THE ORIGIN OF OVERLAND FLOW IN OTUTARU CATCHMENT

by

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I N D E X

GLOSSARY OF TERMS

OTUTIRA : International Hydrological Decade Experimental Basin on the north shore of Lake Taupo some 22.5 kilometres in a direct line west of Taupo township. Vegetation is chiefly scrub, dominated by manuka.

OTUTARU : The northernmost catchment of Otutira. A grass catchment of 4.5 hectares which was developed as part of a Lands and Survey departmental block. The present cover of rye grass and clover is lightly grazed.

RUNOFF PLOTS : 14 runoff plots were installed in Otutaru in 1967 by Dr M.J. Selby, with a further 6 installed in the adjacent scrub and ungrazed area of Ototira. Refer to fig.1 - catchment map-for location of plots in Otutaru. Plot numbers run from 1 to 14.

RAIN GAUGES : 15 gauges are involved. Numbering is complex but falls into three groups:-

(a) automatic gauges : Selby's gauges are known as ARaG1 and ARaG2 (identified by symbol and numbers 1 and 2 on fig.1). Pittams gauge is numbered 5 in accordance with other sites around Otutira.

(b) 5 pairs of vertical and tilted gauges. Known as VR (vertical) and TR (tilted) followed by site identification (identified by symbol and numbers 1 to 5 on fig.1.

(c) reference gauges. Ministry of Works manual gauges restricted to the meteorological station during the study. Comprise a standard manual gauge known as 13 and a vector pluviometer - usually abbreviated to V.P. After ARaG2 was removed at the close of the study a second vector pluviometer was installed (for a few weeks) in its place. This was known as 64 to avoid confusion (not specifically identified on map).

UNITS :

Volume : millimetres
millilitres per 4 square metres
(conversion : one millimetre is equivalent to 4000 millilitres per 4 square metres).

Rate : litres per minute
millilitres per 3 minutes for unit area of 4 square metres.

Conversion : One litre per minute is equivalent to 3000 millilitres per 3 minutes for unit area.

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ABSTRACT:

Data collected from 14 runoff plots and Otutaru catchment indicate that there is a very close relationship between runoff measured at the plots, and rates and volumes recorded at the outlet from Otutaru catchment. This relationship is dependent principally on rainfall intensity and is influenced by soil moisture conditions before and during a storm.

The influence of aspect, storm direction and wind speed are analysed and it is deduced that they are minor influences on runoff. It is concluded that overland flow is generated throughout Otutaru catchment when rain of sufficient intensity occurs. Initially the bulk of this flow is lost by infiltration in the valley bottom but after rain of a certain volume or sufficient intensity has fallen the whole catchment appears to contribute to Otutaru runoff. The slopes produce relatively greater flow, but all areas contribute significantly to catchment runoff.

INTRODUCTION:

Otutaru is the northernmost part of the Otutira catchment situated on the north shore of Lake Taupo 22 kilometres in a direct line west of Taupo town and 32 kilometres south of Mangakino. This area is one of the International Hydrological Decade Basins controlled by the Ministry of Works.

The thalweg of the catchment runs, from its high point of 585m above sea level in the north, south towards Lake Taupo with an average slope of 0.054 metres/metre (3^o). The valley sides face approximately east and west with a maximum slope of 0.355 metres/metre (20^o).

The geology of the catchment has been described by Rishworth (1970). In valleys to the east and west of Otutira there are outcrops which indicate that the basin is underlain by subhorizontal to gently dipping, fissured Mokai ignimbrite. Near the lake the ignimbrite is overlain by lake sediments of the early to middle pleistocene Huka Falls formation, but further inland these beds are deeply buried by pumice lapilli tuff. This tuff extends over many square kilometres to the north of Otutira, and in some places is thought to be as much as 150 metres in thickness. Overlying the tuff is a sequence of late pleistocene and recent ash shower deposits of variable thickness and distribution. The hydrological significance of these beds is that they are all permeable and the groundwater table is very low. In the Omoho valley a series of springs marks the top of the ignimbrite some 200 feet below the level of Otutaru.

The soils of the catchment have been mapped by Cowie and Campbell (unpublished report 1967). Over the study area the soils are derived from Taupo ash overlying Tirau ash, except in the floor of the valley where colluvial, and possibly alluvial Taupo ash has accumulated and forms the parent material. The soils from Taupo ash on Tirau ash have been named Oruanui Sand Soils which are classed as rolling phase, strongly rolling phase, and Oruanui Hill Soils. The soils from reworked pumice are called Waipuhihi Sand Soils. These soils are yellow-brown pumice soils ranging from moderately to very strongly leached. Most of them have very friable black sand topsoils, dark brown to brown sand subsoils, overlying yellow or grey pumice sands and gravelly sands. In a few places, generally on eroded ridge tops and slopes, Taupo ash is absent and a brown fine sandy loam is formed directly on the Tirau ash. With development from scrub vegetation to pasture grasses the soil structure changes from weakly developed crumbs to a fine nutty and granular structure.

Land development of the pumice soils increased rapidly from about 1936. This followed the discovery that top-dressing grass pastures with cobaltised superphosphate prevents bush sickness in stock.

In many areas the land development appears to have been followed by considerable erosion of the thick pumice deposits in the valley bottoms. These deposits had become more or less stabilised by plants after the 130 A.D. Taupo ash eruptions and as most water seeped downward through the porous deposits, there were few surface streams. In all areas reactivation of gully erosion appeared to coincide with the first unusually wet season occurring after land development. Several hypotheses put forward to explain such erosion suggest that an increase in surface water flow has caused the gullies. Many of these hypotheses are concerned with the effects of prolonged or intense rainfalls on surface water flow.

The experiments being conducted at Otutira by the University of Waikato and the Ministry of Works are designed to provide reliable quantitative data on the effects of climate, soils, and vegetation on runoff. The study described in this Thesis is a specific investigation of the effect of rainfall (both intensity and duration) on surface water flow as measured from runoff plots by Dr M.J. Selby of the University of Waikato and from Otutaru catchment by R.J. Pittams of the Ministry of Works.

EXPERIMENTAL DESIGN:

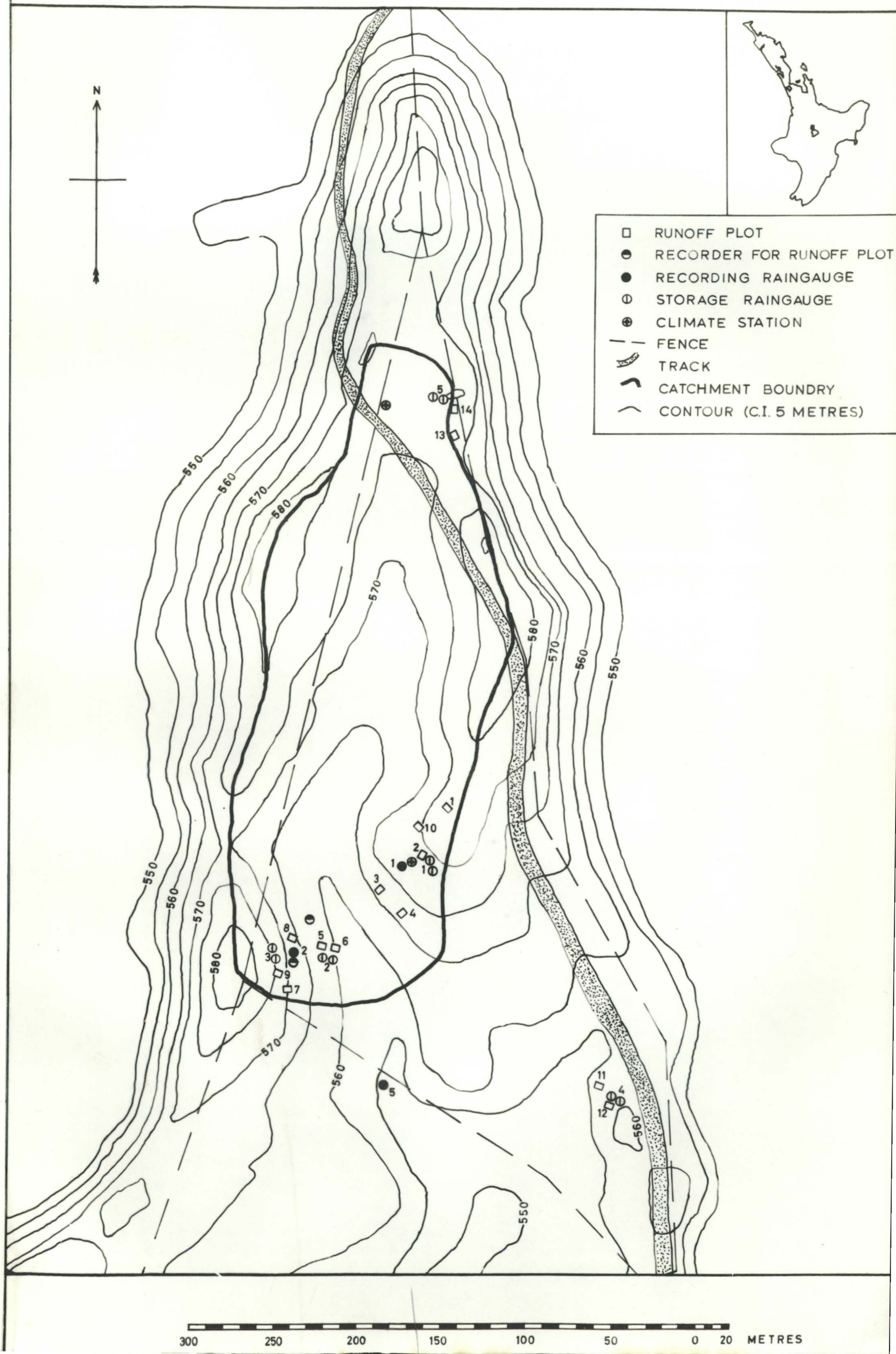
The object of the research reported in this Thesis is to provide information on the relationship between rainfall and overland flow in a pasture catchment on yellow-brown pumice soils. Hydrological research may be conducted at two distinct levels - that of whole drainage basins; and also at the level of small plots, either natural or artificial. The object of drainage basin studies is to obtain an understanding of the relationships between rainfall and runoff (Linsley, 1967) but the importance of individual catchment parameters can seldom be evaluated. Runoff plots are usually small and have homogeneous characteristics so that in experimental conditions one variable can be held constant while each of the others is manipulated. In this way runoff plot studies can be used to evaluate the effect of individual variables such as aspect and slope upon runoff.

The Otutira catchment was instrumented by H. Drost of the Ministry of Works in 1966 for research on whole drainage basins.

The part of the catchment designated as Otutaru had been established in pasture about 1960 and showed evidence of sizeable ephemeral flows. A meteorological recording station was established in the extreme northern end of the catchment and two raingauges were installed, one at each end. The lower raingauge was replaced by a Lambrecht automatic gauge in October 1966 and a Vector Pluviometer was added to the meteorological station in December 1966. In August 1966 a 45 cm H-flume and a 20 cm weir box were installed to record runoff. The fibre-glass approach flumes and weir boxes are easy to install (and if necessary remove) and the double recording ensures that a flawless flow record is obtained. The 30.5 cm direct drive Lea recorders with daily time scale are ideal for the system. In 1968 the 45 cm H-flume was overtopped twice so it was replaced in May 1969 by a 90 cm H-flume with a wooden approach channel.

Dr M.J. Selby decided in 1967 to install a series of plots in Otutaru and the adjacent scrub and ungrazed grass areas so that runoff from small areas under different kinds of vegetation and land use could be studied. The object was to distinguish the chief factors influencing runoff. Each of the runoff plots encloses an area of four square metres and to enable the plots to be fitted flush with the uneven soil surface each plot is restricted to one metre width. Fourteen plots are located within the grazed pasture area and two of these are coupled to modified Lambrecht automatic rain gauges. The runoff water is led into the orifice of the gauge and this has proved to be a satisfactory way of measuring the period and rate of runoff.

OTUTARU


N
RUNOFF PLOT
RECORDER FOR RUNOFF PLOT
RECORDING RAINGAUGE
STORAGE RAINGAUGE
CLIMATE STATION
FENCE
TRACK
CATCHMENT BOUNDRY
CONTOUR (C.I. 5 METRES)
550
560
570
580
300 250 200 150 100 50 0 20 METRES

Storage rain gauges with a 200 square centimetre orifice (the same size as used for Lambrecht automatic gauges) were placed alongside each group of plots. In the pasture area the gauges were placed in five pairs with one tilted normal to the slope and one installed vertically. Two Lambrecht automatic gauges were also placed in the pasture area (fig.1).

Usable data was obtained from the plots in February 1969 and the study was concluded in March 1971. Fortyfour wet periods were obtained during the two years, including some twenty which approximate to single storm events. Ideally data from the instruments should have been collected after each major storm but this was not always possible. In practice visits were made at least once a fortnight.

Ministry of Works equipment was either fully automated or read daily. This makes the two independent sets of data completely compatible, and the entire range of data for this study is therefore based on the 44 periods measured by Dr Selby. For convenience, however, the Ministry of Works abandoned the daily observations at the end of April 1970 so that for the subsequent months the standard manual rain gauge and the vector pluviometer were read weekly. The Lea flow recorder charts were similarly reduced to weekly changes. For this reason the 31 periods between February 1969 and the end of April 1970 are more satisfactory for detailed comparative study, than the remaining 13 periods. On the other hand the installation of an anemograph in April 1970 simplifies the determination of storm direction and wind speed for the later periods.

TABLE 1 : RAINFALL RECORDS FROM VERTICAL GAUGES

(ranked on wind direction derived from vector pluviometer)

Period	Storm Direction (Degrees)	5	VR2	ARaG2	VR3	VR4	VR1	ARaG1	VR5	13
		(Percentages of vector pluviometer total)								
30	01.26	73.8	83.7	70.7	69.9	82.0	92.4	91.3	90.1	86.5
26	05.57	74.4	70.2	70.5	59.1	68.9	70.5	79.3	73.6	89.4
22	07.42	91.2	86.4	(81.4)	76.5	88.6	92.6	98.8	89.8	96.1
11	09.69	90.0	88.0	75.9	77.3	80.5	87.6	89.8	98.5	96.6
12	23.96	75.8	87.1	82.6	72.0	88.3	91.3	90.9	82.9	102.3
1	34.85	100.6	95.0	88.5	81.2	84.0	96.3	97.9	87.0	99.4
20	88.13	101.1	88.1	78.5	69.7	93.6	97.2	97.6	74.3	104.8
31	267.61	101.0	65.8	94.1	90.6	98.0	90.6	94.1	89.6	97.0
7	270.00	104.4	89.4	84.5	89.1	84.5	94.3	97.9	103.4	100.5
13	312.40	84.5	90.7	88.7	95.9	82.5	74.2	87.6	92.8	83.5
4	325.03	97.0	91.1	84.4	76.7	(89.2)	(101.9)	104.3	(101.9)	101.9
42	327.17	92.6	91.6	92.1	86.8	87.9	86.5	92.8	78.1	94.8
34	330.37	87.9	88.6	79.3	66.5	83.0	92.2	88.8	95.7	95.9
16	332.57	89.8	86.6	82.7	86.6	70.9	82.7	94.5	106.3	94.5
24	339.01	100.0	93.3	87.5	84.6	76.9	87.5	98.0	94.2	100.0
10	340.08	91.8	92.3	89.2	82.5	89.7	94.8	99.0	95.4	96.9
18	343.74	103.8	95.6	86.3	86.3	75.0	75.0	96.9	92.5	104.4
9	347.88	94.2	88.3	76.6	84.2	67.8	84.8	86.0	92.4	96.5
6	349.93	73.8	70.2	61.6	58.8	60.1	71.8	72.9	67.9	80.5
25	350.54	145.7	131.4	117.1	128.6	108.6	97.1	140.0	85.7	108.6
Average (of 44 Periods)		93.3	88.1	81.8	75.6	84.0	91.4	95.4	88.6	98.4

TABLE 2

STORM ORIENTATION AND INCLINATION

Period	Rainfall Mass Density (in mms)	Storm Direction V.P.	VR2	VR3	Rainfall Inclination V.P.	VR2	VR3
		(Degrees from North)			(Degrees from Vertical)		
30	47.73	01	359	19	42	52	59
26	48.18	06	354	00	37	56	62
22	113.76	07	16	23	32	43	50
11	44.25	10	23	12	22	35	44
12	26.69	24	54	25	8	30	45
1	84.03	35	?	31	13	?	38
20	61.05	88	85	133	27	38	52
31	20.34	268	273	310	7	49	26
7	40.49	270	259	310	17	31	32
13	10.19	312	293	340	18	30	24
4	68.63	325	274	320	23	33	45
16	15.51	333	310	347	35	45	45
24	13.01	339	308	349	37	42	47
10	21.19	340	292	327	24	32	41
18	16.66	344	265	339	16	23	34
34	86.33	346	24	24	25	36	53
9	21.98	348	309	342	39	47	49
6	81.15	350	347	330	38	56	62
25	4.26	351	?	69	35	?	10
42	75.42	352	32	13	13	27	32

RAINFALL PATTERNS:

Rainfall data are available from nine sites in or near Otutaru catchment. Three sites have automatic gauges, five sites comprise paired vertical and tilted gauges, and one is the meteorological station site with both a standard manual gauge and the vector pluviometer.

Inspection of the records from the vertical gauges gives an indication of variation around the catchment. The pattern is consistent, with the highest values being recorded at the northern end of the catchment while at the southern end there is a sharp decrease in catch from gauges 5 to VR3 up the western slope (table 1).

This considerable decrease in catch up the slope is not readily explained, and more gauges would be needed to test any particular hypothesis. However, certain important facts can be established which are relevant to runoff production at a specified site. Attention is chiefly directed to the south-west corner of the catchment because of the concentration of instruments, and particularly automatic gauges, on this slope.

The three factors which could influence rain gauge catch are aspect, storm direction and rainfall inclination. Aspect may influence catch by changes in relative exposure to storms from different directions. Rainfall inclination may be influenced by local changes in wind speed due to topographic features and irregularities.

Aspect is fixed for a particular site. Its influence can best be considered by grouping storms on the basis of wind direction. The vector pluviometer is particularly important at this stage because the catches in its individual orifices are direct indicators of storm direction and rainfall angle. The vector system can be resolved by using the samples from the four horizontal gauges to derive the storm direction and horizontal component. Resolution of the horizontal and vertical components then gives the rainfall angle and the maximum possible rainfall (termed the rainfall mass density in this study) for that storm. Rain falling near vertically indicates calm wind conditions while large angles reflect strong winds. (table 2).

Rainfall can be calculated for any site by using Fourcade's equation:
(U.S. Dept. Ag. Tech. Bull 1096) :

$$r = R + R \tan a \tan i \cos (B-W)$$

where r = true rainfall sample

R = sample from vertical gauge

a = gradient of slope

i = angle of inclination of rain (from vertical)

so that $\tan i = \dfrac{\tan Re/R}{\sin W}$

and $\tan W = \dfrac{Re}{Rn}$ (Re = East - West) (Rn = North - South)

B = aspect of slope

W = average storm direction

However, the use of Fourcade's equation assumes that the rainfall mass density, the storm direction and the angle of inclination of rain all remain constant for each site. In flat terrain these conditions may be met but the rolling topography in Otutaru is very likely to modify the storm direction for a given site and any local variations in wind speed will influence the angle of inclination of rain. For Otutaru catchment in fact, Fourcade's equation predicts values much higher than those recorded in the tilted gauges.

Data from the paired raingauges can also be resolved, by a vector system, to enable storm direction and inclination of rain to be calculated. The rainfall mass density calculated from the vector pluviometer data can be conveniently used as the third vector requirement. When the site aspect is arbitrarily chosen as one vector direction the solution is

$$l_1 = y = \frac{VR}{pM}$$ (VR: catch from vertical gauge; pM: rainfall mass density)

$$x = \frac{TR}{pM}$$ (TR: catch from tilted gauge)

$$l_2 = \frac{x - y \sin S}{\cos S}$$ (where S is the site slope)

$$l_3 = \pm (1 - l_1^2 - l_2^2)^{\frac{1}{2}}$$

where the three vectors l_1, l_2 and l_3 correspond to the three vectors of the vector pluviometer. Care must be taken with the ambiguity of sign in l_3 and the storm direction must be reoriented to true north, but the

TABLE 3

DATA FROM TWO VECTOR PLUVIOMETERS
AND
MANUAL GAUGES IN THE SOUTH WEST CORNER

Rainfall Mass Density		Storm Direction				Inclination of Rainfall			
13	64	13	64	VR2	VR3	13	64	VR2	VR3
65.05	60.69	354	356	04	02	40	43	46	45
74.61	67.63	304	100	?	?	01	04	?	?
87.17	85.10	348	342	28	15	26	33	29	30
2.00	?	00	00	33	28	00	00	01	41
17.39	13.09	347	00	?	49	32	33	?	21
21.08	18.82	169	165	?	136	29	19	?	39
9.71	9.76	359	344	31	24	26	36	27	38

final results (table 2) agree very well with those from the vector pluviometer. From these results (and similar data from the other three rain gauge pairs) it can be seen that storm orientation in Otutaru may vary by up to about 40 degrees between sites. The inclination of rain from the vertical apparently increases with increasing slope. Site 3 (at 33 degrees) is the steepest of the five sites with paired gauges, and data from it usually shows an angle of inclination some 20 degrees further from the vertical than the angle obtained from the vector pluviometer. Data from site 1 (at 12 degrees) gives an angle of inclination some 6 degrees greater than the angle obtained from the vector pluviometer.

One problem remains to be solved. From time to time the sum of l_1^2 and l_2^2 exceeds unity and the data cannot be resolved. Just why this happens is not clear and the eventuality cannot be anticipated completely by inspection of the records. The simplest and commonest case occurs when the volume in either a vertical or a tilted gauge exceeds the rainfall mass density derived from the vector pluviometer data. The other simple possibility occurs if a rain gauge is defective and the data obtained cannot be resolved. Least difficulty is experienced at sites 2 and 3 where the site slopes are 26 degrees and 33 degrees respectively. The other three site slopes are all about 12 degrees.

Note that the storm direction is entirely from west through north west and north to north east. As analysis continued the variations in rainfall data had to be primarily the result of variation in rainfall mass density rather than variations of storm direction and inclination of rainfall. As a test a second vector pluviometer was installed in November 1971 at the site from which ARaG2 had been removed. The data obtained (table 3) at weekly intervals from both vector pluviometers and from the paired gauges at sites 2 and 3 is limited by the small number and size of storms but does confirm the lower mass density in the south west part of the catchment. The precise effect of storm direction and site aspect on this lowering of rainfall mass density is still not clear but the result will be discussed again later in relation to runoff from individual plots.

Data on storm direction and inclination of rainfall is only useful when a storm has been predominantly from one direction. To test the importance of aspect therefore, it is necessary to use only storms which satisfy this requirement.

The most satisfactory means of storm selection is through the runoff charts. Any particular period may contain several storms, but in many cases runoff only results from one storm. In this case the assumption can usually be made that the wind direction did not change during the time this rain was falling. Twenty such storms (those tabulated above) occurred in the 44 periods of the study. Other rain falling in the individual period had negligible effect on results.

RUNOFF ANALYSIS:

Runoff data are available from Otutaru catchment and fourteen plots - two fitted with automatic recorders - in or near Otutaru, all with comparable soils and grazed pasture. Otutaru is a catchment of extremes. It responds spectacularly to high-intensity rainfalls even if they are of short duration, yet it is little affected by low-intensity storms. Very low intensity rain does not produce runoff, but the highest rainfall intensity recorded (6.4 mm/3 min in storm 26) resulted in almost total runoff.

Data from the plots show considerable variation for any given storm. Certain plots, however, dominate the runoff results. Very low intensity rain does not appear to produce runoff. If observations were made and no runoff occurred then that period was added into the next period. The plot data therefore show some runoff from every storm period - though individual plots may not contribute. The variability of the overall plot record is not easy to explain, especially at the low intensity rainfall end, and low runoff storms comprise approximately half the total record.

For a better understanding of the runoff record a shorter time period than the manual interval is necessary. Runoff in the 44 manual intervals is totally unrelated to total rainfall volume in the corresponding intervals. The automatic records from plots 8 and 9 and from Otutaru are thus very important. A time base of three minutes has been adopted for all work with intensity. This is near the limit of chart accuracy but it is important because really high rainfall intensities rarely last longer than three to six minutes. Such a time unit enables every variation in the rainfall pattern to be considered, where a longer time base results in significant loss of extremes. In a study such as this the extreme values dominate any relationship proposed.

Some 170 intensity values were extracted from 21 storm periods. This was sufficient to cover the complete range and to allow analysis on the basis of constant intensity. Three rainfall factors are involved - intensity, duration, and antecedent moisture conditions. When any one is held constant the relationships between the remaining two can be studied. To allow direct comparision between plots and catchment, the latter was calculated on the basis of flow rate per unit area, where the unit is four square metres.

AUTOMATIC PLOT RESULTS:

The simplest possible data to use, is obtained from isolated storms with uniform intensity and sufficient time without rain for the effect on soil moisture of one storm to be eliminated before the next storm occurs. In some cases the initial intensity in a major storm can be utilised but difficulty in separating runoffs from a series of rainfall bursts can lead to serious calculation errors.

Antecedent moisture conditions must be standardised before the true effects of intensity and duration can be determined. In the absence of any satisfactory relationship for the depletion and recharge of soil moisture the only conditions which can be investigated are those of minimum and maximum antecedent wetness.

A block of rain of uniform intensity can be subdivided into three minute time intervals. The volume of rain falling in each of these three minute intervals is then the unit rate. The runoff resulting from this block of rain will depend both on the unit rainfall rate and on the number of units. If all other parameters were constant the runoff volume would increase in direct proportion to the number of rainfall units, and the runoff total could be subdivided into an equal number of units to give a comparable unit rate.

Inspection of the runoff records from plots 8 and 9 shows that constant parameter conditions are not present. Doubling the rainfall duration for a given unit rate tends to more than double the runoff volume. Nevertheless, expressing the runoff as average unit rates is a useful means of comparison because it tends to offset the errors (in runoff measurement) caused by time of travel differences between the top and bottom of the plot, and inherent storages in the collecting pan and tubing.

All the plot 9 values that represented dry antecedent moisture conditions were plotted (fig.2) in an attempt to evaluate the variation of runoff with duration and intensity. The resulting plot may have too few points to be really meaningful but nevertheless does show a very definite trend towards the 100 percent line with increased duration. All of these points represent rainfall after a dry period of several days. It would appear that changes in soil moisture, during the storms under consideration, had a profound effect on the total runoff.

TABLE 4

STORMS RANKED BY PEAK DISCHARGE

(All in millilitres/3 minutes for 4 square metres)

Period	Otutaru	P	Q9	Q8
42	8,705	15,000	?	?
26	4,742	19,200	15,000	18,000
4	503	9,867	2,000	1,800
31	337	10,000	5,400	3,990
34	202	5,400	500	180
24	41.3	2,267	274	253
22	11.4	3,880	431	38.4
10	10.7	2,000	44.1	19.7
20	5.68	14,000	9,000	7,500
1	2.37	1,000	17.7	2.6
6	1.44	5,200	50.0	25.0
7	1.44	1,700	40.2	28.8
11	0.518	1,467	27.5	3.0
16	0.518	2,933	48.0	37.0
18	0.289	1,120	25.4	45.6
12	0.032	400	4.5	1.5
13	0.032	1,093	11.6	3.0
30	0.018	600	3.3	0.2
25	0.018	1,867	60.0	40.0
9	0.005	222	0.5	-

The plot 9 values that represented completely wet antecedent moisture conditions were also plotted (fig.2) for comparison. The number of points is limited because only a few storms contain discrete recognisable blocks of runoff that can be confidently associated with a particular block of rainfall.

A series of approximate curves can be drawn through points with equal antecedent conditions to highlight the changes. Note in fig.2 that all the "wet" points tend to fall along a single line, well away from the 100 percent maximum. Thus for any given rainfall intensity it should be possible to derive a runoff value corresponding to a particular duration, starting with either dry or wet conditions. Such a graph is interesting but of only limited practical value because most storms exhibit considerable fluctuations in soil moisture conditions during the storm period.

The problem is to know which moisture conditions apply at any given time in a particular storm. With two independent variables and two more or less dependent, the relationships cannot be satisfactorily represented on a piece of graph paper without first solving the dependence of soil moisture conditions on rainfall duration.

An index of rainfall intensity can be derived for the twenty single event storms by ranking on the basis of peak discharge produced at Otutaru structure (table 4). Such a procedure is based on results from previous studies which show that for pumice soils and small areas, peak discharge is dependent principally on rainfall intensity (Pittams, 1970; Selby, 1971).

Plot 9 values were plotted first because certain important storms were inadequately recorded at plot 8. The results from plot 8 endorse those from plot 9 but for most rainfall intensities less runoff occurs at plot 8 - approximately half to two-thirds the runoff at plot 9 - for the same interval. At very high intensities the rates of runoff are approximately equivalent with a tendency for plot 8 to show a faster rate of increase so that runoff from plot 8 may exceed that from plot 9.

Remember (table 1) that rainfall volume decreases in the order of 12.5 percent from plot 8 (paired raingauge site 2) to plot 9 (paired rain gauge site 3). Rainfall intensity will decrease in the same proportion. The tendency for more runoff to be produced at plot 8 than at plot 9 under extreme high rainfall intensities may simply be an expression of the relative intensities. At lower intensities the difference in rainfall makes the difference in runoff values between plot 8 and plot 9 even more interesting.

Fig. 3 OTUTARU RAINFALL RUNOFF INTENSITY RELATIONSHIPS

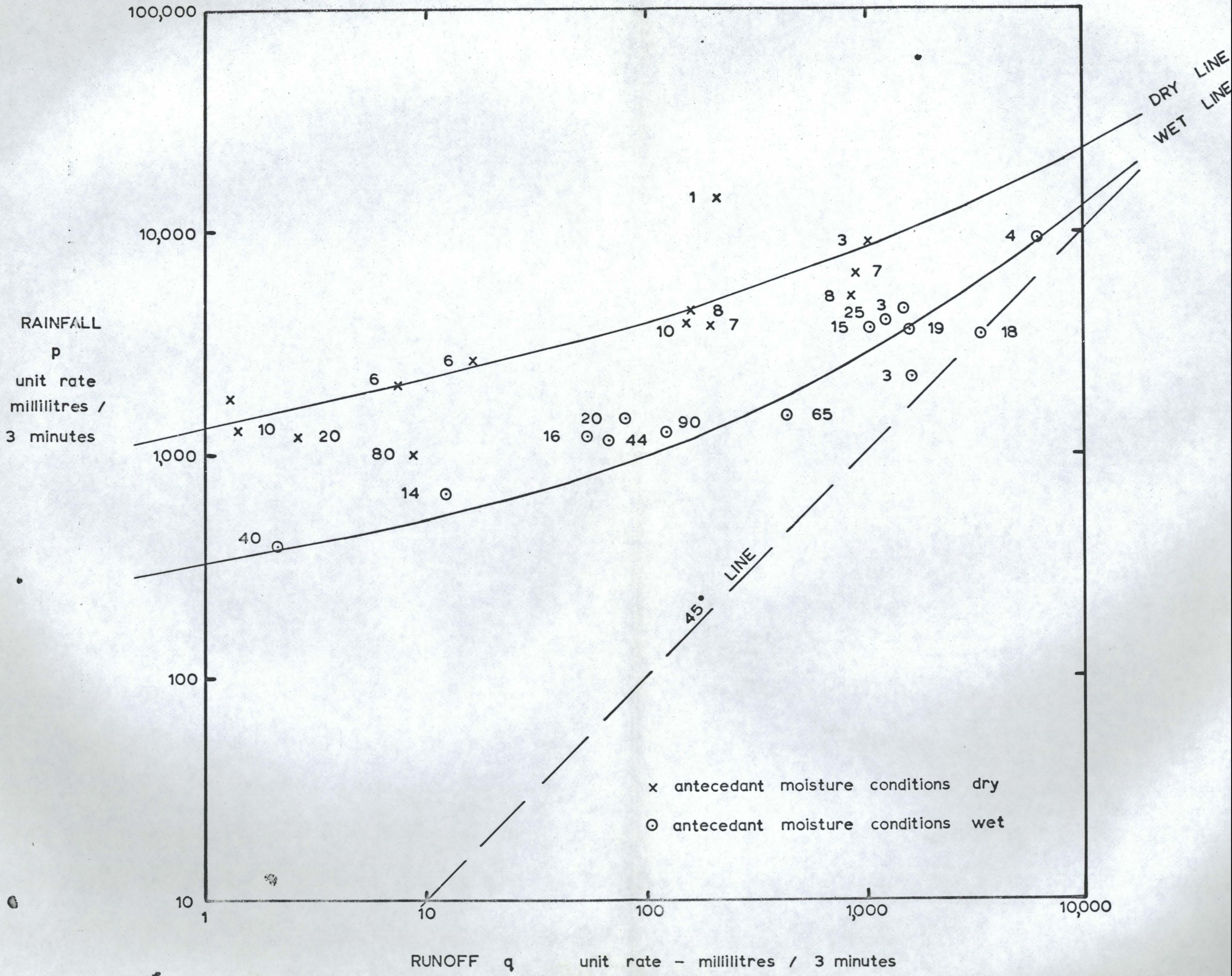


Fig. 4

OTUTARU SINGLE EVENT STORMS

PEAK DISCHARGE V TOTAL STORM RUNOFF

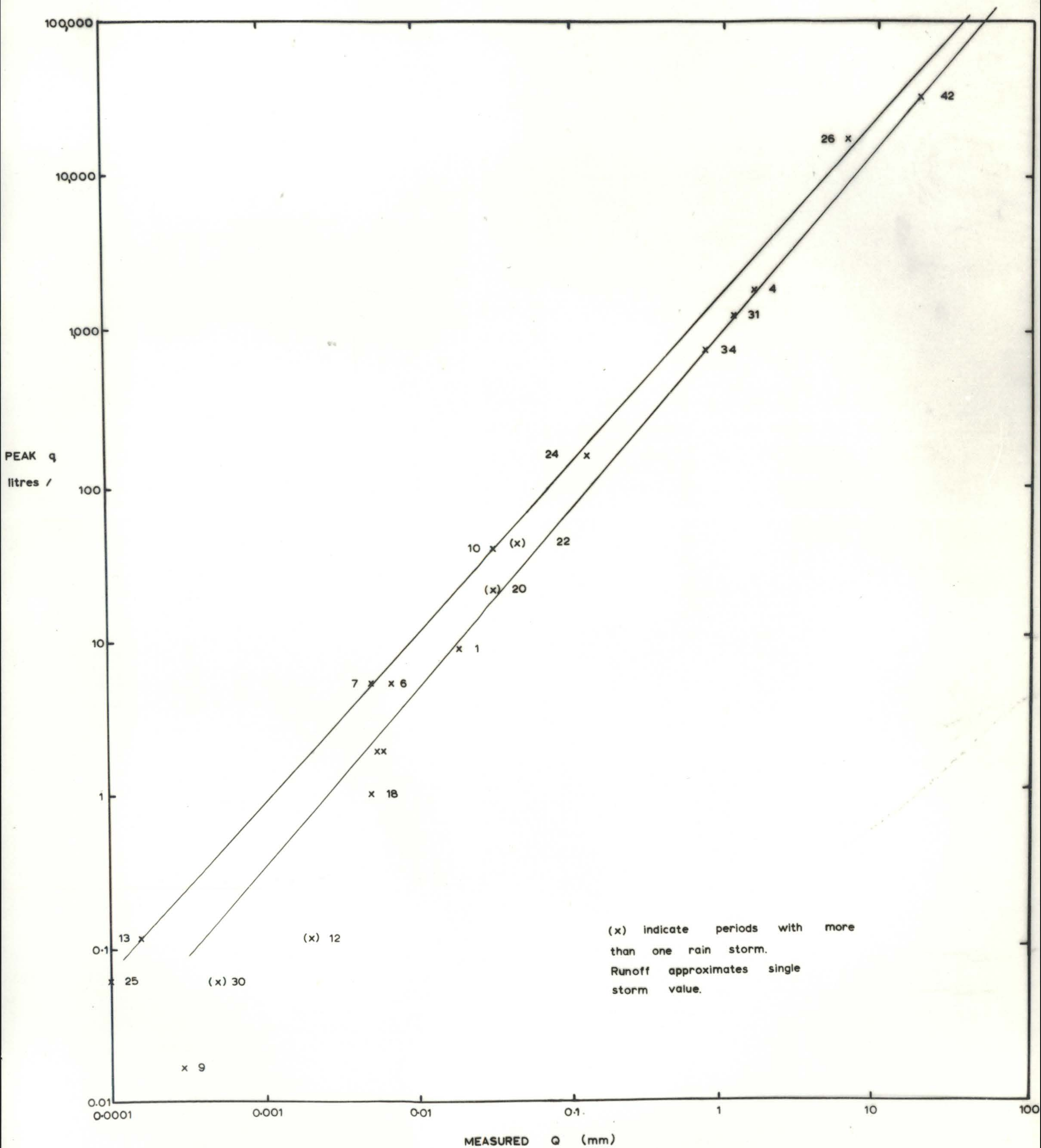


TABLE 5

CALCULATION OF RUNOFF FOR MULTIPLE PEAK STORMS

Period	Interval	Peak Discharge (Litresper Minute)	Q Estimated (mms)	Q Measured (mms)
15	a	28.63	0.0245	
	b	345.9	0.235	
	c	164.1	0.121	
	Total		0.3805	0.926
28	a	286.8	0.196	
	b	1751.15	0.980	
	Total		1.176	1.123
19	a	2008.4	1.105	
	b	1203.1	0.700	
	Total		1.805	2.167
14	a	0.068	-	
	b	26.59	0.023	
	c	37.38	0.030	
	d	16.31	0.015	
	e	59.27	0.048	
	f	12.27	0.011	
	g	53.27	0.043	
	h	3330.6	1.720	
	Total		1.890	1.830
32	a	913.32	0.542	
	b	0.272	0.0003	
	c	0.119	0.0002	
	d	0.731	0.0008	
	e	117.4	0.163	
	f	392.3	0.259	
	g	91.33	0.070	
	h	16.31	0.0145	
	Total		1.050	1.263

OTUTARU RESULTS:

The data from Otutaru were plotted (fig.3) using the same units as for the plots. The resultant graph shows very similar relationships with intensity duration and antecedent moisture conditions to those for the plots.

The main feature of the results is the way in which catchment runoff per unit area, which starts after a much higher intensity of rainfall than is required to produce runoff from a plot, increases until in extreme cases it approaches peak plot runoff rates and may exceed plot runoff volumes.

When the peak discharges are plotted against total runoff from the 20 single event periods (fig.4) a good linear relationship is obtained. The relationship simply means in effect that each of the Otutaru hydrographs is approximately triangular. Departure from triangularity is indicated by failure to fit the upper line, the points on which represent storms dominated by a single burst of high intensity rainfall. Points along the lower line indicate influence from additional lower intensity rainfall.

Runoff has been calculated for five multiple peak storms (table 5) using this relationship and the agreement between predicted values and the total volume recorded is very good. The process amounts to determining the component peak discharges and deriving runoff from each, assuming triangularity for each hydrograph.

TABLE 6

PLOT DATA ARRANGED BY ASPECT AND SLOPE

Plot	Slope (Degrees)	Total % Runoff (44 Periods)	Bulk Density	Organic Matter (Weight As % of Sample)
EAST FACING SLOPES:				
9	33	6.56	0.74	12.8
5	26	3.66	0.58	20.8
14	22	4.85	0.69	16.8
8	20	5.34	0.60	18.8
7	16	6.88	0.76	13.1
13	12	5.06	0.66	16.3
6	10	4.31	0.75	10.7
WEST FACING SLOPES:				
4	25	3.49	0.63	15.1
12	22	5.76	0.69	10.6
1	15	5.23	0.67	11.4
11	13	5.57	0.72	11.5
2	12	2.65	0.61	15.1
3	10	2.92	0.79	10.9
10	7	2.08	0.64	13.6

PLOT CONTRIBUTIONS:

The fourteen plots can be arranged in two sequences - those facing east, and those facing west. Further subdivision for comparison can best be based on slope. When the total rainfall and runoff for the 44 periods are accumulated and compared (table 6) the results exhibit considerable uniformity with a general trend towards greater runoff production on steeper slopes. Selby (1971) in his section on causes of runoff quotes several regression analyses using some 27 variables. Simple linear correlations were determined between each of the independent variables and the dependent variable (runoff), The summarised results show that only precipitation variables are closely correlated with runoff, and that the degree of correlation rises with the increasing intensity of the rainfall. His multiple regression analysis in stepwise form shows that maximum rainfall falling in half an hour explains 55.4 percent of the runoff from pasture areas, The addition of the highest maximum air temperature increases the explanation to 61.2 percent and the further addition of the duration of rainless time increases the explanation to 62.7 percent. The equation at this stage is:-

Predicted runoff = - 16596.516
+ 1586.105 (max. precip. 0.5 hour)
+ 589.993 (highest temperature)
+ 7.171 (duration of rainless time)
(where $R^2 = 0.627$, $F = 343.084$)

The addition of further variables adds little to the explanation and the prediction equations are not carried beyond this step.

In his analyses of plot data from other vegetation types in the adjacent area of Otutira, other important variables emerge. Penetration resistance was the second most important variable in the overall analysis. From this Selby concluded that the importance of many soil properties - each only slightly correlated with runoff - is subsumed in the penetration resistance. Slope angle occurs as the second most important variable in the undeveloped areas but for Otutaru he states that slope is unimportant, having a correlation coefficient of only 0.042 with runoff. Soil particles of 0.63-6.35 mm diameter enter his multiple regression equation for the undeveloped area at the fourth step. This variable is negatively correlated with runoff, indicating that runoff decreases as the proportion of this coarse sand to fine gravel fraction in the soil increases. Dr Selby presumes that this is because the presence of this fraction increases soil permeability.

Dr Selby in his comments on the rather low level of explanation states that "a higher level of explanation would be achieved if instead of

TABLE 7

20 STORMS FOR ANALYSIS (ALL IN MILLIMETRES)

Period	Rainfall	Q9	Q8	Q.AV.	Otutaru	Dominant Plots
1	82.3	0.7295	0.1620	0.1524	0.0192	9, 14
4	61.1	5.2000	6.0000	5.7840	1.5860	12
6	47.3	0.2050	0.1155	0.3391	0.0068	7
7	40.4	0.2010	0.1440	0.2130	0.0051	14
9	16.1	0.0200	0.0115	0.0177	0.0170	Very uniform (11 dry)
10	17.8	0.1905	0.0740	0.2366	0.0325	14
11	36.9	0.0695	0.0125	0.0617	0.0055	14
12	20.0	0.0455	0.0145	0.0363	0.0020	14
13	8.2	0.0435	0.0110	0.0164	0.0006	14, 1
16	11.4	0.0360	0.0275	0.0992	0.0060	12
18	16.6	0.0635	0.0750	0.0792	0.0051	11
20	55.5	1.5000	1.5750	2.3650	0.0320	7, 14
22	87.9	1.4075	0.1710	0.7580	0.0464	1
24	10.4	0.6115	0.6295	1.1160	0.1340	11, 7, 1
25	5.1	0.0290	0.0500	0.0289	0.0001	1
26	28.7	12.7625	14.0250	10.1200	6.4300	11, 7
30	26.2	0.0760	0.0035	0.0072	0.0005	8,9,12 (rest dry)
31	20.4	5.4250	5.2650	4.1540	1.1710	9,8 (but very uniform)
34	68.9	0.8075	0.4090	0.7722	0.7750	1, 3
42	68.1	14.4500	14.2750	12.5300	18.9560	7, 11 (but all high except 2, 3, and 10)

agglomerating data for all observation periods and for the three vegetation types the data were split either for analysis by storm type or by individual plots."

When the data is separated for analysis by individual plots on pasture grass alone site factors such as slope, bulk density and organic matter content - data derived from Table 3.1, page 34, Selby, 1971 - appear to influence runoff totals. The combinations of high organic matter and low bulk density may result in a lower runoff total than the site alone would suggest. In this way, plots 4 and 5 whose soils have low bulk densities and high organic matter content would perhaps be expected to show less runoff than plots 12 and 14 with similar slopes but higher bulk densities and lower organic matter content. The pitfalls in such a conclusion are demonstrated by plot 8 with slightly lower slope where low bulk density and high organic matter content are accompanied by a high runoff total. Rainfall differences possibly become significant at this point.

The storm period which produced the largest volume of runoff was number 42 (Table 7) in February 1971. This period approximates to a single event period. At 15,000 millilitres/3 minutes for 4 square metres, the rainfall intensity was not the largest recorded but it lasted about 15 minutes and the peak discharge for Otutaru catchment was almost twice that of the next most intense storm (in period 26). Unfortunately neither of the automatic recorders on plots 8 and 9 was functioning at this time. All seven plots on the east facing slopes recorded very high runoff values, as did plots 4, 12 and 11 on the west facing slopes. Plots 1 and 10 however recorded rather less runoff and plots 2 and 3 recorded only about a third of the runoff from the other plots.

In period 26 the four steepest plots on each side recorded almost as much runoff as in period 42. The remaining six plots show a very marked decrease in runoff with decrease in slope except that plot 2 recorded least runoff. These two periods (42 and 26) stand out from all the rest on the basis of rates and volumes of runoff produced.

The next biggest storms (4 and 31) show very similar volumes from each of the plots, with no one plot being notable for either high or low runoff. The values fall in two groups with the higher values almost precisely twice the lower values. The interesting feature is that in period 4 the plots on the west facing slopes dominate the higher group (though plots 13, 9 and 14 are present from the east facing slopes) while in period 31 the plots from

TABLE 8

INDIVIDUAL PLOT DOMINANCE IN RUNOFF TOTALS

(In Order Of Response) : Notable Values Underlined

Period															
4	12	3	2	4	13	8	11	1	14	5	7	10	6	9	
31	9	8	2	7	11	12	6	1	13	3	10	5	4	14	(very uniform)
34	1	3	14	12	13	9	5	4	7	6	2	8	11	10	
24	11	7	1	13	4	12	2	6	8	5	9	14	3	10	
22	1	14	9	12	5	7	13	2	8	11	6	3	4	10	
10	7	14	12	13	5	2	11	6	8	9	1	4	3	10	
20	14	1	2	12	3	13	9	7	4	5	11	8	10	6	
1	9	14	7	12	3	11	2	1	8	10	13	6	4	5	
6	7	3	1	4	14	13	12	2	9	11	6	5	8	10	
7	14	4	9	13	7	1	8	12	6	5	2	3	11	10	
11	14	1	2	7	12	9	3	4	5	13	8	10	11	(6 dry)	
16	12	1	11	2	14	6	5	7	9	8	4	10	3	13	
18	11	7	8	14	2	9	12	1	6	5	10	13	(4	3 dry)	
12	14	1	12	8	9	7	5	2	4	13	10	(11	3	6 dry)	
13	1	14	9	7	8	4	2	3	(rest dry)						
30	8	9	12						(rest dry)						
25	1	7	6	8	2	9	3	5	12	10	4	11	14	13	
9	8	7	4	5	10	14	9	1	12	3	13	2	6	(11 dry)	
17	5	3	9	12	8	7	14	13	11	2	4	1	6	(10 dry)	
3	1	12	9	8	11	5	10	14	(rest dry)						
27	10	12	11	4	5	3	6	1	2	14	13	8	(7	9 dry)	

the east facing slopes are very slightly the more important group.

The rainfall direction for storm 4 was northwest with a moderate wind blowing while that for storm 31 was west with a light breeze. This demonstrates the effect aspect and wind speed can have on runoff response.

The remaining sixteen storms can be considered in three size groups (Table 8). Periods 34, 24, 22, 10 and 20 comprise the remaining five storms of any size. Plots 1, 11, 7, and 14 are dominant for the group with combinations of various others. Specific plot dominance is most marked in storm 20 but is important in storm 24 also. Period 20 is the sole representative of rainfall from due east. Wind speed was apparently moderate. Plots 7 and 14, both facing east, recorded notably high runoff values. Plots 9, 8 and 13 also facing east recorded moderate runoff values while the only plot from the west facing slopes with a comparable total is plot 12. Period 24 comprises a north west storm with a strong wind blowing. The plots facing west dominate the runoff values but with plot 7 and to a lesser extent plot 13 from the opposite slopes also recording high values. All the remaining east facing plots recorded low runoff values with the lowest totals from the steepest slopes. The plots with lowest west facing slopes show a decrease in runoff with decrease in slope. The remaining three storms show very uniform totals except for high values from plot 1 in storm 22 and plot 14 in storm 10. All are moderately windy storms from north-north-west to north.

The group of minor storms composed of periods 1, 6, 7, 11, 16, 18, 12 are notable only for the relative importance of plots 14, 7, and 1. These three appear to be particularly responsive to lower rainfall intensities, but no particular explanation is available.

The group of smallest storms can be divided into those (13, 30, 25 and 9) for which runoff was recorded at Otutaru catchment outlet, and those (17, 3, and 27) for which runoff was not recorded at the catchment structure. Although runoff at Otutaru structure was approximately the same for each of storms 13, 30, 25 and 9 the effect of rainfall duration differences is clearly demonstrated for the plots. For these storms increasing intensity is more than balanced by decreasing duration. In this way plots record decreasing runoff from increasing rainfall intensity. Rainfall totals range erratically from 4 millimetres to 48 millimetres.

The runoff values for each of the twenty storms were plotted against

Fig. 5 RUNOFF FROM PLOTS 10 AND 11

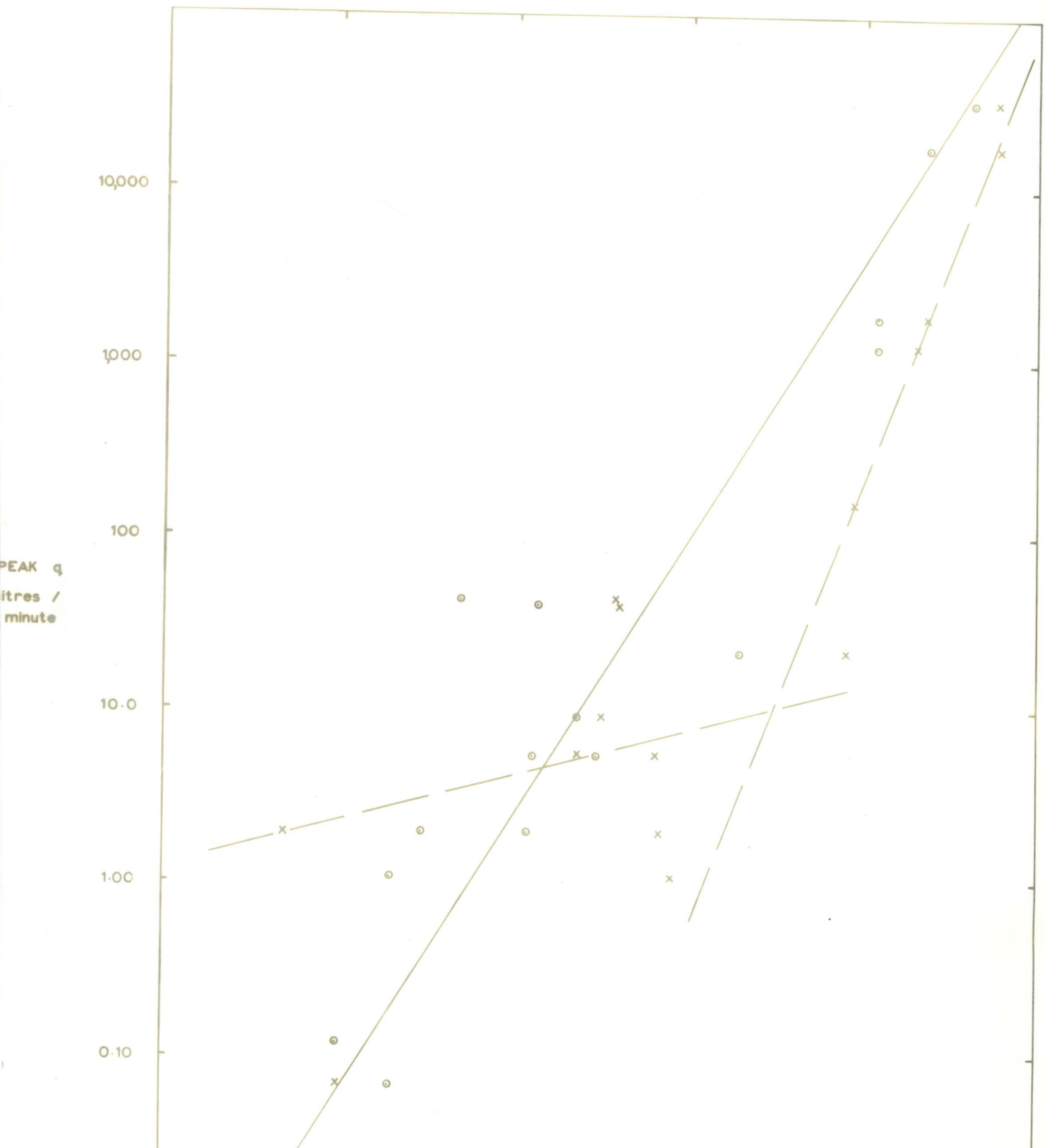
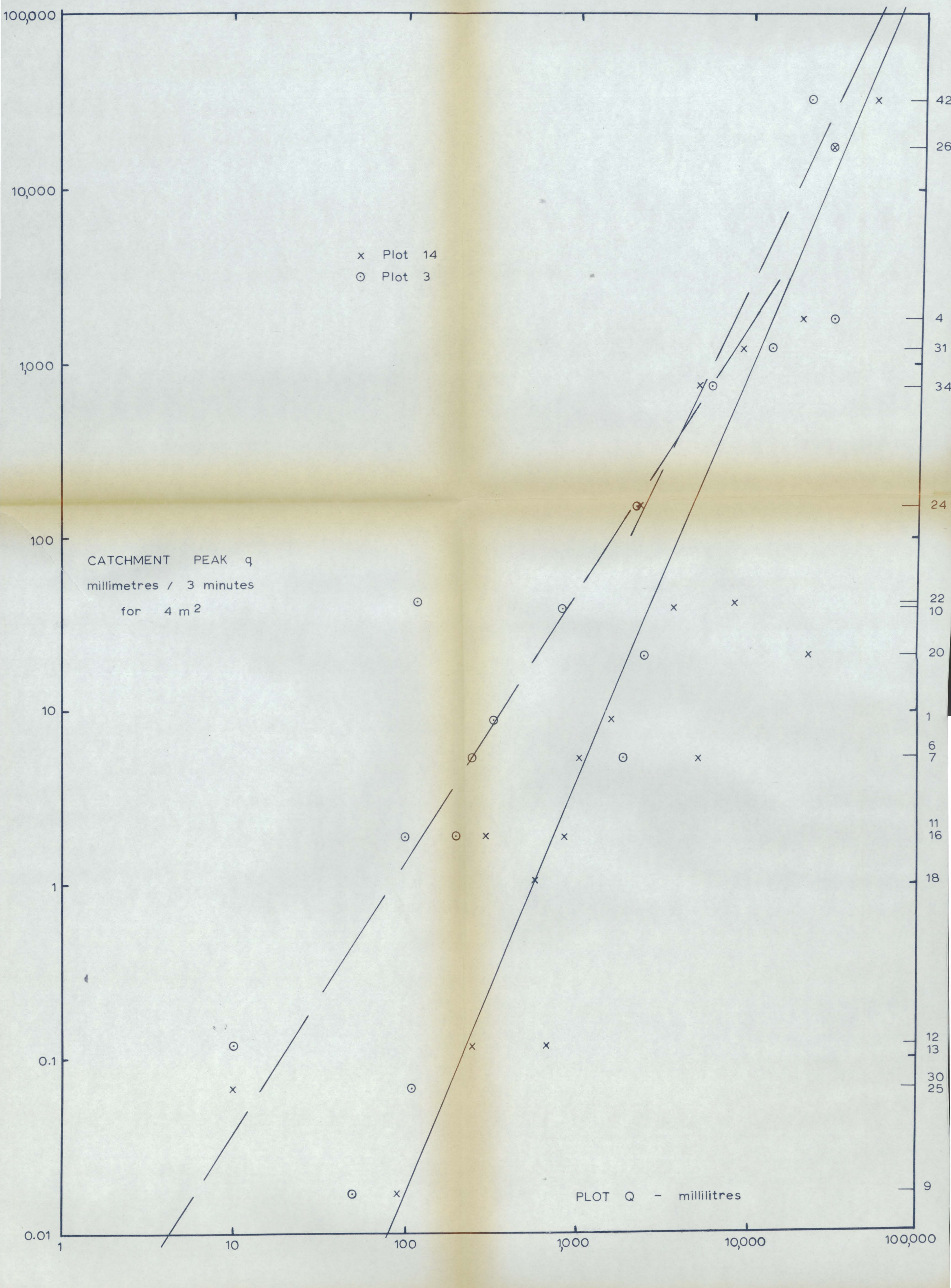


Fig. 6 PLOT RUNOFF V CATCHMENT PEAK DISCHARGE



Otutaru catchment peak discharge for the respective storms, using data from plots 14, 3, 11 and 10 (figs. 5 and 6). Relationships are suggested by the lines to emphasise erratic values such as those for all four plots in storms 22 and 10 where recorded runoff appears inadequate. Both storms resulted in very uniform values for plot runoff (as described earlier) and no simple explanation can be offered for the position of such values on the graph.

Selby, 1971, obtained 62.7 percent explanation of runoff by his multiple regression analysis. The remaining 37.3 percent can probably be partly ascribed to large numbers of variables, each relatively unimportant, and partly because rainfall intensity can be better described with a three minute time interval than with the 15 minute time unit used by Selby.

FIG. 7 PLOT RUNOFF V CATCHMENT RUNOFF

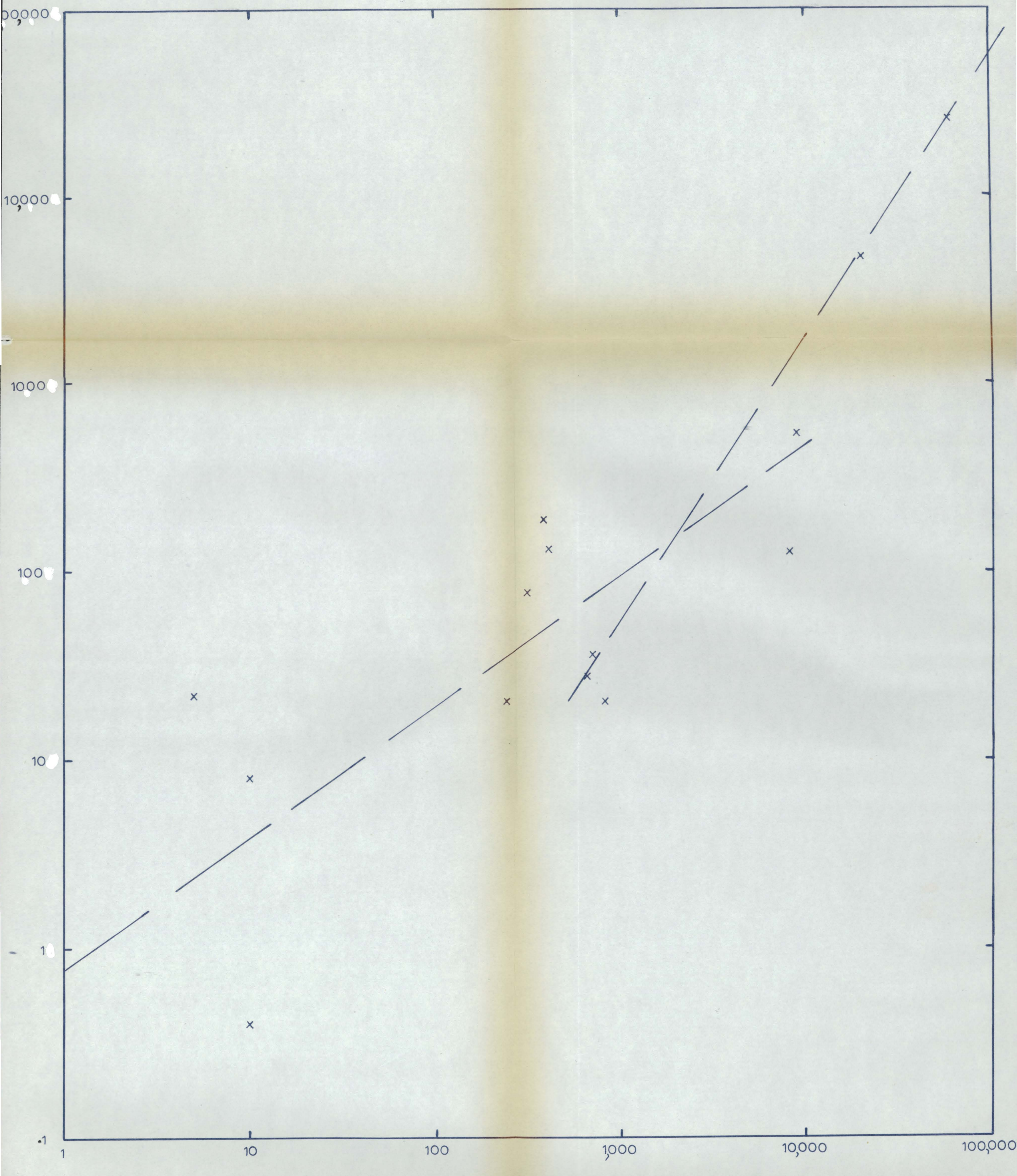


TABLE 9

INVESTIGATION OF MULTIPLE STORMS

Period	Type	Q.Av. (All Plots)	Q.11	Q.Pred. (Plots)	Q.Pred (from 11)	Otutaru
19	Double	24,182	47,210	6,8 00	18,0 00	8,6 66
14	Multiple	11,604	9,100	2,2 00	1,6 00	7,3 18
28	Double	17,070	22,900	3,9 50	6,0 00	4,4 93
15	Triple	4,039	320	4 50	42	3,7 02
5	Triple	1,772	660	1 39	70	6 19
23	Single	497	1,750	58	1 35	56
29	Double	2,945	720	2 80	74	1
37	Multiple	5,007	3,630	6 20	3 80	18,6 59
39	Multiple	14,391	9,100	3,0 00	1,5 50	10,5 40
41	Multiple	23,602	19,500	6,4 00	4,8 00	5,5 02
43	Double	23,084	13,250	6,2 00	2,7 50	1,6 81
33	Triple	792	20	80	6	1,3 92
44	Double	720	250	74	25	40
40	Double	1,495	210	1 22	31	2
38	Double	362	550	46	62	2

All runoff values expressed as millilitres/unit area of 4 square metres.

RELATIONSHIP BETWEEN PLOTS AND CATCHMENT:

There appears to be close agreement between runoff generation from the plots and runoff recorded at the catchment site.

Graphs of plot runoff against Otutaru catchment peak discharge (figs.5 and 6) or total storm runoff (fig.7) give an indication of variability within the individual relationship. Plots very closely related to catchment runoff will show least variation from the suggested relationship.

From these graphs it is concluded that plot 11 in particular is a good indicator of catchment response. Plot 11 is also interesting because it is apparently affected by rainfall in two ways. At low rainfall intensities (below 1000 millilitres/3 minutes for 4 square metres) the plot does not respond at all under single event conditions. Initiation of runoff is evidently dependent on rainfall duration when intensity is low, and runoff variability is high. However after a certain rainfall intensity has been reached (about 3000 ml/3 minutes for unit area of 4 m^2) the relationship steepens and stabilises, indicating a complete dependence on rainfall intensity.

A series of runoff values for multiple storms has been calculated (Table 9) using the plot values to indicate runoff response. The values for plot 11 appear too unreliable to be used by themselves but even the average of all plot values for a given storm does not improve the prediction.

CONCLUSIONS:

In the preceding chapters a number of relationships have been described from which several conclusions about the origin of overland flow in Otutaru may be derived.

It has been shown that almost all rain is accompanied by wind blowing from the directions including west, north and east, and points between. The plots can be grouped into west facing and east facing series for analysis of the influence of aspect, wind direction and wind speed. The major effect of aspect, wind direction, and wind speed is concluded to be the way in which rainfall totals vary on the slopes under investigation. In this study such an effect is referred to as a lowering of rainfall mass density.

Wind direction has a slight effect on relative totals from individual plots if the wind speed is high. Increase in wind speed appears to occur locally around the slopes resulting in a greater rainfall inclination from the vertical than that measured at the flat meteorological site at the north end of the catchment.

The plot records show good relationships between rainfall intensity and runoff volume when antecedent moisture conditions are held constant. The duration of rain is important in that the antecedent conditions change during the storm. It has been shown that there is a trend towards greater runoff production on steeper slopes when the additional site factors such as bulk density and organic matter content are taken into account.

The peak discharge values recorded at Otutaru catchment outlet provide a useful method of integrating rainfall intensity and duration so that the storms can be ranked on a system approximating rainfall effectiveness. Only single event storm periods can be satisfactorily handled by this system but 20 of the 44 periods approximately meet this requirement.

When analysis is concentrated on these 20 periods a number of relationships can be built up between individual plots and Otutaru catchment, using either peak discharge or total runoff. The variation within each postulated relationship is largely inexplicable. Furthermore, such variation becomes accentuated in attempts to relate plot runoff to catchment runoff in the other 24 periods.

Nevertheless it has been shown that the runoff response to rainfall intensity is very similar between each of the plots and between plots and catchment. It is concluded therefore that overland flow is generated throughout Otutaru catchment when rain of sufficient intensity occurs. Initially the bulk of this flow is lost by infiltration in the valley bottom but after rain of a certain volume or sufficient intensity has fallen, the whole catchment appears to contribute very uniformly to Otutaru runoff. Over a period of time the slopes produce relatively greater flow than the hilltops and valley bottoms, but all areas contribute significantly to catchment runoff.

Overland flow is the initial phase of surface runoff. It is sometimes referred to as sheet flow because the water is envisioned as moving in a sheet downslope over a plane surface to the nearest concentration point or channel. Overland flow is both unsteady and spatially varied since it is supplied by rain and depleted by infiltration, neither of which is necessarily constant with respect to time and location (Emmett, 1970).

This emphasis on the role of surface infiltration and the implication that there is a sharp demarcation between the rainfall which infiltrates and the rainfall in excess of infiltration capacity which, as overland flow, is responsible for all immediate storm runoff, is the result of work by R.E. Horton (1945) and subsequent disciples (especially Emmett 1970). The Horton model assumes that, for a prolonged storm of constant intensity, a continuous decrease of the infiltration capacity occurs until a constant low value is reached. If, at any time, the infiltration capacity falls below the rainfall intensity, overland flow begins all over the hillslope. When the whole soil column is saturated, it drains at a transmission capacity which is generally greater than the minimum infiltration capacity, due to the absence of air escaping upwards from the soil voids.

Horton's model of hillslope runoff is most appropriate to unvegetated slopes which have low infiltration capacities and little soil development, or to climates which are dominated by a few prolonged heavy rain storms. In recent years, this model has been questioned in humid areas, where infiltration capacities are high and where, often, storm intensities are relatively low. Where there is appreciable soil and vegetation, and especially where there is a humus or litter cover, surface runoff is said to be slight except in the most extreme storms.

Carson (1971) has summarised the recent investigations of ephemeral flow in the early part of his paper, which is the latest in a series which tends to support the "partial or variable area" concept inferring that saturated areas which develop near to the channel network during storms are extremely important in producing storm runoff. Such saturated areas may contain some new rain - that is, some of the actual drops that fell during the storm - and the other fraction may be what Hewlett and Hibbert (1967) call translatory flow, or flow produced by a process of displacement. Such movement may be regarded as due to thickening of the water films surrounding soil particles and a resulting pulse in soil moisture migrating downhill.

The results obtained for this study from Otutaru catchment therefore comprise a paradox. It is situated in a humid area where infiltration capacities are very high and where, often, storm intensities are relatively low. Some flow may be the result of "throughflow" or "translatory flow" but nevertheless all the results presented in this study indicate that overland flow is the principal form of runoff in the catchment and that if, at any time, the rainfall intensity rises above the infiltration capacity, overland flow will begin all over the hillslope. The variables are difficult to define precisely and the use of a simple procedure for predicting overland flow is beset with many difficulties.

No individual paper has yet been written which completely satisfies all the observed variability or reconciles the various conflicting hypotheses. One of the reasons may be that both the depth of the regolith over the basin and the length of the slope segment feeding the stream are variables which at different times under rainfall tend toward independence of normally measured features of catchments, such as area, slope, channel length, and so on.

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