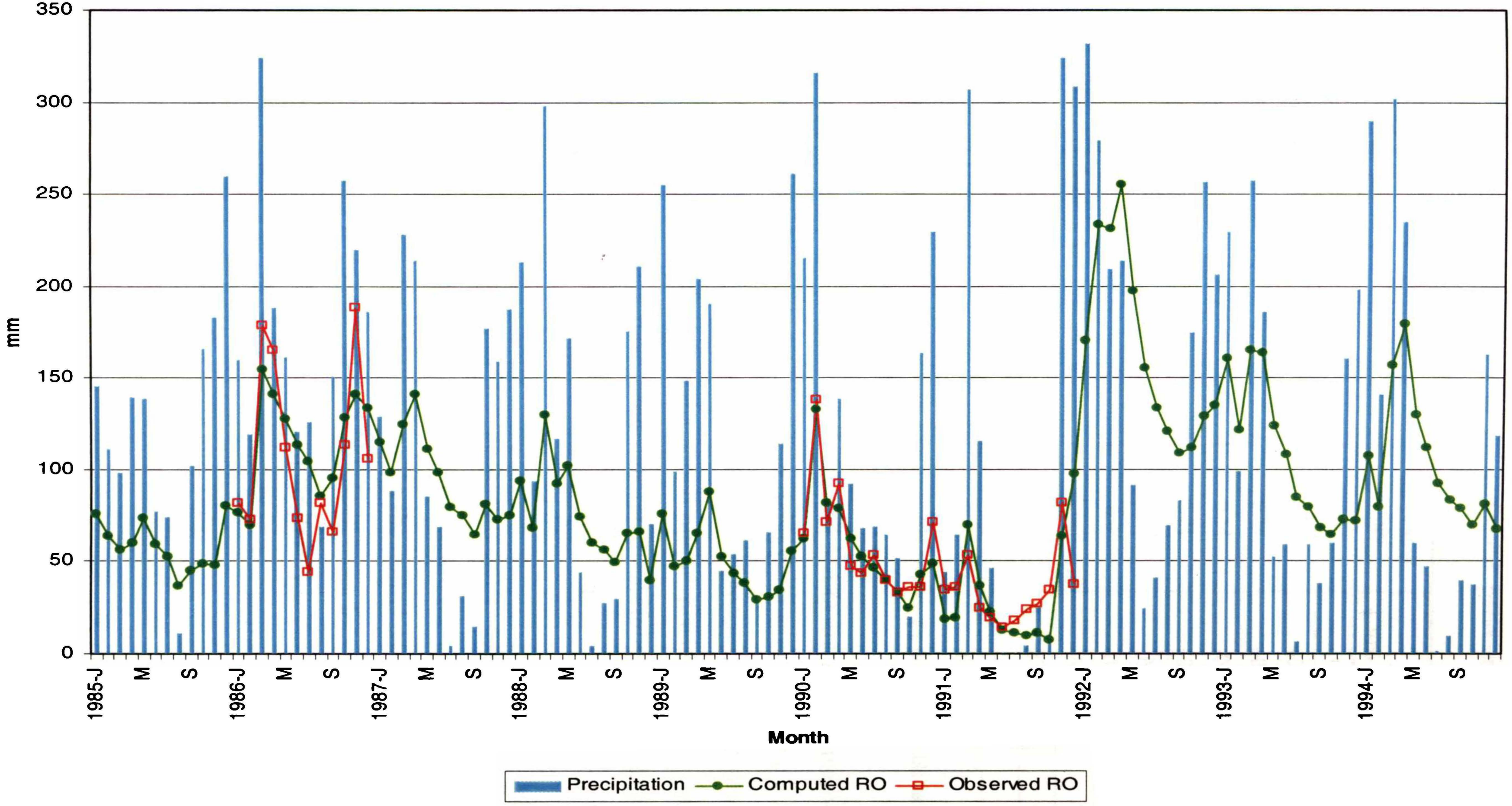


Figure 5.9: The result of calibration using the 1990 data ($r^2 = 0.9395$) and validation using the 1986 and 1991 data ($r^2 = 0.718$).

Table 5.12: Significance analysis of the calibrated parameters using all available observed discharge data. The r^2 value = 0.750.

Parameters	Environment		Calibrated value	Δr^2 (%)	
				+ 10% change	- 10% change
S	Geology 1	Settlement/urban	0.11	-1.23	-0.23
	Geology 2	Settlement/urban	0.26	+0.08	-0.16
		Paddy-field	0.14	+0.12	-0.12
		Dryland	0.14	-0.04	-0.03
		Forest	0.21	+0.05	-0.06
I	Geology 1		0.97	NA	-4.54
	Geology 2		0.9	-0.60	+0.25
M	Geology 1		0.942	NA	-78.82
	Geology 2		0.85	-23.48	-0.72
MAX	Geology 1		210	-1.51	-0.59
	Geology 2		235	-0.10	+0.04

NA: Not applicable because the change in the value of the parameter exceeds the range of possible value.

The geology only related parameters (*I*, *M*, and *MAX*) are more sensitive than the parameter *S* (Table 5.12). A small error in these parameters can give a large error in the actual discharge. Nevertheless, because this thesis focuses on the sensitivity analysis of the output rather than the actual output discharge, they can be given any value as long as they have been calibrated carefully and are kept constant when the model is implemented for the whole study area.

Details of significance analysis for each parameter can also be assessed by examining the change in the output that comes from the area which is affected by the change in the parameter only, rather than the output of the whole area. In other words, the analysis is conducted on cell-by-cell basis by comparing the computed output from one set of determined parameters against the output of altered parameters. All inputs are kept the same. For this analysis, the parameter to be examined is the storm runoff coefficient only. The others, which are geology related parameters, are considered unimportant for the sensitivity analysis even though they can be very significant in determining the absolute quantity of the discharge.

The results (Table 5.13) suggest that the storm runoff coefficient is quite significant in altering the runoff, and this coefficient shows a variation in its significance depending on its geology and land use. In general, the storm runoff of urban area is the most significant. An increase or a decrease in the storm runoff coefficient of this land use type by 10% produces a change in the mean annual runoff by 7.3 to 8.3%, and a change in the mean monthly runoff that varies from 6.7 to 9.0%. Of least significance is the storm runoff coefficient for paddy. A 10% change in this coefficient causes a change in the mean annual runoff by 0.6 to 1.2%, and a change in the mean monthly runoff that varies from 0.15 to 5.6%.

Implicitly, the results also suggest the change in land use can produce a variable effect in the total runoff. This is also supported by an interesting finding, which shows that an increase in the storm runoff coefficient is not always associated with an increase in the total annual runoff. A 10% increase in the storm runoff coefficient for the urban area with geology type 1 (very high infiltration) causes a decrease in the mean annual runoff by 7.6%. On the other hand, a 10% increase in the storm runoff coefficient for the urban area with geology type 2 (relatively lower infiltration than the geology type 1) causes an increase in the mean annual runoff by 7.3%.

Estimating uncalibrated parameters

When the model is implemented into the whole basin, some additional parameters that are not calibrated are required. This is because the pilot area cannot represent all environmental conditions of the whole basin. In particular, geology type 3 is not represented in the pilot area. Therefore, these parameters need to be estimated.

Table 5.13: Significance analysis for the storm runoff (*S*) parameter of various environments.

Environment		S	ΔS (%)	Δ mean annual discharge (%)	Δ mean monthly discharge (%)											
Land use	Geology				Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Urban	1	0.11	+10	-7.60	-7.51	-7.75	-6.54	-6.66	-7.44	-8.17	-8.52	-8.55	-8.81	-8.11	-6.91	-7.09
			-10	7.82	7.62	7.91	6.66	6.70	7.62	8.33	8.85	9.02	8.90	8.28	7.59	7.57
	2	0.26	+10	7.33	8.27	6.99	7.36	6.80	6.03	3.81	3.13	3.95	6.02	8.23	9.05	9.08
			-10	-8.28	-8.30	-9.10	-8.34	-7.92	-7.43	-6.00	-5.56	-6.09	-7.43	-8.86	-9.39	-9.11
Paddy-field	2	0.14	+10	1.20	2.09	-0.15	1.13	-0.52	-1.15	-2.86	-1.41	-0.73	1.04	4.22	5.56	5.20
			-10	-0.62	-1.61	1.06	-0.45	1.02	1.68	4.10	2.62	1.31	-0.57	-3.94	-5.40	-5.00
Dryland	2	0.14	+10	-3.05	-1.72	-4.15	-2.99	-4.47	-5.09	-6.57	-6.80	-4.92	-0.85	1.92	2.36	1.35
			-10	3.34	1.73	4.66	2.98	4.51	5.67	7.11	7.66	5.49	0.93	-1.87	-2.04	-0.91
Forest	2	0.21	+10	4.30	6.69	4.41	5.39	3.38	1.28	-1.68	-3.65	-2.06	1.15	5.40	7.72	8.02
			-10	-4.25	-6.56	-4.66	-5.31	-3.35	-1.16	1.83	3.83	2.22	-1.03	-5.34	-7.69	-8.00

The estimation is conducted by looking at some reported values from studies that have similar geological conditions. In this case a groundwater resources study in Greater Yogyakarta (the Special Province of Yogyakarta) by Sir MacDonald and Partners (1984) is used. This area is divided into three general geological classifications based on their runoff characteristics. They are: recent (young) volcanic deposits (RV); mixed volcanics, recent or mixed volcanics with sediments (MV, RV/S, MV/S); and old volcanics, old volcanics with sediment, or sediment (OV, OV/S, S). Their hydrological parameters are given in Table 5.14.

These geological variations are comparable the Bandung basin, the study area for this thesis. However, a difficulty occurs in classifying the geology of the study area into a similar classification as given in the Greater Yogyakarta area. This is because this classification is not based on a quantitative measurement, for example, the infiltration rate, but it was on a qualitative assessment on the

Table 5.14: Reported values for parameters *S*, *I*, *M* and *MAX* from a groundwater resource study in Greater Yogyakarta, central Java (Source: Sir MacDonald and Partners, 1984.)

Geological class and description	*S*	*I*	*M*	*MAX*
RV High infiltration, unconsolidated material	0.05; 0.15; 0.2	0.9; 0.87; 0.85	0.87; 0.85; 0.83	1500; 800; 600
MV, RV/S, MV/S (Moderate infiltration between the other two geological classes)	No case	No case	No case	No case
OV, OV/S Low infiltration factor. On a volcanic fan deposit, the infiltration factor has a decreasing trend towards the lower basin to reflect the better sorted and more consolidated material at the lower fan.	0.35; 0.2	0.5; 0.45	0.81; 0.5	200; 300
Range of values for all three geological classes	0.05 - 0.35	0.5 - 0.9	0.5 - 0.87	200 - 1500

Note: RV is represented by 3 cases; MV, RV/S, MV/S are not represented (no case); OV, OV/S are represented by 2 cases. For MV, RV/S and MV/S, the values of parameters should be in a range between the values of the other classes.

geological age and geological facies. Nevertheless, a comparable classification can still be assessed in a rather subjective manner from the geological map of the Bandung basin. (See Figure 3.2 in Chapter 3, page 6). The geology of Bandung is classified into three main types as follows:

- *Geology type 1*, comparable to RV, consisting of all of the Quaternary rocks/deposits from Holocene to Late Pleistocene, except alluvial and colluvial deposits (QHa), and lake deposits (QHl);
- *Geology type 2*, comparable to MV, RV/S, and MV/S, consisting of recent alluvial and colluvial deposits (QHa), and undifferentiated volcanic products of Lower to Middle Pleistocene (QPmV);
- *Geology type 3*, comparable to OV and OV/S, consisting of Lower Pleistocene volcanic products (QPlV) and all Tertiary rocks.

A map of the Bandung basin area showing these three geological types is given in Figure 5.10.

For the storm runoff coefficient (*S*), Sir McDonald and Partners (1984) disregarded the land use variation and only considered the geological variation. Land use variation, in fact, has a significant role in the total runoff as shown by the results of significance analysis (Table 5.13). It also controls total discharge and time-lags for floods (e.g. Viessman *et al.*, 1989) as each land use type has significant variation in surface roughness and ability to pass water to the soil through infiltration processes, etc. For sensitivity analysis, with regards to changes in land use patterns, the variation of the storm runoff coefficient with respect to land use and geological variation needs to be estimated.

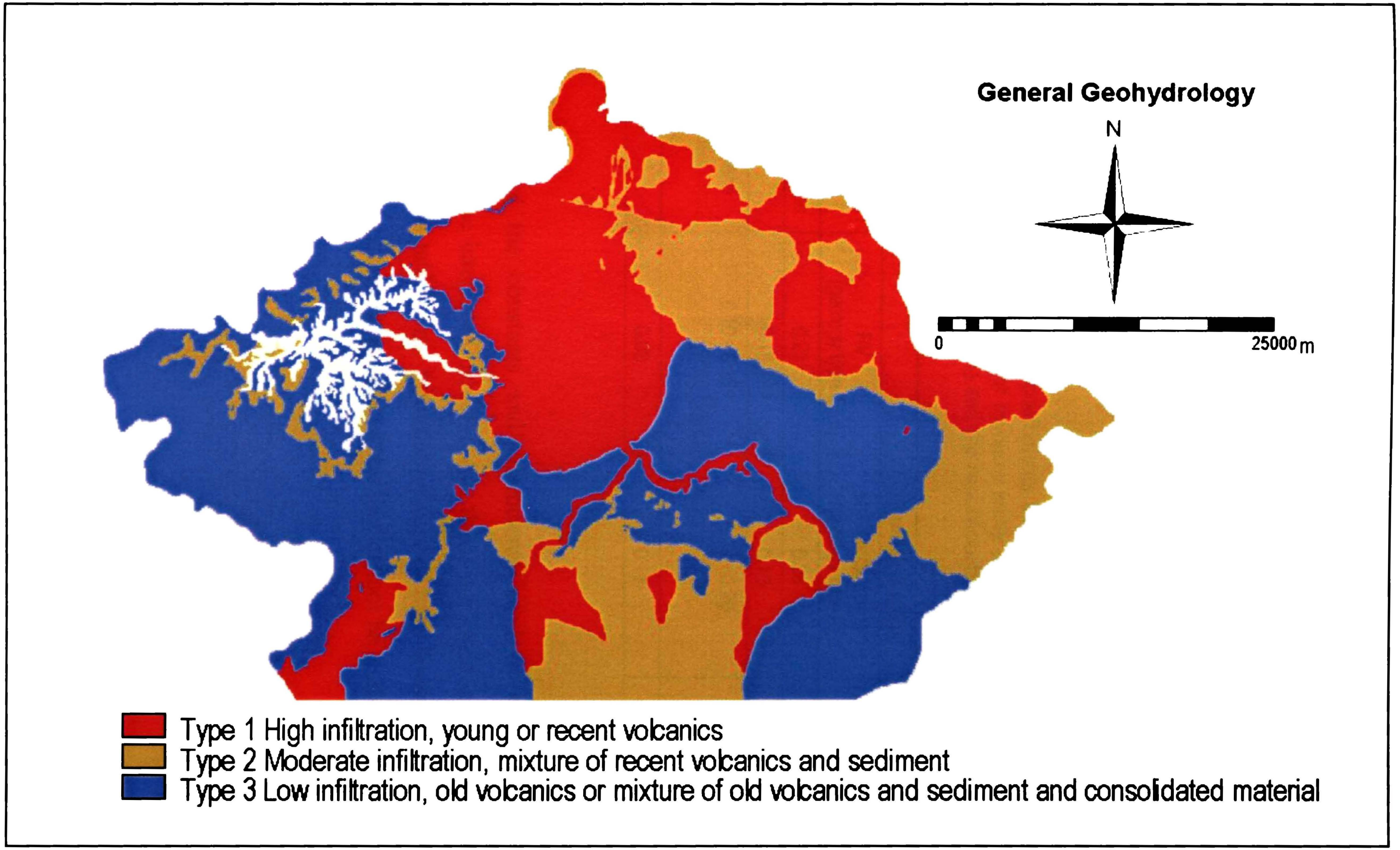


Figure 5.10: Geological classification based on general hydrological characteristics.

The storm runoff coefficients can be estimated by combining the values as given by Sir MacDonald and Partners (1984) (Table 5.14) and the runoff coefficient values (*C*) given by the US SCS method (listed in Viessman *et al.*, 1989), which take into account the land use variation and infiltration capacity. The estimation is conducted by an area-weighted proportion method. (Details are given in Appendix 5.B.) Results of the estimation (Table 5.15) are quite acceptable with respect to the calibrated storm runoff coefficients.

Table 5.15: Estimated storm runoff coefficients for various geology types and land uses, based on data given by a groundwater resource study in Greater Yogyakarta, central Java (Sir MacDonald and Partners, 1984) and the runoff coefficients given by the US SCS (e.g Viessman *et al.*, 1989).

	Geological types		
	RV (geology type 1)	MV, RV/S, MV/S * (geology type 2)	OV, OV/S (geology type 3)
Urban/settlement area	0.21	0.26	0.31
Paddy-field	0.15	0.18	0.26
Dry-agricultural land (tegalan, garden, horticulture)	0.10 - 0.13	0.19 - 0.20	0.27 - 0.29
Forest	0.03	0.11	0.21

In summary, all the constants and coefficients used in the water balance computation for the integrated model of this thesis are listed in Table 5.16. Some of the values in this table come from the process of a calibration, and some from an estimation and adjustment process (when they cannot be calibrated).

Table 5.16: List of all coefficients and constants used in the water balance calculation.

Available water capacity (W) and land use water consumption coefficient (k_l)

Land use	Code	W	k_l											
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Reforested	1	550	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Primary forest	2	550	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Secondary forest	3	550	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Dry-land (tegalan)	4	280	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Mix-garden	5	280	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Vegetable garden	6	280	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Irrigated paddy	7	70	0.96	1.01	1.04	1.04	0.96	0.99	1.00	0.95	0.84	1.10	1.07	1.05
Rainfed paddy	8	70	0.94	0.91	0.90	1.00	0.92	0.80	1.03	0.99	0.84	0.94	1.07	0.89
Urban area	9	160	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Cinchona (quina)	10	300*	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Tea plantation	11	300*	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Lake	12	NA	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05

Surface run-off (S)

Land use	Geol 1	Geol 2	Geol 3
Reforested *Primary forest* *Secondary forest*	0.11*	0.21	0.21*
Dry-land (tegalan) *Mix-garden* *Vegetable garden*	0.13*	0.14	0.29*
Irrigated paddy	0.14*	0.14	0.26*
Rainfed paddy	0.14*	0.14	0.26*
Urban area	0.11	0.26	0.31*
Cinchona (quina)	0.13*	0.14*	0.20*
Tea plantation	0.13*	0.14*	0.20*
Lake	NA		

Infiltration (I)	
Geol 1	0.97
Geol 2	0.9
Geol 3	0.5*

Monthly reces.(M)	
Geol 1	0.94
Geol 2	0.85
Geol 3	0.5*

Max stor. (MAX)	
Geol 1	210
Geol 2	235
Geol 3	150*

IGWST	
Geol 1	376
Geol 2	129
Geol 3	50*

* estimated.

5.8 CONCLUSION

The hydrological model using a water balance conceptual approach has been developed. The computation is conducted on a cell-by-cell basis for the whole study area, which calculates the total runoff for each cell. The overall runoff of the whole basin is calculated as the sum of the total runoff for all cells. Model calibration gives a r^2 value of 0.9395 and validation gives a r^2 value of 0.718.

The hydrological model is designed to allow a sensitivity analysis on the both land use pattern change and climate change. Therefore, there is a need to have straightforward links between this hydrological component and the other components.

The hydrological component links to the land use component in the following ways:

- **Water consumption for each type of land use;**

  This has been established by determining the monthly k_l values (land use coefficient) for each land use type. For agricultural land, the monthly k_l values are determined based on their cropping patterns and crop types. For other land uses such as forests, urban areas and lakes, the monthly k_l values need to be estimated.

- **Storm runoff coefficient** (S);

  The storm runoff coefficient varies with its environment, which is geology and land use. The values of this parameter for each combination of geology and land use have been determined through model calibration, and an estimation process for the required values that cannot be calibrated.

The links between the hydrological component and the climate component are mainly through **precipitation** and **potential evapotranspiration**. These data need to be interpolated and projected to all grid cells in the study area. For this study, the potential evapotranspiration is defined as a temperature function, which is controlled by the elevation. The interpolation and the projection are processed by using a Geographical Information System (GIS).

The next two chapters (Chapter 6 and Chapter 7) will discuss how the land use component and the climate component are developed, and linked to this hydrological component.

REFERENCES

Barnes, S.L. 1996. Analysis of spatial fields containing data gaps. [online] available URL http://www.fsl.noaa.gov/frd/mab/barnes/web101/big-gaps.html, [7 March 2001], submitted as an article to Monthly Weather Review.

Cheng, J.D., Hsia, Y.J., Lu, H.S., Liu, V.C. and Koh, C.C. 1987. Streamflow characteristics of two small, steep and forested watersheds in high elevation areas of central Taiwan. In: R.H. Swanson, P.Y. Bernier and P.D. Woodard (eds.), *Forest Hydrology and Watershed Management.* IAHS Publ. No. 167, 499-508.

Dagg, M. and Blackie, J.R. 1970. Estimates of evaporation in East Africa in relation to climatological classification. *Geographical Journal* 136, 227-234.

Dam, M.A.C. 1994. The Late Quaternary Evolution of the Bandung Basin, West Java, Indonesia. Thesis, Vrije Universiteit Amsterdam.

Dean, J.D. and Snyder, W.M. 1977. Temporarily and areally distributed rainfall. *Journal of the Irrigation and Drainage Division, ASCE* 103 (IR2), Proc. Paper 13002, June, 1977, 221-229.

Delinom, R. and Suriadarma, A. 1993. Influence of groundwater flow in the Upper Cikapundung catchment: A hydrology approach. *Proceedings of the 22nd Annual Convention of the Indonesian Association of Geologists.* Bandung 6-9 December 1993, 560-569.

Dexter, L.R. and Avery, C.C. 1991. Using spreadsheet software in water-balance modelling. *Computers & Geosciences* 17, 527-536.

Dingman, S.L. 1994. *Physical Hydrology.* Prentice Hall, New Jersey.

Directorate of Food Crop Production 1994. *Synthesis of Main Crop Pattern Technology in Boosting the Cropping Index ≥ 300 on Intensive Paddy Land – West Java Province.* Directorate of Food Crop Production, Directorate General of Food Crops and Horticulture.

Donker, N.H.W. 1987. WTRBLN: A acomputer program to calculate water balance. *Computers & Geosciences* 13 (2), 95-122.

Doorenbos, J. and Kassam, A.H. 1979. *Yield Response to Water.* FAO Irrigation and Drainage Paper No. 33, FAO of the United nations, Rome, 193pp.

Doorenbos, J. and Pruitt, W.O. 1977. *Crop Water Requirements - Guidelines for predicting crop water requirements.* FAO Irrigation and Drainage Paper No. 24, FAO of the United Nations, Rome, Revised Edition, 144pp.

Dunne, T. and Leopold, L.B. 1978. *Water in Environmental Planning* W.H. Freeman and Company, San Fransisco

Gilman, C.S. 1964. Rainfall. In: V.T. Chow (ed.) *Handbook of Applied Hydrology.* Section 9, McGraw-Hill, Inc., USA.

Goovaerts, P. 1999. Performance comparison of geostatistical algorithms for incorporating elevation into the mapping of precipitation. Paper submitted to The IV International Conference on GeoComputation, Mary Washington College, Fredericksburg, VA, U.S.A., 25-28 July.

Hadi, P. 1988. A microcomputer package for evaluating water balance. *Majalah Geografi Indonesia* 1 (2), 27-36.

ITC 2001. *Ilwis 3.0 Academic User's Guide.* International Institute for Aerospace Survey and Esrth's scenarios.

Jensen, M.E. 1968. Water consumption by agricultural plants. In: T.T. Kozlowski (ed.) *Water Deficits and Planting Growth* Vol. 2 Plant Water Consumption and Response, Academic Press, 1-22

Katz, B.G., DeHan, R.S., Hirten, J.J. and Catches, J.S. 1997. Interactions between groundwater and surface water in the Suwannee River Basin, Florida. *Journal of the American Water Resources Association* 33 (6), 1237-1254.

Linsley, R.K. Jr., Kohler, M.A. and Paulhus, J.L. 1949. *Apllied Hydrology.* Chapter 6, McGraw-Hill Inc., New York, USA.

Linsley, R.K. Jr., Kohler, M.A. and Paulhus, J.L. 1975. *Hydrology for Engineers, 2nd Edition.* Chapter 3, McGrawhill Inc., USA.

Lynch, S.D. and Schulze, R.E. 1995. Techniques for estimating areal daily rainfall [online] available URL http://pature.ecn.purdue.edu/~aggrass/esri95 /to250/p241.html, [3 March 2001)

Mizzell, H.P. 1999. *Comparison of WSR-88 derived rainfall estimates with gauge data in Lexington County, South Carolina.* MSc Thesis, Department of Geography, University of South Carolina, [online] available URL http://water.dnr.state.sc.us/climate/sco/thesis/thesis.html.

Mock, F.J. 1973. *Land Capability Appraisal Indonesia: Water Availabiility Appraisal.* Report prepared for the Land Capability Appraisal Project, Bogor - Indonesia, FAO of the United Nations.

Mohseni, O. and Stefan, H.G. 1998. A monthly streamflow model. *Water Resources Research* 34 (5), 1287-1298.

Nash, J.E and Sutcliffe, J.V. 1970. River flow forecasting through conceptual models. I-A. Discussion of principles. *Journal of Hydrology* (10), 282-290.

National Weather Service 1972. *National Weather Service River Forecast System Forecast Procedures.* NOAA Tech. Mem. NWS HYDRO 14, Hydrological Research Laboratory, National Weather Service, Silver Spring, MD, December.

Penman, H.L. 1963. *Vegetation and Hydrology.* Commonwealth Bur. Soil. Sci. (Gt. Brit.) Tech. Communication 53, 124pp.

PROSIDA 1976. *Water Requirements for Paddy and Other Crops.* Report to DPUTL (Department of Public Works and Energy).

Reed, S.M., Maidment, D.R., Asante, K. and Akmansoy, S. 1996. *Water balance model for the Souss Basin.* FAO/UNESCO Water Balance of Africa, [online] available URL http://www.ce.utexas.edu/prof/maidment/grad/akmansoy/hydrology/africa/webfiles/ex1.htm, [7 March 2001]

Rutter, A.J. 1968. Water consumption by forests. In: T.T. Kozlowski (ed.), *Water Deficits and Planting Growth* Vol. 2 Plant Water Consumption and Response, Academic Press, 23-84.

Salinger, M.J. 1981. *New Zealand climate: The instrumental record.* PhD Thesis, Victoria University, NZ.

Savenije, H.H.G. 1995. Spreadsheets: flexible tools for integrated management of water resources in river basins. In: S.P. Simonovic, Z. Kundzewicz, D. Rosbjerg and K. Takeuchi (eds.) *Modelling and Management of Sustainable Basin-Scale Water Resource Systems.* IAHS Publ. No. 231, 207-215.

Schwager, J.D. 1995. *Fundamental Analysis* John Wiley and Sons Inc., Toronto, Canada.

Shaw, E.M. 1994. *Hydrology in Practice, 3rd Edition.* Chapter 10, Chapman & Hall, London, U.K.

Singh, V.P. and Chowdhury, P.K. 1986. Comparing some methods of estimating mean areal rainfall. *Water Resources Bulletin* 22 (2), 275-282.

Sir M MacDonald & Partners 1984. *Greater Yogyakarta Groundwater Resources Study - Vol 2 Hydrology.* Report of Groundwater Development Project (P2AT), Directorate General of water Resources Development, Ministry of Public Works, Government of the Republic of Indonesia, Sir M MacDonald & Partners in association with Binnie & Partners, Hunting Technical Services Ltd.

Sumner, G. 1988. *Precipitation: Process and Analysis.* Section 9.1, John Wiley & Sons, Chichester, U.K.

Thornthwaite, C.W. and Mather, J.R. 1957. *Instructions and Tables for Computing Potential Evapotranspiration and The Water Balance.* Publications in Climatology, Vol. X (3), Drexel Institute of Technology - Laboratory of Climatology, Centerton, New Jersey.

Tran, T.D. 1996. *Climate change, extreme temperature events and the implications for mangroves in Northern Vietnam.* MSc Thesis, Waikato University, NZ.

Viessman Jr., W., Lewis, G.L. and Knapp, J.W. 1989. *Introduction to Hydrology, 3rd Edition.* Harper & Row, Publishers, NY.

Wilson, E.M. 1974. *Engineering Hydrology, 2nd Edition.* The McMillan Press Ltd., Hong Kong.

APPENDIX 5-A: THE CONVERSION OF CROP COEFFICIENT TO MONTHLY LAND USE WATER CONSUMPTION (k_l)

The k_l is converted from k_c to using the method below:

1. Several crop patterns of agricultural types under various agroclimatic zones are selected. The annual precipitation of the agroclimatic zones is within a range of 1,300mm to 1,700mm. **(Table App. 5-1.)**

2. Monthly crop coefficient values are assigned for each crop patterns. **(Table App. 5-2.)**

3. Monthly with area-weighted average of k_c values are calculated based on the agroclimatic zone and agricultural types, transforming the monthly average k_l values to. **(Table App. 5-3.)**

4. Average monthly in k_l from each agroclimate zones for each agricultural land is calculated. The shaded cells are the values used, except the dry-agricultural land will use the average value for the entire months. **(Table App. 5-4.)**

Table App. 5-1: Crop patterns of several agricultural land types under various agroclimatic zones and annual precipitation within a range of 1,300 to 1,700mm.

Agroclimate Zone	Agricultural land type	Annual P (mm)	Months												Quantity* (%)
			10	11	12	1	2	3	4	5	6	7	8	9	
E, C2, D2	Fully irrigated paddy field	1,608	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	94
								soybean	soybean	soybean	soybean	soybean	soybean		3
											mungbean	mungbean	mungbean		3
E, C2, D2	Semi-fully irrigated paddy	1,608	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	94
									groundnut	groundnut	groundnut	groundnut	groundnut	groundnut	4
E	Fully irrigated paddy field	1,650	rice	rice	rice	rice		rice	rice	rice	rice				97
E	Rain-fed paddy field	1,650							maize	maize	maize	maize	maize	maize	32
									mungbean	mungbean	mungbean				24
				soybean	soybean	soybean			soybean	soybean	soybean				21
			groundnut	groundnut	groundnut				groundnut	groundnut	groundnut				17
E	Dry land	1,650	cassava	cassava	cassava	cassava	cassava	cassava	cassava	cassava	cassava	cassava	cassava	cassava	30
												mungbean	mungbean	mungbean	26
			maize	maize	maize	maize	maize	maize	maize	maize	maize	maize	maize	maize	21
			soybean	soybean	soybean	soybean	soybean	soybean	soybean	soybean	soybean	soybean	soybean	soybean	15
			groundnut	groundnut	groundnut	groundnut	groundnut	groundnut	groundnut	groundnut	groundnut	groundnut	groundnut	groundnut	8
E	Fully-irrigated paddy field	1,584	rice	rice	rice	rice	rice	rice	rice	rice					91
											soybean	soybean	soybean		7
											mungbean	mungbean	mungbean		2
E	Semi-fully irrigated paddy	1,584	rice	rice	rice	rice	rice	rice	rice	rice					100
E	Dry land	1,584	maize	maize	maize	maize	maize	maize	maize	maize	maize	maize	maize	maize	43
			cassava	cassava	cassava	cassava	cassava	cassava	cassava	cassava	cassava	cassava	cassava	cassava	39
						mungbean	mungbean	mungbean							6
C2, B2	Fully irrigated paddy field	1,300	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	100
C2, B2	Semi-fully irrigated paddy	1,300	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	57
									soybean	soybean	soybean				21
									maize	maize	maize				14
								sweetpotato	sweetpotato	sweetpotato	sweetpotato				8
C2, B2	Rain-fed paddy field	1,300	soybean	soybean		soybean	soybean	soybean	soybean	soybean	soybean			soybean	42
			rice	rice	rice									rice	31
							maize	maize	maize	maize	maize	maize			19
			sweetpotato				sweetpotato	sweetpotato	sweetpotato	sweetpotato		sweetpotato	sweetpotato	sweetpotato	8
C2, B2	Dry land	1,300	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	27
			cassava	cassava	cassava	cassava	cassava	cassava	cassava	cassava	cassava	cassava	cassava	cassava	25
			maize	maize		maize	maize	maize						maize	16
			soybean	soybean	soybean	soybean	soybean	soybean	soybean	soybean	soybean				15
			-potato	-potato	sweetpotato	sweetpotato	sweetpotato	sweetpotato	sweetpotato	sweetpotato	sweetpotato	sweetpotato	sweet-	sweet-	10
B2, C2	Semi-fully irrigated paddy	1,671	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	96
B2, C2	Rain-fed paddy field	1,671	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	81
					maize	maize	maize	maize	maize	maize	maize	maize	maize		19
B2, C2	Dry land	1,671	maize	maize	maize	maize	maize	maize	maize	maize	maize	maize	maize	maize	55
			cassava	cassava	cassava	cassava	cassava	cassava	cassava	cassava	cassava	cassava	cassava	cassava	18
			rice	rice	rice	rice									16
			sweetpotato	sweetpotato	sweetpotato	sweetpotato	sweetpotato	sweetpotato	sweetpotato	sweetpotato	sweetpotato	sweetpotato	sweetpotato	sweetpotato	11

*This is the area in percentage.

Table App. 5-2: Assigning monthly crop coefficient values on the crop patterns. The bolded numbers are the area weighted average of the for the specific block of crop pattern.

Agroclimate Zone	Agricultural land type	Annual P (mm)	Crop type	Monthly Kc												Kc of total growing period	Quantity (%)
				10	11	12	1	2	3	4	5	6	7	8	9		
E, C2, D2	Fully irrigated paddy field	1,608	rice	1.10	1.07	1.05	0.96	1.10	1.07	1.05	0.96	1.10	1.07	1.05	0.96	1.05	94
			soybean					0.44	0.46	0.96	0.75	0.46	0.96	0.75	0.44	0.75	3
			mungbean									0.46	0.96	0.75	0.44	0.75	3
				1.10	**1.07**	**1.05**	**0.96**	**1.10**	**0.46**	**1.05**	**0.96**	**1.02**	**0.96**	**0.75**	**0.44**	0.91	100
E, C2, D2	Semi-fully irrigated paddy	1,608	rice	1.10	1.07	1.05	0.96	1.10	1.07	1.05	0.96	1.10	1.07	1.05	0.96	1.05	94
			groundnut							0.53	0.85	0.72	0.53	0.85	0.72	0.75	4
				0.44	**1.07**	**1.05**	**0.96**	**1.10**	**0.43**	**1.04**	**0.95**	**0.96**	**0.97**	**0.85**	**0.44**	0.85	98
E	Fully irrigated paddy field	1,650	rice	1.10	1.07	1.05	0.96		1.10	1.07	1.05	0.96				1.05	97
				0.44	**1.07**	**1.05**	**0.96**	**0.44**	**0.44**	**1.07**	**1.05**	**0.92**	**0.96**	**0.75**	**0.44**	0.80	97
E	Rain-fed paddy field	1,650	maize							0.37	0.88	0.80	0.37	0.88	0.80	0.68	32
			mungbean							0.46	0.96	0.75				0.75	24
			soybean		0.46	0.96	0.75			0.46	0.96	0.75	0.46	0.96	0.75	0.75	21
			groundnut	0.53	0.85	0.72				0.53	0.85	0.72	0.44			0.75	17
				0.44	**0.45**	**0.86**	**0.75**	**0.44**	**0.44**	**0.43**	**0.93**	**0.75**	**0.41**	**0.92**	**0.41**	0.60	93
E	Dry land	1,650	cassava	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.95	30
			mungbean										0.46	0.96	0.75	0.75	26
			maize	0.37	0.88	0.80	0.37	0.88	0.80	0.37	0.88	0.80	0.37	0.88	0.80	0.68	21
			soybean	0.46	0.96	0.75	0.46	0.96	0.75	0.46	0.96	0.75	0.46	0.96	0.75	0.75	15
			groundnut	0.53	0.85	0.72	0.53	0.85	0.72	0.53	0.85	0.72	0.53	0.85	0.72	0.75	8
				0.52	**0.83**	**0.76**	**0.47**	**0.83**	**0.75**	**0.56**	**0.84**	**0.29**	**0.52**	**0.88**	**0.75**	0.67	100
E	Fully-irrigated paddy field	1,584	rice	1.10	1.07	1.05	0.96	1.10	1.07	1.05	0.96					1.05	91
			soybean									0.46	0.96	0.75		0.75	7
			mungbean									0.46	0.96	0.75		0.75	2
				1.10	**1.07**	**1.05**	**0.96**	**1.10**	**1.07**	**1.05**	**0.96**	**0.46**	**0.96**	**0.75**	**0.44**	0.91	100
E	Semi-fully irrigated paddy	1,584	rice	1.10	1.07	1.05	0.96	1.10	1.07	1.05	0.96					1.05	100
				1.10	1.07	1.05	0.96	1.10	1.07	1.05	0.96	0.44	0.44	0.44	0.44	0.84	100
E	Dry land	1,584	maize	0.37	0.88	0.80	0.37	0.88	0.80	0.37	0.88	0.80	0.37	0.88	0.80	0.75	43
			cassava	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.95	39
			mungbean			0.44	0.46	0.96	0.75	0.44	0.44					0.75	6
				0.37	**0.84**	**0.71**	**0.61**	**0.82**	**0.74**	**0.47**	**0.73**	**0.75**	**0.19**	**0.88**	**0.75**	0.65	88
C2, B2	Fully irrigated paddy field	1,300	rice	1.10	1.07	1.05	0.96	1.10	1.07	1.05	0.96	1.10	1.07	1.05	0.96	1.05	100
				1.10	**1.07**	**1.05**	**0.96**	**1.10**	**1.07**	**1.05**	**0.96**	**1.10**	**1.07**	**1.05**	**0.96**		100
C2, B2	Semi-fully irrigated paddy	1,300	rice	1.10	1.07	1.05	0.96	1.10	1.07	1.05	0.96	1.10	1.07	1.05	0.96	1.05	57
			soybean							0.46	0.96	0.75				0.75	21
			maize							0.37	0.88	0.80				0.75	14
			sweetpotato						0.41	0.68	1.04	0.71				0.75	8
				1.10	**1.07**	**1.05**	**0.96**	**1.10**	**1.07**	**0.71**	**0.95**	**0.82**	**1.07**	**1.05**	**0.96**	0.99	100
C2, B2	Rain-fed paddy field	1,300	soybean	0.44	0.75		0.46	0.96	0.75	0.46	0.96	0.75			0.46	0.75	42
			rice	1.07	1.05	0.96									1.10	1.05	31
			maize					0.37	0.88	0.80	0.37	0.88	0.80			0.75	19
			sweetpotato	0.71				0.41	0.68	1.04	0.71		0.41	0.68	1.04	0.75	8
				1.03	**0.92**	**0.44**	**0.44**	**0.69**	**0.78**	**0.59**	**0.84**	**0.75**	**0.76**	**0.44**	**0.86**	0.71	100
C2, B2	Dry land	1,300	rice	0.94	1.07	1.05	0.96	0.94	1.07	1.05	0.96	0.94	1.07	1.05	0.96	1.00	27
			cassava	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.95	25
			maize	0.88	0.80		0.37	0.88	0.80						0.37	0.75	16
			soybean	0.46	0.96	0.75	0.46	0.96	0.75	0.46	0.96	0.75				0.75	15
			sweetpotato	1.04	0.71	0.41	0.68	1.04	0.71	0.41	0.68	1.04	0.71	0.41	0.68	0.75	10
				0.79	**0.82**	**0.66**	**0.64**	**0.91**	**0.95**	**0.45**	**0.88**	**0.87**	**0.44**	**0.41**	**0.70**		93
B2, C2	Semi-fully irrigated paddy	1,671	rice	1.10	1.07	1.05	0.96	1.10	1.07	1.05	0.96	1.10	1.07	1.05	0.96	1.05	96
				1.08	**1.04**	**1.04**	**0.96**	**1.07**	**1.05**	**1.05**	**0.96**	**1.10**	**1.07**	**1.05**	**0.96**		96
B2, C2	Rain-fed paddy field	1,671	rice	1.10	1.07	1.05	0.96	1.10	1.07	1.05	0.96	1.10	1.07	1.05	0.96	1.05	81
			maize			0.37	0.88	0.80	0.37	0.88	0.80	0.37	0.88	0.80		0.75	19
				1.10	**1.07**	**0.79**	**0.91**	**1.00**	**0.58**	**1.05**	**0.93**	**1.01**	**1.05**	**1.03**	**0.87**		100
B2, C2	Dry land	1,671	maize	0.37	0.88	0.80	0.37	0.88	0.80	0.37	0.88	0.80	0.37	0.88	0.80	0.75	55
			cassava	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.95	18
			rice	0.94	1.07	1.05	0.96									1.00	16
			sweetpotato	0.41	0.68	1.04	0.71	0.41	0.68	1.04	0.71	0.41	0.68	1.04	0.71	0.75	11
				0.65	**0.90**	**0.87**	**0.57**	**0.82**	**0.78**	**0.62**	**0.81**	**0.71**	**0.51**	**0.85**	**0.77**		100

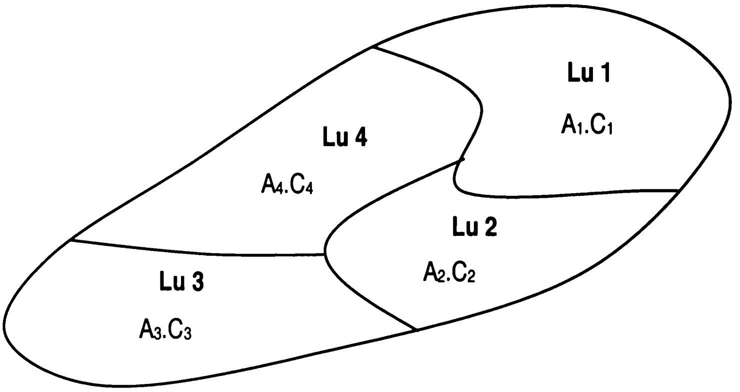
Table App. 5-3: Transforming the Agroclimate zones into monthly average k_c values for each zone in k_l.

Agricultural land type	**Agroclimate Zone**	**Quantity**	**%-age of quantity**	**Annual (mm)**	**Monthly Kc**											
					10	**11**	**12**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Irrigated paddy field																
Fully irrigated	E, C2, D2	143,638	67.2	1,608	1.10	1.07	1.05	0.96	1.07	1.05	1.05	0.95	1.02	1.06	1.01	0.90
	E	21,850	10.2	1,650	1.10	1.07	1.05	0.96	0.44	1.10	1.07	1.05	0.92	0.48	0.46	0.44
	E	10,682	5.0	1,584	1.10	1.07	1.05	0.96	1.10	1.07	1.05	0.96	0.46	0.96	0.75	0.44
	C2, B2	3,859	1.8	1,300	1.10	1.07	1.05	0.96	1.10	1.07	1.05	0.96	1.10	1.07	1.05	0.96
	SUM (A)=	*180,029*	*84.2*	*Max*	1.10	1.07	1.05	0.96	1.10	1.10	1.07	1.05	1.10	1.07	1.05	0.96
				Min	1.10	1.07	1.05	0.96	0.44	1.05	1.05	0.95	0.46	0.48	0.46	0.44
				Average	1.10	1.07	1.05	0.96	0.93	1.07	1.06	0.98	0.88	0.89	0.82	0.69
				d(Max-Mi	0.00	0.00	0.00	0.00	0.66	0.05	0.02	0.10	0.64	0.59	0.59	0.52
Semi-fully irrigated	E, C2, D2	23,206	10.9	1,608	1.10	1.07	1.05	0.96	1.01	0.99	1.00	0.94	1.03	1.02	1.02	0.91
	E	1,880	0.9	1,584	1.10	1.07	1.05	0.96	1.10	1.07	1.05	0.96	0.44	0.44	0.44	0.44
	C2, B2	2,941	1.4	1,300	1.10	1.07	1.05	0.96	0.75	0.73	0.64	0.98	0.92	0.74	0.73	0.68
	B2, C2	5,783	2.7	1,671	1.03	1.04	1.04	0.92	1.05	1.02	0.99	0.91	1.04	1.01	0.99	0.91
	SUM (B)=	*33,810*	*15.8*	*Max*	1.10	1.07	1.05	0.96	1.10	1.07	1.05	0.98	1.04	1.02	1.02	0.91
				Min	1.03	1.04	1.04	0.92	0.75	0.73	0.64	0.91	0.44	0.44	0.44	0.44
				Average	1.08	1.06	1.05	0.95	0.98	0.95	0.92	0.95	0.86	0.80	0.80	0.74
				d(Max-Mi	0.07	0.03	0.01	0.04	0.35	0.34	0.41	0.07	0.60	0.58	0.58	0.47
	SUM (C = A+B)=	213,839	100.0	*Max*	1.10	1.07	1.05	0.96	1.10	1.10	1.07	1.05	1.10	1.07	1.05	0.96
				Min	1.03	1.04	1.04	0.92	0.44	0.73	0.64	0.91	0.44	0.44	0.44	0.44
				Average	1.09	1.07	1.05	0.96	0.95	1.01	0.99	0.96	0.87	0.85	0.81	0.71
				d(Max-Mi	0.07	0.03	0.01	0.04	0.66	0.37	0.43	0.14	0.66	0.63	0.61	0.52
Rain-fed paddy field	E	198		1,650	0.60	0.69	0.69	0.52	0.44	0.44	0.44	0.92	0.75	0.42	0.62	0.57
	C2, B2	6,821		1,300	1.00	0.90	0.74	0.45	0.69	0.78	0.65	0.72	0.76	0.57	0.46	0.78
	B2, C2	1,076		1,671	0.94	1.07	0.89	0.94	0.91	0.90	1.00	0.92	0.80	1.03	0.99	0.84
	SUM (D)=	8,095		*Max*	1.00	1.07	0.89	0.94	0.91	0.90	1.00	0.92	0.80	1.03	0.99	0.84
				Min	0.60	0.69	0.69	0.45	0.44	0.44	0.44	0.72	0.75	0.42	0.46	0.57
				Average	0.85	0.89	0.77	0.64	0.68	0.71	0.70	0.85	0.77	0.67	0.69	0.73
				d(Max-Mi	0.40	0.38	0.20	0.49	0.47	0.46	0.56	0.20	0.05	0.61	0.53	0.27
Dry land	E	884		1,650	0.56	0.84	0.76	0.56	0.84	0.76	0.56	0.84	0.76	0.50	0.91	0.76
	E	80		1,584	0.50	0.64	0.62	0.52	0.80	0.72	0.50	0.71	0.66	0.50	0.64	0.62
	C2, B2	13,571		1,300	0.81	0.86	0.74	0.61	0.84	0.79	0.64	0.76	0.73	0.65	0.63	0.62
	B2, C2	2,968		1,671	0.63	0.91	0.90	0.66	0.79	0.77	0.54	0.83	0.74	0.49	0.87	0.78
	SUM (E)=	17,503		*Max*	0.81	0.91	0.90	0.66	0.84	0.79	0.64	0.84	0.76	0.65	0.91	0.78
				Min	0.50	0.64	0.62	0.52	0.79	0.72	0.50	0.71	0.66	0.49	0.63	0.62
				Average	0.63	0.81	0.76	0.59	0.82	0.76	0.56	0.78	0.72	0.54	0.76	0.70
				d(Max-Mi	0.31	0.27	0.28	0.14	0.05	0.07	0.14	0.13	0.10	0.16	0.28	0.16

Table App. 5-4: Taking average monthly in k_l from each agroclimate zones for each agricultural land. The shaded cells are the values used, except for the dry-agricultural land will use the average value for the entire months.

		MONTHS												
		1	2	3	4	5	6	7	8	9	10	11	12	Average
Fully irrigated	D2	0.96	1.07	1.05	1.05	0.95	1.02	1.06	1.01	0.90	1.10	1.07	1.05	1.02
	E	0.96	0.90	1.07	1.06	0.98	0.92	0.89	0.83	0.72	1.10	1.07	1.05	0.96
	C2 / B2	0.96	1.08	1.05	1.05	0.95	1.03	1.06	1.02	0.91	1.10	1.07	1.05	1.03
Maximum		0.96	1.08	1.07	1.06	0.98	1.03	1.06	1.02	0.91	1.10	1.07	1.05	
Minimum		0.96	0.90	1.05	1.05	0.95	0.92	0.89	0.83	0.72	1.10	1.07	1.05	
Used value		0.96	1.01	1.04	1.04	0.96	0.99	1.00	0.95	0.84	1.10	1.07	1.05	1.00
Semi-fully irrigated	D2	0.96	1.01	0.99	1.00	0.94	1.03	1.02	1.02	0.91	1.10	1.07	1.05	1.01
	E	0.96	1.03	1.01	1.01	0.94	0.92	0.91	0.91	0.82	1.10	1.07	1.05	0.98
	C2 / B2	0.94	0.96	0.94	0.90	0.94	1.01	0.94	0.93	0.85	1.06	1.05	1.04	0.96
Maximum		0.96	1.03	1.01	1.01	0.94	1.03	1.02	1.02	0.91	1.10	1.07	1.05	
Minimum		0.94	0.96	0.94	0.90	0.94	0.92	0.91	0.91	0.82	1.06	1.05	1.04	
Used value		0.96	1.01	1.04	1.04	0.96	0.99	1.00	0.95	0.84	1.10	1.07	1.05	1.00
Irrigated paddy	D2	0.96	1.06	1.04	1.04	0.95	1.02	1.05	1.01	0.90	1.10	1.07	1.05	1.02
	E	0.96	0.92	1.06	1.05	0.97	0.92	0.89	0.84	0.73	1.10	1.07	1.05	0.96
	C2 / B2	0.95	1.04	1.01	1.00	0.95	1.02	1.02	0.99	0.89	1.09	1.06	1.05	1.01
Maximum		0.96	1.08	1.07	1.06	0.98	1.03	1.06	1.02	0.91	1.10	1.07	1.05	
Minimum		0.94	0.90	0.94	0.90	0.94	0.92	0.89	0.83	0.72	1.06	1.05	1.04	
Used value		0.96	1.01	1.02	1.01	0.95	0.99	0.98	0.95	0.85	1.09	1.07	1.05	0.99
Rain-fed paddy	D2													
	E	0.52	0.44	0.44	0.44	0.92	0.75	0.42	0.62	0.57	0.60	0.69	0.69	0.59
	C2 / B2	0.52	0.72	0.80	0.70	0.75	0.77	0.63	0.53	0.79	0.99	0.92	0.76	0.74
Maximum														
Minimum														
Used value		0.52	0.72	0.80	0.70	0.75	0.77	0.63	0.53	0.79	0.99	0.92	0.76	0.74
Dry land	D2													
	E	0.56	0.84	0.76	0.56	0.83	0.75	0.50	0.89	0.75	0.56	0.82	0.75	0.71
	C2 / B2	0.62	0.83	0.79	0.62	0.77	0.73	0.62	0.67	0.65	0.78	0.87	0.77	0.73
Maximum		0.62	0.84	0.79	0.62	0.83	0.75	0.62	0.89	0.75	0.78	0.87	0.77	
Minimum		0.56	0.83	0.76	0.56	0.77	0.73	0.50	0.67	0.65	0.56	0.82	0.75	
Used value		0.57	0.84	0.76	0.57	0.81	0.75	0.53	0.83	0.72	0.61	0.84	0.76	0.72
Irrigated paddy		0.96	1.01	1.02	1.01	0.95	0.99	0.98	0.95	0.85	1.09	1.07	1.05	0.99
Rain-fed paddy		0.52	0.72	0.80	0.70	0.75	0.77	0.63	0.53	0.79	0.99	0.92	0.76	0.74
Dry land		0.57	0.84	0.76	0.57	0.81	0.75	0.53	0.83	0.72	0.61	0.84	0.76	0.72

APPENDIX 5-B: ESTIMATING STORM COEFFICIENT (FOR SPECIFIC LAND USE AND GEOLOGICAL TYPE).



This Figure shows a land with various land use types (Lu 1 to Lu 4), with area A_1 to A_4 and runoff coefficient C_1 to C_4 respectively. The whole area has a uniform geological type g. The storm runoff of with a specific land use (l) and geology (g) is given by;

$$S_{l,g} = C_l \cdot x_{l,g}$$

of which,

$$x_{l,g} = \frac{100 \cdot S_g}{\sum_{l=1}^{n} (A_l \cdot C_l)}$$

where, A_l is the percentage area for land use type l

S_g is the storm runoff for specific type of geology as given in Sir MacDonald and Partners (1984).

C_l is the runoff coefficient for a specific land use type and its corresponding soil type as given by US SCS (cited in Viessman *et al.*, 1989).

An example is given here as follows;

Geology type = OV (old volcanic deposits)

Land use type	A_l	C_l*	$A_l.C_l$	$S_g$$	$x_{l,g}$	$S_{l,g}$
Paddy-field	10	0.70	7.00			0.26
Tegalan	48	0.78	37.44			0.29
Village garden	28	0.73	20.44			0.27
Forest	4	0.56	2.24			0.21
Others (paving, etc.)	10	0.85	8.50			0.31
SUM ($A_l.C_l$)			75.62	0.35	0.37#	

* From US SCS cited in (Viessman *et al.*, 1989).

$ From Sir McDonald and partners (1984).

\# This the average value from three cases, which is used to calculate the $S_{l,g}$ in the above Table. The actual value from this case is 0.46.

CHAPTER 6

LAND USE COMPONENT: CONSTRUCTION OF LAND USE SCENARIOS

6.1 INTRODUCTION

The influence of land use changes on hydrology has been discussed in Chapter 1 (Introduction) and also in Chapter 5 (Hydrological Component). It clearly shows that changes in land use could change the annual yield of water and could also change the seasonal variation of river flows. The land use component is required as part of the proposed integrated model in order to assess the variability of river flows as the result of changes in the land use pattern (Chapter 1, and repeated in Chapter 4).

This component is used to produce scenarios of land use change that will be used as input to the hydrological component for a sensitivity assessment of river flows with respect to changes in land use patterns and climate. It is not designed for the purpose of predicting future land use patterns, but for constructing some scenarios which are driven by various 'storylines'. These storylines are based on policy intervention, and changes in socio-culture, such as attitudes towards the environment, etc. Therefore the scenarios contain some degree of realism. It is also possible, for the purpose of sensitivity analysis, to construct land use patterns of extreme cases.

The literature review of the land use model has been presented in Chapter 4. Chapter 6 will focus on the development of the scenarios, and how the output from this component is used by the hydrological component. In this thesis, the generation of the scenarios is conducted mostly by using a GIS (Geographical Information System) that will also be discussed briefly.

Before constructing the scenarios, there is a need to analyse in some detail the land use change behaviour in the study area. The rates of changes for each land use type and the hierarchy of changes will be discussed. Understanding what causes the land use change will help the scenarios to be constructed with a more realistic pattern, and when certain policies are introduced, they will be reflected in the generated scenarios.

6.2 HOW THE SCENARIOS ARE CONSTRUCTED

The requirements for selecting land use scenario generators for this thesis have already been discussed in Chapter 4. They are easy to construct, not data demanding, and most importantly they can generate and display patterns of scenarios spatially that can be linked to the hydrological component. This leads to the choice of a cellular automata method, which was successfully used for modelling a spatial urban development by White and Engelen (1993).

The cellular automata method belongs to a discrete connectionist technique that allows the pattern to evolve in a self-organised manner (White and Engelen, 1993). This technique is quite simple. It can be considered as an array of cells in which the state of the discrete cells depends on the state of their neighbouring cells. The change in the state of a cell from one state to another state, i.e. from one land use type to another land use type, is guided by a set of deterministic or probabilistic rules. The state of individual cells is then updated based on the state of the neighbouring cells in the previous time period. Based on its nature, this method is spatially explicit.

White and Engelen (1993) used this technique to predict future urban development. This method has been adopted by Hasan (1999) for the development of a scenario generation and evaluation system QUEST (Quite Useful Ecosystem Scenario Tools).

This cellular automata method is spatially explicit and can be done on a raster based GIS. To conduct this method, the GIS must have a kind of neighbourhood connectivity function or a user defined filter for convolution operation, which is very common in any standard GIS. The neighbourhood cells are given certain values according to the degree of their influence on the cell in the centre when this central cell is transforming from one state to another state. The assigned values are dependent on their states and distances from the centre cell. The resultant value from the neighbourhood cells will determine the new state of the discrete cell.

In this thesis, the cellular automata method is made as simple as possible and the rules of transition, including the values for neighbouring cells, are defined with a simple spatial analysis. This thesis is not intended to exhaustively imitate the method as defined by White and Engelen (1993), because the nature of the cases is very different. White and Engelen (1993) used this method to model urban evolution, which was relatively small in comparison to the size of study area, and there is less variation in land use types than exist in the study area. Their study permitted an invasion of any urban element into cells with a vacant state, i.e. growth in the total area is permitted, which is not the case in the study area of this thesis because the area is assumed to be constant and there is no expansion of the area beyond the boundary. Hence, only a change of proportion is possible. In addition, this thesis does not intend to produce accurate scenarios but to present sensitive changes of land use patterns under various policies.

Before constructing the transition rules, there is a need to analyse the behaviour of land use change, its distribution, and the possible driving factors of the change. These are discussed in the next section.

6.3 BEHAVIOURS OF LAND USE CHANGE IN THE STUDY AREA

Information about the characteristics and behaviour of land use changes is necessary in order to define the transition rules. Understanding this information is also useful for assigning the weighted values of neighbouring cells that determine the changes in the discrete cell.

Literature review of the land use transition

A general hierarchical transition of land uses in Indonesia has been reviewed in Chapter 2, Section 2.4. It shows a pattern of land use transition, which can be grouped based on its urban condition. In a non-urbanised area, forest changes to dry-agricultural land; in a slightly urbanised area, the dry non-irrigated land changes to house-gardens whereas irrigated land is favourably preserved (Preston, 1989); in a more urbanised area, gardens are converted to become places for settlement or business; and in a highly urbanised area the cultivated land and paddy-fields may convert to settlements, industries and other constructions. In this case, forest is regarded as the lowest state of the hierarchy and settlement is the highest state.

In a similar way, the process of land use change in Java starts from forest that converts to permanent agricultural land through a gradual change process (Verburg *et al.*, 1999). The permanent agricultural land can be in the form of paddy-field, dryland (*tegalan*), horticulture (vegetable garden) and mixed-garden. Some amount of forest will be converted to dry-agricultural land inspite of some efforts to conserve the forest for environmental protection. There is a tendency in the past and present to conserve irrigated agricultural land, as it is more valuable for agricultural production than the non-irrigated land (Preston, 1989). In the future, however, there is a tendency that the paddy-field may change to vegetable garden or mixed-garden (Verburg *et al.* 1999). This is mainly because of an increasing demand from the society for more varieties of food such as vegetables and fruit[6-1] to partially replace rice in their diet as their income increases. In addition, Verburg *et al.* (1999) also shows that there is a tendency to conserve the agricultural land whenever possible, and resistance to converting land settlements. Hence, it is expected that, depending on the demand for land for settlement and industry, the paddy-field is very likely to reduce in size. The dry-agricultural land may expand by converting some forest land, in particular the secondary forest, and some paddy-fields (less likely), but may also be reduced by conversion to settlements if the demand for settlements is very high.

In the Bandung basin area, the trend of land use change is similar to the trend for Java as a whole. The difference is in the growth of urban area, which is mainly as a result of industrialisation and economic growth (Karsidi, 1998). The pressure from population tends to be higher than the average for Java.

[6-1] Verburg *et al.* (1999) noticed that with increasing income, society tends to change its diet by eating more vegetables and fruit as a proportion of total food consumed, i.e. the people will eat more vegetables and fruit and less rice in comparison to what they ate before.

Statistical analyses

Correlation between land use variables

A spatial statistical correlation analysis in the study area, which is based on the changes in land use from 1986 to 1995, by SEA START RC (1999) revealed that open land, which is a land use unit, is strongly and positively correlated with the change in settlement/industrial area and the grass land area (Table 6.1, the correlation between open land and settlement/industry is +0.7834 and between grassland and settlement/industry is +0.7767). This may suggest that the change in area of open land and grassland is associated with the change in the area of industry and settlement. It may also suggest that to some extent or to some proportion, the open land and the grassland are part of the settlement and industrial area (Karsidi, 1998).

Other land use variables show weak and negative correlations between each other, which may suggest that there is no consistent transition rule for changes. For example, an increase in settlement/industrial area is weakly correlated with a change (decrease) in areas of agricultural land and forest, i.e. forest may be converted into settlements/industrial areas, and part of the forest may also be converted into agricultural land.

Table 6.1: Matrix correlation coefficient of land use variables in Bandung basin (from: SEA START RC, 1999).

Land use variables	1	2	3	4	5
1. Open land, change (ha)	1.0000				
2. Settlement/industry, change (ha)	0.7834	1.0000			
3. Agricultural land, change (ha)	-0.3315	-0.2419	1.0000		
4. Forest, change (ha)	-0.4547	-0.2738	-0.4693	1.0000	
5. Grassland, change (aa)	0.7767	0.6419	-0.3192	-0.3122	1.0000

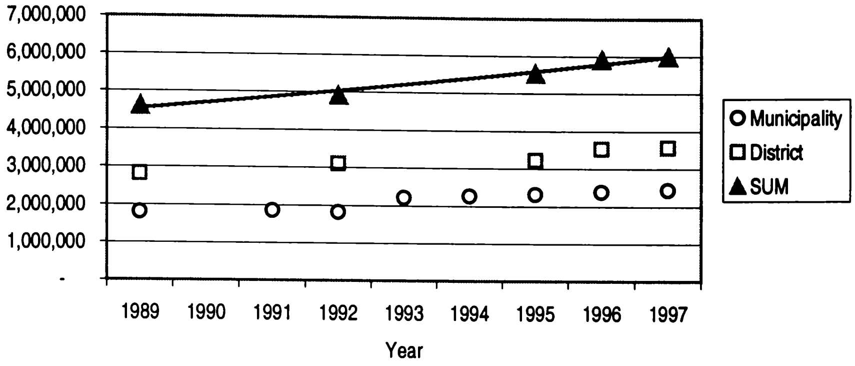
Socio-economic analyses

Analyses of socio-economic variables are used for identifying the underlying causes of the land use change. These are conducted using simple graphical analysis and correlation analysis. The data for the analyses come from publications of the Central Bureau of Statistics of the Municipality of Bandung (1991, 1993, 1998), the Central Bureau of Statistics of the District of Bandung (1990, 1993, 1998), and from published articles (Karsidi, 1998; and SEA START RC, 1999).

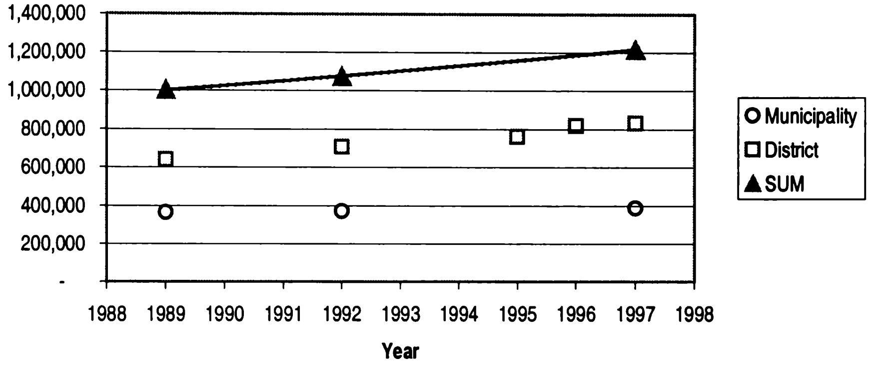
Graphics of some socio-economic variables that are likely to drive the land use change, are given in Figure 6.1a, b, and c. From 1989-1997, the population increased with an average annual growth rate of 3.8% for the municipality, 3.0% for the district, and 3.3% for the two areas combined, with an assumption that the growth is exponential. These values are much higher than the average value mentioned in Dam (1994), which was at 2.3% since 1950.

The number of households in the same period (1989-1997) increased with an average annual growth rate of 0.75% for the municipality, 3.34% for the district, and 2.45% for both areas. In comparison to the population growth, the number of households grew much at a lower rate in the municipality, but at a similar rate in the district.

A. Population



B. Number of households



C. Number of industries

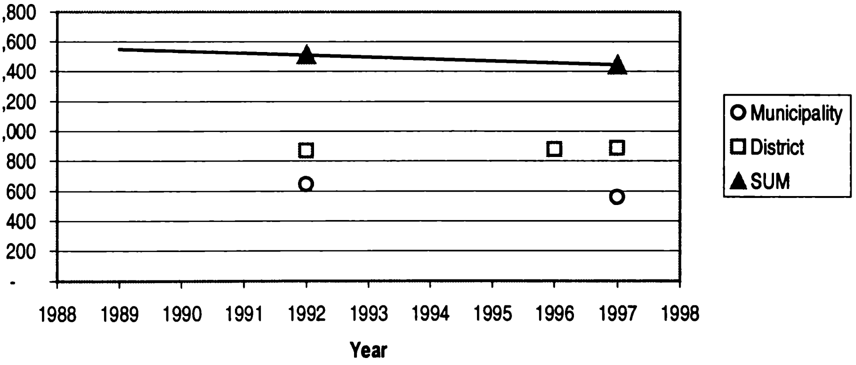


Figure 6.1: Charts of population, number of households and industries. The graphic-line on the charts indicates a trend of growth (or reduction) for both the municipality and the district.

The increase in the number of industries is predicted as one important underlying cause of an increase in urbanisation. Unfortunately, information about total number of firms, industries, and related economic businesses are not available and only numbers of medium sized and large industries are available. From 1992 to 1997, there was a decrease of 13% in the number of medium and large sized industries in the municipality, but an increase of 2.1% in the district. In total, there was a decrease of 4.4%. This fact may indicate that the population increase is not related to the number of industries. However, the decrease in numbers of medium sized and large industries can be interpreted in many ways, with the following examples. Some medium and large industries collapsed, or some of them reduced to the level of small industries. Some industrial companies may also have merged, etc. Thus, this data cannot be directly interpreted as a drop in the economy that may discourage the urbanisation.

A matrix of correlation between the socio-economic variables for the district area is shown in Table 6.2. (The data are from the district area only. The municipality area does not have data from sub-district levels.) The population is very strongly correlated with the number of households (0.96) and number of high school students (0.94). (The number of high school students is chosen as a variable for examining the educational level of the people.) However, the population is weakly correlated with the population density (0.32). These all suggest that the population is well distributed with respect to the number of households and high school students but the population density varies from place to place. The population is also well correlated with the number of industries (0.57), suggesting that the increase in population is also related to the number of industries. The industries are also correlated, even though not strongly, with the number of high school students (0.49), households (0.41) and population density (0.40), which may suggest that the industries to some extent are influenced by demographic factors.

Table 6.2: Matrix correlation coefficient of socio-economic variables for the District of Bandung in 1997.

Land use variables	1	2	3	4	5
1. Population	1.0000				
2. Population density	0.3249	1.0000			
3. Number of households	0.9586	0.2176	1.0000		
4. Number of high school students	0.9410	0.5274	0.9397	1.0000	
5. Number of medium and large industries	0.5675	0.4042	0.4143	0.4934	1.0000

Regression analysis

More information regarding the characteristics of land use change in the study area is given by a regression analysis between the socio-economic variables against the land use variables, which was done by SEA START RC (1999). The results can be seen in Table 6.3.

Table 6.3: Regression coefficient of socio-economic variables against land use variables in Bandung basin (from: SEA START RC, 1999).

Explanatory variables	Dependent variables					
	Settlement / industry		Agricultural land		Forest	
	Coefficient	Se	Coefficient	Se	Coefficient	Se
1. Population growth	213.622	461.353	-231.930	627.404	-214.480	892.984
2. Change in population density	5.779	43.333	16.706	58.929	10.440	83.874
3. Change in dependency ratio	20.878	25.858	12.240	35.165	-37.129	50.050
4. Growth rate of school students	-301.541	-162.591	-207.520	-221.111	560.967	314.708
5. Change in number of school students	33.541	* 8.682	2.108	11.807	-48.519	-16.804
6. Growth rate of households	75.791	173.529	285.277	235.986	-452.470	335.879
7. Number of industries	3.682	* 1.610	-6.062	* -2.190	0.549	* 3.117
Constant	**1428.19**		**-554.890**		**-1104.10**	
R^2	**0.726**		**0.533**		**0.592**	

* = Acceptable result with error between -10% and 10%.

As shown in Table 6.3, there are two significant variables that have positive effects on the increase in the settlement/industrial area. They are the number of school students and the number of industries. These results confirms the trend discussed in Chapter 2, that an increase in the number of school pupils (i.e. educated people) correlates with an increase in the number of industries as more people, in particular the young generation, are becoming less interested in farming activities. An increase in the number of industries usually results in an increase in incomes, and in turns causes an increase in the demand for settlements.

The increase in the number of industries is also a reasonable explanation for the decrease in agricultural land, as shown in Table 6.3 by a negative correlation, which implies that (most of) the industrial area is converted from agricultural land.

Table 6.3 also reveals that the change in forest area is significantly related to the growth rate of the school students (positive) and the change of the number of school students (negative). By comparing the signs of these coefficients in relation to changes in settlement area, it would suggest that the settlement area could have been obtained by converting the forest (SEA START RC, 1999; and Karsidi, 1998).

From these statistical analyses, the information of the likely transition from one land use type to another type can be summarised as follows:

- The decrease in agricultural land is affected by the change in the number of industries;
- The decrease in forest is affected by the percentage change in the number of school students and the growth rate of the school students;
- Open land and grassland to some extent are part of the settlement/industrial area;

- There is no consistent rule in the order of the land use conversion hierarchy. It is possible that agricultural land can be converted into settlement/industrial areas, or forest into settlement/ industrial areas.

Rules of transitional hierarchy in the study area

From the discussion above (literature review and statistical analyses) a schematic hierarchy of land use transition in the study area can be drawn (Figure 6.2). The purpose of this figure is to illustrate a simple transition-rule of main land uses in general. In the actual computation, this land use transition is more complicated allowing more detailed land use types such as primary forest, secondary forest, and transition from dryland (*tegalan*) to non-irrigated paddy-field or irrigated paddy-field, conversion of mixed-garden to vegetable garden and vice-versa.

The conversion of land does not have to be in a sequential order, but it has to follow the transition rule from a low state in the hierarchy to a higher state. Forest (secondary forest) may change to dryland (*tegalan*), paddy-field or settlement. The dryland may change to garden (both vegetable garden and mixed-garden), or settlement, and the garden may change to settlement. Paddy-field may also change to garden or settlement.

The figures beside the arrow-lines (Figure 6.2) indicate relative likeliness of changes from one state to another state on a scale of 0 to 10 for very unlikely to very likely. These values were arbitrary and assigned based on expert knowledge and a field observation in December 1999 to January 2000, supported by the information deduced from the literature review and statistical analyses as discussed above. The change from dryland to garden, for example, is more likely than the change from dryland to settlement, because there is a tendency for the society to protect agricultural land from loss (Verburg *et al.*, 1999). The conversion of paddy-field to settlement is much more likely than the conversion of paddy-field to garden. This was found to be the case in the field, where new settlement areas are usually taken from paddy-field areas while the conversion of gardens to settlement area was less favoured.

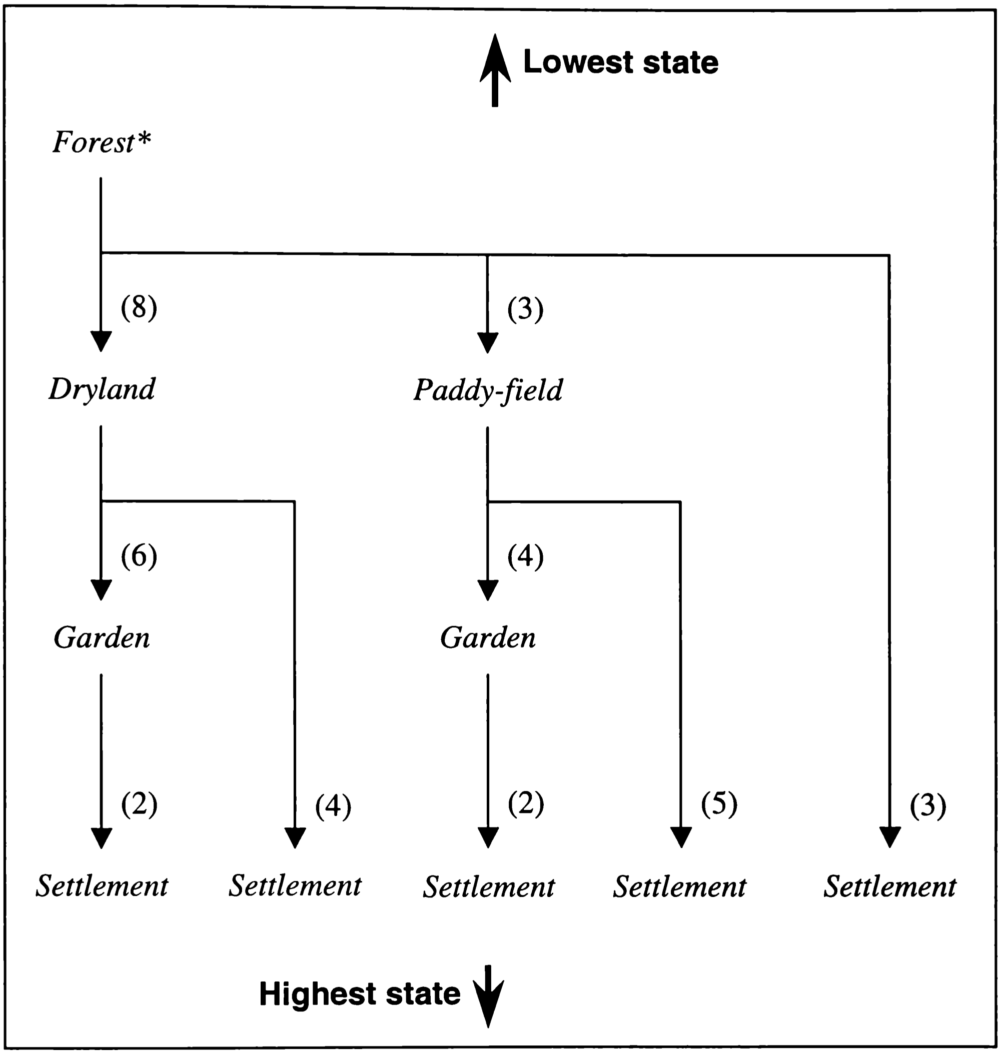


Figure 6.2: The transition hierarchy of land use change in Bandung basin.
*Forest in this case is the secondary type.

Influence of physical factors on land use distribution

Elevation and slopes

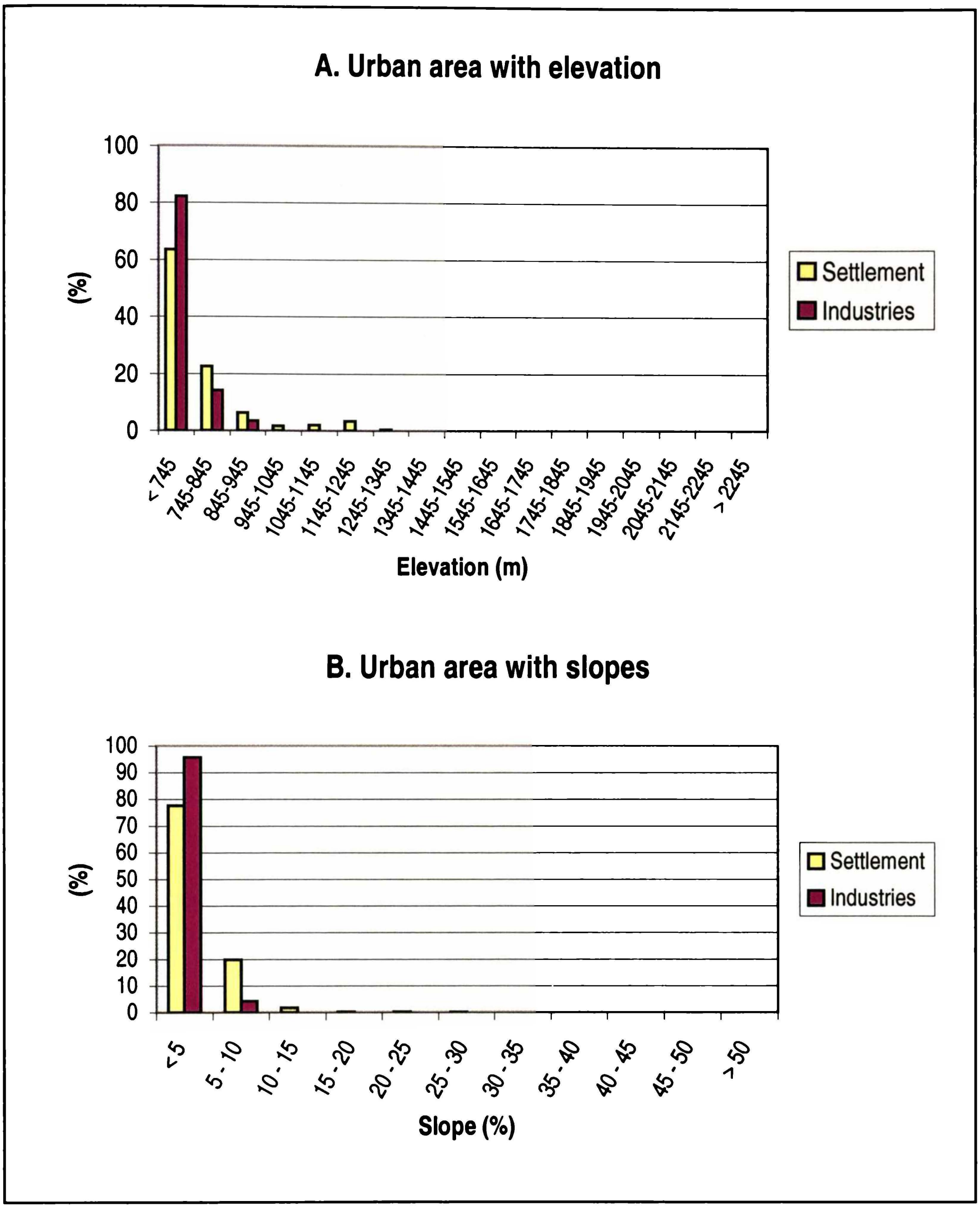
The distribution of each land use type is influenced by the elevation as well as the slope of the land. In general the urban areas are located mostly on a flat land rather than on a steep land and the dry agricultural land is situated mostly on highland. When constructing the scenarios of land use patterns, this kind of information is required in order to develop more realistic scenarios of patterns of land use change.

Details of how each land use type is distributed with respect to factors of elevation and slope are discussed below. The land use data are based on a land use map produced in 1989 (Suhendar, 1989).

Urban (settlement and industrial area)

The urban area that includes settlement and industrial areas is located mostly in the low land area with an elevation from less than 700 m to 1000 m (Figure 6.3a). Some groups of settlements at higher elevation (1100 to 1250 m) exist in the northern part of the study area. Almost all large and medium size industries are located at an elevation of less than 1000 m.

Most of the urban area is located on a relatively flat area with a slope of less than 10% (Figure 6.3b). For settlements, there is a tendency for these to be located in areas with slopes of over 12%, whereas over 95% of industries are on flat land (slope < 5%).



A. Urban area with elevation

B. Urban area with slopes

Figure 6.3: a. Distribution of urban area with respect to elevation, b. Distribution of urban area with respect to slopes.

Dry-agricultural land (tegalan, mixed-garden and vegetable garden)

This group of dry-agricultural land is distributed over a wide range of elevation from lowest elevation (less than 700m) to around 1650 m. However, each type of this agricultural land tends to have its own characteristics. Vegetable gardens (horticulture) tend to be distributed on an elevation between 1000 m and 1500 m, where as majority of mixed garden and dryland areas (*tegalan*) are located at lower elevations of less than 1100 m (Figure 6.4a).

In terms of slope, these land use types are also distributed over a wide range of steepness from relatively flat to very steep. However, the majority of vegetable gardens (90%) are located on a relatively flat to moderately steep slopes (slope < 20%) whereas the majority of the mixed gardens spread up to a steepness of 25% and the dryland (*tegalan*) spreads further up to a steepness of 30% (Figure 6.4b).

Irrigated paddy and rain-fed paddy

Paddy is the main land use type in the low land area. It covers almost 70% of the low land area. In 1989, about 50 to 60% of the paddy land was located at an elevation of less than 745m and its distribution was greatly reduced with an increase in elevation (Figure 6.5a). Nevertheless, the irrigated paddy is still found on high land of over 1500m whereas the rain-fed paddy is no longer found at an elevation of more than 1100m.

The irrigated paddy can also be found on very steep land (> 50%), but the majority (about 62%) is on relatively flat land with a slope of less than 5% (Figure 6.5b). The rain-fed paddy also shows a similar distribution characteristic as the irrigated paddy in terms of slope.

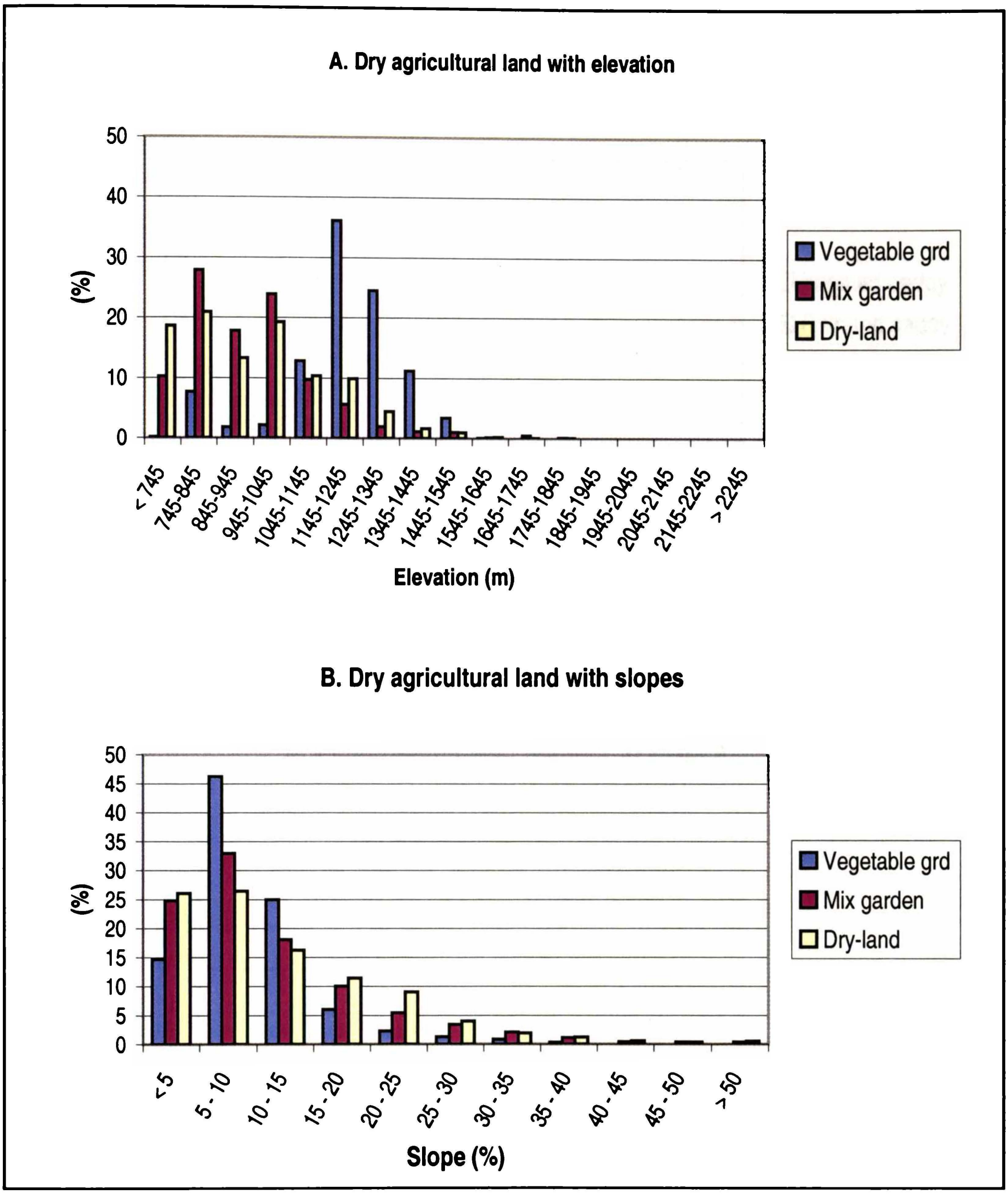


Figure 6.4: a. Distribution of dry-agricultural land with respect to elevation, b. Distribution of dry-agricultural land with respect to slopes.

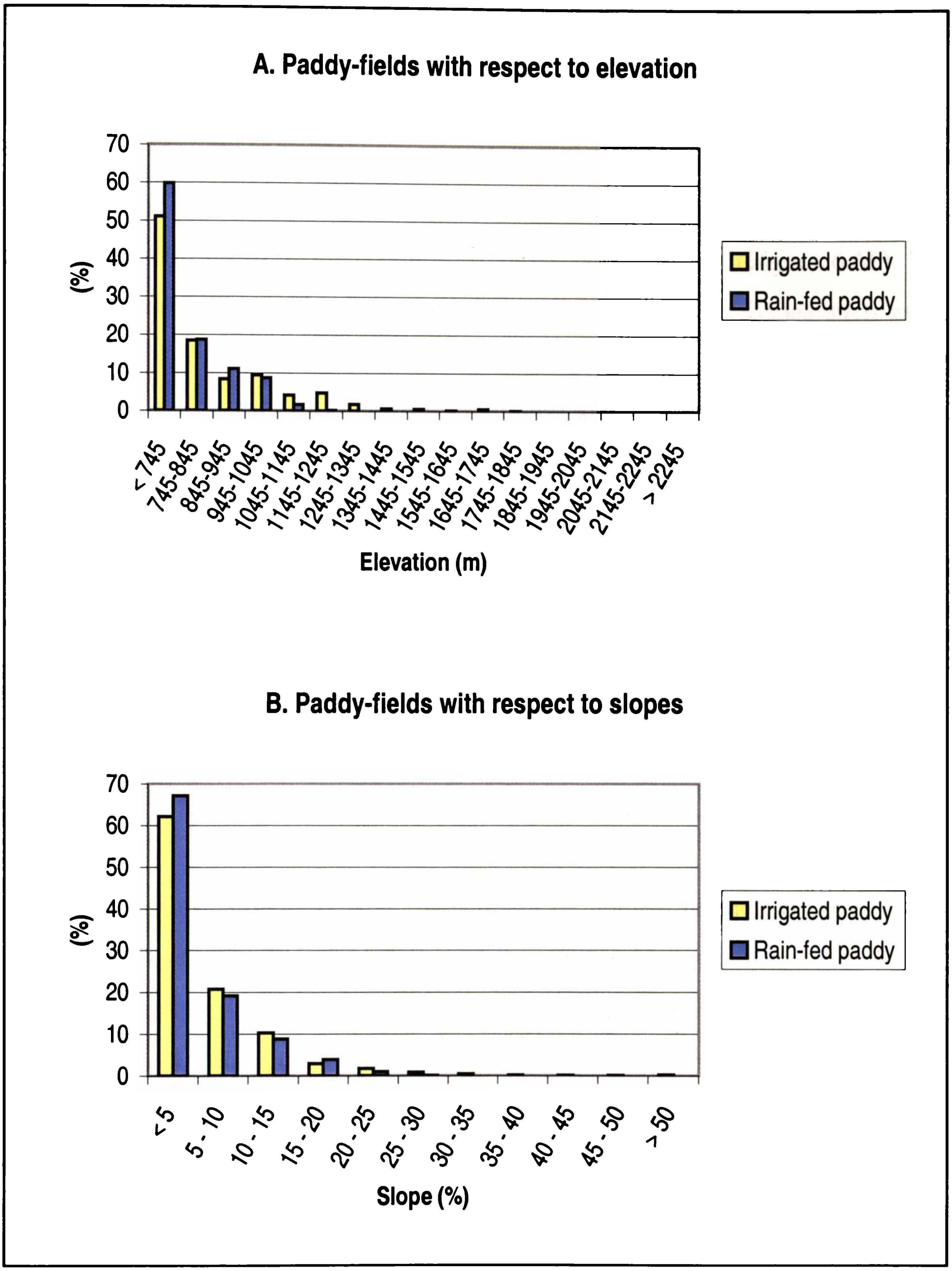


Figure 6.5: a. Distribution of paddy-fields with respect to elevation, b. Distribution of paddy-fields with respect to slopes.

Forests

Each type of forest has its own distribution characteristics in terms of elevation. The primary forest is spread over the whole range of elevation but peaks at an elevation around 1500m (Figure 6.6a). The secondary forest is scattered from the lowest elevation up to around 1800m in an irregular manner (Figure 6.6b). This kind of pattern is probably due to the influence of human activities such as the conventional 'slash-and-burn' method or the expansion of agricultural land. The reforested forest is usually regulated or guided and, therefore, its distribution is more regular than the other types of forest. It is shown in Figure 6.6c that the reforested land is concentrated at elevation over 1000m.

The distribution of forest over the slope also ranges in steepness. In general, the forest is more concentrated in gently sloping area than the steep zones. The primary forest is spread more evenly than the other types. The majority of the secondary forest (90%) is situated on a slope of less than 40%, whereas the majority of the reforested land is on a slope of less than 35%.

There are various 'boundary rules' which can be applied to the expansion of the various land use types discussed above. These are listed below:

- The priority growth areas for urban are in areas with elevation of less than 1000m and with slopes of less than 10%.
- It is preferable for vegetable gardens to expand on land with an elevation between 1000m and 1500m and with a slope of less than 20%. This type of garden is the priority for growth in these conditions, rather than dryland (*tegalan*) and mixed-gardens.
- There are no restricting conditions in terms of slope and elevation for the expansion of dryland (*tegalan*) and mixed-gardens.
- There is no restricting condition in terms of slope and elevation for the expansion of paddy and forest. However, it is very likely that their sizes will

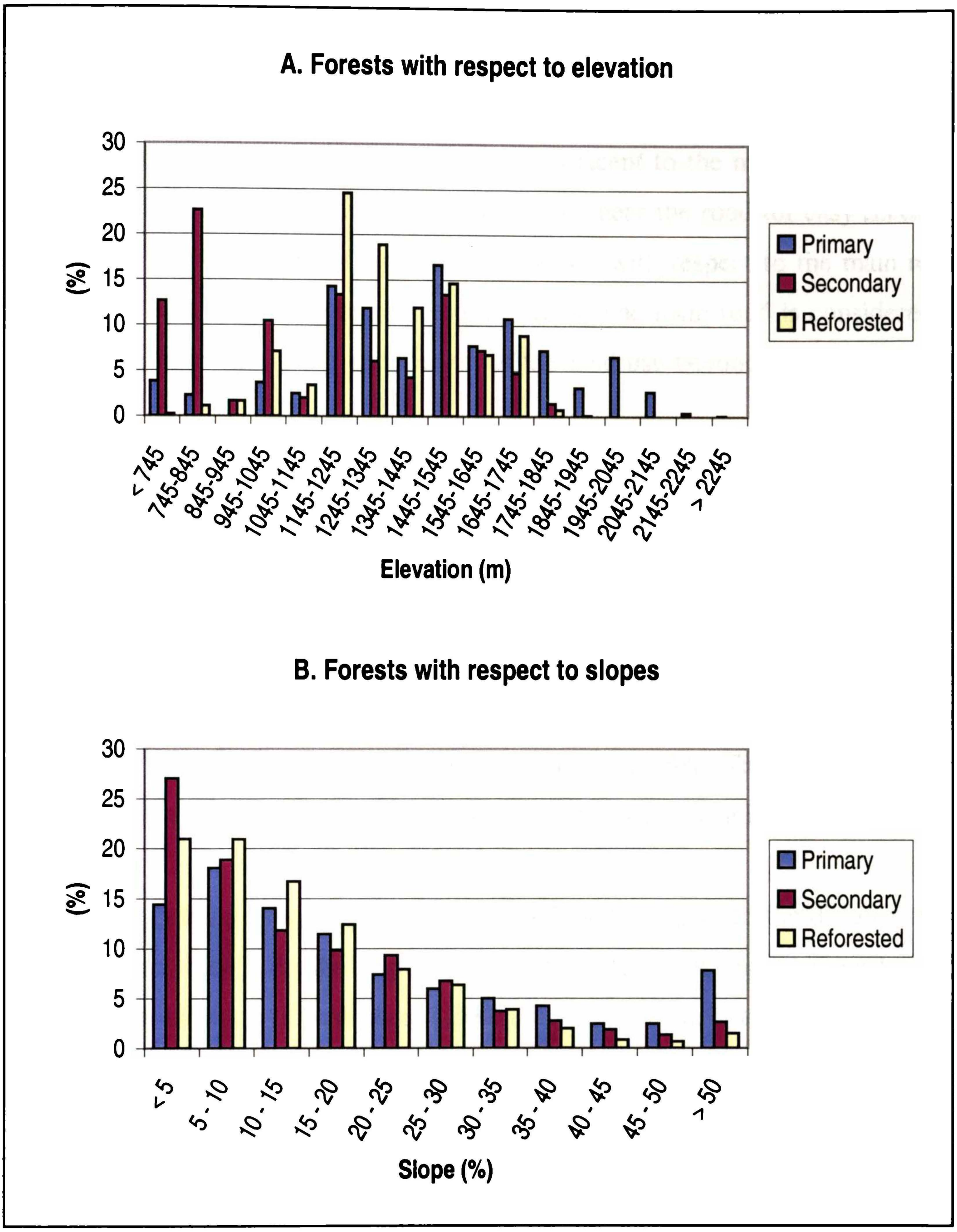


Figure 6.6: a. Distribution of various forest types with respect to elevation, b. distribution various forest types with respect to slopes.

reduce following the expansion of the other land use types (urban and dry-agricultural land).

Distance from the main roads

Roads have a significant influence in controlling the distribution of the land use. In particular, urban areas prefer to be located adjacent to the main road. It is also preferable for some agricultural land to be located near the road for easy access to the market. The behaviour of land use distribution with respect to the main road, is discussed below with reference to some charts. The main road is considered to have has no influence in the distribution of the land use beyond 3,500m from the road.

Figure 6.7 shows the distribution of urban areas with respect to the distance from the main road. It shows that most urban areas are located at a close distance from the main road and their distribution gradually decreases with an increase in the distance. About 60% are located within a distance of less than 500 m and about 90% are within a distance of 1,500 m. This implies that there is a preference for urban areas to be located in places that are easily accessible. The growth of urban areas is likely to take place near the main road if space is available.

The dry-agricultural land is distributed randomly with respect to the distance from the main road, except for the vegetable gardens. Half of the vegetable gardens are located at a distance of less than 1,300m from the main road and distribution decreases with an increase in distance from the main road (Figure 6.8).

Paddy-fields do not appear to be specifically clustering with respect to distance from the main road (Figure 6.9). It can be deduced, however, that half of the area of irrigated paddy-field is located within a distance of less than 1,500m of the main road and there are less irrigated paddy-fields beyond this distance.

Most of forest-land is located a long distance from the main road (Figure 6.10). Nearly 90% of the forestland is located at a distance of more than 2,600m from the main roads.

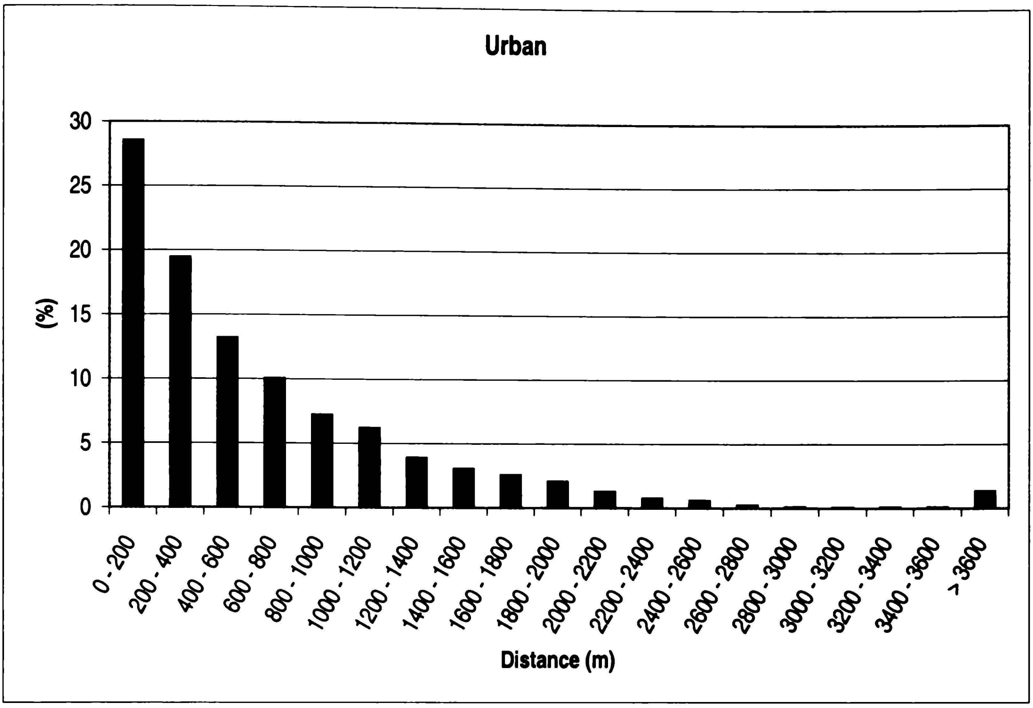


Figure 6.7: Urban distribution with respect to the distance from the main roads.

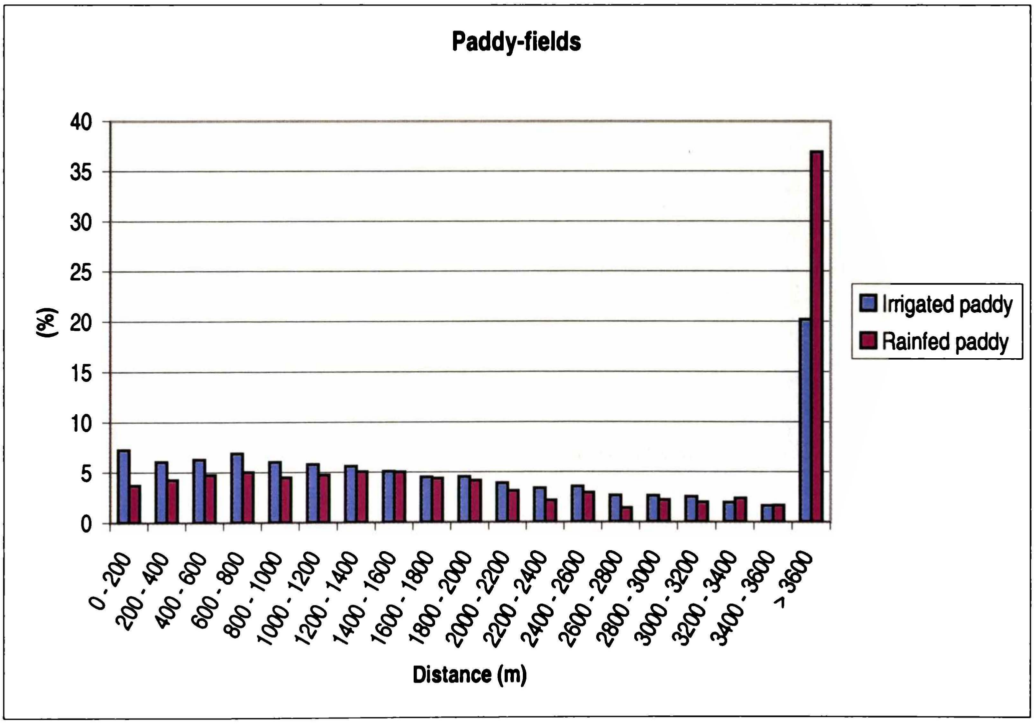


Figure 6.8: The distribution of dry-agricultural land with respect to the distance from the main roads.

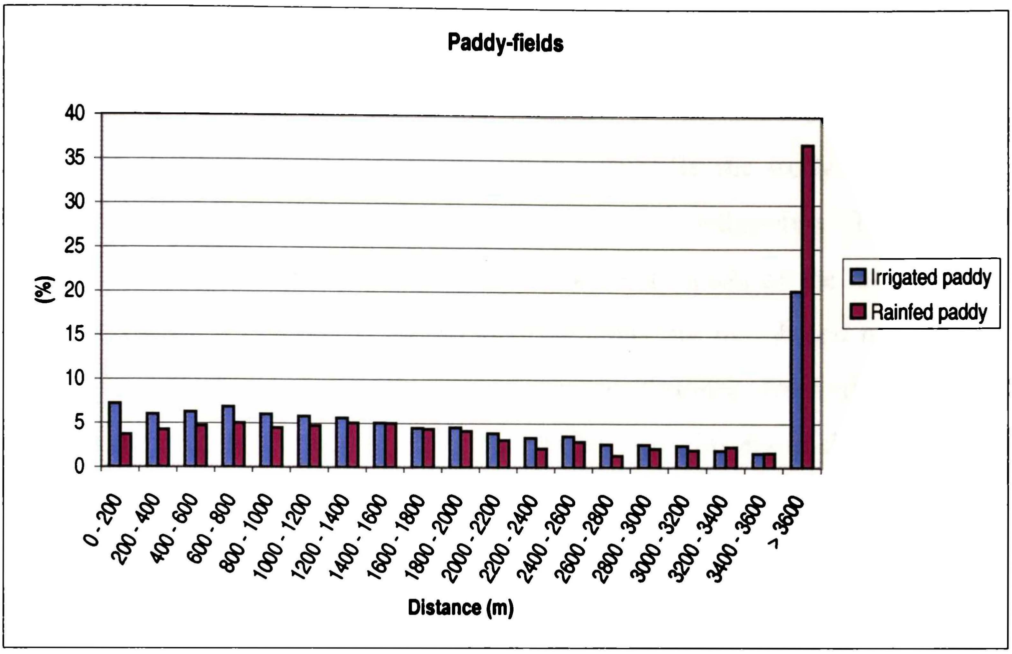


Figure 6.9: The distribution of paddy-fields with respect to the distance from the main roads.

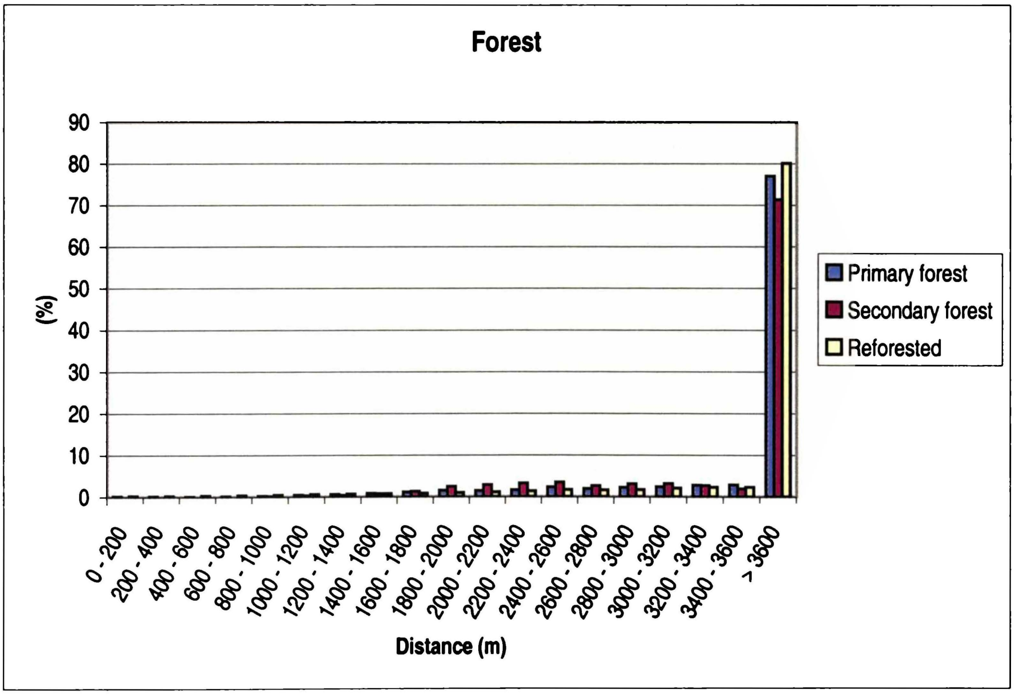


Figure 6.10: The distribution of forest with respect to the distance from the main roads.

Distance from the river

In many cases, the river also has some influence on the distribution of land use. Many cities or urban centres are located near a river. In the study area, however, the river network is very dense because of its many tributaries. Therefore this variable can only weakly explain (influence) the distribution of the land use units. As seen in Figure 6.11, almost all the land use units are distributed near the river and decrease in frequency with an increase in distance from the river. The exception is the rain-fed paddy-field which shows two clusters of distribution. The first cluster is at a distance of less than 1,300m from the river and the other is at a distance between 1,800 and 3,500m.

From the above discussion, it is clear that the distribution of land use is controlled to some degree by physical factors. These are summarised in Table 6.4.

Table 6.4: Summary of distribution characteristics with respect to elevation, slope and distance to the main road.

Land use type	Distribution characteristics		
	Elevation (m)	Slope (%)	Distance from the main road (m)
1. Urban	Majority (90%): < 1,000	Majority: < 8 About 20%: 8 - 12	About 50%: < 500 About 40%: 500 - 1500
2. Dry agricultural land			
2.a Vegetable garden	Majority (90%): 1,100 - 1,500	Majority (90%): < 20	About 50%: < 1300
2.b Mixed-garden	Majority (90%): < 1,100	Majority (90%): < 25	No clustering
2.c Dryland (*tegalan*)	Majority (90%): < 1,200	Majority (90%): < 30	No clustering
3. Paddy			
3.a Irrigated paddy	About 50%: < 745 About 45%: 745 - 1300	Majority (90%): < 15	About 50%: 1500 (gradual decrease with distance)
3.b Rainfed paddy	About 60%: < 745 About 30%: 745 - 1000	Majority (90%): < 15	No clustering
4. Forest			
4.a Primary	-	-	very far from main road
4.b Secondary	-	-	very far from main road
4.c Reforested	> 1000	-	very far from main road

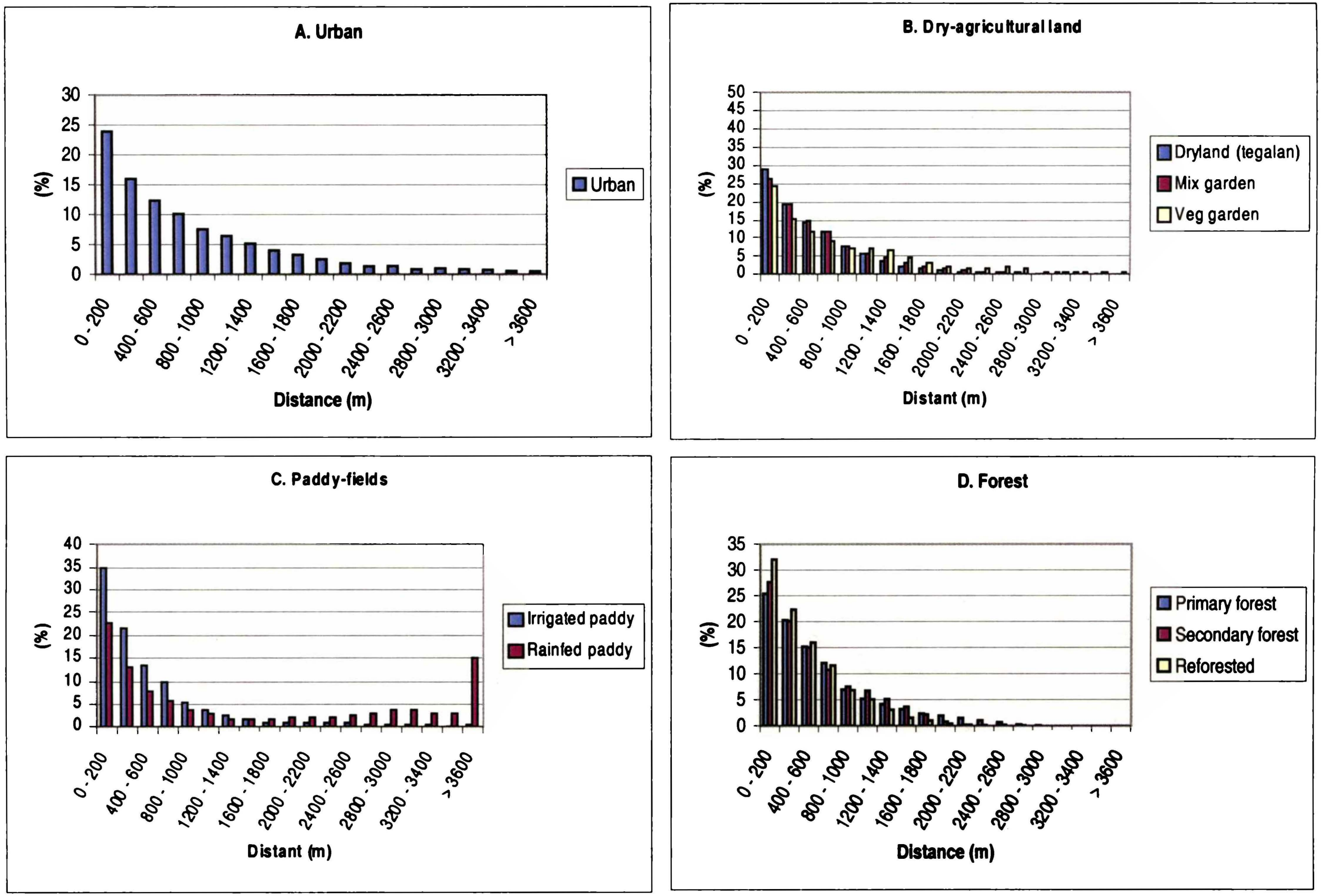


Figure 6.11: Land use distribution with respect to the distance from the river: (a) urban area, (b) dry-agricultural land, (c) paddy-fields, and (d) forest.

6.4 USING GIS FOR GENERATING SCENARIOS

A GIS package named ILWIS 3.0 (Integrated Land and Water Information System - Version 3.0) (ITC, 2001) is used to construct scenarios based on a simple cellular automata method. The following data need to be prepared as inputs to the GIS.

- A digitised land use map and other necessary maps such as a slope map, digital elevation map (DEM), main road map, etc.
- Weighting factors: they need to be defined from the likelihood of transition from one state to another state (which is already given in the hierarchy transition rules), and the likelihood of one cell influencing the conversion of a discrete cell from one state to another state, which depends on its current state and the distance from the discrete cell.
- Resisting boundary, which is a collection of physical factors that may resist or refrain the land use conversion.
- Other factors that may influence the distribution of the land use, such as distance from main roads.
- Rate of change for each land use type if available. Particularly, the rate of change for the main land use type that has a major influence on the overall land use pattern, such as urban area, is necessary.

Before jumping into the process of creating scenarios, there is a need to briefly address the GIS functions for neighbourhood calculations and filtering.

Neighbourhood connectivity and filtering functions in a GIS

The GIS will use a user specified filter to construct the new land use pattern. The calculation works only on a raster format digitised map, of which each individual pixel (cell) contains a numerical value. ILWIS has a predetermined neighbourhood function, which is a filter function that only works on a 3x3 cell (8 connected neighbouring cells, see Figure 6.12) (ITC, 2001). These 8 connected cells fall within a distance of up to √2 units. If the pixel size is 100m, then the real distance is up to 141.4m.

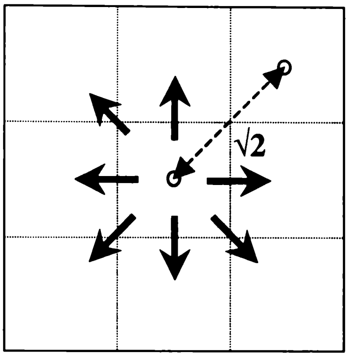
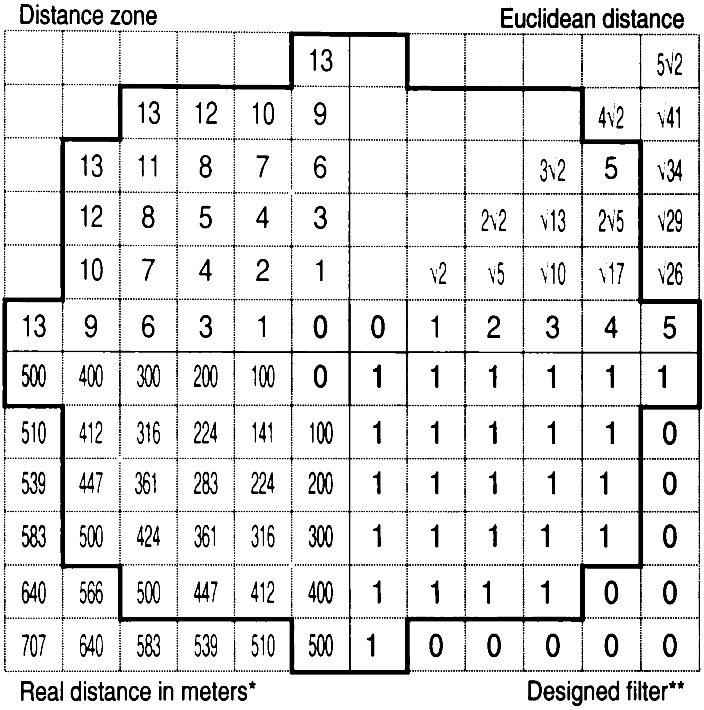


Figure 6.12: A 3x3 filter with 8-connected neighbouring cells around the central cell.

In reality, the influential distance for land use transition is up to 500m or more. Within such a distance, a variation in the degree of influence is likely to occur depending on the state of the cell and the distance from the central cell. To extend the influential distance up to 500m, the designed filter has to be 11x11 for the pixel size = 100m (see Figure 6.13). All cells that fall within a radius of 500m (or up to a distance of zone 13) are given a value of 1, and the rest are given a value of 0. If the influential distance is up to 400m, the corresponding distance zone is 9. All the cells within a distance zone of 9 or less are given a value of 1, and the rest are given a value of 0, and so on. Thus, the size of the distance-influence filter is dependent on the maximum influential distance and the pixel size.

The values of 1 and 0 in the filter designed (Figure 6.13) are called the coefficient of the filter. For many filters, the values are not always 1 or 0. When this filter is assigned to a raster-based map, a convolution operation is performed. It operates by multiplying each pixel value of the map with the corresponding coefficient in the filter. All the values gained are summed and the resulting value replaces the original value of the central pixel.



					13						$5\sqrt{2}$
		13	12	10	9					$4\sqrt{2}$	$\sqrt{41}$
	13	11	8	7	6				$3\sqrt{2}$	5	$\sqrt{34}$
	12	8	5	4	3			$2\sqrt{2}$	$\sqrt{13}$	$2\sqrt{5}$	$\sqrt{29}$
	10	7	4	2	1		$\sqrt{2}$	$\sqrt{5}$	$\sqrt{10}$	$\sqrt{17}$	$\sqrt{26}$
13	9	6	3	1	0	0	1	2	3	4	5
500	400	300	200	100	0	1	1	1	1	1	1
510	412	316	224	141	100	1	1	1	1	1	0
539	447	361	283	224	200	1	1	1	1	1	0
583	500	424	361	316	300	1	1	1	1	1	0
640	566	500	447	412	400	1	1	1	1	0	0
707	640	583	539	510	500	1	0	0	0	0	0

Note: * The pixel size is assumed to be 100 m.
** The influential distance is assumed up to 500 m (distance zone 13).
The shaded cells are assumed to be the central cell.

Figure 6.13: Creating a distance-influence filter for a known distance/radius.

Preparation

Digitised maps

All the thematic digital maps can be prepared or derived using this GIS that come from a topographic map (GTL, 19920); a land use map (Suhendar, 1989); a geological map (Dam *et al.*, 1993) of Bandung Basin area. The land use map dated 1989 is used as the basis for generating future scenarios. Each land use unit has to be separated from each other, which will be used to generate distance maps for an individual land use unit. The elevation map is made by interpolating the contour from the topographic map, which is used to produce a slope map. The main road distance map is made by a applying a distant calculation function to the main road map. All of the prepared maps are in a raster format, in which they all must have the same geo-reference system and the same pixel (cell) size.

Weighting parameters

There are two kinds of weighting parameters. The first kind is land-use-related weighting parameters. These are the weighting parameters that influence the transition of a cell from one state (land use) to another state, because of the state and the distance of a neighbouring cell from the central cell. The other kind is physical-factor-related weighting parameters. These are weighting parameters that usually discourage the transition of a cell from one state to another state because of the presence of the physical factors.

The land-use-related weighting parameters are identified in three steps. The *first step* involves assigning estimated values of the degree of influence of the cells in the neighbourhood for a particular transitional process from one land use type to another type. The values are estimated based on expert knowledge. This process is very subjective, and largely relies on the knowledge gained from field observation and the study of transitional-likelihood in the hierarchy. The *next step* is a readjustment of the values involving a process of assigning the maximum values according to the value of conversion likelihood (see Figure 6.2), while the rest are readjusted by simple proportion. The *last step* is fine adjustment of the weighting parameters which can only be conducted by examining some results of processes that have been computed. This will check whether the process of land use conversion behaves correctly.

Examples of the land use related weighting parameters are listed in Table 6.5. (Two blocks are shown here for the purpose of explanation. A full set of land-use-related weighting-parameters is in the Appendix 6-A at the end of this chapter.) Each block of rows assigned with a Roman numeral, contains the parameters for calculating one potential transition. Each row within the block contains weighting parameters applied to a land use unit in distance zone 1 to 10 (100 m to 412 m). For example: block I - for a conversion from primary forest to urban, if the land use type of a cell is primary forest (first row in block I) and is located either at distance zone 1 or 2, the weighting parameter is -0.3. It means that the presence of primary forest at a short distance of less than 200 m is likely to discourage the conversion of a cell from primary forest to urban. The discouraging influence is indicated with a negative sign. However, the presence of urban area at this distance (last row in the same block) is likely to attract the conversion of the primary forest to urban (weighting parameters = +0.75). Block III shows that the transformation of a cell from irrigated paddy to urban is largely encouraged by the presence of an urban area in its neighbourhood (last row in block III), but its influence decreases gradually with distance (weighting parameter = 5 at the shortest distance and = 1 at the distance zone 8).

The physical-factor-related weighting parameters are the parameters that control the distribution of the changes in land use. The weighting parameters from the physical factors that influence the distribution of the land use changes are listed in Table 6.6. These numerical values of the weighting factors are estimated based on the previous discussion (Section 6.3) and are readjusted after examining the results of some computational processes. If there are no physical factors that restrict the land use conversion, the value is 0.

Table 6.5: Weighting parameters for transition from state *i* to *j*.

	Distance zone, *d*									
State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141	200	224	283	300	316	361	400	412
	Distance in meters (cell size = 100m)									
I	*From:* ***Primary forest***					*to:*	***Urban***			
Primary forest	-0.3	-0.3	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0.75	0.75	0	0	0	0	0	0	0	0
III	*From:* ***Irrigated paddy***					*to:*	***Urban***			
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
tegalan (Dryland)	0.5	0.5	0.5	0.5	0	0	0	0	0	0
Urban	5	5	3	3	1	1	1	1	0	0

A flood zone is another important natural (or physical) factor that can also influence the distribution of certain land use types, especially the urban area. The flood zone is divided into two sub-zones; the annual flood zone and the flood potential zone. The annual flood zone is the zone where floods occur almost every year and therefore the utilisation of this zone is restricted. The flood potential zone is where floods occur occasionally, for example, every 5 or 10 years. This zone is still susceptible to wet-agriculture but not to settlement and industrial areas. The weighting parameters for the flood zone are given in Table 6.7.

Table 6.6: Weighting factors with respect to slopes and distance to the main road.

Land use type	Weighting Factors (WF)					
	Elevation (m)	WF	Slope (%)	WF	Distance from the main road (m)	WF
1. Urban	< 745	Na	< 5	na	< 100	+0.16
	745 - 845	-0.4	5 - 10	-0.6	100 - 200	na
	> 845	-0.6	> 10	-0.8	200 - 400	-0.1
					400 - 1,400	-0.2
					> 1,400	-0.3
2. Dry agricultural land						
2.a Vegetable garden	< 745	-0.4	< 5	-0.3	< 2,200	na
	745 - 1,045	-0.3	5 - 10	na	> 2,200	-0.1
	1,045 - 1,145	-0.2	10 - 15	-0.2		
	1,145 - 1,245	Na	15 - 30	-0.4		
	1,245 - 1,345	-0.1	> 30	-0.5		
	1,345 - 1,445	-0.2				
	1,445 - 1,545	-0.3				
	> 1,545	-0.4				
2.b Mixed-garden	< 745	-0.2	< 5	-0.1		na
	745 - 1,045	Na	5 - 10	na		
	1,045 - 1,245	-0.2	10 - 15	-0.1		
	> 1,245	-0.3	15 - 20	-0.2		
			> 20	-0.3		
2.c Dryland (*tegalan*)	< 1,045	Na	< 10	na		na
	1,045 - 1,245	-0.1	10 - 15	-0.1		
	> 1,245	-0.2	13 - 35	-0.2		
			> 35	-0.3		
3. Paddy						
3.a Irrigated paddy	< 745	Na	< 5	na	< 3,400	na
	745 - 845	-0.3	5 - 10	-0.4	> 3,400	-0.1
	845 - 1,045	-0.4	10 - 15	-0.5		
	> 1,045	-0.5	> 15	-0.6		
3.b Rainfed paddy	< 745	Na	< 5	na		na
	745 - 845	-0.4	5 - 10	-0.5		
	845 - 1,045	-0.5	10 - 20	-0.6		
	> 1,045	-0.6	> 20	-0.7		
4. Forest						
4.a Primary		Na		na		na
4.b Secondary		Na		na		na
4.c Reforested		Na		na		na

Note: na = not assigned

Table 6.7: Weighting parameters of land use conversion in a flood zone.

Land use	Annual flood zone	Potential flood zone
1. Urban	-4	-1
2. Dry agricultural land	N/A	N/A
3. Paddy		
3.a Irrigated paddy	-0.5	-
3.b Rainfed paddy	-0.5	-
4. Forest	N/A	N/A

Note: N/A = Not applicable

Weighted map

Creating weighted maps is the final preparation required before applying the filter function. A weighted map is made for individual land use units, for each story-line leading to one scenario. Rigid boundaries that do not allow any land use to cross such as the lake, reforested land[6-2], estate crops, are not included in the map and are assumed to remain unchanged during the process.

To create a weighted map for changes of any land use type to a specific land use, for example to create a weighted map for an urban area, the land-use-related weighted maps and the physical-factor-related weighted maps have to be created first before they are all combined to produce the weighted map for urban change. This is illustrated in Figure 6.14 and is explained below.

Land-use-related weighted maps

Creating land-use-related weighted maps involves two steps. The first one is creating distant maps for each land use type, except for urban area. This process can be done using a distant calculation function available in the GIS. The second step involves creating land-use-related weighted maps with respect to urban area

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[6-2] Reforested land is considered a rigid boundary for the scenario of 'business-as-usual'. It can be changed for other scenarios.

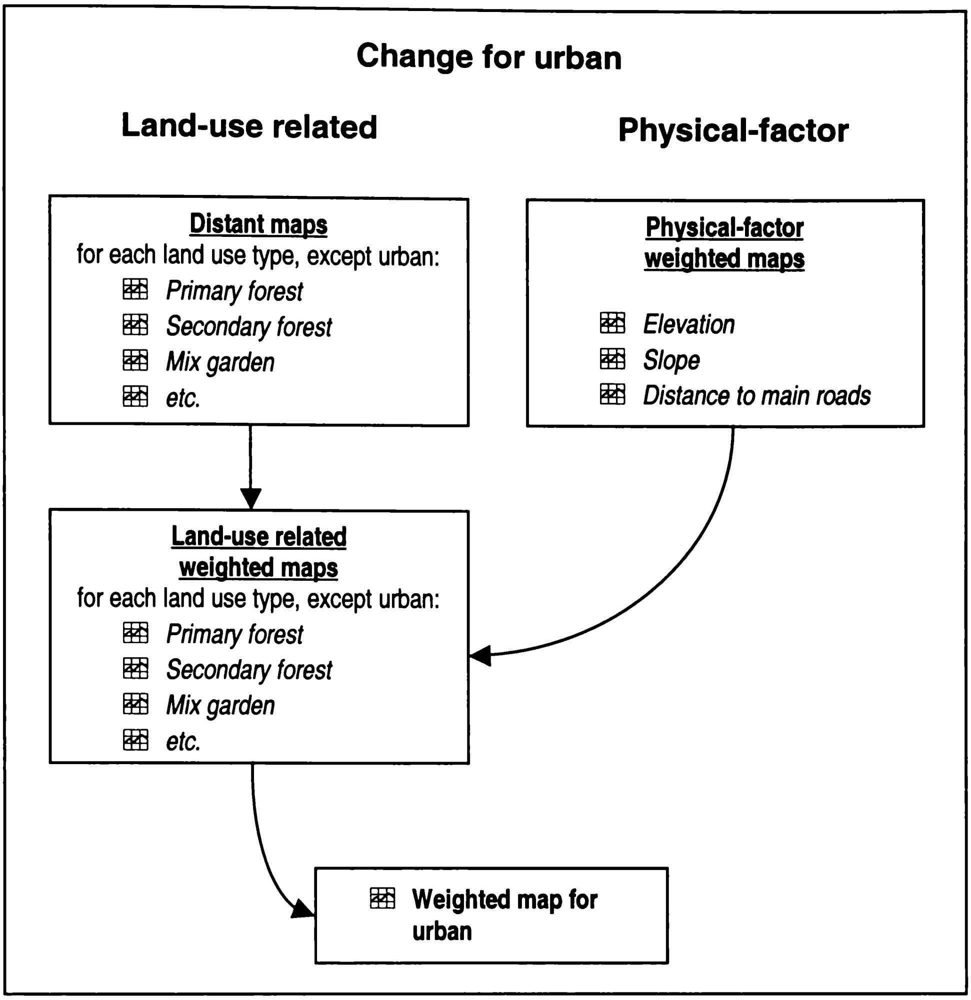

Figure 6.14: The procedure to create a weighted map, with an example for changes to urban area.

by utilising the distant maps produced in the first step. This step is basically transferring the weighted parameters (Table 6.5) for each potential transitional process of land use unit state *i* to state *j* spatially, for example the transition from primary forest (state *i*) to urban (state *j*), in order to produce a weighted map specific for this potential transition. The process requires a map calculation function, which can be described, for example:

```
If a neighbouring cell at a distance < 200 m is "primary forest",
   assign the value = -0.3

If a neighbouring cell at a distance < 200 m is "urban", assign
   value = 5; if between 200 m and 283 m, value = 3; if between 283
   m and 361 m, value = 1
```

The first statement above refers to the first row in block I, Table 6.5, and the second statement refers to the last row in block III. The same procedure is conducted for the potential transition from other land use types to urban (i.e. secondary forest to urban, vegetable garden to urban, etc.).

Physical-factor-related weighted maps

The physical-factor-related weighted maps are created for each restricting factor, i.e. elevation, slope, and distance from the main roads, with respect to urban area. These physical-factor-related weighted maps are created by using a simple slicing method. Some examples are given here: the elevation-related weighted map for urban area is created by assigning any elevation between 745m and 845m with a value = -0.4, and those higher than 845m are assigned with a value = -0.6 (Table 6.6). The same applies to slope; any slope between 5 and 10% is assigned with a value = -0.6, and those higher than 10% are assigned with a value = -0.8, and so on.

To create a weighted map for this urban area, all the land-use-related weighted maps and physical-factor-related weighted maps are combined by simple summation, i.e. the sum of all land-use-related weighted maps plus the sum of all physical-factor-related weighted maps.

Computing land use change patterns

The process of calculation is conducted by applying a filter function to the weighted map. The filter is designed based on the distance zone (see Figure 6.13) and is used for performing a convolution operation. After each convolution, the change in the related land use is analysed by generating the statistics from the map. If the new total area of the specified land use reaches the pre-estimated area, the process is stopped. If not, the procedure is repeated, starting with the creation of a new weighted map based on the newly generated map until the specified land use reaches the estimated target area. The rate of change for each land use type, or at least the land use type at the highest level in the hierarchy and the one that causes major changes, which is the urban area, must be known. The rate of change of the land use generated from the computation should match with the estimated or predetermined rate by conducting finely adjusting the weighting parameters. This is a kind of a **calibration process** for the land use change model to ensure that the model behave correctly as expected.

The method used to calculate the land use change is different from the method used by White and Engelen (1993) even though the basic principle is similar. The main reason is to reduce the complexity of the computation. In addition, the circumstances of the two studies are different and the target for output is also different. The main differences are the way the weighting parameters are assigned and the transitional potential calculation. White and Engelen's method does not give zero values in its computation, and possible transitions are calculated simultaneously. The new land use is automatically determined by the highest potential transition value in White and Engelen's method.

In contrast, the method used in this thesis can produce any values, negative and positive. If a cell gains a positive value, it means that a change occurs. If the cell gains a negative value or zero, it means that the change does not occur. This method results in changes mostly along the margin of the related land use, even though in some places a new cluster can emerge in a distant location from the related land use if the conditions are permitting. The growth of land use can be in any direction and magnitude, depending on the preferences set in the weighted map. The transitional calculation from one land use type to another is conducted manually starting with a land use type, which is the highest level in the hierarchy and is then followed by the next highest, and so on. In the case of two land-use types of equal level, the selection is decided by the physical factors that have more influence over changes. This manual method therefore permits more freedom for monitoring and assessing the changes in land use than the automatic method.

6.5 SCENARIOS

Set of scenarios

The proposed integrated model can be classified as a future study and it requires a set of scenarios to estimate plausible future land use patterns. Each scenario contains a coherent and internally consistent set of parameters, with reasonable descriptions of possible future states. Therefore, a scenario is not a prediction of a future state. For this land use component, the scenarios are selected based on various conditions that can reflect the future land use patterns.

The policy-scenarios are selected with the aim of looking for a wide range of possible patterns. Each scenario contains a defined story-line or some conditions which will determine the future patterns of the land use. The scenarios are: business-as-usual, ecological/environmental concern, pro-industrialisation, and pro-agriculture.

Business-as-usual

The business-as-usual scenario is based on conditions of the last 10 to 15 years. The rate of change for each land use is kept constant. This business-as-usual scenario is considered as the reference policy. This scenario uses the weighting parameters that have been constructed as discussed in the previous section (Section 6.4).

Ecological/environmental concern

In this scenario, some regulations regarding land use are strictly enforced. They include protected zones as described in the Presidential Decree No. 32/1990 regarding the definitions of protected zones, and regulations regarding land use in the North Bandung region[6-3] as stated in the Governor's Decree No. 181.1/SK.1624/Bapp/1982[6-4] regarding the recommendation of land use allocation in the North Bandung region, and the Governor's Decree No. 413.21/SK.222-Huk/91 regarding the locality criteria and technical standard for spatial land use for Puncak region, which is adopted for the North Bandung region (Dinas PU Cipta Karya, 1996). The North Bandung region has special treatment because this region contributes at least 60% of all groundwater that of the Bandung basin and there is a great concern that those responsible for the development in this region have paid little attention to its ecology, in particular to its water and soil resources as stated in the Letter of State Minister for Environment No. B-755/MENLH/5/1995 regarding the regional environmental impact assessment for the North Bandung region.

Relevant guidelines are extracted and simplified from the regulations mentioned above (cited in Dinas PU Cipta Karya, 1996).

- The ***protected zone*** (based on **the Presidential Decree No. 32/1990**) is defined as the ***protected forest***, ***recharge zone***, and ***locally protected zones*** including river banks up to a distance of 50 m from the edge of the river, an

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[6-3] The North Bandung region is defined as the northern part of Bandung basin at an elevation of 750m or greater.

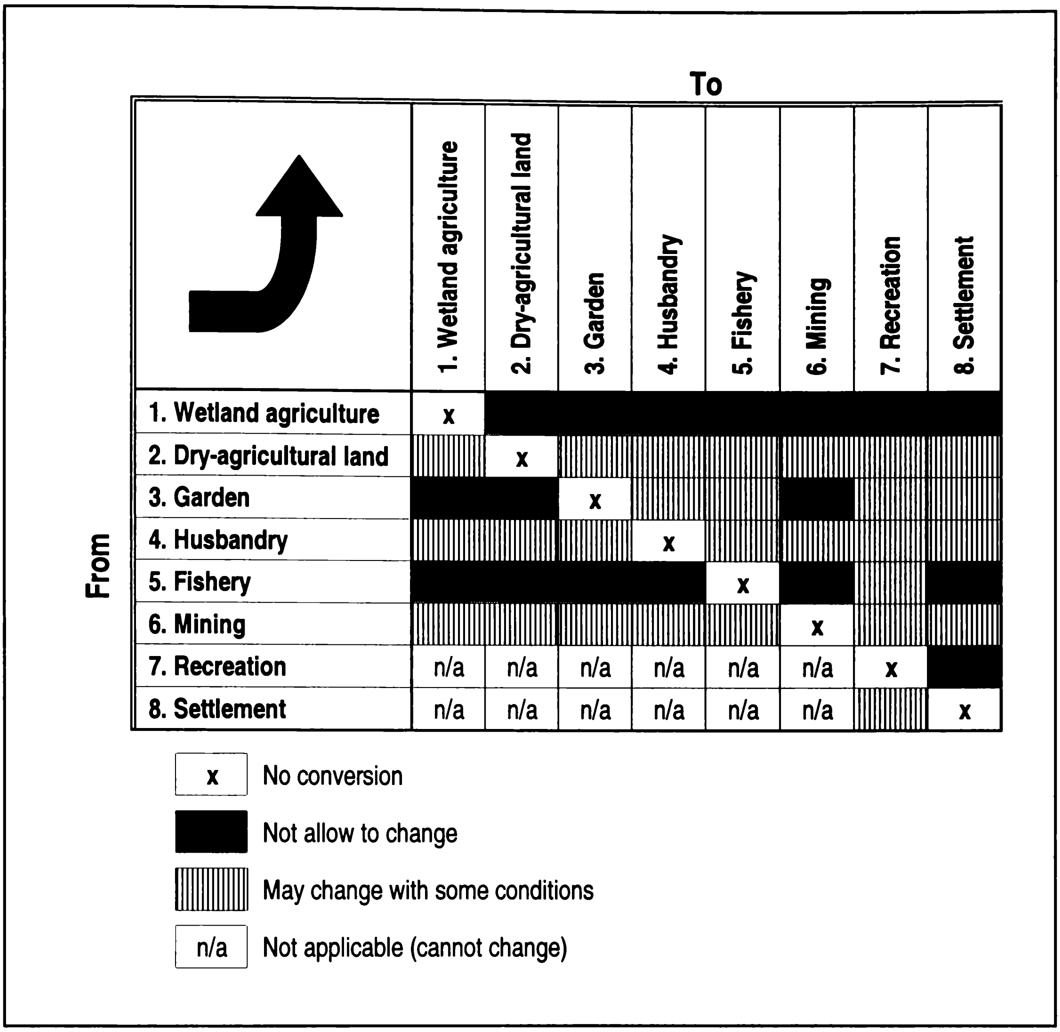
[6-4] This regulation covers recommendations for land use conversion from the land use state at that time (1982) to irrigated paddy for villages in the North Bandung region. It seems that the regulation emphasised on the allocation of irrigated paddy-field by defining the level of productivity of the land for paddy.

area within a radius of up to 200 m from a spring, and ***potential natural hazard zones*** including fault zones, land slide areas, and potential lahar-flow zones. This Presidential Decree applies to the whole country in general, including the Bandung Basin. The protected forest is defined based on the steepness of the slope, average hourly precipitation, and soil sensitivity. In addition, all forest located at an elevation of more than 2000m or slope of more than 40% is considered protected forest. The local protected zones are only small areas and on a map with a cell size of 100m to 1 km, they are negligible. Specifically for the North Bandung region, the ***protected zone*** covers an area 28,452.5 ha, or approximately 74% of the North Bandung region (Dinas PU Cipta Karya, 1996).

- Criteria for land use allocation for the North Bandung region based on elevation are listed in Table 6.8, which also includes the slope factor. These criteria come from the **Governor's Decree No. 413.21/SK.222-Huk/91**.
- Conversion from one land use type to another type is regulated, and is given in the form of a matrix (Figure 6.15). In a simple way: wetland agriculture (paddy-field) **may not** convert to any other land use types, dryland (*tegalan*) **may** convert to any other types, and garden (vegetable and mixed-garden) **may not** convert to paddy-field and dryland (*tegalan*).

Table 6.8: Land use allocation in the North Bandung region.

Elevation (m)	Slope (%)	Land use	Remark
750 - 1000	< 40	• Annual crops • Dry-agriculture	Zone of potential natural hazard.
	< 30 < 15	• Wetland agriculture (paddy) • Settlement, including urban.	Non-zone of potential natural hazard.
1000 - 2000	> 40	• Production forest	In the zone of natural hazard. No settlement is allowed.
	25 – 40	• Annual crops and gardens	Unprotected zone.
> 2000	> 40	• Protected forest	No settlement is allowed, neither is cultivation.



From \ To	1. Wetland agriculture	2. Dry-agricultural land	3. Garden	4. Husbandry	5. Fishery	6. Mining	7. Recreation	8. Settlement
1. Wetland agriculture	x	■	■	■	■	■	■	■
2. Dry-agricultural land	▥	x	▥	▥	▥	▥	▥	▥
3. Garden	■	■	x	▥	▥	■	▥	▥
4. Husbandry	▥	▥	▥	x	▥	▥	▥	▥
5. Fishery	■	■	■	■	x	■	▥	■
6. Mining	▥	▥	▥	▥	▥	x	▥	▥
7. Recreation	n/a	n/a	n/a	n/a	n/a	n/a	x	■
8. Settlement	n/a	n/a	n/a	n/a	n/a	n/a	▥	x

x No conversion

■ Not allow to change

▥ May change with some conditions

n/a Not applicable (cannot change)

Figure 6.15: Matrix of land use conversion for the North Bandung region in the utilised zone (zone for cultivation and other uses). [Source: Dinas PU Ciptakarya, 1996.]

For generating land use patterns with this scenario, the weighted parameters need to be adjusted to fit the conditions as given by the regulation. All forest in the North Bandung region is classified protected and should not be converted to any other land use types.[6-5] Therefore, the parameter for forest is given a very heavy negative value in order to forbid this type of land use to convert into another land use type. The paddy-field in the North Bandung region is not allowed to convert to other types, whereas the dryland is allowed to convert to other land use types,

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[6-5] In this thesis, the whole forest is assumed protected and conversion of forest is not allowed.

etc. Some of the land uses which are actually not supposed to be in their location, (e.g. based on the land use map dated in 1989, some paddy-fields, vegetable gardens, and cinchona plantations already occupy the protected forest zone) are left as they are, but they may convert to another type of land use following the conversion matrix (Figure 6.15). Other parameters, which are not bounded by the rules in the above guidelines or mentioned otherwise, will use the same parameters as the parameters for the business-as-usual scenario.

Pro-industrialisation

By encouraging industrialisation, it is expected that more jobs will be created in this sector and the GRDP will rise quickly. Industrialisation is usually followed by other job opportunities in other sectors such transportation, services, etc. and therefore attracts more people to relocate to the urban area which causes a rapid increase in urbanisation and demand for settlements. Some agricultural land, in particular paddy-fields, are expected to convert into settlement and industrial areas with a higher rate than the rate of conversion with in 'business-as-usual' scenario.

The weighting parameters for this scenario require an adjustment to allow the expansion of the urban area into agricultural land by increasing the land-use-related weighting parameters. Both the distance-influence zones and the weighting factors are increased to allow rapid conversion of agricultural land to urban area. The parameters that resist the conversion of forest to urban and to agricultural land are also weakened relative to the business-as-usual scenario. However, some degree of conservation to protect the forest is still present.

Pro-agriculture

With this pro-agriculture scenario, the agriculture sector is encouraged, for example for self-sufficient food-crops. In this scenario, the loss of agricultural land, in particular the irrigated paddy is designed to be minimal, while the area for agricultural land is allowed to expand onto the forestland. However, this scenario will use the same hierarchical rule as already set for the business-as-usual scenario, where the paddy-field is allowed to convert to mixed-garden and vegetable garden. Therefore, it is expected that with time the relative proportion of the dry-agricultural land will be higher than its current proportion.

The description of each policy as described above is summarised in Table 6.9 and the weighting parameters for each scenario are given in Appendix 6-A. The way the value is chosen is subjective, but the condition of 'business-as-usual' should be used as a reference.

Table 6.9: Conditions for various land use scenarios.

	Policy/condition	**Description of policy/condition**
1	Business-as-usual	Applying the same conditions and rates of change as for the last 10 to 15 years.
2.	Ecological/environmental concern (Green policy)	A condition that prioritises the protection of environment and ecology. With this condition, forest cutting is not permitted. The government regulation regarding the land use in the northern Bandung basin is strictly enforced, and zones around the riverbanks are protected or restored according to the regulation.
3.	Pro-industrialisation	A condition that encourages industrialisation, and therefore may encourage rapid urbanisation. Conversion of agricultural land and forest to industrial and settlement areas are permitted.
4.	Pro-agriculture	A condition that encourage activities in the agricultural sector. Conversion of forest to agricultural land is permitted. The conversion of agricultural land to urban areas is discouraged and the urbanisation rate is reduced to a low level.

Rates of change

The rates of change for the land use must be known for generating a time series of change in the land use pattern. At least the rate of change of the land use at the highest state in the hierarchy, which is the urban area, must be known. By knowing the rate of change of the urban area, the growth of the urban area for a specific year can be calculated. This can be converted into the number of processes required from the computer to process the change in land use until the target amount of growth in the urban area for a specific time is met. Therefore, a time-series for change in land use can be produced.

However, the rate of urbanisation in this study area has not been well studied and documented. A study in this basin by Karsidi (1998) showed that the increase in the area of settlement and industries was at an average of 7.8% per year for the period 1984-1996. The forest area was reduced by 2.9%, and the agricultural land was reduced by 4.4% every year in the same period. At a national scale, Cobban (1996) estimated the urbanisation rate for the whole country at 5% per year, and for the island of Java 1.7% per year for the period of 1980-1990, which is much lower than the national figure. Another study (Verburg *et al.*, 1999) estimates that the people the percentage of the Java's population living in the urban areas increased from 39% in 1994 to 47% in 2000, and 57% in 2010, or the rate of increase for people living in the urban area is on average 3.16% per year from 1994 to 2000, and 1.95% from 2000 to 2010.

The rate of urbanisation is different from the rate of increase in settlement and industrial areas. Therefore, the rate of increase in the area of settlement and industries as given by Karsidi (1998) represents the actual change of land use better than the urbanisation rates given by Cobban (1996) or Verburg *et al.* (1999). However, it seems that the value given by Karsidi (1998) overestimates the actual increase in the urban area because the likely demand for settlement areas (not including industries), as indicated by the annual growth rate of population (3.3% for 1989-1997 period) and number of households (2.45% for

1989-1997 period), is much less than the rate of increase in the number of settlement and industrial (urban) areas as given by Karsidi.[6-6] In addition, the influence of industries on the growth of the industrial area is questionable because the number of large and medium size industries is declining (see Figure 6.1). This thesis, therefore, uses an estimated rate of increase in the urban area of 5% per year for the business-as-usual condition, which is quite modest in comparison to the value given by Karsidi (1998), which is 7.8%, and slightly higher than the estimated current rate of urbanisation for Java and the rate of increasing population in the study area, which are 3.16% (Verburg *et al.*, 1999) and 3.3% respectively. The rate of growth is assumed to reduce by 4.7% per year, following the reduction in the rate of urbanisation as estimated by Verburg *et al.* (1999).

Rates of change in other land use types are not well studied. Collected information shows very different results. Data from Karsidi (1998) suggested that, for the period 1984 to 1996, the forestland reduced by 2.9% per year and the agricultural land reduced by 4.4% per year. A linear extrapolation using these rates shows that all agricultural land and forest in the Bandung basin would vanish by 2015 and 2022 respectively. Collier, *et al.* (1993) [cited in Verburg *et al.* (1999)] also foresaw that in the year 2025 all of Java except the most eastern and western parts will be totally urban.[6-7] However, a land use model for Java by Verburg *et al.* (1999) indicates that in 2010, in spite of high absolute changes in the land use, the changes take place dominantly in the lowland areas where there is a decrease in paddy-fields due to an increase in housing area, and estate crops and, in addition, there is also an increase in dry-agricultural land (i.e. agricultural land still exists, and in particular dry-agricultural land is increasing). The changes in highland areas, in particular the forest area, are less pronounced.

[6-6] Data from Karsidi (1998) indicated that the increase in the area of settlement/industries was at an average of 7.8% per year. With this rate, a linear projection indicates that by the year 2000, the settlement/industrial area is estimated to cover about 58% of the whole basin. By 2022, the whole basin will be covered by settlement/industries.

[6-7] Another pessimistic condition was also expressed in an article in a local newspaper, saying that the agricultural land in the island of Java might vanish in 2015 if the rate of conversion of agricultural land is maintained at about 15% per year (Azwar, 2001).

For this thesis, the rate of land use change relies only on the growth rate of the urban area (settlement and industrial area). This is considered the main type of land use that drives land use change because it is controlled directly by demand from society. In this model, it is also possible to include the rates of change of one or two other land use types. However, this may cause exhaustive adjustment of the weighting parameters, which may not be necessary for this study. Furthermore, as discussed earlier, definite rates of land use change are not yet known.

The rates of growth for the urban area for each scenario are set as follows: business-as-usual = 5%, which is the reference condition; ecological concern = 5%, which is equal to the rate of the business-as-usual condition[6-8]; pro-industrialisation = 7.5%, which is slightly lower than the rate given by Karsidi (1998); and pro-agriculture scenario = 2.5%, which is significantly lower than the current rate of urbanisation in Java (3.13%). It is selected with a difference of 2.5% between the top extreme (pro-industrialisation) and the reference, and between the low extreme (pro-agriculture) and the reference, in order to illustrate the significant results given by these various scenarios.

The rates as given here are not fixed. This is because the static nature of the model. It depends on the rules and conditions that are set from the outset. These rules and conditions remain the same throughout the whole process of land use change in the model. The growth in the urban area, for example, will decrease because during the growth process, it will encounter many restricting boundaries and factors such as slope, elevation and forest. The main road, which promotes urban growth and influences the direction of growth will also be less important because the distance between the main road and areas where the urban areas may expand has increased. Unless there is a change in rules, or additional main roads, the expansion of the urban area will terminate.

[6-8] The final result, as expected, is at a slightly lower rate (4.7%) than the rate for the business-as-usual scenario because of restrictions in its growth such as: the conversion of paddy-field to settlement is forbidden, forest is strictly kept unchanged, etc.

Changes in the land use patterns based on various scenarios

The change in land use pattern composition under various scenarios can be seen in Figure 6.16. This figure shows a time-series change in sectoral land use. In general, the results show that the urban area reaches the largest area in 2100 under the pro-industrialisation policy, and the lowest under the pro-agriculture policy. The business-as-usual and the ecology concern policies produce almost similar results. For agricultural land, the highest by proportion for the year of 2100 is when the pro-agriculture policy is implemented, in spite of the decrease in the paddy-field. This reflects the trend of change in agricultural land use because of change in diets as suggested by Verburg *et al.* (1999). The ecological concern policy produce nearly similar outcomes as the business-as-usual scenario. The main difference is that the ecological concern policy keeps the forest area at the same size as in 1990, whereas the business-as-usual scenario allows conversion of the secondary forest into different land use types.

Business-as-usual (Figure 6.17)

Under the business-as-usual scenario, the urban area will expand first by filling the gap between the existing urban areas and along the east-west main road, and later, it will expand outward to the south. This is similar to what was predicted by Verburg *et al.* (1999) that the outskirts of Bandung city would be one hot spot of change in 2010. The paddy-field will be quickly reduced by the expansion of the urban area, and by 2060 almost all irrigated land is converted to urban area, except in the upland.

Ecological concern (Figure 6.18)

With this scenario, the forest remains unchanged for the whole process of land use change. The growth of the urban area is similar to the growth under the business-as-usual scenario, except for the North Bandung region (north of the main city) where the urban area is not allowed to expand. The forest remains unchanged all the time.

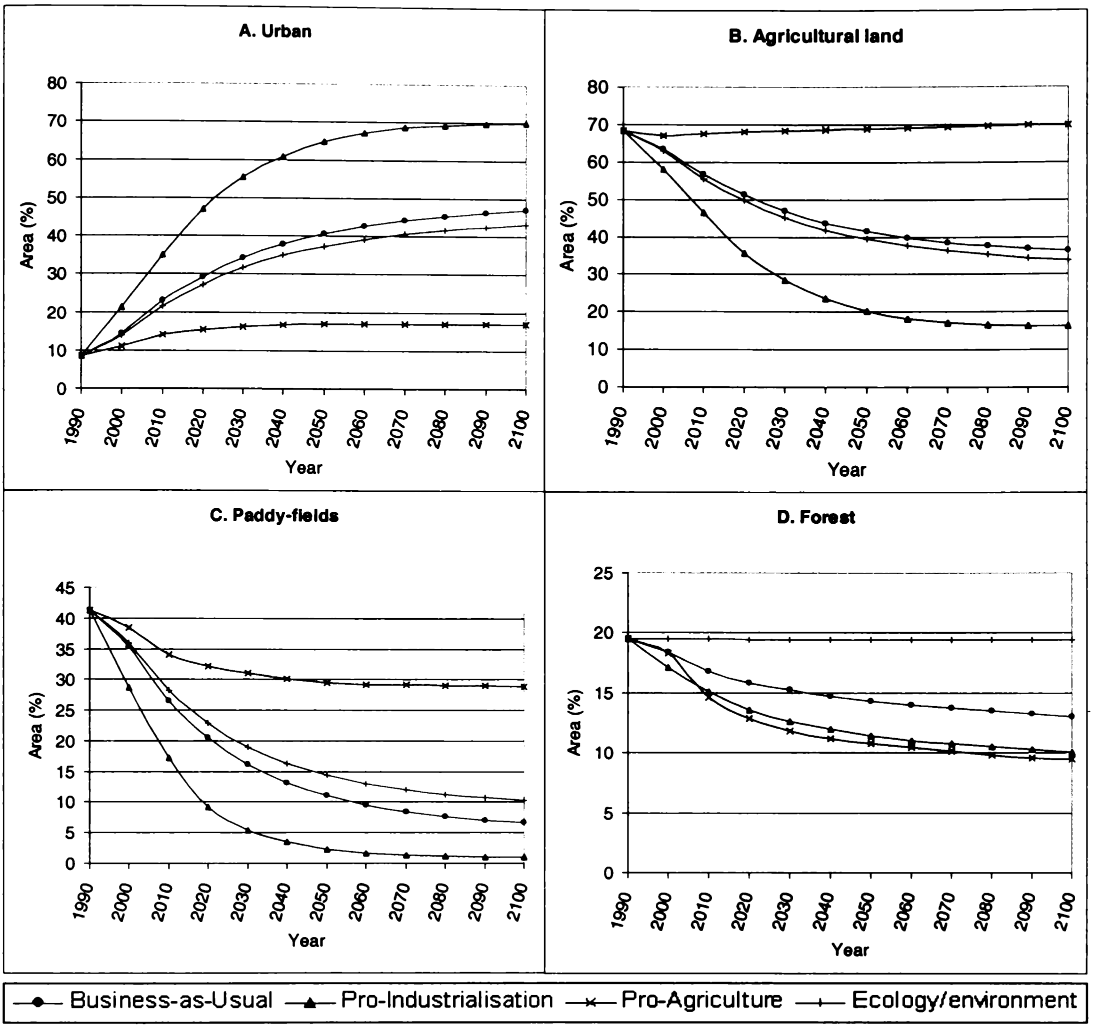

Figure 6.16: Sectoral change in land use.

Pro-industrialisation (Figure 6.19)

This scenario simulates the rapid increase in the urban area, with the growth in the urban area being 1½ times higher than the reference scenario (business-as-usual). The urban area expands quickly by converting the paddy-field and mixed-garden, and by 2020, nearly all the paddy-field will be converted to urban area. This rate of expansion may decrease quickly as the area becomes saturated. By 2100, about 70% of the basin will be covered by the urban area, leaving some space for forest and vegetable garden.

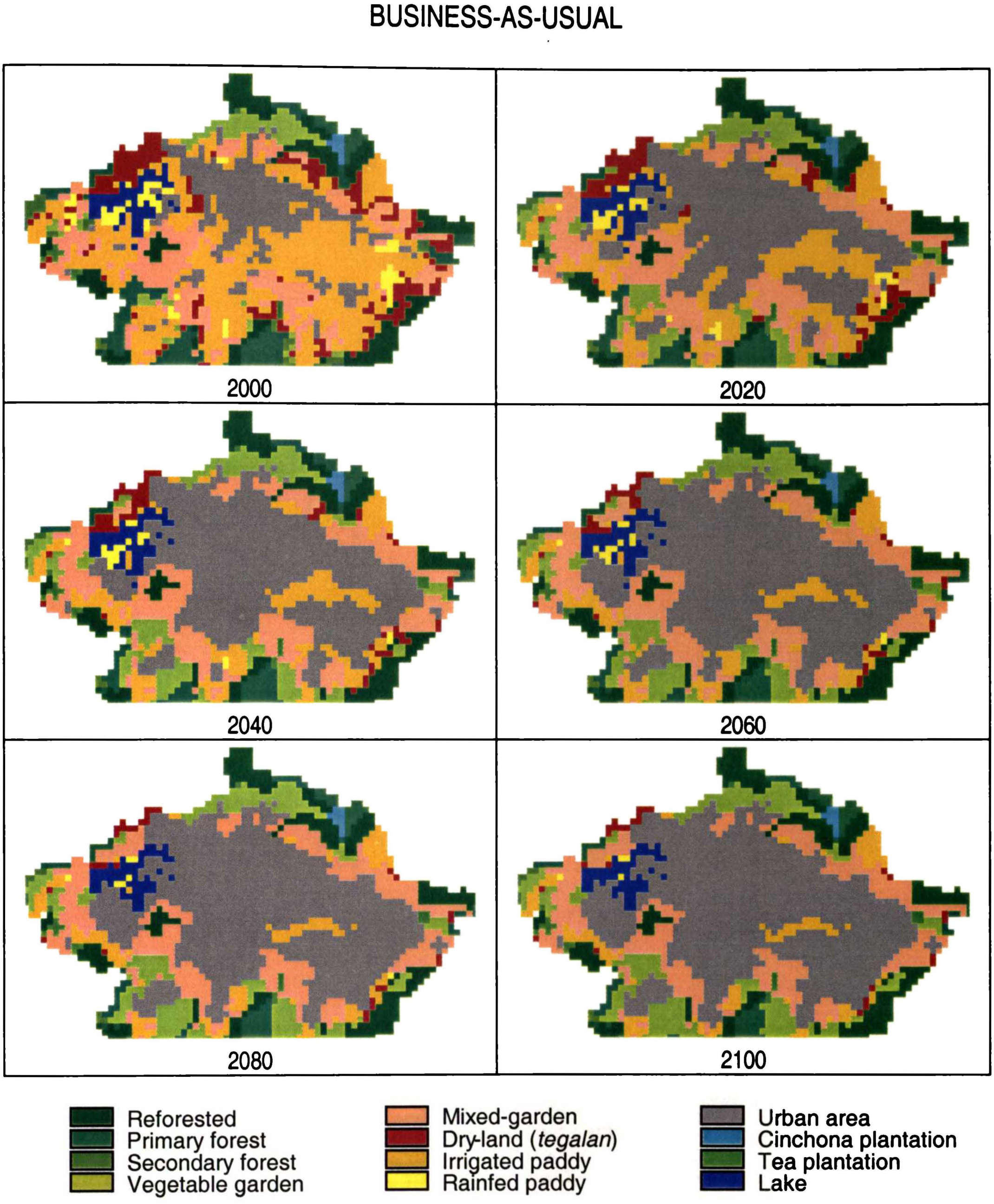

Figure 6.17: Change in the land use pattern under a business-as-usual scenario over a time series from the year 2000 to 2100, with a 20-year intervals.

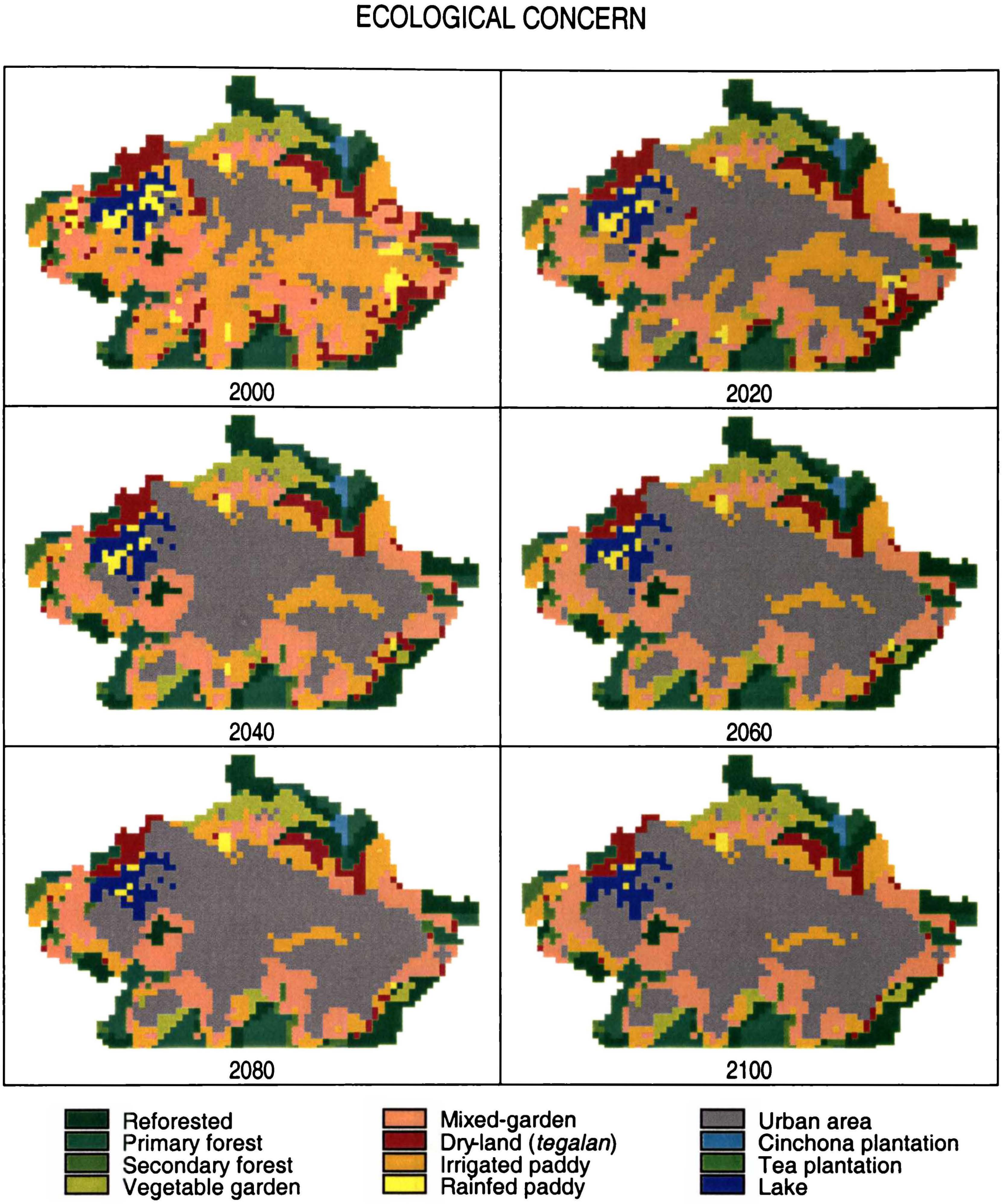

Figure 6.18: Change in the land use pattern under an ecological concern scenario over a time series from the year 2000 to 2100, with a 20-year intervals.

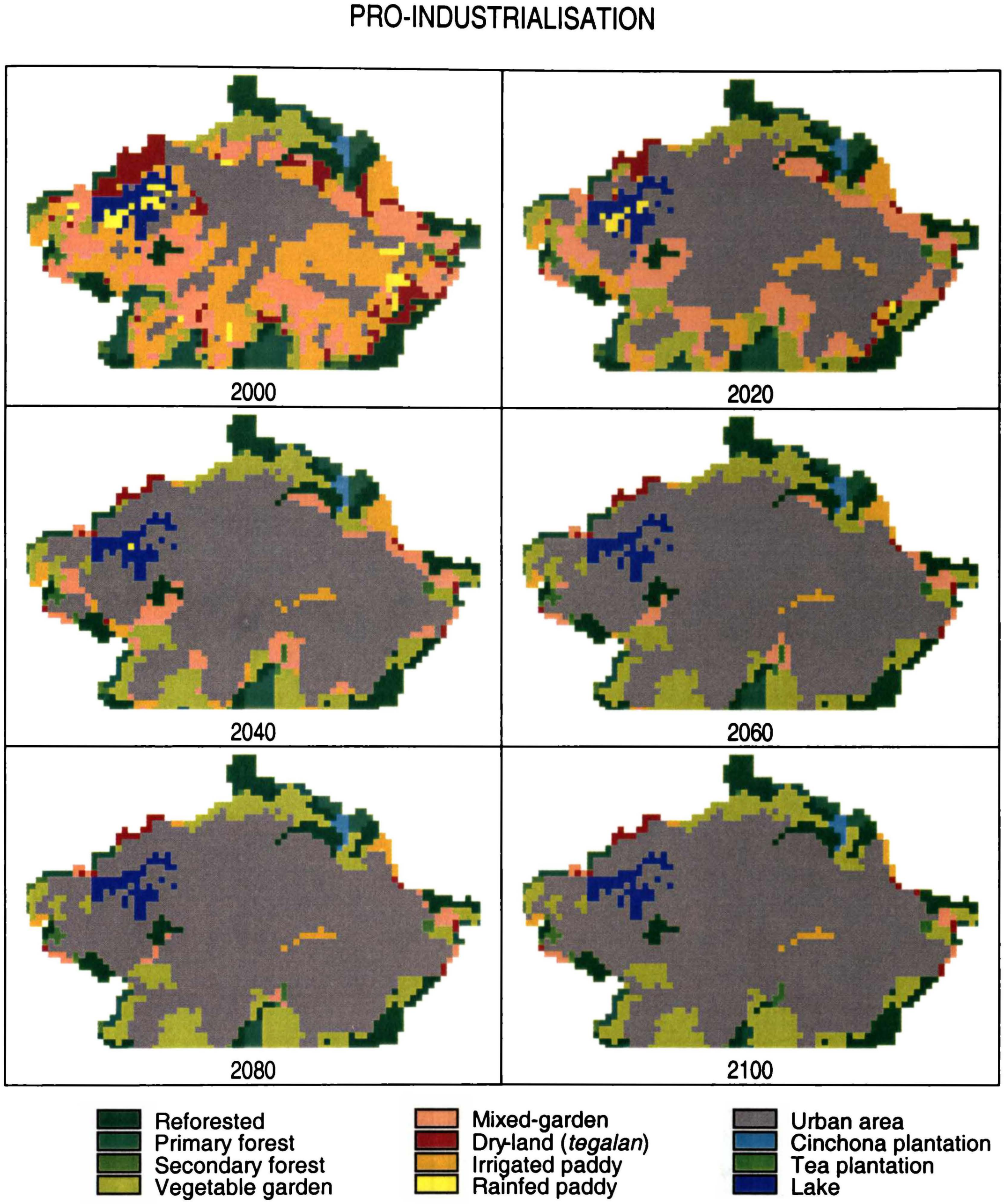

Figure 6.19: Change in the land use pattern under a pro-industrialisation scenario over a time series from the year 2000 to 2100, with a 20-year intervals.

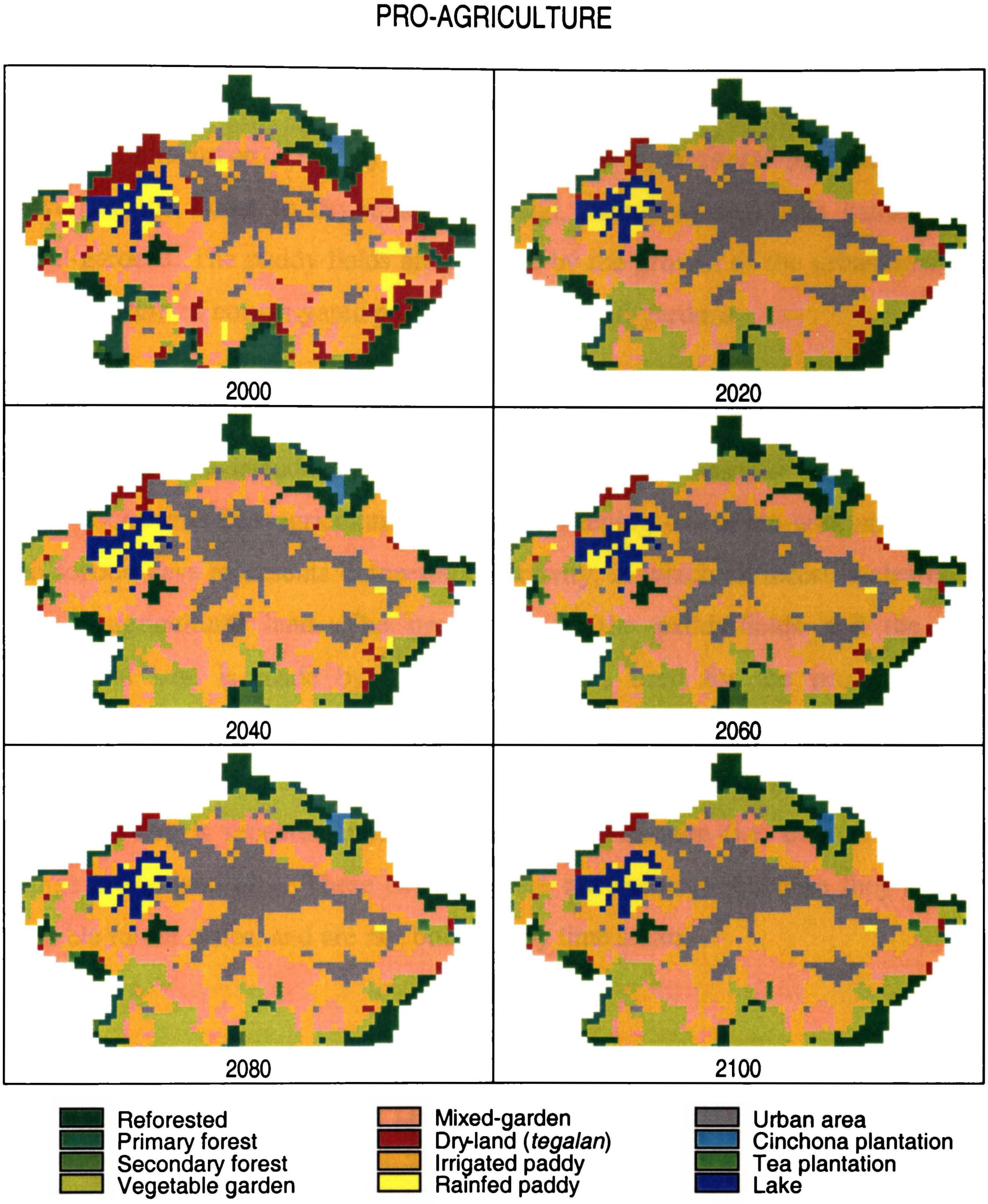

Figure 6.20: Change in the land use pattern under a pro-agriculture scenario over a time series from the year 2000 to 2100, with a 20-year intervals.

Pro-agriculture (Figure 6.20)

This scenario simulated a low rate of urban growth. The urban area expands slowly until the year 2040 at about 17% of the total area, and there is no further growth of the urban area beyond this year. The agricultural land expands by converting the forest to dry-agricultural land, mainly to vegetable gardens and mixed-gardens. The paddy-fields are reduced by the growth of the urban area and the conversion of non-irrigated paddy-fields to mixed-gardens.

In addition to the scenarios listed in Table 6.8, for the purpose of comparison, two extreme cases are introduced. They are: (1) the whole basin is forested, (2) all forest is converted to agricultural land while keeping the urban area unchanged. The second case represents deforestation activity, in which all forest is cleared to become agricultural land. The proportion of the paddy-fields and the dry-agricultural land is made by applying the rules used for the pro-agriculture scenario, with some changes to allow for the expansion of the agricultural land into all forest areas while the urban area is kept constant, and the process of land use conversion is repeated until it reaches an equilibrium (i.e. there is no more change in the land use). These two cases are not scenarios because they are not plausible future states, and are not bounded by time series.

6.6 LINKING WITH THE HYDROLOGICAL COMPONENT

The land use patterns from these scenarios need to be linked to the hydrological component in order to integrate them into one system, together with the climate component. This thesis uses land use scenarios that have been generated by using a GIS. Producing patterns of change involves several processes that require a large capacity computer, and may require a long process. If the whole processes of creating land use change patterns are conducted within the proposed integrated system, it may require heavy computation and may take much time to process before the output patterns can be passed to the hydrological component. In addition, users must also be familiar with the GIS. Therefore, conducting the whole processes of creating land use change patterns within the proposed integrated model is not effective for conducting sensitivity analysis, which is the purpose of this study.

For simplicity reasons, the land use patterns for each pre-selected scenario are kept off-line. They are stored as library files within the computer system. For this thesis, the library files contain various land use patterns from scenarios that have been discussed earlier (i.e. business-as-usual, ecological concern, pro-industrialisation and pro-agriculture), in a time series from 1990 (reference year) to 2100 with a 10-year time intervals. The users will have to choose one scenario from these pre-selected scenarios in order to run the model.

The land use patterns are already in a spatial format with a compatible grid size with the hydrological component, which is 1 km^2 for each cell. The hydrological component will read this land use map cell-by-cell and transform the information on the land use type into specific values for the appropriate hydrological parameters, which are; the land use water consumption coefficient (k_l), the available water capacity (W), and the storm runoff coefficient (S). These values are required for the water balance calculation (Chapter 5).

6.7 CONCLUSION

The land use change scenarios have been constructed as part of the development of an integrated model. Four sets of policy relevant scenarios have been selected; business-as-usual, ecological concern, pro-industrialisation, and pro-agriculture. Each scenario generates a time-series of land use change patterns.

These land use change patterns have been created by using a GIS, based on the principle of a cellular automata method (White and Engelen, 1993). It involves several steps:

- Defining the hierarchical transition rules, that includes identification of likeliness for a conversion from one state to other states, and understanding the distribution behaviour of land use in the study area;
- Defining the physical-factors related weighting parameters (i.e. slope, elevation, distance from the main road, and restricting boundaries such as flood zones, reforested land, and lake); and the land-use related weighting parameters (i.e. land use influence distance, and land use influence weighting factor);
- Creating weighted map;
- Processing the land use conversion.

The land use change patterns can also be transformed into a time series by knowing the rate of change of the most important land use type that drives the whole change in pattern.

To keep the integrated model simple and practical, these land use change patterns under various scenarios are stored off-line in the form of library files within the integrated system, which links to the hydrological component. Users will need to select one scenario from these pre-selected scenarios in order to conduct the sensitivity analysis on the variability of streamflows.

REFERENCES

Azwar, K. 2001. In 12-15 years will vanish: Agricultural land reducing at a rate of 15% per year. *Republika Online* [online] available URL http://www.republika.co.id/cetak_berita.asp?id=23809&kat_id=21&edisi=Online (in Indonesian), [9 April 2001]

Central Bureau of Statistics the District of Bandung 1998. *Kabupaten Bandung Dalam Angka - 1997 (The District of Bandung in Numbers - 1997).* Central Bureau of Statistics the District of Bandung (in Indonesian).

Central Bureau of Statistics the District of Bandung 1993. *Kabupaten Bandung Dalam Angka - 1997 (The District of Bandung in Numbers - 1997).* Central Bureau of Statistics the District of Bandung (in Indonesian).

Central Bureau of Statistics the District of Bandung 1990. *Kabupaten Bandung Dalam Angka - 1989 (The District of Bandung in Numbers - 1989).* Central Bureau of Statistics the District of Bandung (in Indonesian).

Central Bureau of Statistics the Municipality of Bandung 1998. *Kotamadya Bandung Dalam Angka - 1997 (The Municipality of Bandung in Numbers - 1997).* Central Bureau of Statistics the Municipality of Bandung (in Indonesian).

Central Bureau of Statistics the Municipality of Bandung 1993. *Kotamadya Bandung Dalam Angka - 1992 (The Municipality of Bandung in Numbers - 1992).* Central Bureau of Statistics the Municipality of Bandung (in Indonesian).

Central Bureau of Statistics the Municipality of Bandung 1991. *Kotamadya Bandung Dalam Angka - 1989 (The Municipality of Bandung in Numbers - 1989).* Central Bureau of Statistics the Municipality of Bandung (in Indonesian).

Cobban, J.L. 1996. Indonesia: Insular contrasts of the Java core with other islands. In: A.K. Dutt (ed.) *Southeast Asia: A Ten Nation Region.* The Geojurnal Library, Kluwer Academic Press, 135-152.

Dam, M.A.C. 1994. *The Late Quaternary Evolution of the Bandung Basin, West Java, Indonesia.* Thesis, Vrije Universiteit Amsterdam.

Dinas PU Ciptakarya 1997. *Technical Guidance for Spatial and Building Organisation in Northern Bandung Region, Final Report Book 1.* Dinas Pekerjaan Umum Ciptakarya and Lembaga Pengabdian Kepada Masyarakat ITB, 1995/1996 (in Indonesian).

GTL 1992. *Environmental Geology for Landuse and Regional Planning Bandung Basin.* Directorate of Environmnetal Geology, Indonesia.

Hasan, N.M.H. 1999. A large scale ecosystem scenario development tool based on QUEST. *Information Paper For NETTLAP Regional Conference – Making A Difference: Progress in Environmental Education, Training and Research in Asia and the Pacific.* 30 September – 2 October 1999, Phuket, Thailand

Karsidi, A. 1998. Land use–land cover changes (Indonesia case study). *Land Use/Cover Change-Data and Information System (LUCC-DIS) Workshop, 13-18 August 1998.* [online] available URL http://www.start.or.th/ luccdis_98/indonesia_case.htm (20 April 2000).

Preston, D. 1989. *Getting by with little land: The evolution of household strategies in two hamlets in Central Java.* Working Paper 520, School of Gegoraphy University of Leeds.

SEA START RC 1999. Indonesia: land use and land cover change case study. [online] available URL http://www.start.or.th/LUCC/indonesia_lucc.htm (20 April 2000).

Suhendar, R. 1990. Present land use. *Environmental Geology for Landuse and Regional Planning Bandung Basin.* Directorate of Environmnetal Geology.

Verburg, P.H., De Koning, G.H.J., Kok, K., Veldkamp, A. and Bouma, J. 1999. A spatial explicit allocation procedure for modelling the pattern of land use change based upon actual land use. *Ecological Modelling* 116, 45-61.

White, R. and Engelen, G. 1993. Cellular automata and fractal urban form: a cellular modelling approach to the evolution of urban land-use patterns. *Environment and Planning A* 25, 1175-1199.

APPENDIX 6-A: WEIGHTING PARAMETERS FOR LAND USE CONVERSION

Business-as-usual

State, *k*	Distance zone, *o*									
	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From: **Primary forest**			to:	**Urban**					
Primary forest	-0.3	-0.3	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0.75	0.75	0	0	0	0	0	0	0	0
II	From: **Secondary forest**			to:	**Urban**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	3	1	1	0	0	0	0	0	0	0
III	From: **Irrigated paddy**			to:	**Urban**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0.5	0.5	0.5	0.5	0	0	0	0	0	0
Urban	5	5	3	3	1	1	1	1	0	0
IV	From: **Rainfed paddy**			to:	**Urban**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	5	5	3	3	1	1	1	1	0	0
V	From: **Veg Garden**			to:	**Urban**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	2	0	0	0	0	0	0	0	0	0
VI	From: **Mix garden**			to:	**Urban**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	4	4	1	1	0.5	0.5	0	0	0	0
VII	From: **Dryland (*tegalan*)**			to:	**Urban**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	4	4	4	1	1	1	0	0	0	0

State, *k*	Distance zone, *o*									
	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From: **Primary forest**			to:	***Tegalan***					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0.2	0.2	0	0	0	0	0	0	0	0
Rainfed paddy	0.2	0.2	0	0	0	0	0	0	0	0
Vegetable garden	0.8	0.8	0	0	0	0	0	0	0	0
Mixed garden	0.8	0.8	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0.8	0.8	0	0	0	0	0	0	0	0
Urban	0.25	0.25	0.25	0	0	0	0	0	0	0
II	From: **Secondary forest**			to:	***Tegalan***					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	1.5	1.5	1.5	0	0	0	0	0	0	0
Rainfed paddy	1.5	1.5	1.5	0	0	0	0	0	0	0
Vegetable garden	5	5	5	0	0	0	0	0	0	0
Mixed garden	5	5	5	0	0	0	0	0	0	0
Tegalan (Dryland)	5	5	5	0	0	0	0	0	0	0
Urban	2	2	2	1.5	1.5	0	0	0	0	0
III	From: **Irrigated paddy**			to:	***Tegalan***					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From: **Rainfed paddy**			to:	***Tegalan***					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From: **Veg Garden**			to:	***Tegalan***					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From: **Mix garden**			to:	***Tegalan***					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From: **Tegalan**			to:	***Tegalan***					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Note: (NA) Not applicable

Continuation from the previous page

Business-as-usual

	Distance zone, o									
State, k	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From: **Primary forest**			to:	**Mix garden**					
Primary forest	-0.1	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0	0	0	0	0	0	0	0
Mixed garden	0.5	0.5	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From: **Secondary forest**			to:	**Mix garden**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	2	2	0	0	0	0	0	0	0	0
Mixed garden	2	2	0	0	0	0	0	0	0	0
Tegalan (Dryland)	3	3	0	0	0	0	0	0	0	0
Urban	0	0	0.2	0.2	0.2	0.2	0	0	0	0
III	From: **Irrigated paddy**			to:	**Mix garden**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	-0.2	-0.2	-0.2	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0.2	0.2	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From: **Rainfed paddy**			to:	**Mix garden**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0.5	0	0	0	0	0	0	0
Mixed garden	0.5	0.5	0.5	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From: **Veg Garden**			to:	**Mix garden**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0.2	0.2	0.2	0.2	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From: **Mix garden**			to:	**Mix garden**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From: **Dryland (tegalan)**			to:	**Mix garden**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0.5	0	0	0	0	0	0	0
Mixed garden	4	4	1	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Note: (NA) Not applicable

	Distance zone, o									
State, k	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From: **Primary forest**			to:	**Veg garden**					
Primary forest	-0.1	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0	0	0	0	0	0	0	0
Mixed garden	0.5	0.5	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From: **Secondary forest**			to:	**Veg garden**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	5	5	0	0	0	0	0	0	0	0
Mixed garden	5	5	0	0	0	0	0	0	0	0
Tegalan (Dryland)	5	5	0.5	0.5	0.5	0.5	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From: **Irrigated paddy**			to:	**Veg garden**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.4	0.4	0.4	0.3	0.2	0	0	0	0	0
Mixed garden	0.3	0.3	0.2	0.2	0	0	0	0	0	0
Tegalan (Dryland)	0.2	0.2	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From: **Rainfed paddy**			to:	**Veg garden**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0	0	0	0	0	0	0	0
Mixed garden	0.5	0.5	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0.2	0.2	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From: **Veg garden**			to:	**Veg garden**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From: **Mix garden**			to:	**Veg garden**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0	0	0	0	0	0	0	0
Mixed garden	-1	-0.5	-0.5	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From: **Tegalan**			to:	**Veg garden**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	4	4	2	0	0	0	0	0	0	0
Mixed garden	0.5	0.5	0.5	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Continuation from the previous page.

Business-as-usual

State, *k*	Distance zone, *o*									
	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From: **Primary forest**			to:	**Rainfed paddy**					
Primary forest	-5	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0.2	0.2	0	0	0	0	0	0	0	0
Rainfed paddy	0.2	0.2	0	0	0	0	0	0	0	0
Vegetable garden	0.2	0.2	0	0	0	0	0	0	0	0
Mixed garden	0.2	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From: **Secondary forest**			to:	**Rainfed paddy**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	5	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From: **Irrigated paddy**			to:	**Rainfed paddy**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From: **Rainfed paddy**			to:	**Rainfed paddy**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From: **Veg garden**			to:	**Rainfed paddy**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From: **Mixed garden**			to:	**Rainfed paddy**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From: **Dryland (*tegalan*)**			to:	**Rainfed paddy**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0.5	0.5	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

State, *k*	Distance zone, *o*									
	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From: **Primary forest**			to:	**Irrigated paddy**					
Primary forest	-5	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0.5	0.5	0.5	0.5	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From: **Secondary forest**			to:	**Irrigated paddy**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	2	0.5	0.5	0.5	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From: **Irrigated paddy**			to:	**Irrigated paddy**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From: **Rainfed paddy**			to:	**Irrigated paddy**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From: **Veg garden**			to:	**Irrigated paddy**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From: **Mixed garden**			to:	**Irrigated paddy**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From: **Dryland (*tegalan*)**			to:	**Irrigated paddy**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0.2	0.2	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Note: (NA) Not applicable

Continuation from the previous page.

Business-as-usual

State, *k*	Distance zone, *o* 1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From:	**Primary forest**		to:	**Secondary forest**					
Primary forest	-0.5	-0.5	-0.5	-0.2	-0.2	0	0	0	0	0
Secondary forest	0.2	0.2	0.2	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0.2	0.2	0.2	0	0	0	0	0	0	0
Rainfed paddy	1	1	1	0	0	0	0	0	0	0
Vegetable garden	1	1	0.5	0.5	0.5	0.5	0	0	0	0
Mixed garden	1	1	0.5	0.5	0.5	0.5	0	0	0	0
Tegalan (Dryland)	1	1	0.5	0.5	0.5	0.5	0	0	0	0
Urban	0.5	0.5	0	0	0	0	0	0	0	0
II	From:	**Secondary forest**		to:	**Secondary forest**					(NA)
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From:	**Irrigated paddy**		to:	**Secondary forest**					(NA)
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From:	**Rainfed paddy**		to:	**Secondary forest**					(NA)
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From:	**Veg garden**		to:	**Secondary forest**					(NA)
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From:	**Mixed garden**		to:	**Secondary forest**					(NA)
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From:	**Dryland (*tegalan*)**		to:	**Secondary forest**					(NA)
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

State, *k*	Distance zone, *o* 1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From:	**Primary forest**		to:	**Primary forest**					(NA)
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From:	**Secondary forest**		to:	**Primary forest**					(NA)
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From:	**Irrigated paddy**		to:	**Primary forest**					(NA)
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From:	**Rainfed paddy**		to:	**Primary forest**					(NA)
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From:	**Veg garden**		to:	**Primary forest**					(NA)
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From:	**Mixed garden**		to:	**Primary forest**					(NA)
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From:	**Dryland (tegalan)**		to:	**Primary forest**					(NA)
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Note: (NA) Not applicable

Ecological concern

Distance zone, *o*

State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
Distance in meters (cell size = 100m)										
I	From:	**Primary forest**		to:	**Urban**				(NA)	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From:	**Secondary forest**		to:	**Urban**				(NA)	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From:	**Irrigated paddy**		to:	**Urban**				NBR	-5
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0.5	0.5	0.5	0.5	0	0	0	0	0	0
Urban	5	5	3	3	1	1	1	1	0	0
IV	From:	**Rainfed paddy**		to:	**Urban**				NBR	-5
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	5	5	3	3	1	1	1	1	0	0
V	From:	**Veg Garden**		to:	**Urban**				NBR	-5
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	2	0	0	0	0	0	0	0	0	0
VI	From:	**Mixed garden**		to:	**Urban**				NBR	-5
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	4	4	1	1	0.5	0.5	0	0	0	0
VII	From:	**Dryland (*tegalan*)**		to:	**Urban**				NBR	-5
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	4	4	4	1	1	1	0	0	0	0

Note: All forests are given a weighting factor of -4

(NA) Not applicable

NBR North Bandung region, and the corresponding weighting value

Distance zone, *o*

State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
Distance in meters (cell size = 100m)										
I	From:	**Primary forest**		to:	***Tegalan***				(NA)	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From:	**Secondary forest**		to:	***Tegalan***				(NA)	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From:	**Irrigated paddy**		to:	***Tegalan***					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From:	**Rainfed paddy**		to:	***Tegalan***					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From:	**Veg Garden**		to:	***Tegalan***					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From:	**Mixed garden**		to:	***Tegalan***					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From:	**Tegalan**		to:	***Tegalan***				(NA)	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Continuation from the previous page.

Ecological concern

	Distance zone, o									
State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From:	**Primary forest**			to:	**Mixed garden**				
Primary forest	-0.1	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0	0	0	0	0	0	0	0
Mixed garden	0.5	0.5	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From:	**Secondary forest**			to:	**Mixed garden**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	2	2	0	0	0	0	0	0	0	0
Mixed garden	2	2	0	0	0	0	0	0	0	0
Tegalan (Dryland)	3	3	0	0	0	0	0	0	0	0
Urban	0	0	0.2	0.2	0.2	0.2	0	0	0	0
III	From:	**Irrigated paddy**			to:	**Mixed garden**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	-0.2	-0.2	-0.2	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0.2	0.2	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From:	**Rainfed paddy**			to:	**Mixed garden**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0.5	0	0	0	0	0	0	0
Mixed garden	0.5	0.5	0.5	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From:	**Veg Garden**			to:	**Mixed garden**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0.2	0.2	0.2	0.2	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From:	**Mixed garden**			to:	**Mixed garden**				(NA)
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From:	**Dryland (tegalan)**			to:	**Mixed garden**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0.5	0	0	0	0	0	0	0
Mixed garden	4	4	1	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Note: All forests are given a weighting factor of -4
(NA) Not applicable
NBR North Bandung region, and the corresponding weighting value

	Distance zone, o									
State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From:	**Primary forest**			to:	**Veg garden**				(NA)
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From:	**Secondary forest**			to:	**Veg garden**				(NA)
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From:	**Irrigated paddy**			to:	**Veg garden**			NBR	-5
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.4	0.4	0.4	0.3	0.2	0	0	0	0	0
Mixed garden	0.3	0.3	0.2	0.2	0	0	0	0	0	0
Tegalan (Dryland)	0.2	0.2	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From:	**Rainfed paddy**			to:	**Veg garden**			NBR	-5
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0	0	0	0	0	0	0	0
Mixed garden	0.5	0.5	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0.2	0.2	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From:	**Veg garden**			to:	**Veg garden**				(NA)
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From:	**Mixed garden**			to:	**Veg garden**			NBR	-5
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0	0	0	0	0	0	0	0
Mixed garden	-1	-0.5	-0.5	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From:	**Tegalan**			to:	**Veg garden**			NBR	-5
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	4	4	2	0	0	0	0	0	0	0
Mixed garden	0.5	0.5	0.5	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Continuation from the previous page.

Ecological concern

	Distance zone, *o*									
State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From:	**Primary forest**		to:	**Rainfed paddy**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From:	**Secondary forest**		to:	**Rainfed paddy**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From:	**Irrigated paddy**		to:	**Rainfed paddy**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From:	**Rainfed paddy**		to:	**Rainfed paddy**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From:	**Veg garden**		to:	**Rainfed paddy**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From:	**Mixed garden**		to:	**Rainfed paddy**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From:	**Dryland (*tegalan*)**		to:	**Rainfed paddy**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0.5	0.5	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

	Distance zone, *o*									
State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From:	**Primary forest**		to:	**Irrigated paddy**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From:	**Secondary forest**		to:	**Irrigated paddy**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From:	**Irrigated paddy**		to:	**Irrigated paddy**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From:	**Rainfed paddy**		to:	**Irrigated paddy**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From:	**Veg garden**		to:	**Irrigated paddy**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From:	**Mixed garden**		to:	**Irrigated paddy**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From:	**Dryland (*tegalan*)**		to:	**Irrigated paddy**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0.5	0.5	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Note: All forests are given a weighting factor of -4

(NA) Not applicable

NBR North Bandung region, and the corresponding weighting value

Continuation from the previous page.

Ecological concern

Distance zone, o

State, k	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From: **Primary forest**			to:	**Secondary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From: **Secondary forest**			to:	**Secondary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From: **Irrigated paddy**			to:	**Secondary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From: **Rainfed paddy**			to:	**Secondary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From: **Veg garden**			to:	**Secondary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From: **Mixed garden**			to:	**Secondary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From: **Dryland (tegalan)**			to:	**Secondary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Distance zone, o

State, k	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From: **Primary forest**			to:	**Primary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From: **Secondary forest**			to:	**Primary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From: **Irrigated paddy**			to:	**Primary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From: **Rainfed paddy**			to:	**Primary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From: **Veg garden**			to:	**Primary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From: **Mixed garden**			to:	**Primary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From: **Dryland (tegalan)**			to:	**Primary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Note: All forests are given a weighting factor of -4
(NA) Not applicable
NBR North Bandung region, and the corresponding weighting value

Pro-Industrialisation

Distance zone, *a*

State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From: **Primary forest**		to: **Urban**							
Primary forest	-0.1	-0.1	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0.5	0	0	0	0	0	0	0	0	0
II	From: **Secondary forest**		to: **Urban**							
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	6	6	3	3	3	1	1	1	1	0
III	From: **Irrigated paddy**		to: **Urban**							
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0.6	0.6	0.6	0.6	0	0	0	0	0	0
Urban	9	9	6	6	3	3	1.5	1.5	1.5	1.5 •
IV	From: **Rainfed paddy**		to: **Urban**							
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	1	1	0	0	0	0	0	0	0	0
Urban	9	9	6	6	3	3	1	1	1	1 •
V	From: **Veg Garden**		to: **Urban**							
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	3	2	1	1	1	0	0	0	0	0
VI	From: **Mixed garden**		to: **Urban**							
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	6	3	3	3	2	2	1	1	0	0
VII	From: **Dryland (*tegalan*)**		to: **Urban**							
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	6	6	6	2	2	2	1	1	1	0

Distance zone, *a*

State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From: **Primary forest**		to: ***Tegalan***							
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0.2	0.2	0	0	0	0	0	0	0	0
Rainfed paddy	0.2	0.2	0	0	0	0	0	0	0	0
Vegetable garden	0.8	0.8	0	0	0	0	0	0	0	0
Mixed garden	0.8	0.8	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0.8	0.8	0	0	0	0	0	0	0	0
Urban	0.25	0.25	0.25	0	0	0	0	0	0	0
II	From: **Secondary forest**		to: ***Tegalan***							
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	1.5	1.5	1.5	0	0	0	0	0	0	0
Rainfed paddy	1.5	1.5	1.5	0	0	0	0	0	0	0
Vegetable garden	5	5	5	0	0	0	0	0	0	0
Mixed garden	5	5	5	0	0	0	0	0	0	0
Tegalan (Dryland)	5	5	5	0	0	0	0	0	0	0
Urban	2	2	2	1.5	1.5	0	0	0	0	0
III	From: **Irrigated paddy**		to: ***Tegalan***							
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From: **Rainfed paddy**		to: ***Tegalan***							
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From: **Veg Garden**		to: ***Tegalan***							
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From: **Mixed garden**		to: ***Tegalan***							
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From: **Tegalan**		to: ***Tegalan***						**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Note: (NA) : Not applicable

Continuation from the previous page.

Pro-industrialisation

	Distance zone, *o*									
State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From:	**Primary forest**		to:	**Mixed garden**					
Primary forest	-0.1	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0	0	0	0	0	0	0	0
Mixed garden	0.5	0.5	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From:	**Secondary forest**		to:	**Mixed garden**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	2	2	0	0	0	0	0	0	0	0
Mixed garden	2	2	0	0	0	0	0	0	0	0
Tegalan (Dryland)	3	3	0	0	0	0	0	0	0	0
Urban	0	0	0.2	0.2	0.2	0.2	0	0	0	0
III	From:	**Irrigated paddy**		to:	**Mixed garden**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	-0.2	-0.2	-0.2	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0.2	0.2	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From:	**Rainfed paddy**		to:	**Mixed garden**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0.5	0	0	0	0	0	0	0
Mixed garden	0.5	0.5	0.5	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From:	**Veg Garden**		to:	**Mixed garden**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0.2	0.2	0.2	0.2	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From:	**Mixed garden**		to:	**Mixed garden**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From:	**Dryland (tegalan)**		to:	**Mixed garden**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0.5	0	0	0	0	0	0	0
Mixed garden	4	4	1	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

	Distance zone, *o*									
State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From:	**Primary forest**		to:	**Veg garden**					
Primary forest	-0.1	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0	0	0	0	0	0	0	0
Mixed garden	0.5	0.5	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From:	**Secondary forest**		to:	**Veg garden**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	5	5	0	0	0	0	0	0	0	0
Mixed garden	5	5	0	0	0	0	0	0	0	0
Tegalan (Dryland)	5	5	0.5	0.5	0.5	0.5	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From:	**Irrigated paddy**		to:	**Veg garden**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.4	0.4	0.4	0.3	0.2	0	0	0	0	0
Mixed garden	0.3	0.3	0.2	0.2	0	0	0	0	0	0
Tegalan (Dryland)	0.2	0.2	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From:	**Rainfed paddy**		to:	**Veg garden**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0	0	0	0	0	0	0	0
Mixed garden	0.5	0.5	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0.2	0.2	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From:	**Veg garden**		to:	**Veg garden**					**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From:	**Mixed garden**		to:	**Veg garden**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0	0	0	0	0	0	0	0
Mixed garden	-1	-0.5	-0.5	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From:	**Tegalan**		to:	**Veg garden**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	4	4	2	0	0	0	0	0	0	0
Mixed garden	0.5	0.5	0.5	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Note: (NA) : Not applicable

Continuation from the previous page.

Pro-industrialisation

	Distance zone, *a*									
State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From: **Primary forest**			to: **Rainfed paddy**						
Primary forest	-5	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0.2	0.2	0	0	0	0	0	0	0	0
Rainfed paddy	0.2	0.2	0	0	0	0	0	0	0	0
Vegetable garden	0.2	0.2	0	0	0	0	0	0	0	0
Mixed garden	0.2	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From: **Secondary forest**			to: **Rainfed paddy**						
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	5	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From: **Irrigated paddy**			to: **Rainfed paddy**						**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From: **Rainfed paddy**			to: **Rainfed paddy**						**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From: **Veg garden**			to: **Rainfed paddy**						**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From: **Mixed garden**			to: **Rainfed paddy**						**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From: **Dryland (*tegalan*)**			to: **Rainfed paddy**						
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0.5	0.5	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

	Distance zone, *a*									
State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From: **Primary forest**			to: **Irrigated paddy**						
Primary forest	-5	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0.5	0.5	0.5	0.5	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From: **Secondary forest**			to: **Irrigated paddy**						
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	2	0.5	0.5	0.5	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From: **Irrigated paddy**			to: **Irrigated paddy**						**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From: **Rainfed paddy**			to: **Irrigated paddy**						**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From: **Veg garden**			to: **Irrigated paddy**						**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From: **Mixed garden**			to: **Irrigated paddy**						**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From: **Dryland (*tegalan*)**			to: **Irrigated paddy**						
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0.2	0.2	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Note: (NA) : Not applicable

Continuation from the previous page.

Pro-industrialisation

Distance zone, *a*

State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From: **Primary forest**			to:	**Secondary forest**					
Primary forest	-0.5	-0.5	-0.5	-0.2	-0.2	0	0	0	0	0
Secondary forest	0.2	0.2	0.2	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0.2	0.2	0.2	0	0	0	0	0	0	0
Rainfed paddy	1	1	1	0	0	0	0	0	0	0
Vegetable garden	1	1	0.5	0.5	0.5	0.5	0	0	0	0
Mixed garden	1	1	0.5	0.5	0.5	0.5	0	0	0	0
Tegalan (Dryland)	1	1	0.5	0.5	0.5	0.5	0	0	0	0
Urban	0.5	0.5	0	0	0	0	0	0	0	0
II	From: **Secondary forest**			to:	**Secondary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From: **Irrigated paddy**			to:	**Secondary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From: **Rainfed paddy**			to:	**Secondary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From: **Veg garden**			to:	**Secondary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From: **Mixed garden**			to:	**Secondary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From: **Dryland (*tegalan*)**			to:	**Secondary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Distance zone, *a*

State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From: **Primary forest**			to:	**Primary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From: **Secondary forest**			to:	**Primary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From: **Irrigated paddy**			to:	**Primary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From: **Rainfed paddy**			to:	**Primary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From: **Veg garden**			to:	**Primary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From: **Mixed garden**			to:	**Primary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From: **Dryland (tegalan)**			to:	**Primary forest**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Note: (NA) : Not applicable

Pro-Agriculture

Distance zone, *a*

State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From: **Primary forest**			to:		**Urban**				
Primary forest	-0.3	-0.3	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0.1	0	0	0	0	0	0	0	0	0
II	From: **Secondary forest**			to:		**Urban**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	4	1.3	1.3	1.3	0.7	0.7	0.7	0.7	0.7	0
III	From: **Irrigated paddy**			to:		**Urban**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0.1	0.1	0	0	0	0	0	0	0	0
Urban	1	0.1	0.1	0	0	0	0	0	0	0
IV	From: **Rainfed paddy**			to:		**Urban**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	1	0.6	0.6	0.6	0	0	0	0	0	0
V	From: **Veg Garden**			to:		**Urban**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From: **Mixed garden**			to:		**Urban**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0.8	0.8	0.2	0.2	0.2	0	0	0	0	0
VII	From: **Dryland (*tegalan*)**			to:		**Urban**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	4	4	2	2	2	2	0	0	0	0

Distance zone, *a*

State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From: **Primary forest**			to:		***Tegalan***				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0.2	0.2	0	0	0	0	0	0	0	0
Rainfed paddy	0.2	0.2	0	0	0	0	0	0	0	0
Vegetable garden	0.8	0.8	0	0	0	0	0	0	0	0
Mixed garden	0.8	0.8	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0.8	0.8	0	0	0	0	0	0	0	0
Urban	0.25	0.25	0.25	0	0	0	0	0	0	0
II	From: **Secondary forest**			to:		***Tegalan***				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	1.5	1.5	1.5	0	0	0	0	0	0	0
Rainfed paddy	1.5	1.5	1.5	0	0	0	0	0	0	0
Vegetable garden	5	5	5	0	0	0	0	0	0	0
Mixed garden	5	5	5	0	0	0	0	0	0	0
Tegalan (Dryland)	5	5	5	0	0	0	0	0	0	0
Urban	2	2	2	1.5	1.5	0	0	0	0	0
III	From: **Irrigated paddy**			to:		***Tegalan***				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From: **Rainfed paddy**			to:		***Tegalan***				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From: **Veg Garden**			to:		***Tegalan***				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From: **Mixed garden**			to:		***Tegalan***				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From: **Tegalan**			to:		***Tegalan***				**(NA)**
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Note: (NA) : Not applicable

Continuation from the previous page.

Pro-agriculture

State, *k*	Distance zone, *o*									
	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From:	**Primary forest**			to:	**Mixed garden**				
Primary forest	-0.1	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0	0	0	0	0	0	0	0
Mixed garden	0.5	0.5	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From:	**Secondary forest**			to:	**Mixed garden**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	2	2	0	0	0	0	0	0	0	0
Mixed garden	2	2	0	0	0	0	0	0	0	0
Tegalan (Dryland)	3	3	0	0	0	0	0	0	0	0
Urban	0	0	0.2	0.2	0.2	0.2	0	0	0	0
III	From:	**Irrigated paddy**			to:	**Mixed garden**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	-0.2	-0.2	-0.2	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0.2	0.2	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From:	**Rainfed paddy**			to:	**Mixed garden**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0.5	0	0	0	0	0	0	0
Mixed garden	0.5	0.5	0.5	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From:	**Veg Garden**			to:	**Mixed garden**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0.2	0.2	0.2	0.2	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From:	**Mixed garden**			to:	**Mixed garden**				(NA)
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From:	**Dryland (tegalan)**			to:	**Mixed garden**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0.5	0	0	0	0	0	0	0
Mixed garden	4	4	1	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

State, *k*	Distance zone, *o*									
	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From:	**Primary forest**			to:	**Veg garden**				
Primary forest	-0.1	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0	0	0	0	0	0	0	0
Mixed garden	0.5	0.5	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From:	**Secondary forest**			to:	**Veg garden**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	5	5	0	0	0	0	0	0	0	0
Mixed garden	5	5	0	0	0	0	0	0	0	0
Tegalan (Dryland)	5	5	0.5	0.5	0.5	0.5	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From:	**Irrigated paddy**			to:	**Veg garden**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.4	0.4	0.4	0.3	0.2	0	0	0	0	0
Mixed garden	0.3	0.3	0.2	0.2	0	0	0	0	0	0
Tegalan (Dryland)	0.2	0.2	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From:	**Rainfed paddy**			to:	**Veg garden**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0	0	0	0	0	0	0	0
Mixed garden	0.5	0.5	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0.2	0.2	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From:	**Veg garden**			to:	**Veg garden**				(NA)
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From:	**Mixed garden**			to:	**Veg garden**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0.5	0.5	0	0	0	0	0	0	0	0
Mixed garden	-1	-0.5	-0.5	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From:	**Tegalan**			to:	**Veg garden**				
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	4	4	2	0	0	0	0	0	0	0
Mixed garden	0.5	0.5	0.5	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Note: (NA) : Not applicable

Continuation from the previous page.

Pro-agriculture

	Distance zone, *a*									
State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From: **Primary forest**			to:	**Rainfed paddy**					
Primary forest	-5	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0.2	0.2	0	0	0	0	0	0	0	0
Rainfed paddy	0.2	0.2	0	0	0	0	0	0	0	0
Vegetable garden	0.2	0.2	0	0	0	0	0	0	0	0
Mixed garden	0.2	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From: **Secondary forest**			to:	**Rainfed paddy**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	5	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From: **Irrigated paddy**			to:	**Rainfed paddy**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From: **Rainfed paddy**			to:	**Rainfed paddy**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From: **Veg garden**			to:	**Rainfed paddy**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From: **Mixed garden**			to:	**Rainfed paddy**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From: **Dryland (*tegalan*)**			to:	**Rainfed paddy**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0.5	0.5	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

	Distance zone, *a*									
State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
	Distance in meters (cell size = 100m)									
I	From: **Primary forest**			to:	**Irrigated paddy**					
Primary forest	0.5	0.5	0.5	0.5	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From: **Secondary forest**			to:	**Irrigated paddy**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	2	0.5	0.5	0.5	0.2	0.2	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From: **Irrigated paddy**			to:	**Irrigated paddy**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From: **Rainfed paddy**			to:	**Irrigated paddy**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From: **Veg garden**			to:	**Irrigated paddy**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From: **Mixed garden**			to:	**Irrigated paddy**				**(NA)**	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From: **Dryland (*tegalan*)**			to:	**Irrigated paddy**					
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	1	1	1	0.5	0.5	0.5	0.5	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Note: (NA) : Not applicable

Continuation from the previous page.

Pro-agriculture

Distance zone, *a*

Distance in meters (cell size = 100m)

State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
I	From:	**Primary forest**		to:	**Secondary forest**					
Primary forest	-0.5	-0.5	-0.5	-0.2	-0.2	0	0	0	0	0
Secondary forest	0.5	0.5	0.5	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0.2	0.2	0.2	0	0	0	0	0	0	0
Rainfed paddy	1	1	1	0	0	0	0	0	0	0
Vegetable garden	1	1	0.5	0.5	0.5	0.5	0	0	0	0
Mixed garden	1	1	0.5	0.5	0.5	0.5	0	0	0	0
Tegalan (Dryland)	1	1	0.5	0.5	0.5	0.5	0	0	0	0
Urban	0.5	0.5	0	0	0	0	0	0	0	0
II	From:	**Secondary forest**		to:	**Secondary forest**				(NA)	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From:	**Irrigated paddy**		to:	**Secondary forest**				(NA)	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From:	**Rainfed paddy**		to:	**Secondary forest**				(NA)	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From:	**Veg garden**		to:	**Secondary forest**				(NA)	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From:	**Mixed garden**		to:	**Secondary forest**				(NA)	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From:	**Dryland (*tegalan*)**		to:	**Secondary forest**				(NA)	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Distance zone, *d*

Distance in meters (cell size = 100m)

State, *k*	1	2	3	4	5	6	7	8	9	10
	100	141.4	200	223.6	282.8	300	316.2	360.6	400	412.3
I	From:	**Primary forest**		to:	**Primary forest**				(NA)	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
II	From:	**Secondary forest**		to:	**Primary forest**				(NA)	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
III	From:	**Irrigated paddy**		to:	**Primary forest**				(NA)	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
IV	From:	**Rainfed paddy**		to:	**Primary forest**				(NA)	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
V	From:	**Veg garden**		to:	**Primary forest**				(NA)	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VI	From:	**Mixed garden**		to:	**Primary forest**				(NA)	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0
VII	From:	**Dryland (tegalan)**		to:	**Primary forest**				(NA)	
Primary forest	0	0	0	0	0	0	0	0	0	0
Secondary forest	0	0	0	0	0	0	0	0	0	0
Reforested	0	0	0	0	0	0	0	0	0	0
Irrigated paddy	0	0	0	0	0	0	0	0	0	0
Rainfed paddy	0	0	0	0	0	0	0	0	0	0
Vegetable garden	0	0	0	0	0	0	0	0	0	0
Mixed garden	0	0	0	0	0	0	0	0	0	0
Tegalan (Dryland)	0	0	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0

Note: (NA) : Not applicable

CHAPTER 7

CLIMATE COMPONENT WITHIN THE FRAMEWORK OF AN INTEGRATED SYSTEM

7.1 INTRODUCTION

The climate component in this thesis is part of the proposed integrated model used to conduct a sensitivity analysis of river flow variability with respect to changes in land use and climate. This climate component is used to create climate scenarios. These, together with the land use scenarios (Chapter 6), will be used by the hydrological component as the inputs for calculating the streamflow.

Basic methods used to generate climate scenarios have been reviewed in Chapter 4. This chapter will focus on how to create climate change scenarios within the integrated system family of CLIMPACTS and its new variant created for this thesis, called INDOCLIM. The CLIMPACTS integrated system was selected for generating the climate change scenarios because of its flexibility enabling it to be easily adapted to any region in the world and to be designed for sensitivity studies of any climate change related issue (Warrick *et al.*, 1996; 2001; Kenny *et al.*, 1995; 1999a; 1996b). The discussion in this chapter includes the creation of baseline data, identification and selection of the underlying greenhouse gas (GHG) emission scenarios, and the general circulation model (GCM) patterns to be used, which will be accomplished through reviewing some regional climate change studies in relation to the study area.

7.2 CONCEPT OF THE CLIMPACTS FAMILY OF MODELS

CLIMPACTS is a computer-based integrated system that combines models and data sets for the purpose of undertaking climate change impact assessments for New Zealand. The original CLIMPACTS model was used to assess three sectors: natural vegetation (tree species), agriculture (grasslands and arable crops), and horticulture (kiwifruit). Many of its variants have been developed and used in parts of the world for a similar use, that is to conduct impact assessments of climate change focusing on selected sectors (Warrick, in press). BDCLIM, for example, was developed for Bangladesh with a focus on the water resources sector (Warrick *et al.*, 1996), and PACCLIM was developed for Pacific Island countries, and focuses on coastal resources, agriculture, water resources and health sectors (Kenny, 1999). These variants were reproduced with a similar concept and core code of the CLIMPACTS model. The key aspects of this family of model are simplicity and flexibility. The models can also be adapted quickly to follow developments in climate change science.

The conceptual structure of the CLIMPACTS family consists of several models and analytical tools, which can be divided into two main stages (Figure 7.1). The first stage is a **scenario generator** (above the dashed line in Figure 7.1) and the second stage consists of **sectoral models** (below the dashed line).

The scenario generator component comprises a global climate model which links with a regional climate change scenario generator. The regional climate change is derived by bringing together: all historical climate data (temperature and rainfall) for base-line construction; patterns of climate change from GCMs; and temperature and sea-level change patterns which are the output of the global climate model. They are then processed in the regional climate change scenario generator.

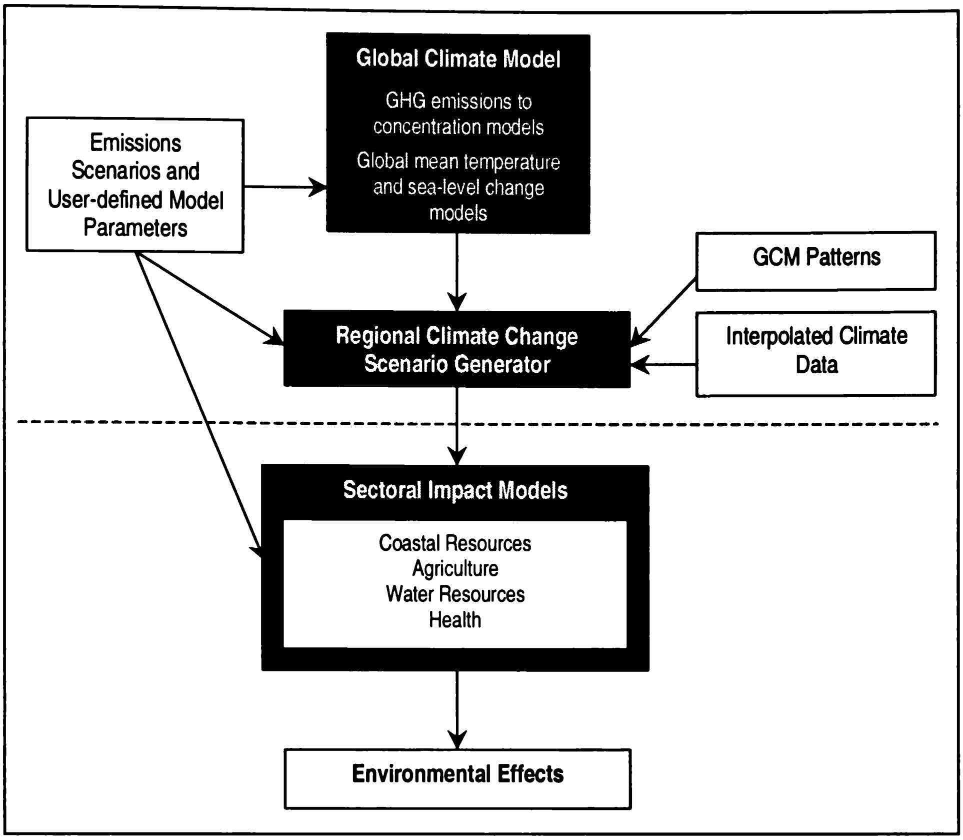

Figure 7.1: Schematic representation of the PACCLIM model system (a variant of CLIMPACTS) and its main components. (Source: Kenny *et al.*, 1999.)

The global climate model used in CLIMPACTS is MAGICC (Model for Assessment of Greenhouse gas Induced Climate Change). It is classified as a simple climate model (Harvey *et al.*, 1997) and can be used to generate time-dependent global temperature and sea-level change induced by the emission of GHGs (Wigley and Raper, 1992; Wigley *et al.*, 2000; Hulme *et al.*, 2000[7-1]).

The sectoral models are used to generate regional sectoral environmental effects from the selected scenarios. They use the outputs from the scenario generators as inputs in order to assess the sectoral impacts. The number of models in this

---

[7-1] MAGICC 2.4 is the latest version that has been developed with a similar concept to the earlier versions. This version was used in the IPCC Second Assessment Report to produce global mean-temperature projections (Kattenberg *et al.*, 1996) and sea-level projections (Warrick *et al.*, 1996).

section of the CLIMPACTS model depends on the number of impact assessments required.

The recent variants of CLIMPACTS use two key sets of GHG emissions scenarios; the IPCC IS92 policy scenarios (first published by Leggett *et al.*, 1992; and revised by Houghton *et al.*, 1995), and the SRES marker scenarios (A1, A2, B1, B2 story-line families) (IPCC, 2000). The global mean temperature change for the SRES marker scenarios is shown in Figure 7.2.

There are several options with regard to GCM patterns to be used. A selection of patterns to be used will be discussed in a later section, together with the base-line construction.

The prototype of the integrated model for this thesis (INDOCLIM) is produced based on the concept of this family model. The INDOCLIM generates climate data as required by the hydrological component, and simultaneously processes the impact of such changes through the hydrological component (water balance model) which is attached to this integrated system. Details of this integrated model are discussed in a later section.

The next section discusses the selection of GHG emission scenarios and GCM patterns for INDOCLIM, by reviewing some regional climate change studies in relation to the study area.

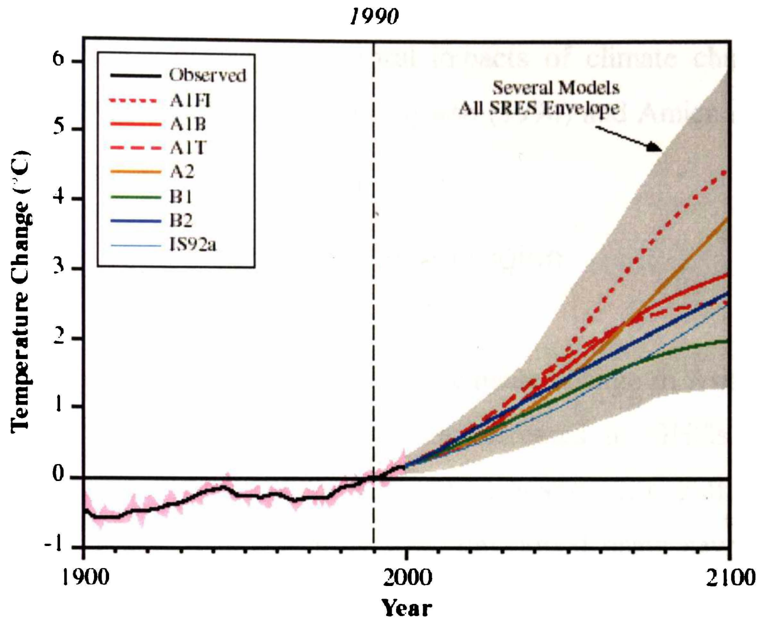

Figure 7.2: The range of projected global average temperature increase relative to 1990 as estimated by Working Group I of the IPCC for scenarios from the Special Report on Emissions Scenarios (SRES). The shaded envelope is the maximum to minimum range of global average temperature derived from several GCMs with all SRES (Source: McCarthy *et al.*, 2001.)

7.3 REGIONAL AND LOCAL CLIMATE CHANGE

Global warming causes changes in the climate that may vary in magnitude from place to place (IPCC-TGCIA, 1999; Kattenberg *et al.*, 1996). Published reports on future climate change in tropical regions are few in comparison to the mid-latitude regions, probably because the climate in the tropics is less subject to change than in the mid-latitude areas, or maybe because of the dominance of mid-latitude climate change impact studies, or maybe because of difficulties in dealing with specific problems in the tropics such as the deep tropical convection and tropical cyclones (Hulme and Viner, 1998). The most comprehensive report on future climate changes for the tropical region of Southeast Asia is perhaps the article in the Third Assessment Report (TAR) of the IPCC Working Group II (Lal *et al.*, 2001). Hulme and Viner (1998) presented one of the few reports on the climate change specifically in tropical areas. At a country level, Hulme and Sheard (1999) presented some details of climate change scenarios for the Indonesian region. Some earlier reports focusing on sectoral impacts of climate change for some parts of Indonesia were presented by Murdiyarso (1996) and Amien *et al.* (1996).

Southeast Asian region

Lal *et al.* (2001) reported scenarios of future climate change in Asia based on the radiative forcing inferred from likely future increases in GHGs and sulphate aerosols as prescribed under IS92a emission scenarios (Leggett *et al.*, 1992; Houghton *et al.*, 1995). The scenarios were developed using several AOGCMs (Coupled Atmospheric-Ocean General Circulation Models), which were selected after validation on the basis of pattern correlation coefficients and root mean square errors between the observed and model-simulated seasonal mean sea-level pressure, surface air temperature, and rainfall patterns over some Asian regions. (An example is given here for the Southeast Asian region [Figure 7.3], which shows that ECHAM4, HadCM2 and CCSR produced superior results to other models.) The IPCC report uses four models for the analysis of climate change in the Asian region, namely HadCM2 (Hadley Climate Centre, U.K.) (Mitchell *et al.*, 1999), ECHAM4 (German Climate Research Centre) (Rockener *et al.*, 1996), CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia) (Hirst *et al.*, 1999), and CCSR (Center for Climate System Research, Japan) (Emori *et al.*, 1995).

A summary of climate changes in the Asian region and its sub-regions is given in Table 7.1. The mean air temperature for the area is given at the top of the table, and precipitation at the bottom of the table. The shaded rows are the values for the Southeast Asian tropical region. The scenarios of changes in air temperature and precipitation were developed with a 1961-1990 baseline, with three future time periods of projection centred around the 2020s (2010-2029), the 2050s (2040-2069), and the 2080s (2070-2099).

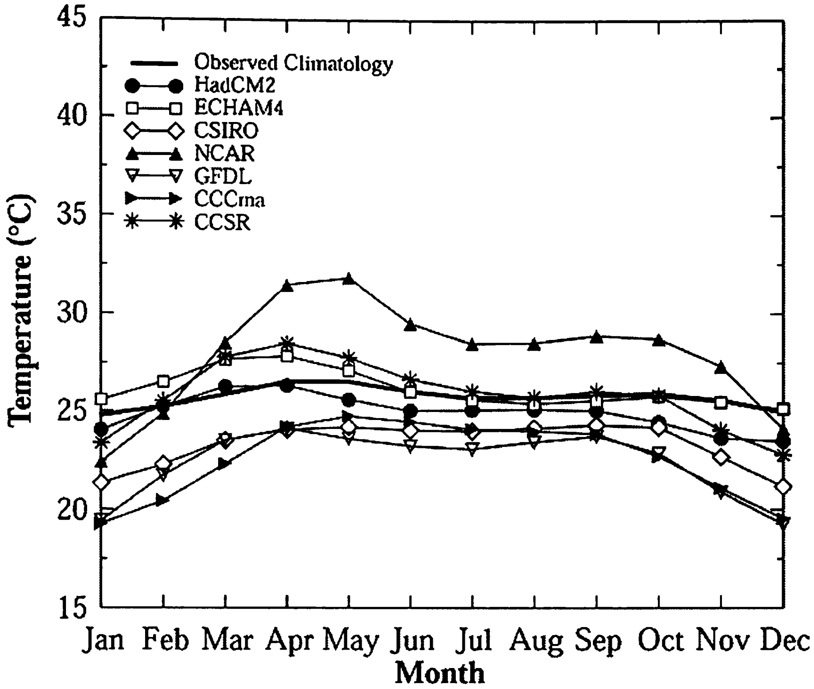

Figure 7.3: Validation of simulated and observed area-averaged annual cycle of surface air-temperature over Southeast Asia. (Source: Lal *et al.*, 2001.)

With an increase in atmospheric concentration of GHGs under the IS92a emission scenarios, the annual mean warming over the whole land region of Asia is projected to increase by 1.6°C in the 2020s, 3.1°C in the 2050s, and 4.6°C in the 2080s. A combined influence of GHGs and sulphate aerosols will limit the increase of surface warming to 1.4°C in the 2020s, 2.5°C in the 2050s, and 3.8°C in the 2080s. For the Southeast Asian sub-region, under an increased concentration of GHGs only, the annual mean warming is projected to increase by 1.05°C in the 2020s, 2.15°C in the 2050s, and 3.03°C in the 2080s. With a combination of GHGs and sulphate aerosols, the annual mean warming is restricted to 0.96°C in the 2020s, 1.72°C in the 2050s, and 2.49°C in the 2080s. As can be seen in Table 7.1, the seasonal variations over the land regions of Asia also change, with the warming in the winter being higher than the warming in summer. These different magnitudes of seasonal warming are also expected to occur in the Southeast Asia region, but with relatively lower magnitudes.

Table 7.1: Plausible changes in area-averaged surface air temperature (top) and precipitation (bottom) over Asia and its subregions as a result of future increases in greenhouse gases (under IS92a emission scenarios), as inferred from an ensemble of data generated in experiments with CCSR/NIES, CSIRO, ECHAM4, and HadCM2 AOGCMs. Numbers in parentheses are area-averaged changes when direct effects of sulphate aerosols are included. (Source: Lal *et al.*, 2001.)

	Temperature change (ºC)								
	2020s			2050s			2080s		
Regions	Annual	Winter	Summer	Annual	Winter	Summer	Annual	Winter	Summer
Asia	1.58	1.71	1.45	3.14	3.43	2.87	4.61	5.07	4.23
	(1.36)	(1.52)	(1.23)	(2.49)	(2.77)	(2.23)	(3.78)	(4.05)	(3.49)
Boreal	2.17	2.66	1.71	4.32	5.52	3.29	6.24	8.04	4.82
	(1.88)	(2.21)	(1.47)	(3.52)	(4.46)	(2.83)	(5.30)	(6.83)	(4.24)
Arid/Semi-arid									
- *Central Asia*	1.61	1.56	1.77	3.18	2.81	3.55	4.83	4.41	5.34
	(1.47)	(1.55)	(1.49)	(2.69)	(2.61)	(2.59)	(4.15)	(3.78)	(4.36)
- *Tibet*	1.77	1.90	1.62	3.38	3.55	3.19	5.04	5.39	4.69
	(1.56)	(1.83)	(1.40)	(2.62)	(2.94)	(2.27)	(4.06)	(4.32)	(3.73)
Temperate	1.49	1.74	1.23	2.86	3.26	2.48	4.34	5.11	3.67
	(1.19)	(1.50)	(0.99)	(2.10)	(2.40)	(1.72)	(3.31)	(3.83)	(2.77)
Tropical									
- *South Asia*	1.36	1.62	1.13	2.69	3.25	2.19	3.84	4.52	3.20
	(1.06)	(1.19)	(0.97)	(1.92)	(2.08)	(1.81)	(2.98)	(3.25)	(2.67)
- *SE Asia*	1.05	1.12	1.01	2.15	2.28	2.01	3.03	3.23	2.82
	(0.96)	(0.94)	(0.96)	(1.72)	(1.73)	(1.61)	(2.49)	(2.51)	(2.34)

	Precipitation change (%)								
	2020s			2050s			2080s		
Regions	Annual	Winter	Summer	Annual	Winter	Summer	Annual	Winter	Summer
Asia	3.6	5.6	2.4	7.1	10.9	4.1	11.3	18.0	5.5
	(2.3)	(4.3)	(1.8)	(2.9)	(6.5)	(1.5)	(7.0)	(12.1)	(3.5)
Boreal	6.1	11.1	2.6	12.8	23.8	5.1	20.7	39.5	7.7
	(6.7)	(10.7)	(3.3)	(12.0)	(19.7)	(7.1)	(18.9)	(31.5)	(10.3)
Arid/Semi-arid									
- *Central Asia*	1.3	3.0	-2.1	1.3	6.9	-2.3	-1.3	6.9	-4.0
	(1.1)	(2.7)	(5.9)	(0.6)	(1.4)	(0.7)	(-3.6)	(1.0)	(-1.8)
- *Tibet*	5.9	8.9	4.4	9.0	19.2	4.7	12.8	25.6	5.7
	(3.4)	(7.4)	(1.7)	(7.5)	(14.8)	(1.7)	(11.5)	(18.8)	(3.8)
Temperate	3.9	4.2	3.7	7.9	13.3	5.4	10.9	20.1	7.8
	(0.9)	(0.4)	(1.2)	(1.3)	(4.3)	(0.7)	(4.8)	(7.1)	(3.1)
Tropical									
- *South Asia*	2.9	2.7	2.5	6.8	-2.1	6.6	11.0	5.3	7.9
	(1.0)	(-10.1)	(2.8)	(-2.4)	(-14.8)	(0.1)	(-0.1)	(-11.2)	(2.5)
- *SE Asia*	2.4	1.4	2.1	4.6	3.5	3.4	8.5	7.3	6.1
	(1.7)	(3.3)	(1.2)	(1.0)	(2.9)	(2.6)	(5.1)	(5.9)	(4.9)

Precipitation is also expected to increase in most parts of Asia as the result of an increase of atmospheric concentration of GHGs (under the IS92a emission scenarios). The annual area-mean precipitation over the land regions of Asia is projected to increase by 3.6% in the 2020s, 7.1% in the 2050s, and 4.61% in the 2080s. When sulphate aerosols are combined with the GHGs, the increase is limited to 2.3% in the 2020s, 2.9% in 2050s and 7.0% in the 2080s. A similar case is encountered in Southeast Asia, where under the IS92a emission scenarios the precipitation is projected to increase by 2.4% in 2020s, 4.6% in the 2050s, and 8.5% in the 2080s. With the inclusion of sulphate aerosols, the increase is 1.7% in the 2020s, 1.0% in the 2050s, and 5.1% in the 2080s.

In summary, results from the four best AOGCM experiments (HadCM2, ECHAM4, CSIRO, and CCSR) suggest that with the prescribed emissions scenarios of GHGs (and sulphate aerosols), the climate of the Southeast Asian region will be warmer and wetter in all seasons than the current climate condition.

Country level: Indonesia

In general, the changes in Indonesia's climate show a similar trend to the changes in the Southeast Asian region. Hulme and Sheard (1999) generated climate change scenarios for Indonesia based on four SRES scenarios (B1, B2, A1 and A2). These four SRES scenarios represent GHG emissions ordered from low levels of emission to high levels.[7-2] Three different sensitivity values were chosen: 1.5°C (low), 2.5°C (medium), and 4.5°C (high). Future global warming was calculated by using a simple climate model created from a combination of the SRES scenarios and climate sensitivity (i.e. B1-low, B2-mid, A1-mid, and A2-high). The simulations of the climate response to the increased GHG concentrations for

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[7-2] The change in carbon emissions from energy/industrial sources in comparison to the year 2000 emissions (estimated) for the four scenarios ranges from a decrease of 4% (scenario B1 - the lowest) to an increase by 320% (scenario A2 - the highest). Atmospheric CO_2 concentrations increase for all scenarios from about 370 ppmv to 550 ppmv by 2100 (the lowest) and to over 830 ppmv (the highest).

Indonesia were performed by seven climate laboratories located in six different countries. The results described here are the median responses of the climate model simulations.

The air temperature in Indonesia will increase rather slowly in the future compared to the global average, with a rate in a range between about 0.1°C/decade for the B1-low scenario and 0.3°C/decade for the A2-high scenario compared to the global average, which is in a range between 0.1°C/decade for the B1-low and 0.4°C/decade for the A2-high.[7-3] This rate of warming is quite uniform throughout the year for the whole region, including Java.

The future annual average precipitation over the Indonesian region increases across the majority of Indonesia, except in the southern part including Java. During the high rainfall season (December to February), parts of Sumatra and Borneo become 10 - 30% wetter in the 2080s. However, the southern part of Indonesia (including Java and Bali) may become drier by about 5 - 15% (under B-1 low and A2 high scenarios respectively). During the June to August months (low rainfall season), the changes in precipitation are generally smaller. Negative changes (drier) may occur in the south, particularly in Java with a range of changes from 0% (B-1 low scenario) to about 15% drier in west and central Java (A-2 high scenario) and from 0% (B-1 low scenario) to 25% drier in east Java (A-2 high scenario).

A previous study by Hulme and Viner (1998) based on the IS92 emission scenarios and UKTR (U.K. Meteorological Office Model with Transient Response) experiment over the Indonesian region shows an increase in precipitation at the beginning of the rainy season (September to November), and a

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[7-3] The temperature data from 12 carefully selected climate stations in Indonesia show an increasing trend of temperature at a rate between 0.2 and 0.4°C/decade since 1970 (De Rozari, 1993). In 1998, the increase was almost 1°C higher than the average increase in the 1960-1990 period (Hulme and Sheard, 1999).

reduction towards the end of the season (December to February), while the March to August period shows little precipitation change.

Local level: West Java

The number of studies on the impacts of climate change which include climate change scenarios is very small. Some of them are by Murdiyarso (1996) and Amien *et al.*, (1996).

Murdiyarso applied scenarios generated by the relatively low spatial resolution GISS (Goddard Institute for Space Studies) model of the equilibrium response type GCM to study water resources in a large sized catchment in west Java. It was found that doubling atmospheric CO_2 concentration would increase the precipitation which causes a significant increase in the water surplus of 132%.

Another study at a local scale (west Java) used GCMs (GISS, GFDL, and UKMO) to simulate climate changes in order to assess the impact of such changes on rice yields. The three models indicated that a direct doubling of atmospheric CO_2 concentrations would increase minimum and maximum temperatures by 7.6 - 16.8°C and precipitation by 20.5 - 91.7%. The GISS transient climate scenarios show that the maximum and minimum temperatures increase respectively by 3.5% and 4.9% in 2010, 6.9% and 9.8% in 2030, and 11.1% and 15.75% in 2050. The precipitation increase for west Java varies from 7 - 8.7% in 2010.

The results of these local studies are different to the results of a study by Hulme and Sheard (1999). In particular, the local studies show scenarios of increasing precipitation in west Java, which is in contrast to decreasing precipitation as shown by Hulme and Sheard. This difference is very significant and may cause a high degree of uncertainty. The cause of the difference may be due to the resolution, where low resolution GCMs tend to average the climatic variation that may exhibit a higher resolution. In fact, a similar trend of increasing mean temperature and precipitation were shown by these two local studies and the area-mean climate change simulation at a regional scale. Another possible cause is simply scientific and model improvement (i.e. different GCMs produce different results).

Extreme events and variability (El Niño and Southern Oscillation)

As already discussed in Chapter 2 Section 2.6, the extreme events such as El Niño and La Niña have significant impacts in Indonesia. The El Niño causes severe drought in Indonesia while the other extreme, La Niña (the opposite of El Niño), causes unusually heavy rainfall.

This kind of inter-annual variation of extreme events can be examined from the climate record. Based on precipitation data recorded since early 1980s, it was found that Indonesia has been affected by severe drought (El Niño) in 1982/1983, 1986/1987 and 1997/1998 (Hulme and Sheard, 1999). When El Niño is followed by La Niña, a very high inter-annual variation may occur (Brookfield and Byron, 1993).

IPCC has recognised that extreme events in the Asian region (not only ENSO related events) have increased in intensity and frequency (Lal *et al.*, 2001). This is supported by Irawan (2002) who reported that, based on the Southern Oscillation Index (SOI) values during the 1876-2000 period, the frequency of El Niño tended to increase from once in every 8 years during the 1876-1976 period to once in every 4 years during 1977-2000. The El Niño events with the highest intensity were recorded in 1982 and 1997 with the annual average SOI values were -21.4 and -18.1 respectively.

Being able to model the changes in the variations of these extreme events is important for anticipating in advance the occurrence of these events. The mechanism of the El Niño phenomenon is commonly associated with the Southern Oscillation. However, the repeatability of this phenomenon is still unpredictable because what triggers the mechanism of this event is still not well understood (Cuny, 2001). It has been claimed that the inter-annual climate variations, such as El Niño, are possible to model using the complex AOGCMs (Harvey *et al.*, 1997; Tet, 1995) but for now little confidence has been gained from modelling (Hulme and Viner, 1998).

Therefore, the proposed integrated model does not include the interannual variation of the climate even though the variability of this interannual variation, in particular El Niño and La Niña, are important for adaptation planning. The model will only calculate average climatic values. In interpreting the results for adaptation planning, users will have to consider possible variability by assuming that the variability of climate will go along in parallel with the average values.

In summary, it is clear that various GCM experiments and GHG emission scenarios can result in a large variation in climate variables such as temperature and precipitation (see the summary on Table 7.2). Another important finding noted by Hulme and Sheard (1999) and Hulme and Viner (1998) is that the seasonal variations of precipitation also change. This may affect the seasonal streamflow variability. In particular for Java, the dry season has no or little change in terms of precipitation, and the rainy season becomes drier but with a possible precipitation increase at the beginning of the rainy season and a reduction at the end of the rainy season, i.e. shorter rainy season but with more intense precipitation and prolonged dryness in the dry season. For the inter-annual variability and extreme events, at present the modelling is still weak.

Table 7.2: Summary of regional and local climate change (impact) studies with respect to the study area, Bandung basin, west Java.

Area	**Reference**	**GCM experiments**	**GHG emission scenario**	**2xCO_2**	**Temperature increase 2080 (no SO_2 aerosol)***	**Precipitation increase 2080 (no SO_2 aerosol)***
SE Asia	Lal *et al.* (2001)	HadCM2 ECHAM4 CSIRO CCSR	IS92a		3.03°C	7.0%
Indonesia	Hulme and Sheard (1999)	Median response from 7 Climate Laboratories in 6 different countries	SRES (B1, B2, A1 and A2)	Climate sensitivity: 2.5°C (1.5 ~ 4.5)	0.8°C (B1) ~ 2.4°C (A2)	**DJF:** Sumatra/Borneo: +10 ~ 30% (B1-A2) Java/Bali: -5~-15% (B1-A2) **JJA:** generally little change over the region, west/central Java: 0~-15% (B1-A2) east Java: 0~-25% (B1-A2)
	Hulme and Viner (1998)	UKTR	IS92			**SON:** increase **DJF**: decrease **MAM JJA:** little change
West Java	Murdiyarso (1996)	GISS		Precipitation: +132%		
	Amien *et al.* (1996)	GISS GFDL UKMO		Temperature: +7.6°C ~ 16.8°C Precipitation: +20.5% ~ 91.7%		
		GISS transient			Year 2010: 3.5% ~ 4.9%	Year 2010: 7% ~ 8.7%

* With SRES scenarios, the SO_2 gas emission is included and therefore it may result in lower temperature increase than the IS92 scenarios.
DJF = December, January, February; **MAM** = March, April, May; **JJA** = June, July, August; **SON** = September, October, November.
Blank cell means no information.

7.4 DEVELOPMENT OF INDOCLIM

This section discusses in some detail the development of a new variant of the CLIMPACTS family for the purpose of integrating the climate scenarios, land use scenarios and the hydrology component into one system in order to produce streamflows as the output. This new variant is called INDOCLIM. Its concept is similar to other variants of the CLIMPACTS family. In addition, because INDOCLIM is developed for the study area of this thesis, there is a need to understand how the baseline is constructed behind this model, and how the GHG emission scenarios and GCM patterns are selected.

Concept of INDOCLIM: Integrating land use, climate and hydrological components

One of the main advantage of the CLIMPACTS family models is the flexibility to add (and remove) sectoral impact models as an integrated model within this system. This allows the variants of this family to be designed according to the user's wish. Hence, the outputs are sectoral, depending on the models that are attached to this system.

INDOCLIM is a prototype model, which is developed for the purpose of this thesis, that is for the assessment of seasonal streamflow variability under the influence of land use pattern change and climate change. It is a member of CLIMPACTS family, and therefore the structure of this model does not differ greatly from the CLIMPACTS model and its other variants.[7-4] The differences are only in the sectoral model section, where two components are added. One

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[7-4] The INDOCLIM structure is not discussed further in this section, because of a similarity between its structure and the CLIMPACTS (or PACCLIM in Figure 7.1). Refer to section 7.2 for discussion of the CLIMPACTS family.

component is a water balance model, and the other one is a library of land use change patterns (Figure 7.4). The water balance model is added into the system in order to compute the total monthly runoff directly. This water balance model has been designed separately (see Chapter 5). The land use scenario component is also added into the system in order to be able to find out the impacts of both land use change and climate change on the streamflows. This land use scenario component is in a form of a library file containing several sets of land use scenarios that have also been constructed separately (see Chapter 6). Therefore, by bringing together the land use scenario component and the water balance model into INDOCLIM, a complete integrated model is produced.

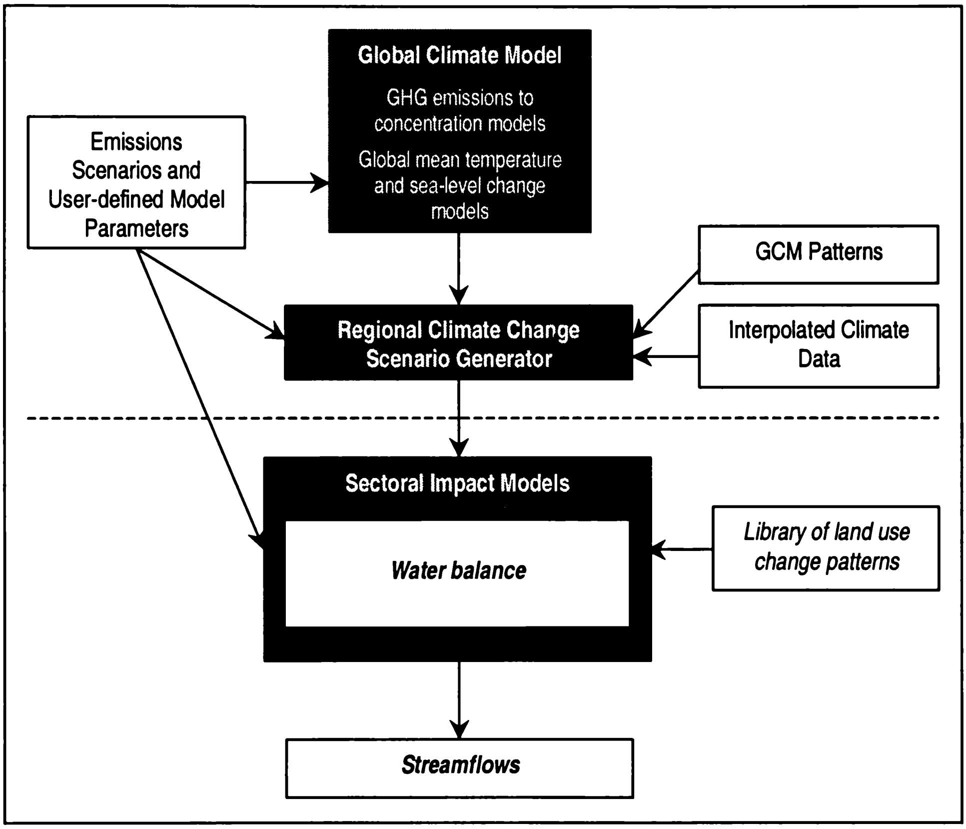

Figure 7.4: Schematic representation of INDOCLIM (a variant of CLIMPACTS) and its main components.

Baseline construction

Several types of climate data are required for the base line. These are a set of data that are to be projected from this model. They consist of **long-term monthly mean data** that are distributed over the basin on grid cells of 1 km^2 in size. For this study, the data consist of the average daily temperature (T_{avr}) and precipitation (P).

The climate time series data are the average monthly data from a long-term record, preferably a 30-year record (e.g. Kenny *et al.*, 1995; Hulme *et al.*, 2000). However, due to the limited availability of data, only 10 continuous years (1985 - 1994) of data records are used. The precipitation data come from 22 rain stations all over the Bandung basin area. These data are interpolated by using a GIS tool with an inverse distance method.[7-5] The remaining climate data come from one station only.[7-6] The later ones are good quality data from the Meteorological and Geophysical Office in Bandung (see Chapter 3 for the availability of data). The temperature data are interpolated over the whole basin area based on a temperature gradient relationship, of which a 100m increase in the elevation causes a 0.6°C drop in temperature. All the data are interpolated into grid squares of 1x1 km that cover the whole basin.

[7-5] Several methods of interpolation are available in the ILWIS 3.0 GIS package (ITC, 2001). Among them are the Thiessen Polygon method, inverse distance method, linear decrease method, and moving surface method. The Thiessen Polygon method is unfavourable because the rain stations are not evenly distributed over the basin. The inverse distance method creates a bull's eye pattern around the source points. The linear distance method eliminates this kind of pattern and tends to average the input data. Thus, the linear method eliminates local variations. In many cases, local variations are important, especially when conducting a sensitivity study with a specific time/period and locally distributed parameters. Probably, the best method is the moving surface method, in which the bull's eye patterns are reduced and local varitions are preserved. However, this method requires more densely and evenly distributed data source points.

[7-6] There are two climate stations in the Bandung region from where the climate data can be obtained. One station has continuous and high quality records of data (BMG Bandung). The other one (Ciparay) produces climate records with a significant proportion of blank records (see Chapter 3 for more detail).

GHG emissions scenarios and GCM experiments

The GHG emission scenarios provide a tool to explore how human activity may change the composition of the atmospheric gases. In the end, it will be reflected in the climate change scenarios. The emission scenarios are normally selected from predefined emission scenarios, and the selection of these scenarios will determine the radiative forcing of the climate change (i.e. different emission scenarios will result in a different amount of global warming).

There are sets of emissions scenarios that have been accepted by IPCC: the SRES (Special Report on Emissions Scenarios) (IPCC, 2000) and IS92 (1992 IPCC Scenarios) (Leggett *et al.*, 1992; and revised by Houghton *et al.*, 1995). A comparison of these two sets of scenarios and their environmental consequences is given in Table 7.3. Both sets are available as options in the CLIMPACTS family of models. However, for reasons of simplicity and practicality, this prototype model limits the selection of scenarios to the recent SRES only. Climate sensitivity may also be set from low (1.5°C) to high (4.5°C) and, therefore, can increase the range of exploration further. In this case, Table 7.3 can be used as a rough guide for selecting the scenarios. (See also Figure 7.2 as a graphic illustration of temperature range resulting from SRES.)

The choice of GCMs pattern is also quite wide. In general, the transient response AOGCMs with 'warm' start at present are considered as the most advanced model that can represent physical processes of climate change. Therefore, old GCMs with equilibrium response should not be used. (Now, the IPCC Data Distribution Centre provides data from the transient response AOGCM experiments only. These are available on-line http://ipcc-ddc.cru/uea.ac.uk/crudata/examine/emissions/emissions.html.)

Table 7.3: Summary of comparison between the IS92 scenarios (top) and SRES scenarios (bottom) together with their estimated environmental consequences. Model calculations are by the IPCC SAR version of MAGICC (Wigley and Raper, 1992; Version 2.3, May 1997). Changes are with respect to the 1961-1990 average. Aerosol effects are included. (Source: IPCC-TGCIA, 1999.)

Scenario estimates	1990	IS92 scenarios for 2100					
		IS92a	IS92b	IS92c	IS92d	IS92e	IS92f
Population (billion)	5.252	11.3	11.3	6.4	6.4	11.3	17.6
Economic growth rate (annual GNP; % per year)	-	2.3	2.3	1.2	2	3	2.3
CO_2 concentration (ppmv)[a]	354	708	685	471	542	954	820
Global annual-mean temperature change (°C)[b]	-	2.18	2.13	1.47	1.75	2.64	2.52
Range (°C)[c]	-	1.50-3.14	1.46-3.06	1.29-2.18	1.18-2.56	1.83-3.73	1.74-3.59
Global mean sea-level rise (cm)[b]	-	51	50	40	45	57	56
Range (cm)[c]	-	20-90	20-89	14-76	16-82	24-98	23-96

Scenario estimates	1990	SRES marker scenarios for 2100			
		A1	A2	B1	B2
Population (billion)	5.252	7.1	15.1	7.2	10.4
Economic growth rate (annual GNP; % per year)	-				
CO_2 concentration (ppmv)[a]	354	680	834	547	601
Global annual-mean temperature change (°C)[b]	-	2.52	3.09	2.04	2.16
Range (°C)[c]	-	1.70-3.66	2.12-4.41	1.37-2.99	1.45-3.14
Global mean sea-level rise (cm)[b]	-	58	62	50	52
Range (cm)[c]	-	23-101	27-107	19-90	20-93

[a] best-guess assumptions re. C cycle; [b] assuming 2.5°C climate sensitivity; [c] based on 1.5°C and 4.5°C climate sensitivity range.

As has been discussed in section 7.3 (see also Figure 7.3), some GCMs can show better correlation with the observed data than the other models. Notably, for the Southeast Asian region the experiments using HadCM2, ECHAM4, CSIRO and CCSR are better than the others. This should not limit the use of other GCM patterns, particularly for conducting sensitivity analysis. However, for reasons of simplicity and practicality, this integrated prototype model will use only those four GCM patterns.

Scaling method: calculating change in climate variable using GCM patterns

The pattern of change in a climate variable for some distant future time on a specific grid point on earth, $\Delta X_{,i}$(t), can be calculated by taking the corresponding climate variable generated by a GCM corresponding to a global mean-warming of ΔT_c ($\Delta X_{c,i}$) and scaling it by $\Delta T(t)/\Delta T_c$ (Wigley *et al.*, 2000; Hulme *et al.*, 2000). The climate variable can be, for example, temperature, precipitation, or sun radiation. This scaling method assumes that the patterns of future climate change remain quite similar regardless of the overall global-mean climate change (Wigley *et al.*, 2000). Mathematically, it can be expressed as (Wigley *et al.*, 2000):

$$\Delta X_i(t) = \Delta X_{c,i} \cdot \frac{\Delta T(t)}{\Delta T_c} \qquad \text{(Eq. 7-1)}$$

where:

$\Delta X_i(t)$ is the pattern of change in a climate variable X as a function of position (grid point i) and time (t);

$\Delta X_{c,i}$ is the change in a climate variable X at a grid point i corresponding to a global mean temperature change obtained from a GCM;

$\Delta T(t)$ is the global mean temperature change at future time t produced as output from a global climate model (e.g. MAGICC)[7-7];

ΔT_c is the global mean temperature change obtained from a GCM.

The grid resolution in this scaling method corresponds to the output resolution of the GCM patterns, usually at 5°x5° in latitude and longitude.

The ratio of the change of climate pattern at a grid point i per 1°C increase in global temperature, i.e. $\Delta X_{c,i}/\Delta T_c$, is known as a normalised pattern. This normalised pattern simplifies the calculation of the climate variable change in

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[7-7] MAGICC uses 1961-1990 as the baseline period.

response to global warming, by multiplying the corresponding normalised pattern with the change in global-mean temperature.

Each GCM has its own normalised pattern. The normalised patterns of precipitation and mean temperature from four GCMs for the study area are listed in Table 7.4. These are for a grid cell between 5° - 10° southern latitude and 105° to 110° eastern longitude, obtained from climate scenario generator SCENGEN (Hulme *et al.*, 2000). (The location of Bandung basin is about 6°43' - 7°04' southern latitude, and 107°15' and 107°55' eastern longitude.)

All of the models show a future increase in the mean temperature, but a variation in changes in precipitation (Table 7.4, see also Figure 7.5). The largest increase in temperature is generated by HadCM2, with significant monthly variation from 0.8 - 1.2°C/°C_{global} while the smallest increase is by CCSR-NIES. A future increase in annual precipitation is shown by CSIRO-TR and CCSR-NIES with the largest increase of 9% by CCSR-NIES in October. A future decrease in annual precipitation is shown by HadCM2 and ECHAM4, with the largest decrease of 22% by HadCM2 in August.

Using GCM results for the hydrological component

The climate variables from the GCM results, as required by the hydrological component, need to be downscaled to a basin scale in order to conduct a streamflow sensitivity analysis. In fact, these climate variables need to be distributed over the basin area for the cell-by-cell water balance calculation.

The integrated model of this study uses a simple method to downscale the GCM patterns, which has been used in SCENGEN (Hulme *et al.*, 2000).[7-8] This method

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[7-8] The methods to downscale the GCM results have been discussed in Chapter 4.

Table 7.4: Normalised patterns of changes in mean temperature (ΔT_{mean}) and precipitation (ΔP) in the grid area between latitudes of 5-10°S and longitudes of 105-110°E containing Bandung basin, for 1°C increase in the global-mean temperature. The values were obtained by using MAGICC/SCENGEN version 2.4 (Hulme, 2000). Baseline is the 1961-1990 period.

	ΔT_{mean} (ºC/ºC$_{global}$)					ΔP (%/ºC$_{global}$)				
	HadCM2	**CSIRO-TR**	**CCSR-NIES**	**ECHAM4**	**Average***	**HadCM2**	**CSIRO-TR**	**CCSR-NIES**	**ECHAM4**	**Average***
January	1.1	0.8	0.9	0.8	0.9	-4.0	-0.7	7.1	-2.2	0.1
February	1.1	0.8	0.9	0.9	0.9	-1.7	0.9	0.2	-3.0	-0.9
March	1.2	0.8	0.9	0.9	0.9	-2.7	3.9	0.3	-3.2	-0.4
April	1.1	0.8	0.8	0.9	0.9	-3.3	4.8	-1.7	-1.3	-0.4
May	1.0	0.8	0.8	0.9	0.9	6.1	5.4	-1.2	-6.6	0.9
June	1.0	0.8	0.8	0.9	0.9	-0.5	4.4	2.2	-5.9	0.0
July	0.9	0.8	0.7	0.9	0.8	-9.6	0.8	-2.8	-11.1	-5.7
August	0.8	0.8	0.7	0.9	0.8	-22.0	5.0	-1.5	-14.5	-8.3
September	0.9	0.8	0.8	0.9	0.8	-18.8	8.0	3.6	-8.1	-3.8
October	1.0	0.8	0.8	0.9	0.9	-11.1	5.2	9.1	-17.6	-3.6
November	1.1	0.8	0.8	0.9	0.9	-8.5	-2.9	-0.9	-7.9	-5.1
December	1.1	0.8	0.9	0.9	0.9	-6.2	-0.1	-0.5	4.4	-0.6
ANNUAL	**1.0**	**0.8**	**0.8**	**0.9**	**0.9**	**-6.9**	**2.9**	**1.2**	**-6.4**	**-2.3**

* Average value is from the four GCMs used here.

of downscaling requires an interpolation of the GCM results to a finer scale grid size of 0.5° in latitude and longitude. The interpolated data are then combined with the observed data in order to obtain the change in the climate data at a basin scale. These climate data are distributed for every cell in the basin area.

Two climate variables from the climate scenarios are required by the hydrological component as the inputs for conducting the sensitivity analysis on streamflows. Precipitation is required as the input for the water balance model. The mean temperature is used to calculate PET (potential evapotranspiration).

The PET is calculated using the Penman method that requires many types of climate data. There is only one climate station that supplies reliable data for a long period of observation. Of all of the data required for calculating the PET, temperature is the only variable that can be projected for the whole basin area

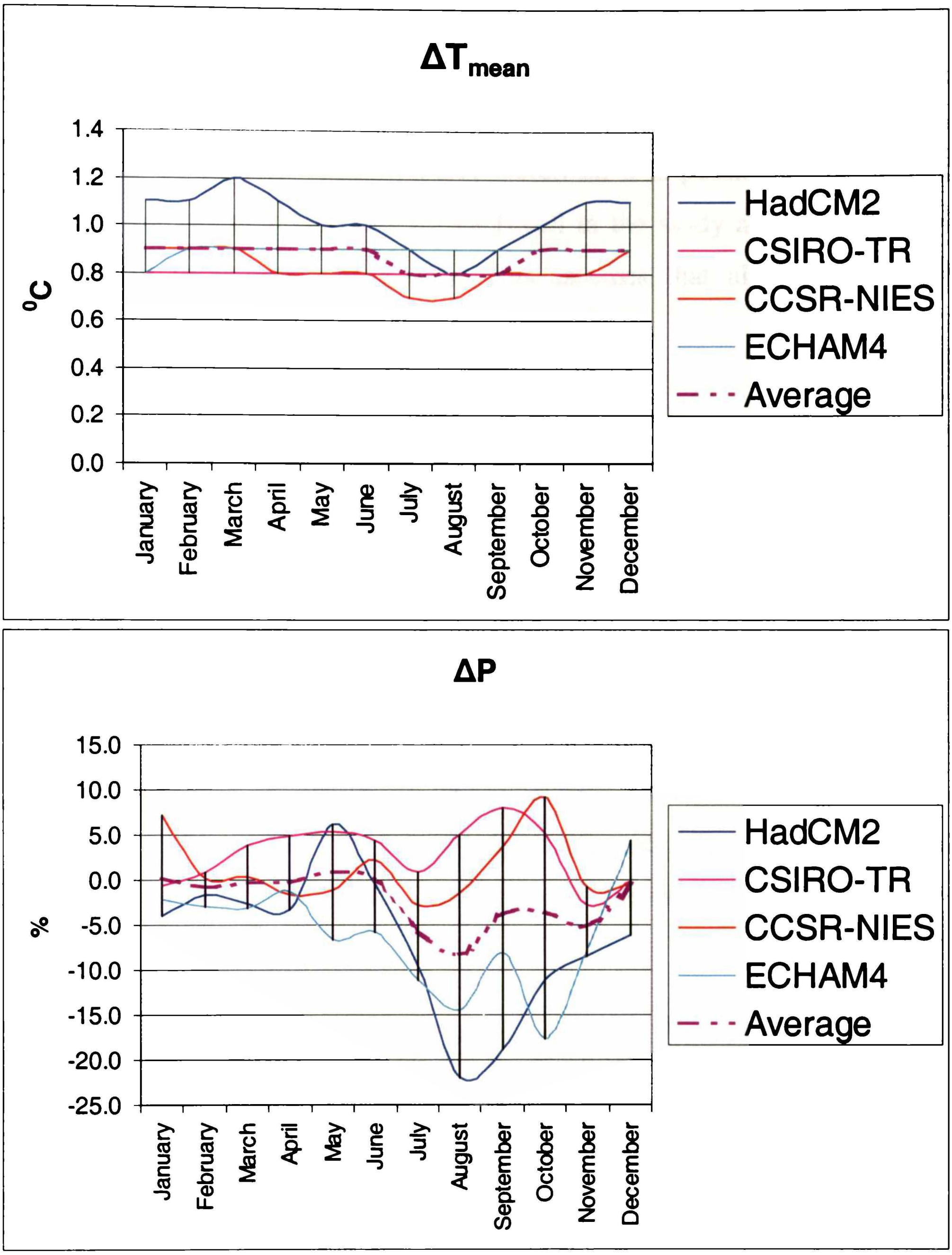


Figure 7.5: Monthly variation of normalised patterns from various GCM patterns; change in temperature (top), and change in precipitation (bottom).

based on the defined temperature gradient. Other variables; sunshine hours, relative humidity, and wind speed do not show any strong functional relationship with the elevation (Chapter 5 Section 5.5). Therefore, the monthly PET calculation for each cell relies on the temperature change only (assuming other variables have uniform values for each month).

In calculating the average monthly PET, therefore, it is possible to calculate the PET on an average monthly basis for each cell in the study area as a functional relationship of mean-temperature only. This assumes that all climate variables will use the same monthly values.

7.4 CONCLUSION

- INDOCLIM is based on the structures of the CLIMPACTS family of models. It makes use of the flexible structure of CLIMPACTS, in particular the sectoral-impact models section, where a previously developed water balance model is added. A library of land use patterns from a range of policy scenarios is connected into the system so that users can select the land use change patterns for analysis. The output of the model is a hydrograph of monthly streamflows.

- INDOCLIM contains four emission scenarios (SRES) and four GCM patterns. Users can choose any combination of these emission scenarios and GCM patterns, together with the land use scenarios, in order to perform sensitivity analysis. This enables exploration of the sensitivity of the impacts from a wide range of possibilities.

REFERENCES

Amien, I., Rejekiningrum, P., Pramudia, A. and Susanti, E. 1996. Effects of inter-annual climate variability and climate change on rice yield in Java, Indonesia. *Water, Air and Soil Pollution* 92, 29-39.

Brookfield, H. and Byron, Y. (eds.) 1993. Editorial comment to Chapter 7: ENSO, drought and flooding rain in south-east Asia. In: H. Brookfield and Y. Byron (eds.), *South-East Asia's Environmental Future - the Search for Sustainability,* United Nations University Press - Oxford University Press, Kuala Lumpur, 178.

Cuny, J.F. 2001. El Nino, a possible trigger mechanism. *Journal of Theoretics*, Commentary, 3 (5). [online] available URL http://www.journaloftheoretics.com/Articles/3-5/commentary3-5.htm, [8 April 2003]

Emori, S. Nozawa, T., Abe-Ouchi, A., Numugati, A., Kimoto, M. and Nakajima, T. 1999. Coupled ocen-atmosphere model experiments of future climate changes with an explicit representation of sulfate aerosol scattering. *Journal of Meteorological Society Japan* 77, 1299-1307.Harvey, D., Gregory, J., Hoffert, M., Jain, A., Lal, M., Leemans, R., Raper, S., Wigley, T. and de Wolde, J. 1997. *An Introduction to Simple Climate Models used in the IPCC Second Assessment Report.* IPCC Technical Paper II, IPCC, 51pp.

Harvey, D., Gregory, J., Hoffert, M., Jain, A., Lal, M., Leemans, R., Raper, S., Wigley, T. and de Wolde, J. 1997. *An Introduction to Simple Climate Models used in the IPCC Second Assessment Report.* IPCC Technical Paper II, IPCC, 51pp.

Hirst, A.C., Gordon, H.B. and O'Farrell, S.P. 1996. Global warming in a coupled climate model including oceanic eddy-induced advection. *Geophysical Research Letters* 23, 3361-3364.

Houghton, J.T., Meira-Filho, L.G., Bruce, J., Lee, H., Callander, B.A., Haites, E., Harris, N., and Maskell, K. (eds.) 1995. *Climate Change 1994: Radiative Forcing of Climate Change and An Evaluaion of the IPCC IS92 Emission Scenarios.* Cambridge University Press, Cambridge, U.K.

Hulme, M. and Sheard, N. 1999. *Climate Change Scenarios for Indonesia.* Climatic Research Unit, Norwich, U.K. 6pp.

Hulme, M. and Viner, D. 1998. A climate change scenario for the tropics. *Climatic Change* 39, 145-176.

Hulme, M., Wigley, T., Barrow, E., Raper, S., Centella, A., Smith, S. and Chipanshi, A. 2000. *Using a Climate Scenario Generator for*

Vulnerability and Adaptation Assessments: MAGICC and SCENGEN Version 2.4 Workbook, Climatic Research Unit, Norwich, U.K. 52pp.

IPCC 2000. *Emissions Scenarios.* A Special Report of Working Group III of the IPPC, Cambridge University Press, Cambridge, U.K.

IPCC-TGCIA 1999. *Guidelines on the Use of Scenario Data for Climate Impact And Adaptation Assessment.* Version 1. Prepared by T.R. Carter, M. Hulme and M. Lal, Intergovernmental Panel on Climate Change, Task Group on Scenarios for Climate Impact Assessment, 69pp.

Irawan, B. 2000. *Stabilization of Upland Agriculture under El Nino Indiced Climate Risk: Im Assessment and Mitigation Measures in Indonesia.* CGPRT Centre Working Paper No. 62, 78pp.

Kattenberg, A., Giorgi, F., Grassl, H., Meehl, G.A., Mitchell, J.F.B., Stouffer, R.J., Tokioka, T., Weaver, A.J., Wigley, T.M.L. 1996. Climate model - Projections of future climate. In: J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskel (eds.) *Climate Change 1995 - The Science of Climate Change.* Cambridge University Press, Cambridge, U.K.

Kenny, G., Warrick, R., Ye, W. and De Wet, N. 1999a. *VANDACLIM: the island version - Description and Users Guide.* International Global Change Institute (IGCI), University of Waikato, New Zealand.

Kenny, G., Ye, W., Warrick, R. and De Wet, N. 1999b. *The PACCLIM Scenario Generator Description and Users Guide.* Prepared for PICCAP, International Global Change Institute (IGCI), University of Waikato, New Zealand.

Kenny, G.J., Warrick, R.A., Mitchell, N.D., Mullan, A.B. and Salinger, M.J. 1995. CLIMPACTS: an integrated model for assessment of the effects of climate change on the New Zealand environment. *Journal of Biogeography* 22, 883-895.

Lal, M., Harasawa, H., and Murdiyarso, D. 2001. Asia. In: J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken and K.S. White (eds.) *Climate Change 2001: Impacts, Adaptation, and Vulnerability.* Contribution of Working Group II to the Third Assessment Report of the IPCC, Cambridge University Press, Cambridge, U.K.

Leggett, J., Pepper, W.J. and Swart, R.J. 1992. Emissions scenarios for the IPCC: an update. In: J.T. Houghton, B.A. Callander and S.K. Varney (eds.) *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment.* Cambridge University Press, Cambridge, U.K.

Mitchell, J.F.B., Johns, T.C., Eagles, M., Ingram, W.J., and Davis, R.A. 1999. Towarsa the construction of climate change scenarios. *Climatic Change* 41, 547-581

Murdiyarso, D. 1996. Climate change impacts on water resource management. Paper presented in: Workshop on Living with Global Change – Linking Science and Policy in Southeast Asia, Bogor, Indonesia, 13-15 August 1996. Sponsored by START and IC-SEA.

Rockener, E., Arpe, K., Bengtsson, L., Christoph, M., Clussen, M., Dumenil, L., Esch, M., Giorgetta, M., Schlese, U. and Schulzweida, U. 1996. The atmospheric general circulation model ECHAM-4: Model description and simulation of present-day climate. *Max-Planck Institute for Meteorology.* Report No. 218, Hamburg, Germany, 90pp.

Tet, S. 1995. Simulation of El Niño/Southern Oscillation like variability in a global AOGCM and its response to CO_2 increase. *Journal of Climate* 8, 1473-1502.

Warrick, R.A. 2002. The CLIMPACTS model and its derivatives: Tools for assessing the effects of climate variability and change at national to local scales. In: G. Knight and J. Jager (eds.) *Issues in Integrated Regional Assessment* (in Press).

Warrick, R.A., Kenny, G.J. and Harman, J.J. (eds.) 2001. *The Effects of Climate Change and Variation in New Zealand, An Assessment Using the CLIMPACTS System.* International Global Change Institute, University of Waikato, Hamilton, New Zealand.

Warrick, R.A., Kenny, G.J., Sims, G.C., Ericksen, N.J., Ahmad, A.K. and Mirza, M.Q. 1996. Integrated model systems for national assessments of the effects of climate change: applications in New Zealand and Bangladesh. *Water, Air, and Soil Pollution* 92, 215-227.

Wigley, T.M.L. and Raper, S.C.B. 1992. Implications for climate and sea level of revised IPCC emissions scenarios. *Nature* 357, 293-300.

Wigley, T.M.L., Raper, S.C.B., Hulme, M. and Smith, S. 2000. *The MAGICC/SCENGEN Climate Scenario Generator: Version 2.4, Technical Manual.* Climatic Research Unit, UEA, Norwich, UK, 48pp.

CHAPTER 8

IMPLEMENTATION OF THE INTEGRATED MODEL: IMPACT ASSESSMENTS OF VARIOUS LAND USE AND CLIMATE CHANGE SCENARIOS ON RIVER FLOWS

8.1 INTRODUCTION

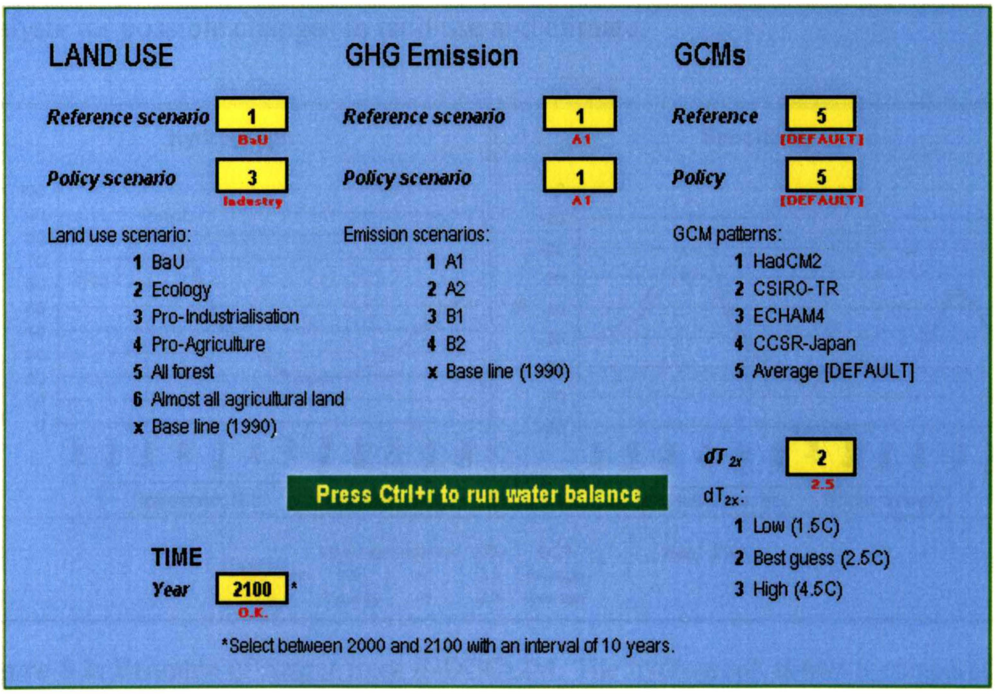
The prototype of an integrated model has been created by integrating the land use, climate and hydrological components in one system called INDOCLIM (Chapter 7). The model has the specific purpose of conducting sensitivity analysis on river flows with respect to changes in land use patterns and climate, and combinations thereof.

This chapter describes results of the implementation of this integrated model in the study area. It gives a detailed assessment of the effects of these two components on the flows of the Citarum River, which is the only river system in the study area. It is conducted by assessing the effect of various land use change scenarios alone on the river flows with the climate component turned off, another assessment by assessing the effect of the climate change alone with the land use component turned off, and by assessing the effect of various combinations of land use change scenarios and climate change scenarios. This chapter also makes an evaluation of the integrated model based on its use in the preliminary assessment.

8.2 PARAMETER SELECTION

The integrated model is designed to be user-friendly. It is created as a decision support tool for land use planners and decision makers to examine possible changes in land use and how these changes would affect the river flows. Users with limited knowledge of hydrology can use this model.

The model provides users with selections of pre-determined parameters as shown in Figure 8.1. The selections include: policy-related land use scenarios; changes in global temperature based on GHG emission scenarios; and downscaled GCM patterns. Additional parameters are the climate sensitivity (ΔT_{2x}) and the year of projection. The land use patterns consist of four time series scenarios (business-as-usual, ecological concern, pro-industrialisation and pro-agriculture), two non-time series patterns (all forested land and almost all agricultural land), and a baseline which is the land use pattern in 1990. The projections of global climate



LAND USE

Reference scenario: 1 (BaU)

Policy scenario: 3 (Industry)

Land use scenario:
- 1 BaU
- 2 Ecology
- 3 Pro-Industrialisation
- 4 Pro-Agriculture
- 5 All forest
- 6 Almost all agricultural land
- x Base line (1990)

GHG Emission

Reference scenario: 1 (A1)

Policy scenario: 1 (A1)

Emission scenarios:
- 1 A1
- 2 A2
- 3 B1
- 4 B2
- x Base line (1990)

GCMs

Reference: 5 ([DEFAULT])

Policy: 5 ([DEFAULT])

GCM patterns:
- 1 HadCM2
- 2 CSIRO-TR
- 3 ECHAM4
- 4 CCSR-Japan
- 5 Average [DEFAULT]

dT_{2x}: 2 (2.5)

dT_{2x}:
- 1 Low (1.5C)
- 2 Best guess (2.5C)
- 3 High (4.5C)

TIME

Year: 2100* (O.K.)

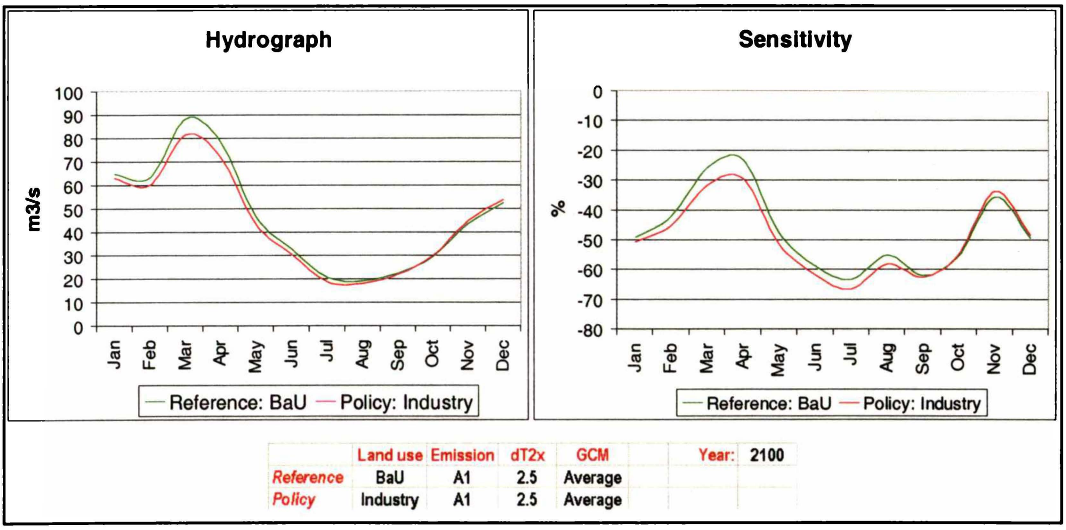
*Select between 2000 and 2100 with an interval of 10 years.

Figure 8.1: Example of the menu page of INDOCLIM (Excel version).

changes consist of the four IPCC SRES emission scenarios (A1, A2, B1 and B2) (IPCC, 2000) and a baseline (no change). The selections of GCM patterns consist of HadCM2 (Mitchell *et al.*, 1999), CSIRO-TR (Hirst *et al.*, 1999), ECHAM4 (Rockener *et al.*, 1996), CCSR-NIES Japan (Emori *et al.*, 1995), and the average of the previous four GCM patterns.

The range of parameter selections as given above allows many combinations of parameters to be analysed. Two combinations of selections can be analysed at the same time. Therefore, the results of two different scenarios can be compared immediately. The effects of land use change or climate change can be switched off by selecting their respective baselines. Therefore, it allows an analysis based on the selections for land use change or climate change only, or a combination of both land use change and climate change.

An example of the output is shown in Figure 8.2. It shows comparative results in terms of the actual discharge and percentage of monthly changes with respect to the baseline. These two charts provide quick visual representations of sensitivity analysis for possible changes in land use and climate.



	Land use	Emission	dT2x	GCM		Year:	2100
Reference	BaU	A1	2.5	Average			
Policy	Industry	A1	2.5	Average			

Figure 8.2: Example of output from INDOCLIM. The hydrograph shows a comparative change between the reference scenario and the policy scenario. The sensitivity chart shows percentages of monthly changes relative to the baseline. The table under the charts shows selected parameters used in this example.

8.3 VARIABILITY OF RIVER FLOWS UNDER VARIOUS LAND USE AND CLIMATE CHANGE SCENARIOS

Impacts of land use change scenarios on river flows

The effects of various land use patterns on the river flows can be analysed by switching off the climate component. The analysis can be done in time-series with respect to the selected policy scenarios. In addition, non-time series extreme cases and a baseline are used for a more comprehensive analysis.

Change in annual discharge under various land use change scenarios

The four policy-related land use change scenarios result in various effects on river flows (Figure 8.3). In general, the pro-agriculture scenario produces higher annual discharge than the other land use scenarios. The effect of this scenario is greater with time, i.e. when more land is converted. The ecological concern and pro-industrialisation scenarios show a decrease in the annual discharge whereas the business-as-usual policy shows a small change in the annual discharge.

Table 8.1 summarises the effects of these various land use scenarios on the annual yields, which is also presented graphically in Figure 8.4. Extreme cases can cause a considerable decrease of 44.7% in the river flows relative to the current baseline if the whole area is forested, and an increase of 36.2% if deforested (all forest is converted to agricultural land). The land use change scenarios with a time-series between 2000 and 2100 suggest a non-linear variability of changes. The highest discharge is obtained under the pro-agriculture scenario which shows an increase of 15% in the mid-century (2050) and nearly 18% in 2100 relative to the current

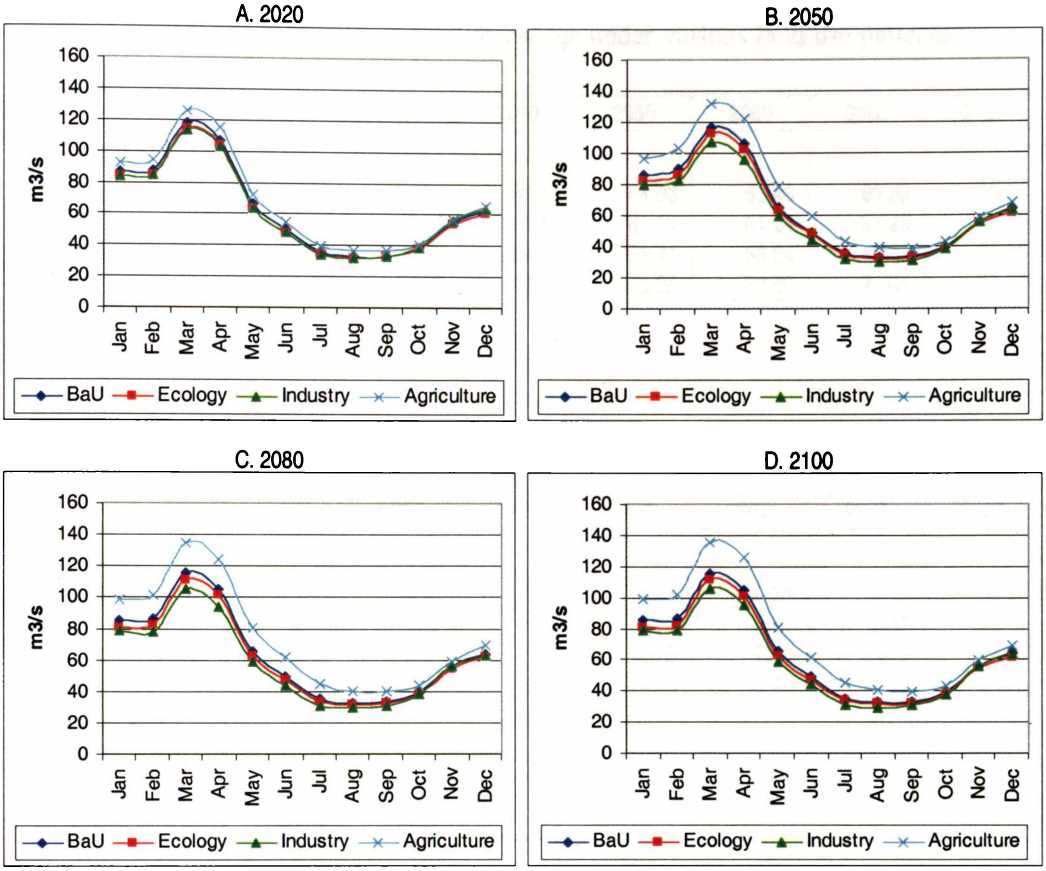


Figure 8.3: Effects of various land use change scenarios on the river flows. The climate component is switched off.

baseline. The lowest discharge is obtained under the pro-industrialisation scenario which shows a decrease of 6.8% in 2050 and about 8% in 2080 and 2100.

Effects of land use change on seasonal variability of river flows

Seasonal variability is also affected by the land use patterns. This can be easily examined by looking at the relative changes in monthly discharge from various land use scenarios relative to the baseline (Figure 8.5). The pro-agriculture scenario produces an increase of seasonal variability in the discharge with the highest increase in July and lowest increases in March and November. The pro-industrialisation scenario produces a large seasonal variation in the discharge,

Table 8.1: Changes in average annual discharge under various land use patterns.

A. Annual discharge (m^3/s)

	2000	2020	2040	2050	2060	2080	2100
Time series							
Business-as-usual	63.51	64.03	63.78	64.03	63.49	63.85	63.66
Ecology	63.10	62.14	61.58	61.91	61.24	61.25	61.09
Pro-Industrialisation	64.00	62.40	59.91	59.41	58.64	58.63	58.91
Pro-agriculture	64.42	68.93	72.10	73.28	73.60	74.61	75.03
Non-time series							
Baseline	63.73						
Forestation	35.23						
Deforestation	86.78						

B. Percentage of change relative to the current baseline (%)

	2000	2020	2040	2050	2060	2080	2100
Time series							
Business-as-usual	-0.35	0.47	0.08	0.47	-0.38	0.19	-0.11
Ecology	-0.99	-2.49	-3.37	-2.86	-3.91	-3.89	-0.14
Pro-Industrialisation	0.42	-2.09	-5.99	-6.78	-7.99	-8.00	-7.56
Pro-agriculture	0.49	8.16	13.13	14.99	15.48	17.07	17.73
Non-time series							
Baseline	-						
Forestation	-44.72						
Deforestation	36.17						

with a large decrease in January to September in comparison with the other scenarios and an increase in November and December. Figure 8.5 also shows that the lowest low flow is produced under the pro-industrialisation scenario whereas the highest low flow is under the pro-agriculture scenario.

Extreme cases can demonstrate the effect of land use change on the river flows more clearly. If the whole basin is forested, the discharge is significantly reduced (Figure 8.6). The monthly discharge is reduced within a range of 24% in November and 62% in July. The opposite result is produced if the basin is deforested, i.e. forest is converted to agricultural land and the urban area is unchanged with respect to the baseline. The discharge reaches the highest increase of 54% in July and the lowest increase of 24% in November.

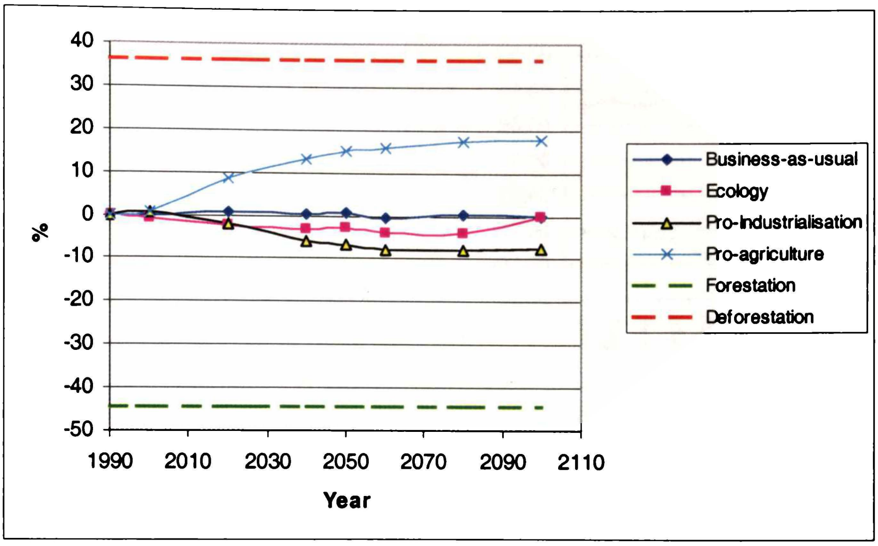


Figure 8.4: Percentage of changes in annual discharge relative the baseline as the result of changes in land use patterns. The climate component is switched off.

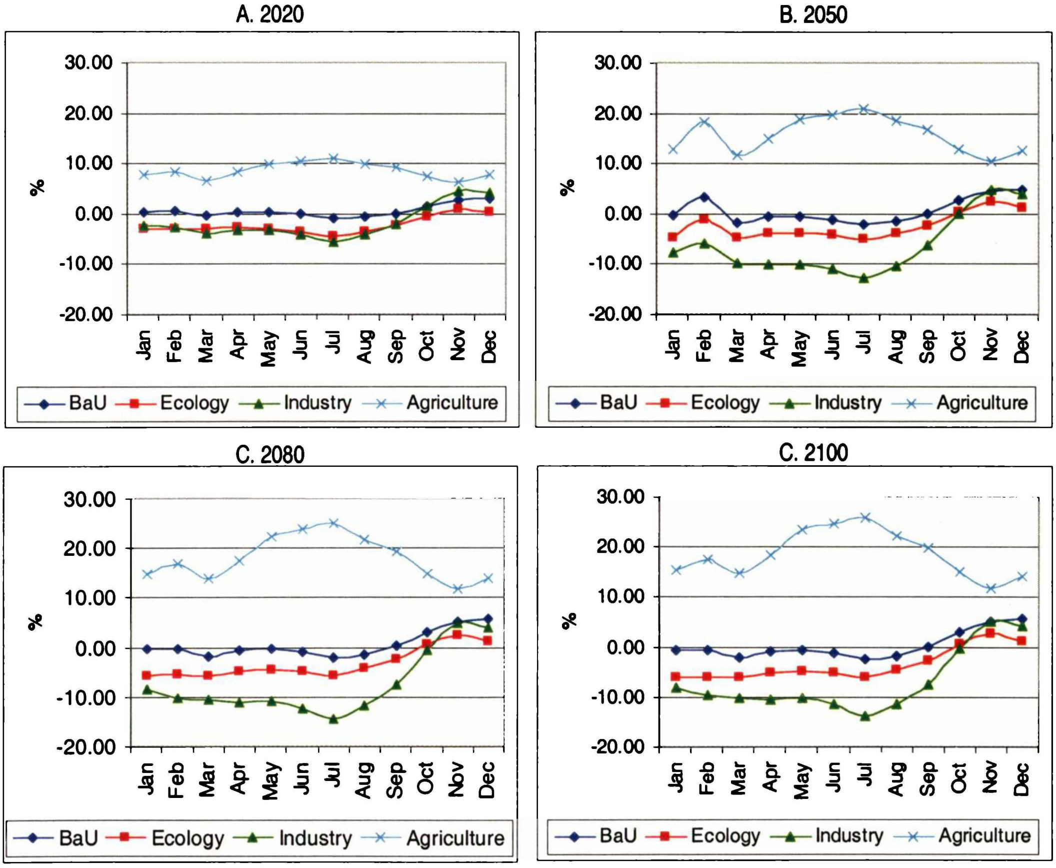


Figure 8.5: Percentage changes in monthly discharges relative to the baseline under various land use scenarios. The climate component is switched off.

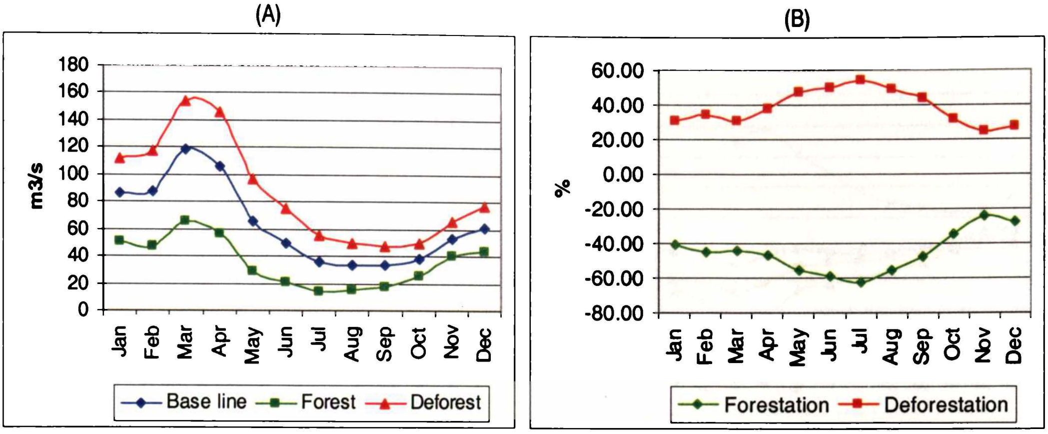


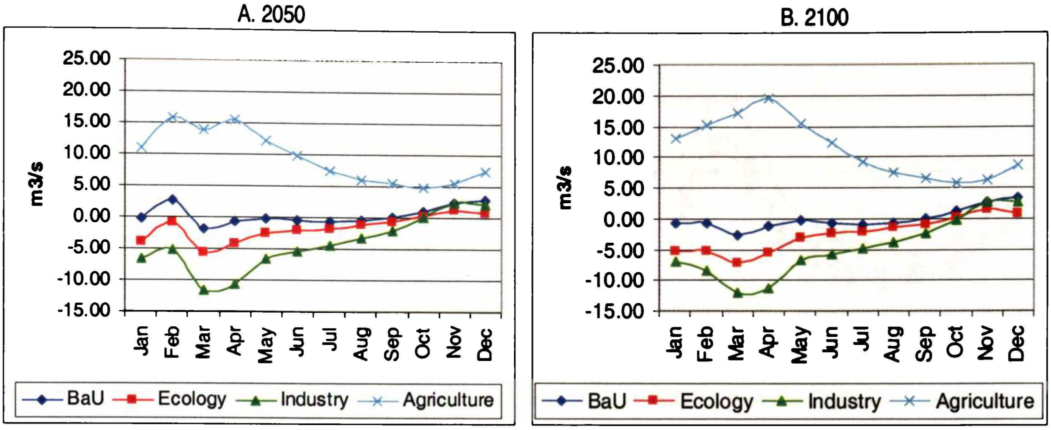
Figure 8.6: Changes in monthly discharge under extreme land use patterns for all forest and deforestation (a), and percentage of changes relative to the baseline (b). The climate component is switched off.

The actual change in the quantity of the monthly discharge may provide useful information for understanding the implications of the changes (Figure 8.7). It shows, for example, how much the actual change in the high flow may increase the risk of floods. It also can show how much the water may decrease during the dry season which could affect water supplies.

Variability of river flows under climate change

INDOCLIM allows a simulation of climate change under various conditions. It requires a selection of emission scenarios and GCM pattern combinations such as shown in Figure 8.1. Therefore, there are many possible combinations that can be derived from this wide selection of emission scenarios and GCM patterns.

The impacts of various IPCC SRES emission scenarios (A1, A2, B1 and B2) on the river flows are assessed in order to reveal the possible changes resulted from these emission scenarios. The assessment is conducted using the model with the climate sensitivity set to the best guess (2.5°C) and the GCM pattern to average. These various emission scenarios result in a decrease in the annual runoff for 2050 in a range between 11.5% and 26% relative the baseline. The variation in the

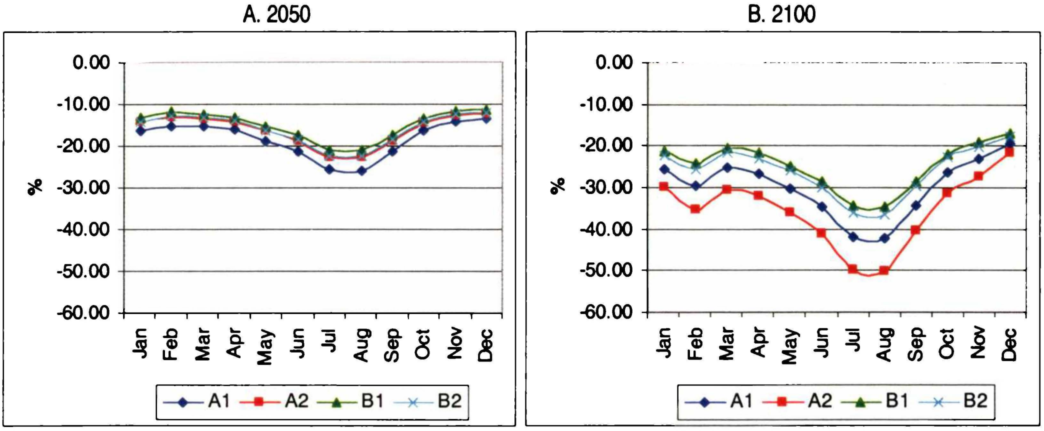

A. 2050

B. 2100

Figure 8.7: Change in the actual monthly discharge (in m^3/s) under various land use scenarios. The climate component is switched off.

monthly discharge between these various emission scenarios ranges from 2.2% to 4.8% in 2050. In 2100, this variation becomes wider with a range between 4.6% and 15.5% (Figure 8.8).

A variation in climate sensitivity also results in a variation in the monthly discharge (Figure 8.9). The percentage of changes for monthly discharge in 2050 relative to the baseline for the lowest climate sensitivity (1.5°C) to the highest (4.5°C) differs by 6.8 to 15.3% if the land use component is switched off, the emission scenario is set to A2 and GCM to the average. With time, the difference


A. 2050

B. 2100

Figure 8.8: Effects of various emission scenarios on the percentage changes of monthly discharge relative to the baseline for 2050 (a), and 2100 (b). The land use scenario is switched off, GCM is set to the average, and $\Delta T_{2x} = 2.5°C$.

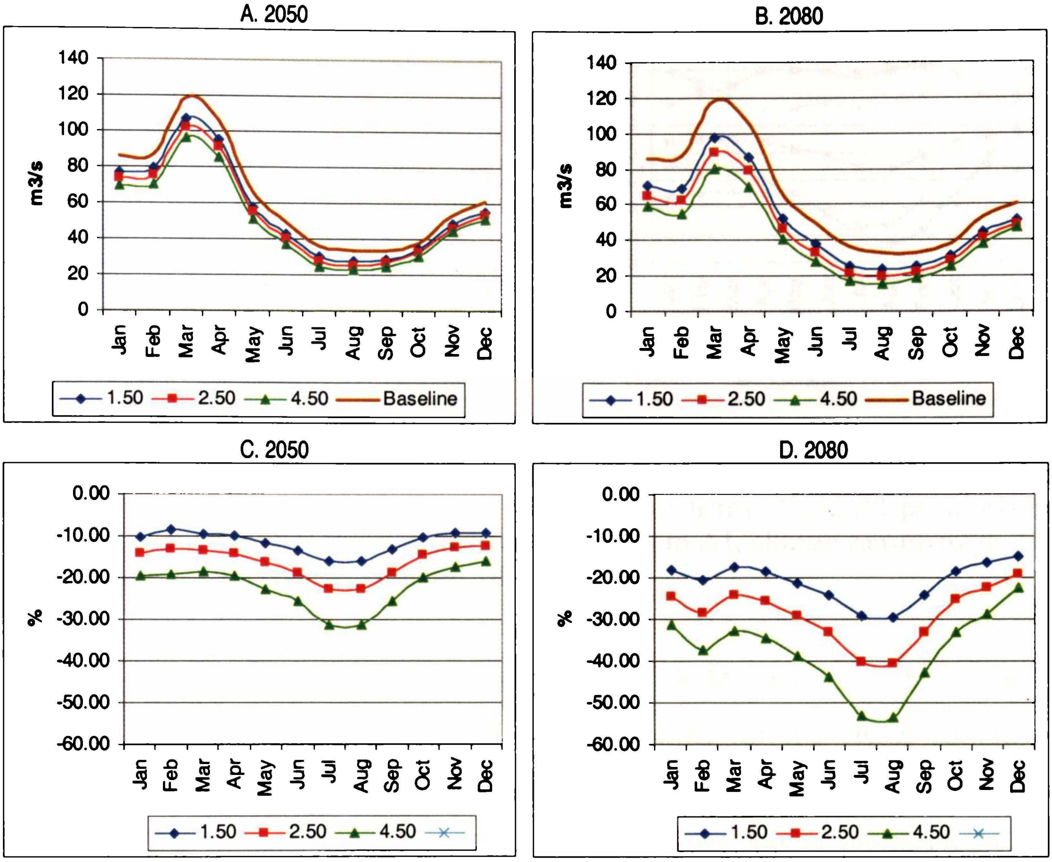


Figure 8.9: The effect of variation in climate sensitivity on the monthly discharge for 2050 (a) and 2080 (b), and the corresponding percentages of change relative to the baseline (c) and (d) respectively. The GHG emission scenario is set to A2, GCM is set to the average, and the land use scenario is switched off.

in the percentage of changes also increases, i.e. the range of uncertainty from this variation in climate sensitivity becomes wider. This range of differences depends on the GCM pattern used and the selected emission scenario. In other words, if a different emission scenario or GCM pattern is used, the percentage change in the monthly discharge may be different. In general, the results show that the magnitude of changes in the monthly discharge is magnified with an increase in the climate sensitivity (GCM is set to the average.)

The future climate variables are determined by the selection of GCM patterns (see Table 7.2 in Chapter 7). Therefore, under different GCM patterns, the output of the model may also be different. This is shown in Figure 8.10 where variation in

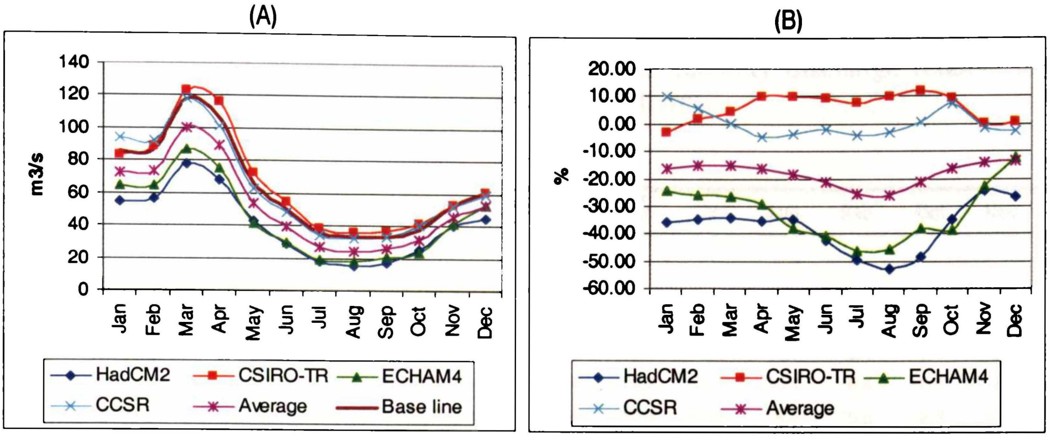


Figure 8.10: Variation in the monthly discharge as the result of variation in GCM patterns for 2050 (a), and the percentage of changes relative to the baseline (b). The CSIRO-TR produces the largest increase (September) whereas HadCM2 produces the largest decrease (August). The emission scenario is set to A1, climate sensitivity to 2.5, and the land use component is switched off.

monthly discharge is produced under various GCM patterns. The monthly discharge shows an increase relative to the baseline for the GCM pattern of CSIRO-TR from March to October and a decrease in January, whereas the remainder are virtually unchanged. An opposite condition is produced by the CCSR-NIES pattern which shows an increase in the discharge for January, February and October, and a decrease from March to August. Other GCMs (HadCM2 and ECHAM4) show a decrease in the monthly discharge with time, with the largest decrease produced by the HadCM2 in August. The average of the four GCM patterns used in this model also shows a decrease in monthly discharge with the largest decrease being in August.

Table 8.2 shows monthly discharge variations resulting from land use scenarios with the climate component switched off (upper part), and from climate change scenarios under various GCM patterns with the land use component switched off (lower part). In general, the climate change has larger impacts on the runoff than the land use change. The land use change causes monthly variation in the monthly discharge with a range of –12.92% to 20.6% in 2050 and –14.46% to 24.76% in 2080 whereas the climate change can cause monthly variation with a range of –53.15% to 11.73% in 2050, and –71.47% to 18.19% in 2080.

Table 8.2: Summary of the percentage of changes in monthly discharge relative to the baseline under various land use scenarios and GCM patterns.

A. 2050

	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Land use change													
Business-as-usual	0.5	-0.4	3.2	-1.7	-0.7	-0.5	-1.2	-2.2	-1.5	0.0	2.5	4.3	4.8
Ecology	-2.9	-4.7	-1.2	-4.9	-4.0	-4.0	-4.3	-5.2	-4.0	-2.4	0.4	2.2	1.1
Pro-Industry	-6.8	-7.7	-6.1	-9.9	-10.1	-10.1	-11.2	-12.9	-10.4	-6.4	-0.1	4.7	3.7
Pro-Agriculture	15.0	12.7	18.2	11.7	14.7	18.5	19.6	20.6	18.4	16.6	12.8	10.4	12.3
Max	**15.0**	**12.7**	**18.2**	**11.7**	**14.7**	**18.5**	**19.6**	**20.6**	**18.4**	**16.6**	**12.8**	**10.4**	**12.3**
Min	**-6.8**	**-7.7**	**-6.1**	**-9.9**	**-10.1**	**-10.1**	**-11.2**	**-12.9**	**-10.4**	**-6.4**	**-0.1**	**2.2**	**1.1**
GCM pattern													
HadCM2	-36.4	-36.2	-34.9	-34.5	-35.7	-35.1	-42.5	-49.8	-53.2	-48.7	-34.9	-24.7	-27.0
CSIRO-TR	5.0	-3.5	1.8	4.2	9.6	9.9	8.9	7.7	9.4	11.7	9.3	-0.2	0.3
ECHAM4	-30.2	-24.8	-26.4	-27.0	-29.4	-38.1	-40.8	-46.4	-45.8	-38.4	-38.8	-22.9	-12.7
CCSR	0.2	9.5	5.3	0.1	-4.9	-4.2	-2.4	-4.4	-3.5	0.3	7.0	-1.8	-2.6
Average	-17.3	-16.3	-15.5	-15.3	-16.2	-18.8	-21.4	-25.8	-26.0	-21.4	-16.6	-14.4	-13.7
Max	**5.0**	**9.5**	**5.3**	**4.2**	**9.6**	**9.9**	**8.9**	**7.7**	**9.4**	**11.7**	**9.3**	**-0.2**	**0.3**
Min	**-36.4**	**-36.2**	**-34.9**	**-34.5**	**-35.7**	**-38.1**	**-42.5**	**-49.8**	**-53.2**	**-48.7**	**-38.8**	**-24.7**	**-27.0**

B. 2080

	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Land use change													
Business-as-usual	0.2	-0.4	-0.4	-1.8	-0.7	-0.3	-1.0	-2.2	-1.6	0.1	2.9	5.0	5.5
Ecology	-3.9	-5.9	-5.6	-5.8	-4.8	-4.6	-4.9	-5.9	-4.5	-2.7	0.4	2.4	1.0
Pro-Industry	-8.0	-8.5	-10.4	-10.7	-11.2	-11.1	-12.4	-14.5	-11.9	-7.6	-0.6	4.8	3.8
Pro-Agriculture	17.1	14.7	16.7	13.9	17.5	22.3	23.6	24.8	21.7	19.3	14.6	11.5	13.8
Max	**17.1**	**14.7**	**16.7**	**13.9**	**17.5**	**22.3**	**23.6**	**24.8**	**21.7**	**19.3**	**14.6**	**11.5**	**13.8**
Min	**-8.0**	**-8.5**	**-10.4**	**-10.7**	**-11.2**	**-11.1**	**-12.4**	**-14.5**	**-11.9**	**-7.6**	**-0.6**	**2.4**	**1.0**
GCM pattern													
HadCM2	-48.4	-44.7	-47.5	-47.3	-50.2	-46.5	-56.5	-66.6	-71.5	-64.5	-45.4	-32.5	-33.5
CSIRO-TR	7.3	-5.1	-2.5	6.5	15.3	16.2	14.5	12.4	14.8	18.2	14.3	-0.4	0.6
ECHAM4	-42.0	-32.9	-40.1	-38.7	-41.8	-53.7	-57.2	-64.4	-62.4	-50.4	-52.7	-30.2	-13.8
CCSR	-0.4	14.6	2.6	0.2	-7.3	-6.2	-3.7	-7.0	-5.6	0.3	10.6	-2.9	-4.0
Average	-25.6	-23.2	-26.7	-22.7	-24.0	-27.3	-31.2	-37.7	-38.1	-31.0	-23.9	-21.0	-18.3
Max	**7.3**	**14.6**	**2.6**	**6.5**	**15.3**	**16.2**	**14.5**	**12.4**	**14.8**	**18.2**	**14.3**	**-0.4**	**0.6**
Min	**-48.4**	**-44.7**	**-47.5**	**-47.3**	**-50.2**	**-53.7**	**-57.2**	**-66.6**	**-71.5**	**-64.5**	**-52.7**	**-32.5**	**-33.5**

Note: All unit in %.
The climate change is simulated with emission scenario set to A2, and climate sensitivity to 2.5°C.
Red numbers indicate the minimum figure in the column, whereas green numbers indicate the maximum.

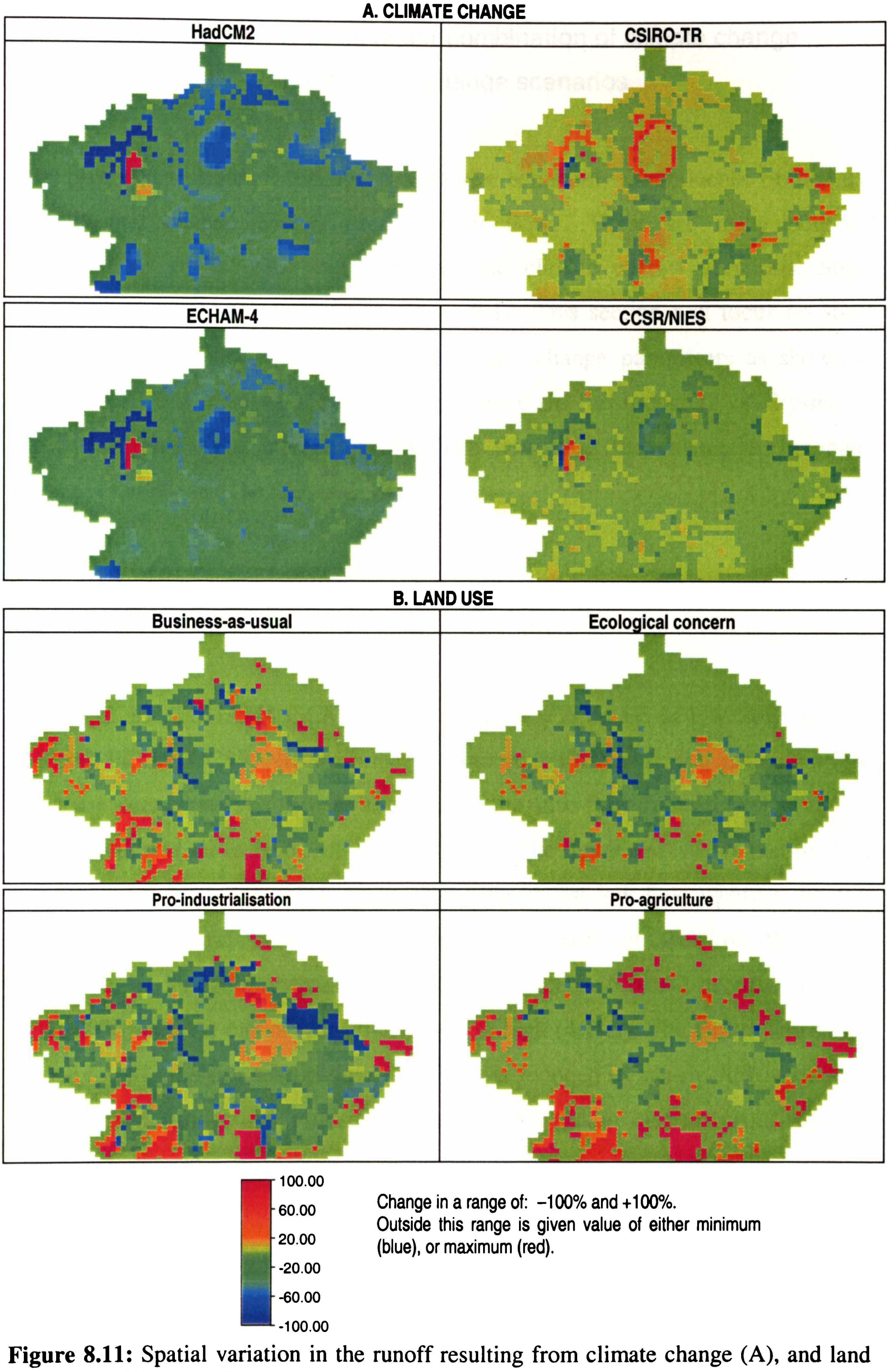
Spatial variation of the runoff

The integrated system allows a spatial analysis for examining the variation in the runoff resulting from the land use change and climate change. This spatial analysis can be performed because the integrated system uses a cell-by-cell basis in its calculation.

Figure 8.11 shows changes in average annual volume of runoff (in mm) relative to the baseline. In this analysis, the climate component and the land use component are analysed separately in order to find the characteristics of changes from each component. The time frame is set to 2050. The climate change is analysed under various GCM patterns, with the emission set to A2 and the climate sensitivity to 2.5°C.

In general, the HadCM2 and ECHAM4 patterns cause a decrease in the runoff, with some local larger decreases as indicated by the blue shading. An increase in the runoff is very pronounced by the lake site (red). The CSIRO-TR gives an increase in the runoff (yellowish green) and some pronounced increases locally. The CCSR pattern produces relatively small changes compared to the other GCM patterns. A relatively small decrease occurs slightly north of the basin centre, and an increase by the lake side.

The runoff variation resulting from the changes in land use shows significantly different patterns. The land use changes cause very distinct local variations in comparison to the climate change which shows a more gradual change of patterns. In general, the pro-industrialisation scenario causes the largest local variations, followed by the business-as-usual pattern. The pro-agriculture scenario shows an increase in the runoff mainly by the boundary of the basin, which is mostly the result of conversion of forest to agricultural land. The ecological concern policy scenario shows no changes in the Northern Bandung region. The change in the runoff mainly occurs in the centre of the basin.



A. CLIMATE CHANGE

HadCM2

CSIRO-TR

ECHAM-4

CCSR/NIES

B. LAND USE

Business-as-usual

Ecological concern

Pro-industrialisation

Pro-agriculture

Change in a range of: −100% and +100%.
Outside this range is given value of either minimum (blue), or maximum (red).

Figure 8.11: Spatial variation in the runoff resulting from climate change (A), and land use change (B), in 2050.

Variability of river flows under combination of climate change and land use change scenarios

The previous sections of this chapter describe separately the influence of land use change and climate change on the river flows. There are many potential combinations of the land use scenarios and climate change scenarios. Some possible combinations are given in Figure 8.12. This section will focus on some combinations of land use scenario and climate change parameters as shown in Figure 8.12 that may have significant influence on the reduction of dry-season flow (low flow), the increase in the high flow, and the change in variability between the dry and the wet seasons.

Low flow

HadCM2 and ECHAM4 GCM patterns produce a decrease in low flow whereas CSIRO-TR and CCSR-NIES produce a decrease in the low flow depending on the land use scenarios. The largest decrease in the low flow is produced when the GCM pattern is set to HadCM2 (Figure 8.12a). The figure also shows that the land use policy of pro-industrialisation produces the lowest low flow whereas the pro-agriculture scenario produces the smallest decrease in the low flow. The sensitivity of change is increased if the emission scenario of A2 occurs (for years after 2050) and the climate sensitivity is set to high (4.5°C). The model also shows that by 2100, the dry-season flow in August is reduced by nearly 90% relative to the baseline (under A2 emission scenario, best guess climate sensitivity and HadCM2 pattern).

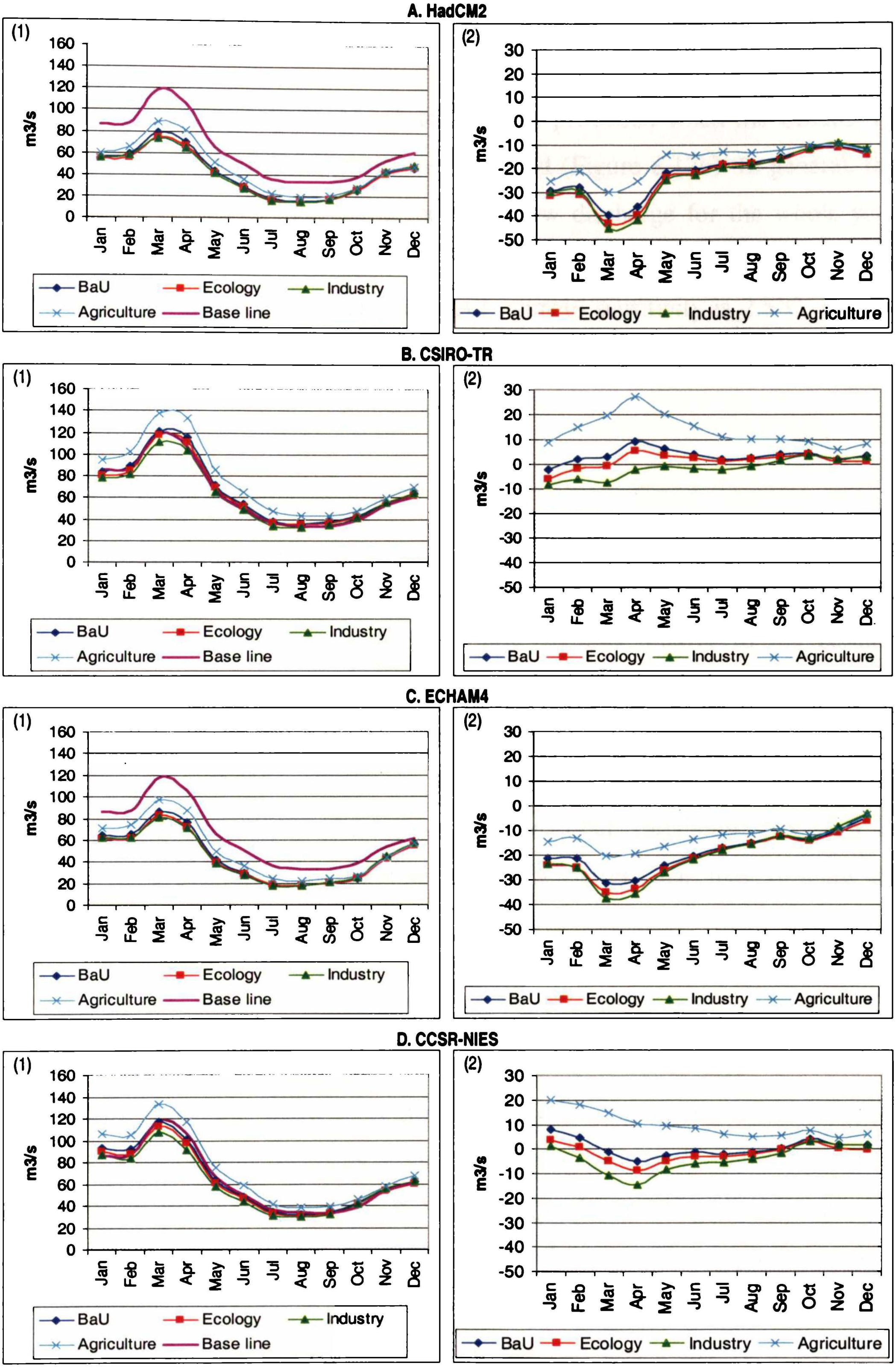


Figure 8.12: The effect of various land use change scenarios and climate change on the river flows under various GCM patterns in 2050. (1) The hydrograph, (2) The relative difference with respect to the baseline. The emission scenario is A1, $\Delta T_{2x} = 2.5°C$.

High flow

An increase in the high flow (March to April) is produced when the CSIRO-TR pattern and pro-agriculture scenario are combined (Figure 8.12b). In general, this GCM pattern causes an increase in the river flow discharge for the whole year. The percentage increase from May to September is the highest relative to the baseline (the emission scenario is set to A2, climate sensitivity is 2.5°C, and the land use is pro-agriculture). However, the highest discharge occurs in April.

Changes in seasonal variability

The change in seasonal variability can be measured from the changes in the discharge of high flow months and low flow months relative to the baseline (graphs 2 in Figure 8.12). An increase in the high flow followed with a decrease in the low flow results in a greater variability whereas a decrease in the high flow in combination with an increase in the low flow causes a reduction in the variability. In many cases, the changes in seasonal variability may also be followed by a change in the overall annual discharge that may obscure the changes in variability (Figure 8.12).

Figure 8.12 also shows that the change in the variability depends on both the GCM pattern and the land use pattern. The business-as-usual scenario in combination with the CSIRO-TR pattern produces a significant increase of discharge in April and relatively small increases in July and August. The pro-agriculture scenario with the same GCM pattern produces a large increase in April and relatively small increases from October to January. The opposite result is produced when the CCSR-NIES pattern is used. A decrease in discharge occurs in April (except for the pro-agriculture land use scenario), and relatively small increases are produced from October to February depending on the land use scenarios. The HadCM2 and ECHAM4 show large decreases in March and April with any land use patterns and relatively small decreases from October to December.

8.4 IMPLICATIONS OF RESULTS FOR THE STUDY AREA

The results from the model indicate that the projected monthly discharge may increase or decrease depending on the selected land use and climate scenarios. These findings have a significant implication for the study area. These may help policymakers and land use planners to anticipate the impacts of future climate conditions. It should be noted, however, that these are scenarios and not future predictions. Some implications from the results are discussed as follows:

- **A decrease in the annual discharge**

  A possible decrease in the annual discharge has been noted. The decrease is caused by the combination of land use change (pro-industrialisation land use scenario) and the HadCM2 GCM pattern. The annual discharge may cause a reduction in the volume of water in the Saguling dam that may disturb the operation of power water generation at this dam. It may also force the wet agricultural land to be converted to less water consumptive agriculture such as vegetables and secondary crops (*palawija*). A change from planting paddy to planting secondary crops because of the shortage of water has occurred in Madiun, east Java (Kompas, 2000). Implementing a pro-agriculture policy focusing on dry-land agriculture may minimise the severe dryness that may be caused climate change.

- **An increase in the annual discharge**

  A possible increase in monthly discharge has been noted in particular under a combination of the CSIRO climate change pattern and the pro-agriculture land use scenario. The high flow may cause an increase in the risk from floods. Minimising the risk may require, for example, a construction of flood prevention structures. The risk of floods may also be minimised by implementing a specific land use policy, such as reforestation, in order to reduce the runoff, as suggested by INDOCLIM.

- **Spatial variation**

  Spatial changes in the runoff are influenced by both the climate and land use. In general, the climate change causes a gradual change in local variation whereas the land use change causes a more distinct change. This suggests that there are opportunities for controlling the runoff locally in order to manage the entire river flows, as part of an integrated river management programme.

8.5 EVALUATION OF THE INTEGRATED MODEL FOR A PRELIMINARY ASSESSMENT

The integrated model is useful if it can be used for conducting impact assessments by comparing impacts with and without change of conditions (Major and Frederick, 1997). This is the basic purpose of the integrated model INDOCLIM, which brings together the complex relationship between land use, climate and hydrological components into one system for comparing the impact (i.e. sensitivity analysis) under various conditions (i.e. 'what if' questions). The integrated model is, therefore, evaluated based on the ease of conducting this kind of sensitivity analysis and whether it helps the users (policymakers and planners) in examining the impacts under various pre-determined scenarios of land use changes and climate changes. In addition, this evaluation serves as a base for future improvement or development of this trial model.

The evaluation specifically will discuss the model design and its performance (i.e. the characteristics of the model), and some feedbacks from potential users.

Characteristics of the integrated model

INDOCLIM is designed to be **simple and easy** to use. It is a user-friendly system with pre-selected options or parameters of land use and climate scenarios (see Figure 8.1). Users can explore the impacts of many possible combinations from the provided options for answering 'what if' questions. They can assess the impact of land use changes solely on the streamflows, or climate change only, or the combined effects of the land use change and the climate change. The output results are visualised in the form of charts. The model allows two sets of selected combinations of parameters (reference scenario and policy scenario) to be analysed and compared at the same time, and these charts provide a **quick visualisation of results for comparative and sensitivity analysis** from those sets of combinations. The model also allows the results to be compared with the baseline condition for quick visualisation of sensitivity analysis. These all make the model easy to use even by users without having any hydrological knowledge.

In any impact assessment studies using any model, the results of analysis should be carefully interpreted. This is because some values of parameters used in the model were estimated and may not be transported or adopted directly to a different area (Conway, 2001). In this integrated model, the projected monthly discharge resulting from various sets of selected parameters shows a wide range of values that may increase or decrease (Table 8.1 and Table 8.2). Therefore, there is some degree of **uncertainty** involved.

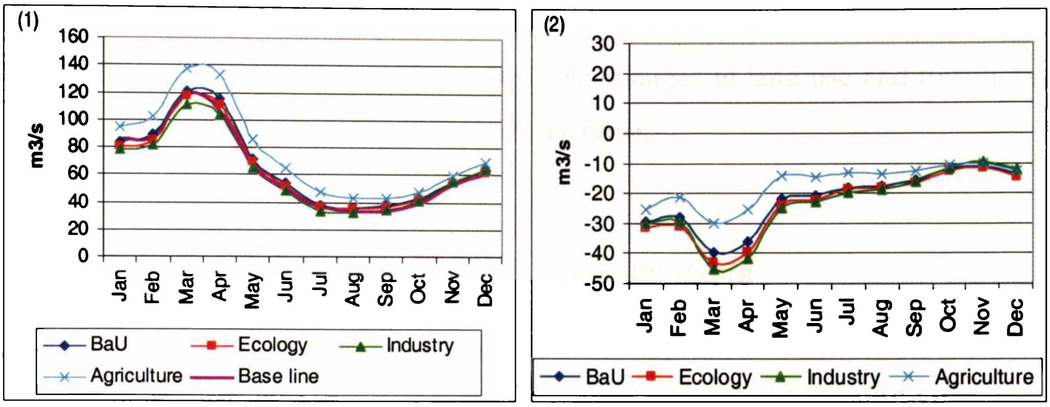
The uncertainty in the integrated model comes from several points: the uncertainty in the climate change scenarios; the uncertainty in the land use component, in particular, how certain the real future patterns will match with the patterns shown by the model; and the uncertainty on the values of parameters used in the hydrological component.

The uncertainty in the climate scenarios mainly comes from the climate sensitivity and the GCM patterns (see Table 4.4 in Chapter 4). This integrated system provides three values: 1.5°C for the lowest, 4.5°C for the highest, and 2.5°C for the best guess. The probability distribution for the uncertainty assessment of these values is not yet known. The model, however, allows users to explore the effects from this variation in the climate sensitivity values on the results. The GCM patterns, which are created by a number of centres, also show some differences that need to be assessed by means of validation. Some efforts on validating the patterns have been conducted for the Southeast Asia region (see Figure 7.3 in Chapter 7). The results however are still not conclusive, in particular for the Indonesian region or specifically Java.

In regards to future land use patterns resulting from the model, the uncertainty is due to the nature of the model itself. The land use component uses an empirical spatial type model, which is static (Chapter 4 Section 4.5). The land use model is selected based on the ease in creating land use change scenarios in a spatial format for sensitivity analysis. The more complex dynamic model promises better results on the modelled patterns. However, creating more accurate land use change patterns is not the purpose of the thesis. The purpose is to be able to demonstrate the sensitivity of river flows under various policies. Therefore, the policy-related scenarios in this thesis, as described in Chapter 6 Section 6.5, can only provide some guidance on the sensitivity impacts of those scenarios on the river flows.

The uncertainty on the hydrological component comes mainly from the estimated values of parameters used. A different result may be produced when the estimated value is set differently. For example, if the estimated water consumption (k_l) of the urban area is changed from 1.0 to 0.8, a significantly different output with an increase in the monthly discharge is obtained (Figure 8.13). This parameter needs

A. k_l urban area = 1.0



B. k_l urban area = 0.8

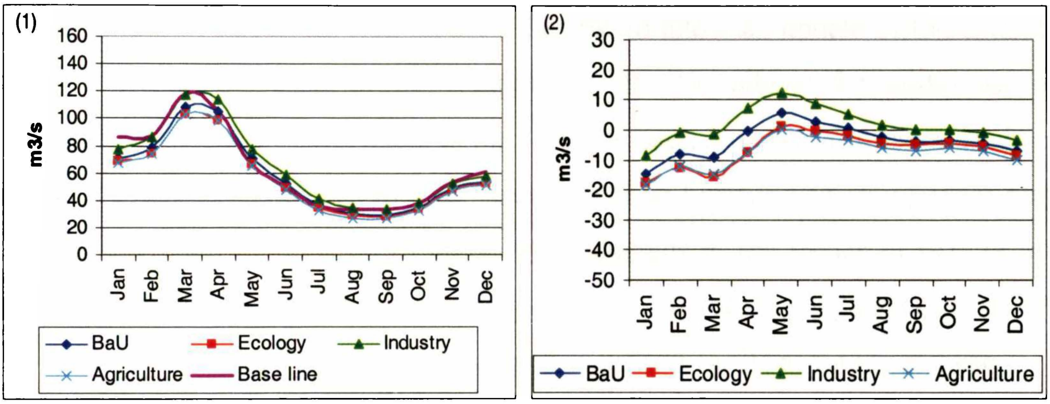


Figure 8.13: Effects of different water consumption (k_l) values for urban area on the monthly discharge under various land use scenarios. (a) k_l of urban area = 1.0, which is used in INDOCLIM, and (b) k_l of urban area = 0.8. The climate component is set with emission scenario = A1, GCM = HadCM2, and ΔT_{2x} = 2.5°C.

to be studied further in order to reduce some degrees of uncertainty, probably through a number of detail studies on small size catchments. However, it is possible for future model to provide a range of possible values for the parameters which area not calibrated well, ranging from the likely minimum to the likely maximum and possible best guess values, such as optional climate sensitivity values as provided by the climate component. It is also possible to provide an option for advanced users with good hydrological knowledge to have some flexibility in putting the values. By providing such facilities, the users can explore the range of possible results from the model.

In summary, policymakers should anticipate the impact of changes very carefully (Hobbs *et al.* 1997). INDOCLIM, in this case, is used as a decision supporting tool for the policymakers to examine possible changes in land use and the climate and how these changes would affect the river flows.

Feedbacks from potential users

This integrated model is one step towards a better integrated model for conducting sensitivity analysis under the influence of land use and climate change scenarios. The structure of this integrated model is flexible to allow an update of the data set or an upgrade for each of its components. It also allows for additional or replacement of library files, such as the land use scenarios file, for better analysis in order to answer specific 'what if' questions. The hydrological component may also be upgraded or updated to allow some changes in the values of parameters and assumptions when new values are identified. Therefore, this structure allows the model to be continuously developed and improved for its accuracy and use.

Feedbacks were received after an informal introduction of this integrated system in late July 2002 to about 50 people representing several institutions involved in policymaking and water resources research in the West Java province. These include: Environmental Protection Agency of West Java, the Provincial Government Office of West Java, the Government Office of the Bandung Municipality, Bandung Institute of Technology, Research and Development Centre for Water Resources, Directorate of Environmental Geology, Research Centre for Geotechnology - LIPI, Engineering Consulting companies, member of Parliaments for the West Java Province, and some non-government organisations. Some of the feedbacks are:

- **Scenarios of land use change patterns need to be flexible**, which allows any kind of patterns to be assessed using this integrated system. The aim is to produce an integrated system as a learning tool as well as an analytical tool. Hence, the system becomes more like a game of which the users can change the patterns to what they like, and view the results quickly. This method will allow the creation of non-time series and unrealistic patterns, that can be included in the future version of the model;

- **Methods for explicitly assessing adaptation measures need to be included in the integrated system.** Some adaptation measures can already be assessed, even though indirectly. For example, the effects of application of methods to conserve the hydrological parameters, which could allow the urban area to expand widely, can already be assessed using this model. Such procedures involve changing the parameter values. However, because this involves a different purpose of the model, it will be useful if adaptation could be treated separately as a new component to the integrated system;

- **The model needs to be able to assess where reforestation and check-dams for regulating the river flows can take place** in order to get the most effective results. This can be done by a detailed spatial analysis on sub-cathments that will determine the nature of runoff from each sub-catchments;

- **Specific water balance components need to be analysed.** In particular, the baseflow component, is an interest to some potential users for an assessment on the availability of water during the dry season. This water balance component can be extracted easily from the integrated model and displayed on a separate window;

- **The effect of forest cutting on the climate, at a catchment scale, needs to be integrated into the system.** The relationship between forest and climate, in particular the precipitation, has been studied for the Bandung basin based on long-term existing data. The preliminary results show that this kind of relationship exists but there has not been a conclusive result gained from this study (Setiawan, personal communication, August 2002). With a flexible nature of the model, this relationship between the forest and precipitation can be included in the model that will allow a better assessment on how this particular land use may influence the river flows.

8.6 CONCLUSION

This chapter demonstrates the operation of the integrated model and the use of the model for conducting a sensitivity analysis of the effects of land use and climate changes on the river flows. This model is suitable as a decision support tool for the users, particularly policymakers, for examining the possible changes in land use patterns and how these changes could affect the river flows, even though some improvements and developments are required for direct use by the policymakers.

This integrated model provides a selection of land use change scenarios and climate change scenarios. This wide range of selection allows a comprehensive analysis for exploring ‘what if’ questions. The model also allows two different sets of parameter combinations (reference scenario and policy scenario) to be analysed at the same time. The results can be compared immediately for a sensitivity analysis of two different conditions.

The model can be used to identify scenarios that may produce some significant changes in the river flows that may have significant impacts on the area, such as the possibility of extreme low flows, highest high flows, and changes in seasonal variability. This would be very useful for determining anticipating actions that may be required in terms of land use management.

The trial model of this integrated system has been used for conducting some analyses. It has been found that changes in seasonal river flows can be as the result of both land use and climate changes. The climate change has a larger impact in changing the discharge at a regional scale, but may also cause local variation. The land use change has distinct influence at a local scale. This left some opportunity to anticipate and manage the variation in the river flows that may be caused by climate change.

An evaluation of the integrated model shows that some degree of uncertainty involved in the model. The users are asked to treat and interpret the results carefully. The flexible structure of the model allows the model to be continuously developed and improved for providing options that allow the users to explore a range possible results that may be influenced by variation in the estimated parameters, and for accommodating feedbacks from the potential users.

REFERENCES

Conway, D. 2001. Understanding the hydrological impacts of land-cover and land-use change. *IHDP Update* 1/01, 5-6.

Emori, S. Nozawa, T., Abe-Ouchi, A., Numugati, A., Kimoto, M. and Nakajima, T. 1999. Coupled ocen-atmosphere model experiments of future climate changes with an explicit representation of sulfate aerosol scattering. *Journal of Meteorological Society Japan* 77, 1299-1307.

Hirst, A.C., Gordon, H.B. and O'Farrell, S.P. 1996. Global warming in a coupled climate model including oceanic eddy-induced advection. *Geophysical Research Letters* 23, 3361-3364.

Hobbs, B.F., Chao, P.T. and Venkateshi, B.N. 1997. Using decision analysis to include climate change in water resources decision making. *Climatic Change* 37, 177-202.

IPCC 2000. *Emissions Scenarios.* A Special Report of Working Group III of the IPPC, Cambridge University Press, Cambridge, U.K.

Kompas 2000. Petani di Madiun beralih ke tanaman Kacang hijau (Farmers in Madiun shift to mungbean plant). *Kompas* 20 Sept. 2000 (in Indonesian) http://www.kompas.com/kompas-cetak/0009/20/DAERAH/peta34.htm [20 Sept. 2000].

Major, D. and Frederick, K.D. 1997. Water resources planning and climate change assessment methods. *Climatic Change* 37, 25-40.

Mitchell, J.F.B., Johns, T.C., Eagles, M., Ingram, W.J., and Davis, R.A. 1999. Towarsa the construction of climate change scenarios. *Climatic Change* 41, 547-581.

Rockener, E., Arpe, K., Bengtsson, L., Christoph, M., Clussen, M., Dumenil, L., Esch, M., Giorgetta, M., Schlese, U. and Schulzweida, U. 1996. The atmospheric general circulation model ECHAM-4: Model description and simulation of present-day climate. *Max-Planck Institute for Meteorology.* Report No. 218, Hamburg, Germany, 90pp.

CHAPTER 9

SUMMARY AND CONCLUSION

9.1 INTRODUCTION

This thesis has sought to develop a policy-relevant, integrated system for examining the effects of changes in land use patterns and climate on the quantity and variability of river flows. It began with the question: "Is the increase in river flow variability the result of climate change or land use changes?" This highlighted the need for an integrated model as a tool that can help policymakers in managing a water resource, in particular the variability of river flows under uncertain changes in land use patterns and climate. This tool is particularly necessary for a basin that undergoes rapid changes in its land use pattern, such as the Bandung basin in Indonesia, which has been selected as the study area for this thesis.

This chapter summarises the main focus of this thesis, which is the construction of the integrated model that has been covered in a large proportion of this thesis (Chapters 4, 5, 6 and 7). It also describes the value of this model, the broader implication that may result from this thesis, and the contributions of this thesis to knowledge.

9.2 SUMMARY OF THE MODEL DEVELOPMENT AND RESULTS

How the model is constructed

The integrated system, INDOCLIM, has been created by integrating policy oriented land use change scenarios and climate change scenarios which are linked to a hydrological component for calculating the monthly discharge as output. It is a user-oriented program, created as a decision support tool for policymakers in examining the possible changes in land use patterns and how these changes together with the changes in climate would affect the river flows. This integrated system adopts a physically-distributed parameter type of model to allow the changes in land use patterns to be calculated immediately on a cell-by-cell basis.

Each component was developed separately. The hydrological component uses a water balance fundamental equation for its calculation. The calculation is on a cell-by-cell basis to allow the changes from the other components (land use and climate) that are distributed on 1x1 km^2 grid cells over the study area to be calculated immediately. The land use component is used to generate scenarios of land use change patterns. These changes of patterns were constructed by using a GIS based on the principle of a cellular automata method which was introduced in White and Engelen (1993). The climate component adopts the integrated framework system used in the CLIMPACTS family of models (Warrick *et al.*, 1996; 2001; Kenny *et al.*, 1995).

Capability and the value of the integrated model

INDOCLIM provides users with selections of pre-determined parameters, including the land use scenarios, GHG emission scenarios, GCM patterns, climate sensitivity and the year of projection. Many possible combinations can be generated from these selections to answer 'what if' questions. These are inputs that need to be determined by users in order to assess the impacts of the selected combination of inputs on the river flows. Two sets of selected combinations can be assessed and compared at the same time in the form of a chart for immediate sensitivity analysis. The changes in land use patterns and climate are in a time-series between 2000 and 2100, so that the impact of these changes on the river flows can also be assessed in a time-series.

This capability of accommodating many possibilities makes INDOCLIM suitable for policymakers in examining the impact of possible changes in land use and climate on the river flows. INDOCLIM can demonstrate the importance of changes in land use patterns only by switching off the climate component, or the changes in the climate component only by setting the land use to the baseline, or it can also assess the impact of a combination of land use and climate scenarios on the quantity and variability of river flows. Therefore, this integrated model can provide a tool for a comprehensive and integrated analysis in exploring 'what if' questions.

The model is **simple**, **accommodative** and **transportable**. It is simple in that it is easy to use. Any user without knowledge of hydrology can use this model. It is accommodative by providing a wide range of selections for answering 'what if' questions. The flexible structure of this integrated system allows for an update to the data set to be used, and an additional or a replacement of library files to answer specific 'what if' questions that the users wish. This model is transportable in that its structure and methods for generating the land use change as well as climate change scenarios can be applied to different river basins. In particular, it can be transported to areas with similar characteristics in terms of data availability such as different places in Indonesia and other countries in southeast Asia. In addition, the output of this integrated model is also easily visualised in the form of charts, which is an advantage for quick comparison analysis and sensitivity assessment.

The model can be used to examine the impacts of land use and climate change on runoff on every cell in the study area. This capability allows spatial examination to identify local variation caused by the changes in the land use and climate.

This integrated model has been implemented in the study area, the Bandung basin, Indonesia.

Results

This thesis shows that:

- **Both the changes in land use and climate have impacts on the river flows** (the annual yield, monthly discharge and seasonal variation);
- **Climate change has a greater possible impact on the change in the annual discharge than land use.** Changes in land use only can cause the annual discharge to decrease by 8% (under pro-industrialisation scenario) and increase by 18% (under pro-agriculture scenario), for the year 2080. (Extreme cases where all forested areas and all deforested areas are replaced by agricultural land show a decrease in discharge of 44.7% and an increase of 36.2%, respectively.) Climate change alone can cause a decrease of between 11.5% and 26% relative to the baseline (with the GCM pattern set to the average of HadCM2, CSIRO-TR, ECHAM4, and CCSR/NIES; and a climate sensitivity of 2.5°C);

- **The climate has a greater possible impact on monthly variation than the land use** (relative to the baseline). The change in monthly discharge caused by the land use change varies between –14.46% and 24.76% in 2080, and for climate change varies between –71.47% and 18.19% in 2080.
- **A superimposed effect of land use change and climate change can have an effect of exacerbating the impacts.** Low flow is the lowest under the pro-industrialisation and HadCM2 pattern (reduced by 90% in 2080 with A2 emission scenario, and 2.5°C climate sensitivity), whereas the largest high flow is produced under a combination of the pro-agriculture policy and the CSIRO-TR pattern. (The highest increase of 51.45% occurs in May, but the actual increase in discharge of 45.2m^3/s occurs in April. Conditions include: A2 emission scenario; best guess climate sensitivity; and for the year 2100.);
- **The change in land use has a more significant impact at a local scale than climate.** The spatial runoff variation shows that the climate change causes a gradual change in local variation whereas the land use change causes a more distinct change, and therefore has more local importance.

These findings suggest that climate change has a greater influence on the variability of the river flows. However, the findings also show the important aspect of land use which can increase or reduce the impacts of the changes caused by climate change. In addition, the pronounced change in runoff at a local scale is more likely caused by land use change. Therefore, the issue of land use management as part of the integrated management programme in order to achieve sustainable development is very relevant.

9.3 BROADER IMPLICATION AND CONTRIBUTION TO KNOWLEDGE

This thesis has an implication for increasing awareness of an integrated assessment to examine the possible changes in the quantity and variability of river flows as the result of changes in both land use patterns and climate. In particular, it shows the importance of both the land use component and the climate component in assessing the possible future quantity and variability of river flows.

Specifically, the thesis contributes to knowledge in several ways:

First, this thesis has made a significant contribution to the **development of a policy-related integrated system** that links the land use component and the climate component into the hydrological component for assessing the impacts of changes in land use and climate on river flows. This is the first model to be developed for this specific purpose, in particular for an Indonesian catchment. The model has specific characteristics in comparison to existing integrated models such as Hasan (1999) (QUEST) and Vörösmarty *et al.* (1991) as follows:

- It is a **catchment scale model**

  This integrated model that brings together the land use scenarios and climate change scenarios is applicable for a catchment scale. The land use scenarios are in time-series to allow assessment of variability of river flows under selected land use policies over time, and may be combined with the time-series climate scenarios for a more comprehensive analysis. This kind of model is not available anywhere else, particularly in Indonesia;

- It is **user oriented**

  The model is designed specifically for policymakers and planners, and is facilitated by constructing policy-oriented land use scenarios, even though the model can be useful as a learning tool for general users;

- It is **transportable**

  The framework and method of the integrated model can be applied to any other catchment with similar data availability. The land use change scenarios and climate change scenarios are site specific. However, the flexible structure of the integrated system that has been adopted from the CLIMPACTS family of models allows replacement of necessary library files in order to transport it to different places.

Second, this thesis has made a significant methodological contribution in the development of the integrated system. Specifically, the contribution to the methodology is as follows:

- **For the hydrological component**
  - a). A method to calculate the monthly variation in the **land use water consumption coefficients** (**k_l**), particularly for agricultural land, has been introduced. These coefficients are necessary for determining the monthly consumption of water for specific land use types. In an area where one land use type is predominant over other types, or when one land use type has grown to become the dominant type, this can be very significant in causing variability of monthly discharge;
  - b). A method to **estimate uncalibrated storm runoff parameters** has been introduced. This method combines the runoff coefficient given in the US SCS method, which is land use dependent, and the storm runoff values that take into account geological factors only into storm runoff coefficients that take into account both geology and land use.

- **For the land use component**

  The procedures used to create these policy-related land use patterns for the purpose of this thesis are different from the approach used by White and Engelen (1993), even though the principal method is the same (cellular automata). The new procedures and methods introduced in this thesis include:

  a). A method to define the hierarchical transition rules, including the identification of likeliness of conversion from one state of land use to another state;

  b). A method to define the weighting parameters for each selected policy-related scenario; and

  c). A method to construct the changes in the land use pattern and to convert them into a time-series change.

9.4 LIMITATIONS OF THE MODEL AND SUGGESTED FUTURE IMPROVEMENT

The main limitation of this model is the number of assumptions and simplifications used in the model. The lack of data also creates limitations in the model. In addition, because this model is the first of its kind, there is plenty of room for improving it to become a better model. These limitations and improvements are described on a component basis.

Hydrological component

- Limited amount of data are used for **calibration** and **validation** of the hydrological model. The amount of available data, in terms of length of periodical records and data distribution over the study area, is not adequate for proper calibration and examination of the validity of the model. If a larger area was chosen for calibration and validation, providing data are adequate, a better representation of the whole area may result. In the future, more data may become available that allow better calibration and validation of the model.

- Another limitation is the lack of more definite **water consumption coefficient values (k_l)** for reducing uncertainty in interpreting the results of this integrated model for some estimated values. In particular, the k_l values for forest, urban area and dry-agricultural land need to be investigated further. A different k_l value, for example by changing the k_l value for urban from 1.0 to 0.8, significantly changes the annual volume of runoff as well as the seasonal variability of the river flows (Chapter 8, Figure 8.10). The monthly k_l values for forest may need to be determined from some detail studies, and also need to be classified in detail based on the characteristics of the forest, i.e. primary forest, secondary forest and reforested land. The k_l for urban areas may be quite unique because the overall consumption of water in the urban area may also depend on the population density and types of urban areas (i.e. housing, industries, park, etc.) For the dry agricultural land, the improvement requires details of crop patterns, in particular knowing when the land is planted, fallow, or abandoned.

- Some **storm runoff coefficients** are estimated that need to be investigated in more detail, in order to be able to reduce uncertainty, and in particular, for replacing the completely estimated values (for geology type 3 in the study area). The relative difference in the storm runoff coefficients may create a significant difference in the output as has been analysed in Chapter 5. A method to estimate these coefficients has been developed, but it still requires some tests. Poor data availability in regards to geology type 3 area also prevents a proper calibration of these values. A more detail study to investigate the correct values needs to be conducted ideally on an area with homogeneous land use and with good data input and output, and with more data become available in the future, the calibration can also be conducted.

Land use component

- A different approach in generating land use change scenarios may be required to **replace the static model with a dynamic model for a better land use change allocation procedure**. For example, the roading network and the rules of urban allocation are assumed to stay unchanged for the whole time series. In reality, some new roads may be constructed that can alter the distribution of urban areas and gardens, such as the new toll road which was opened in 1991. With advancements in technology for construction or soil conservation, it may be possible to allow the urban area to expand to a higher slope, or there may some changes with regard to the elevation at which the settlement could expand, and so on.

- The method used to determine the likelihood of conversion from one land use state to another state as used in this thesis is very subjective. Further study may be required to **standardise the method in determining the weighting parameters**. A more quantitative approach is preferred to allow better judgments in deciding the weighting factors.

- The land use model used in this thesis uses a limited number of physical factors, which are: slope, elevation, distance to the main road, and distance to the river. There could be **some other important physical factors** that need to be included in the construction of scenarios, which can contribute locally to the land use distribution patterns such as soil fertility and groundwater conditions. These were not analysed in this thesis because of the lack of data. The analysis of distribution patterns of land use would be more comprehensive if more possible land use distribution influencing factors were included, and those that have significant influence on the land use patterns could be selected in a systematic way from the list of available factors.

Climate component

- **Interannual climate variation** and **extreme events** such as El Niño and La Niña are excluded from this integrated model because of difficulty in modelling with good confidence (see Chapter 7 Section 7.3). This climate variability is an important aspect to be considered in implementing the adaptation measures. The future model will need to include the variability aspect of the climate.

As mentioned earlier, data availability is the main constrain in developing the model well. In particular, it prevents well calibration and validation to be properly conducted. Good long-term and well distributed data, which includes the hydrological, land use and climate data, can increase the confidence in, and the reliability of, the integrated model. Availability of multi-temporal land use data such as land use maps, air photos, or satellite images can help to calibrate and validate the land use change model. A long term climate data set can reveal and make possible the assessment of the interannual climate variability in more detail, including the possible decadal climate variability as mentioned by Dam (1994) (see Chapter 3 Section 3.2).

In dealing with uncertainty that comes from model parameter values, additional options for allowing users with some hydrological knowledge to choose the values should be provided in the future model developments. These would give a flexibility to the users for exploring the possible range of results that may be produced from the variation in the parameter values.

In addition, as described in Chapter 8, Section 8.5, several other improvements and developments are also required for the model to be more useful for the policymakers and other potential users, as follows:

- The land use change patterns need to be flexible (i.e. accommodative);
- Possible methods of adaptation need to be included in the integrated system;
- The model needs to be able to determine where reforestation and check-dams for regulating the river flows can be effectively placed;
- The model needs to be able to analyse specific water balance component such as baseflows;
- The effect of forest cutting on the climate at a catchment scale needs to be included in the integrated system.

The integrated system that has been developed omits the dynamic feedback links. As already discussed in Chapter 4, Section 4.2, such dynamic links exist. Within each of the components of this model, the dynamic feedbacks also exist. For example, the nature of land use is dynamic because of the dynamic interaction of the socio-economic drivers (see Chapter 4, Section 4.5 on Land use component). The change in the climate, which influences the agroclimate, may affect the cropping pattern that in the end causes changes in the distribution of monthly crop-coefficient factors (Chapter 5, Section 5.5). At this stage, this kind of fully dynamic model is still difficult and beyond the scope of this thesis. In the future, the possibility to develop a dynamic integrated model type may be explored.

Finally, despite the limitations described above, the trial model can demonstrate well the impacts of land use change and climate change on the variability of the river flow in a medium sized river basin. Combinations of various scenarios of both land use and climate change can give various results on the hydrograph of the river flows. Therefore, the users of this model can look at a wide range of possible impacts of such uncertain changes. More importantly, the users may learn how to anticipate such changes by assessing the favourable land use policy in order to minimise the risk resulting from the likely unavoidable climate changes. By doing this, one step towards sustainable water resources for sustainable development is gained.

REFERENCES

Dam, M.A.C. 1994. *The Late Quaternary Evolution of the Bandung Basin, West Java, Indonesia.* Thesis, Vrije Universiteit Amsterdam.

Hasan, N.M.H. 1999. A large scale ecosystem scenario development tool based on QUEST. *Information Paper For NETTLAP Regional Conference – Making A Difference: Progress in Environmental Education, Training and Research in Asia and the Pacific.* 30 September – 2 October 1999, Phuket, Thailand

Kenny, G.J., Warrick, R.A., Mitchell, N.D., Mullan, A.B. and Salinger, M.J. 1995. CLIMPACTS: an integrated model for assessment of the effects of climate change on the New Zealand environment. *Journal of Biogeography* 22, 883-895.

Vörösmarty, C.J., Moore III, B., Grace, A., Peterson, B.J., Rastetter, E.B. and Melillo, J. 1991. Distributed parameter models to analyze the impact of human disturbance of the surface hydrology of a large tropical drainage basin in Southern Africa. In: F.H.M. van de Ven, D. Gutknecht, D.P. Loucks and K.A. Salewicz (eds.), *Hydrology for the Water Management of Large River Basins.* IAHS Publ. No. 201, 233-244.

Warrick, R.A., Kenny, G.J. and Harman, J.J. (eds.) 2001. *The Effects of Climate Change and Variation in New Zealand, An Assessment Using the CLIMAPCTS System.* International Global Change Institute, University of Waikato, Hamilton, New Zealand.

Warrick, R.A., Kenny, G.J., Sims, G.C., Ericksen, N.J., Ahmad, A.K. and Mirza, M.Q. 1996. Integrated model systems for national assessments of the effects of climate change: applications in New Zealand and Bangladesh. *Water, Air, and Soil Pollution* 92, 215-227.

White, R. and Engelen, G. 1993. Cellular automata and fractal urban form: a cellular modelling approach to the evolution of urban land-use patterns. *Environment and Planning A* 25, 1175-1199.