THE GLOBAL HYDROLOGY EDUCATION RESOURCE

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ABSTRACT

This article is a selective overview of a range of contemporary teaching resources currently available globally for university hydrology educators, with an emphasis on web-based resources. Major governmental and scientific organizations relevant to the promotion of hydrology teaching are briefly introduced. Selected online teaching materials are then overviewed, i.e. PowerPoint presentations, course materials, and multimedia. A range of websites offering free basic hydrology modeling software are mentioned, together with some data file sources which could be used for teaching. Websites offering a considerable range of general hydrology links are also noted, as are websites providing international and national data sets which might be incorporated into teaching exercises. Finally, some discussion is given on reference material for different modes of hydrology teaching, including laboratory and field exercises.

Keywords: hydrology, hydrology education, web-based materials, online teaching resources, teaching modules

1. INTRODUCTION

Hydrology is an interdisciplinary natural science taught within both science and engineering courses concerned with the occurrence, properties, distribution, and movement of water in the natural and man-made environment (Elshorbagy, 2005). It is a relatively recent arrival as a fully developed science and has borrowed heavily from more established sciences including hydraulics, geology, and meteorology (Langbein, 1958). By the 1970’s significant water resource developments on the one hand and a developing awareness of environmental problems on the other brought about the need for recognition of appropriate educational modes, both in the science and the profession of hydrology (Nash, Philip, & Van Der Molen, 1990). In this context there has been some discussion as to the best disciplinary framework for locating hydrological teaching – see, for example, (Klemes, 1988).

There was a strong call in the 1990's for the development of hydrology as an established taught science because few undergraduate programs existed (Eagleson et al, 1991). Part of subsequent educational and training development included the establishment in 2003 of the UNESCO-IHE (International Institute for Hydraulic and Environmental Engineering) which carries out research, education and capacity building activities in the fields of water, environment, and infrastructure (UNESCO-IHE, 2011).

More recently, Wagener et al (2007) conducted an online survey of 158 university hydrology educators, mainly from USA. The result showed little commonality of hydrology teaching resources. Many instructors were using original material so that they needed to spend considerable time to prepare lectures via multiple resources. Most participants reported they spent three to five hours to prepare for one hour of class time. Even while teaching the same course subsequently they still needed to spend one to two hours of preparation and updating. This overview is motivated in part by a desire to give reference to a selection of currently available resources, recognizing that any such selection can become quickly dated.

The basic aim for any teaching is to deliver ideas, knowledge, information, and data to students. Ideally, teaching should inspire students to think further about the subject area. However, the university-level teaching resource for hydrology in its many facets is somewhat scattered and is always changing. This review seeks to present a selective overview of current available university hydrology teaching resources with emphasis on the undergraduate level. It is recognized that the selection process will mean some potentially useful material is omitted and some content will be seen as irrelevant. However, the hope is that hydrology educators will find some material that will aid them in gathering resources more efficiently. There is no implication of judgment as to what material should be taught and within what framework. Such considerations must remain the domain of those involved in the teaching process. However, a few general concluding comments will be offered on aspects of hydrology teaching.

2. TEACHING RESOURCE CATEGORIES

2.1 Hydrology Texts and Journals

No attempt is made in this overview to carry out a comprehensive review of available hydrology texts as numerous reviews are available. Textbooks can be helpful as either providing selective support material or providing a framework for course organization. Langbein (1958) cites the first hydrology textbook as printed in 1862, and a large and growing number of texts have subsequently appeared. However, in the United States at least, there does not appear to be any single general hydrology text presently dominating the market. The survey by Wagener et al (2007) indicated that 39% of the 158 survey participants did not use a textbook at all, while the rest collectively gave reference to some 52 different texts. There were just three texts used with some degree of commonality - *Physical Hydrology* (Dingman, 2002), *Applied Hydrogeology* (Fetter, 2001), and *Elements of Physical Hydrology* (Hornberger et al, 1998).

A good starting point to check currently available hydrology texts is *Geometry.net* which is an Amazon-linked online learning center:

General hydrology: http://www.geometry.net/science/hydrology.php

Groundwater: http://www.geometry.net/science/groundwater.php

Water resources: http://www.geometry.net/earth_sciences/water_resources.html

There are a large number of published hydrology-related journals concerned with research publication. However, to our knowledge there are none with specific focus on presenting material for university teaching purposes. Some review journals such as *Progress in Physical Geography* provide good sources of teaching material from time to time for specific subject areas. The practicalities of cost can be a significant factor in gaining access to teaching resources in developing nations. The Directory of Open Access Journals (DOAJ) may be of help here and a search at http://www.doaj.org will reveal hydrology material among the many open-access journals listed.

2.2 Major National Science Agencies and International Scientific Societies

Though not specifically concerned with hydrological education, national science organizations and the scientific societies can be good sources of material. The main players with a strong hydrology link are:

- **United States Geological Survey** http://water.usgs.gov/

The United States Geological Survey (USGS) was established in 1879. It collects, monitors, analyses, and provides scientific understanding about natural resource conditions, issues, and problems, including water resources.

- **American Geophysical Union** http://www.agu.org/

The American Geophysical Union (AGU) was established in 1919 and is now an international non-profit scientific association. It provides a forum for earth, atmospheric, oceanic, hydrological, space, and planetary scientists to advance research and collaborate with colleagues across disciplines. Much hydrology-related material suited to teaching can be obtained via the AGU web site. Of particular interest is the lecture video archive which includes hydrology presentations from AGU Spring and Fall meetings. http://www.agu.org/meetings/lv_archive.shtml.

- **European Geosciences Union** http://www.egu.eu/

The European Geosciences Union (EGU) was founded in 2002 as a merger of the European Geophysical Society and the European Union of Geosciences. Like AGU, it is interdisciplinary learned association devoted to the promotion of the sciences of the Earth and its environments. The EGU's online journals are freely available and can be relevant to hydrology teaching. Since April 2010, a hydrology education session has been part of the EGU annual General Assembly meeting.

- **International Union of Geodesy and Geophysics** http://www.iugg.org/

The International Union of Geodesy and Geophysics (IUGG), established in 1919, is the world international body for Earth Sciences. It incorporates the major world Earth Science scientific bodies, including IAHS (see below).

- **International Association of Hydrological Sciences**
  http://www.iugg.org/associations/iahs.php

The International Association of Hydrological Sciences (IAHS) has many links giving access to hydrological information which could be included in university hydrological teaching. It has a recently established a Working Group on Education in the Hydrological Sciences which met for the first time as part of the IUGG conference in Melbourne, in July 2011.

2.3 Online Material Directly Related to Hydrology Teaching

There are a large and growing number of resources for support of university hydrology teaching on the web, ranging from full course material to collections by enthusiastic individuals. The sites listed below, in no particular order, should only be taken as a sample of what is available because new material is constantly appearing. However, some web sites might no longer be maintained and no guarantee is made that any web sites listed here or elsewhere in this review will be available into the future.

- **HydroViz** http://hydroviz.cilat.org/hydro/index.html

HydroViz is designed to support active learning in Engineering Hydrology. It developed as a joint effort between researchers in the Civil Engineering Department and the Centre for Innovative Learning and Assessment Technologies at the University of Louisiana at Lafayette. HydroViz is primarily designed to be used in junior/senior/graduate level courses on hydrology, water resources engineering, or other related subjects. Its selected modules can also be used in introductory-level courses for new engineering and Earth science students to deliver basic hydrological concepts.

- **MetEd** https://www.meted.ucar.edu/

Meteorology Education (MetEd) is a distance education project operated by COMET (Cooperative Program for Operational Meteorology, Education and Training). The COMET programme at UCAR in Boulder, Colorado routinely develops web-based teaching and training material in collaboration with government agencies and the university community. Hydrology-related topics presently available include hydrological analysis and forecasting, quantitative precipitation estimation and forecasting, drought, and forecast verification. These subjects are presented in the form of online modules and courses and supported by case studies.

- **MOCHA** http://www.mocha.psu.edu/

The Modular Curriculum for Hydrologic Advancement (MOCHA) was established to form an online faculty learning community for hydrology education and to develop a modular hydrology curriculum. The overall objective is to create a continuously evolving core curriculum that overcomes traditional disciplinary biases develops from inputs in the Wikipedia tradition. This will be a good first port of call when developing hydrology course material. The MOCHA project was awarded the 2011 Education and Public Service Award from the US Universities Council for Water Resources.

- **MIT OpenCourseWare (OCW) – Hydrology**

OCW at the Massachusetts Institute of Technology is a web-based free publication of course materials (lectures, exams, and video) that reflect almost all the undergraduate and graduate subjects taught at MIT. Hydrology courses are more at the graduate level (Department of Civil and Environmental Engineering) available at http://ocw.mit.edu/courses/civil-and-environmental-engineering/.

- **Geology724 - Introduction to Groundwater Modelling**

This is a groundwater course website developed by Professor Mary Anderson at the Department of Geoscience, University of Wisconsin-Madison. The site contains useful material on groundwater flow modeling, PowerPoint presentations, texts and related websites, and other course material. http://www.geology.wisc.edu/courses/g724/

- **CE 394K.2 - Hydrology**

This site was developed by Professor David Maidment at the Department of Civil, Architectural and Environmental Engineering, University of Texas at Austin. Again, detailed course material is provided freely, aimed in this case more toward general hydrology.

http://www.ce.utexas.edu/prof/maidment/GradHydro2007/gradhydro2007.htm

- **Professor Todd C. Rasmussen – Hydrology and Water Resources**

This website is the collection of the course materials of Professor Todd Rasmussen, at the Warnell School of Forestry and Natural Resources, University of Georgia. The courses are comprised of: Soils and Hydrology; Introduction to Water Resources; Field Methods in Hydrology; Quantitative Methods in Hydrology; Hydrology, Geology and Soils of Georgia; Aquifer Mechanics; and Hydrologic Modeling.

http://www.hydrology.uga.edu/rasmussen/

- **Rice University – Hydrology and Contaminant Transport**

This site provides a good collection of PowerPoint presentations and other course material on hydrology and contaminant transport, developed by a number of staff at the Department of Civil and Environmental Engineering, Rice University.

http://doctorflood.rice.edu/envi518/handouts.html

- **Earth Science Australia – Groundwater**

The on-line material in Earth Science Australia has been provided by visitors to the site or collected by students since 1992. This includes a collection of groundwater lecture notes which have been adapted to HTML format. The teaching resource has been developed by Professor Stephen Nelson from Tulane University, New Orleans.

http://earthsci.org/education/teacher/basicgeol/groundwa/groundwa.html

2.4 Maps, Glossaries, and Encyclopedia

Though not directly part of hydrology education, suitable maps and other reference material can provide good base data when constructing hydrology exercises. Again, the below listing should be taken only as an indicative sample of available material.

- **GGIS Global Overview**

The Global Groundwater Information System (GGIS) is part of IGRAC (International Groundwater Resources Assessment Centre). It is an interactive portal to information and knowledge of groundwater in different regions. A Global Overview component can be saved as pictures when preparing courses about global comparisons on groundwater quantity, quality, development, and problems.

http://igrac.nitg.tno.nl/ggis_map/start.html

- **HYDRO1k Elevation Derivative Database**

HYDRO1k is a geographic database developed at the USGS Center for Earth Resources Observation and Science. It supplies comprehensive global coverage of topographically derived data sets including streams, drainage basins and ancillary layers derived from the USGS 30 arc-second digital elevation model of the world. HYDRO1k provides a suite of geo-referenced data sets, which could be of use for course content linking to continental and regional hydrology.

http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30/hydro.

- **Glossary of Hydrologic Terms**

This glossary is provided by the USGS Oregon Water Science Center. Definitions here are from *The Federal Glossary of Selected Terms: Subsurface-Water Flow and Solute Transport*, Department of Interior, U.S. Geological Survey, Office of Water Data Coordination, August 1989. This glossary can be used by students when checking hydrological terms, with particular reference to subsurface hydrology.

http://or.water.usgs.gov/projs_dir/willgw/glossary.html.

- **The WQA Glossary**

This site was established by the Water Quality Association (WQA). Emphasis is with respect to water quality.

http://www.wqa.org/glossary.cfm?CFID=5494653&CFTOKEN=35261812.

- **Water Footprint Glossary**

This site is part of Water Footprint Framework (http://www.waterfootprint.org/?page=files/home), an international non-profit foundation under Dutch law, and launched in 2008. A “water footprint” is an indicator of freshwater use that looks at both direct and indirect water use of a consumer or producer. The glossary is aimed specifically at terms associated with water use.

The water footprint glossary is available at http://www.waterfootprint.org/?page=files/Glossary

Water footprint calculators and videos are available at

http://www.waterfootprint.org/index.php?page=files/LinksWaterFootprints

- **Water Encyclopedia**

This encyclopedia contains articles related to water science and issues. Users can ask questions, give comments, or add new information onto the article after reading it. User contributions are kept at the end of the article for new users’ reference.

http://www.waterencyclopedia.com/

2.5 Hydrological Computer Models and Software

Hydrological models suited to teaching are highly dependent upon the skill of the instructor. A model suited to one academic may be unsuited to another without some additional support. Also, some software may contain better tutorial modules than others, and cost may be a factor also. No attempt is made here to review the plethora of hydrological models available, or make judgement as to their suitability as teaching resource material. Rather, a few specific web sites and models are referenced – all providing models as freeware. Explicitly not mentioned here are the many general-purpose packages which might also be incorporated as a teaching resource – for example, statistical packages which might be used in support of hydrological data analysis.

By way of brief background, the initial use of computers in hydrology teaching gave emphasis to code writing skills and also recognized the importance of developing skills in the application of basic computer models (Kirkby and Naden, 1988; Eagleson et al, 1991; Nash et al, 1990). Hydrological models in general have evolved into often highly-complex simulation tools (Wagener et al, 2004), though not always suited as a teaching resource. More recently, two major initiatives, *The Consortium for Universities for the Advancement of Hydrologic Science* and the *Collaborative Large-Scale Engineering Analysis Network for Environmental Research* have stressed the critical role of computer simulation models applied to data in the future development of both hydrological and engineering education (Aghakouchak and Habib, 2010). An overview of current groundwater modeling software is given by Zheng (2011). Bigham (2010) presents a comparison table for different environmental software providers, including water-related software.

A selective listing of specific freeware web sites / models is given below.

- **USGS Hydrologic and Geochemical Models**

The U.S. Geological Survey (USGS) has been a leader in the development of hydrologic and geochemical simulation models since the 1960's. Their site provides water resources applications software including groundwater, surface water, and water quality:

http://water.usgs.gov/nrp/models.html

In addition, the USGS *Surface-water quality and flow Modeling Interest Group* (SMIG) has listed many archives of models and modeling tools which are provided by government, commercial, or non-profit organizations. They are available at http://smig.usgs.gov/SMIG/model_archives.html

- **Groundwater Modelling –Web Links, University of California**

The Groundwater Cooperative Extension Program of the University of California at Davis offers links related to groundwater modelling software and reviews. Although some links are commercial, this website offers a wide range of freeware also.

http://groundwater.ucdavis.edu/Materials/Groundwater_Modeling__Web-Links/

- **Interactive Models for Groundwater Flow and Solute Transport – University of Illinois**

This site is developed at the Department of Civil and Environmental Engineering, University of Illinois at Urbana – Champaign. It offers interactive models, available as Java applets, for groundwater flow and solute transport. Those models can be operated with the help from their solution tutorials.

http://hydrolab.illinois.edu/gw_applets//?q=gw_applets/

- **JAMS**

Jena Adaptable Modeling System (JAMS) is a modular freeware system for catchment modelling established in 2007 at Department of Geoinformatics at the Friedrich-Schiller University of Jena, Germany. It includes solute transport modules, as well modules for model optimisation, sensitivity analysis, and visualization.

http://jams.uni-jena.de/.

2.6 Hydrology-Related Calculators

A web search can find easy-to-use calculators with reference to special-purpose use, with potential use in support of specific class exercises. Two examples are:

- **VISUALAB** Hydraulics / Hydrology Calculators

Hydraulics and hydrology calculators developed by the Department of Civil, Construction, and Environmental Engineering at San Diego State University, California.

http://ponce.sdsu.edu/online_calc.php

- **SWRC** Soil Water Retention Curve Fitting

The Soil Water Retention Curve (SWRC) module can fit several models to measure soil water retention data. Written by Dr. Katsutoshi Seki at the Faculty of Business Administration, Toyo University, Japan.

http://seki.webmasters.gr.jp/swrc/

2.7 Multimedia

Multimedia products which could be incorporated into hydrology teaching include videos, posters, photo galleries, podcasts and sound files. Sources of free material are widespread. A selection is listed below.

- **Water Resources Multimedia Products** (USGS)

Covers a variety of topics in hydrology and the environment, including groundwater, floods, hurricanes and tsunamis.

http://water.usgs.gov/multimedia.html

- **Water Resources Seminar Series** (USGS)

This database is a compilation of selected videotaped lectures in MP4 format and typically 60-90 minutes long, within an Archive of video streamed WRD (Water Resources Discipline) research seminar series.

http://wwwrcamnl.wr.usgs.gov/wrdseminar/pastseminarsonvideo.htm

- **Circle of Blue**

A water news website providing an international collection of multimedia items including videos, motion-graphics, infographics, slideshows, and radio.

http://www.circleofblue.org/waternews/

- **TheWaterChannel**

This site is a repository of visual water material and a media facility. It is not aimed toward scientific analysis but could provide material giving the human dimension in teaching support. http://www.thewaterchannel.tv/

- **GlobalOneness Groundwater; Hydrology Archives**

The two sites include offerings of videos and articles (extracted from encyclopedia) related to hydrology.

http://www.experiencefestival.com/groundwater

- **The Hydrogeologist Time Capsule**

Comprises video archive containing a collection of interviews of eminent hydrogeologists. Many of the videos are complemented by a biographical note published in *Hydrogeology Journal*.

http://timecapsule.ecodev.ch/video.html

A search of various university departments may also reveal useful video sources suited to hydrology teaching support. See, for example, Professor V. M. Ponce's video website (San Diego State University Department of Civil, Construction, and Environmental Engineering) http://ponce.sdsu.edu/videos1.php and the groundwater video and audio website at the University of California Groundwater Cooperative Extension Program.

http://groundwater.ucdavis.edu/publications.htm

2.8 General Web Links

Some web sites contain useful references to other sites, often maintained by enthusiastic individuals, which contain resources from which teaching material could be derived. It is not always easy to make the distinction between "hydrology resource" and a hydrology teaching resource. The various search engines may also in themselves provide links to useful educational reference material. See, for example:

http://www.dmoz.org/Science/Environment/Water_Resources/

http://dir.yahoo.com/Science/Earth_Sciences/Hydrology/

- Hydrology Link of C. P. Kumar

Material here includes references to forums, online journals and books, dictionaries, encyclopedia, models and software downloads. More than 800 items are listed in alphabetical order at

http://www.angelfire.com/nh/cpkumar/hlinks.html

See also some groundwater PowerPoint presentations located at the end of the section: http://www.angelfire.com/nh/cpkumar/publication/.

- **Water Librarians' Home Page**

As a librarian in a California water agency, R. Teeter has developed links to material covering a wide range of hydrology-related material which could be incorporated in teaching programs. http://www.interleaves.org/~rteeter/waterlib.html

2.9 Sources of Hydrology Data Files for Teaching

With increased available computer power, large national and international data sets can be incorporated into class exercises for many forms of hydrological analysis. Such data sets are research resources as well, but a selection of data sources are given here on the basis that there is software available to allow the data to be used in support of student assignments.

- **Global Precipitation Climatology Centre (GPCC)**

GPCC is located in Offenbach, Germany and was established in 1989. The Centre contributes to the World Climate Research Program's Global Precipitation Climatology Project and the Global Climate Observing System. To date, GPCC has collected monthly precipitation data from about 40,000 stations world-wide. Data from 7,000 stations are routinely updated and presented in near real-time. The other data are delivered in delayed time from 150 countries on a voluntary basis. The global gridded products as reanalysis data are accessible via the internet. A starting point is the global precipitation map

http://kunden.dwd.de/GPCC/Visualizer

Complete data sets can be downloaded via ftp at

ftp://ftp-anon.dwd.de/pub/data/gpcc/html/download_gate.html

- **Global Runoff Data Centre (GRDC)**

The GRDC was established at the Federal Institute of Hydrology in Koblenz, Germany in 1988. It provides a mechanism for international exchange of data pertaining to river flows on a continuous, long-term basis. The scope of data collection is global, regional and river basin- scale. Currently GRDC's database contains time series of daily and/or monthly river discharge data of more than 7500 stations from 156 countries, comprising around 300,000 station-years with an average time series length of about 39 years. The earliest data are from 1807. The database is updated with standard services of river discharge data, data products, and special databases, available at http://www.bafg.de/cln_016/nn_266918/GRDC/EN/02__Services/services__node.html?_nnn=true.

- **Global Network for Isotopes in Precipitation (GNIP)**

The GNIP is operated by the Isotope Hydrology Section of the International Atomic Energy Agency (IAEA) in Vienna. This world-wide survey of the isotopic composition of monthly precipitation started in 1961 in co-operation with WMO to study rising tritium levels in the atmosphere caused by nuclear weapon tests. Information is available at http://www-naweb.iaea.org/napc/ih/IHS_resources_gnip.html

The program also aims to provide systematic data on global stable isotope content of precipitation as a basis for the use of environmental isotopes in hydrological investigations. For several years the whole database has been available on line from the IAEA-WISER (Water Isotope System for Data Analysis, Visualization and Electronic Retrieval) webpage. A starting point is http://nds121.iaea.org/wiser/

- **World Hydrological Cycle Observing System (WHYCOS)**

The WHYCOS was launched by WMO in 1993 with the aim of promoting co-operation in the collection and exchange of hydrological data at the river basin, regional and international levels and in developing products of interest to the participating countries. Information is available at http://www.whycos.org/cms/.

WHYCOS is global in concept, but implemented on a regional basis. Reporting frequency is daily or shorter (3-hourly), thus providing near real-time access to data. Its webpage of data and products provides easy access to the various WHYCOS components implemented or under implementation and direct access to station description, data and other hydrological products.

http://www.whycos.org/cms/content/data-and-products.

- **NOAA/National Climatic Data Center (NCDC)**

The NCDC is part of the US National Oceanic and Atmospheric Administration (NOAA). It produces numerous climate publications and responds to data requests from all over the world. Data from individual countries could be retrieved at

http://cdo.ncdc.noaa.gov/CDO/cdo

- **GWSP Digital Water Atlas**

The Global Water System Project (GWSP) is an international coordination for integrated research on water. The GWSP Digital Water Atlas was launched in 2008 and is part-funded by the German Federal Ministry of Education and Research. The purpose of the *Atlas* is to describe the basic elements of the global water system via a set of annotated maps. The Atlas currently contains 50 global maps and datasets on water-related topics and more than 100 links to other data and information sources.

http://atlas.gwsp.org/

See also

http://atlas.gwsp.org/index.php?option=com_weblinks&catid=15&Itemid=23

- **The Flood Observatory**

The Observatory was founded in 1993 at Dartmouth College, Hanover, NH USA and moved to the University of Colorado in 2010. The *Observatory* facilitates practical use of space-based information for international flood detection, flood response, future risk assessment, and hydrological research.

http://floodobservatory.colorado.edu/index.html

In addition, there are many sources for specific national data sets maintained by government agencies such as the UK National Environment Research Council (NERC) and the US Geological Survey. Such data file sources can be discovered via a search of relevant government agencies and are too numerous to list here as part of teaching support material. Sometimes, however, teaching material is better set up as data of previous hydrological case studies. In this context, mention is made of the US Agriculture Research Service (ARS) Water Database collection of precipitation and stream flow data from selected small agricultural watersheds in the United States

http://amser.org/index.php?P=AMSER--ResourceFrame&resourceId=4350

and also the *Chronology of British Hydrological Events*

http://www.dundee.ac.uk/geography/cbhe/

3. Material Related to Hydrology Teaching Modes

The material discussed above is all hydrology reference material which, in one form or another, might serve to supplement existing course material. Also of interest are contributions by educators who advocate particular frameworks for presenting specific subject areas. As mentioned earlier, no judgement is made here as to the relative merits of different teaching approaches. Rather, a selection of material is referenced below, in no particular order, with a view to introducing readers to material which might suggest alternative teaching modes for hydrological content.

A system dynamics (SD) modeling approach has been suggested to be a useful tool for introducing and teaching hydrological modeling generally (Lee, 1993), and watershed hydrology in particular (Elshorbagy, 2005). The latter employed an incremental object-oriented simulation environment which was stated to be effective in teaching. Williams et al (2009) mention the success of a dynamic simulation software package used in a University of Arizona undergraduate water resources course. In a similar vein, Aghakouchak and Habib (2010) describe an Excel-based modeling tool used by the University of Louisiana for teaching hydrological process interaction (free copies are available from the authors). In the context of engineering hydrology, Ouet al (2009) described their design and application of a project-based teaching environment at the Zhenjiang Water Conservancy and Hydropower College, China. These authors also claimed that engineering hydrology educators needed to pay more attention to teaching methods and processes than teaching content and results.

Working at the Department of Earth Science, Northeastern Illinois University, Sanders (1994) criticized the conventional approach to teaching hydrological analytical methods as not preparing students to formulate and solve more complex problems. She describes an alternative problem-based approach in a graduate hydrology course. This appeared more effective relative to students taking the old course in previous years. Case-based approaches of this type have been widely used in business and administration education and also appear helpful to enrich water-resources management education. Grigg (1995) reported the experience at Colorado State University with case studies added to existing programmes of a graduate course in water-resources management. This successfully raised students' interest level and gave a sense of participation in real-world political situations.

In the context of alternative approaches to hydrology laboratory reports, an alternative "Vee map" graphic organiser has been applied at the University of Arizona (Luft et al, 2001). The majority of students believed they thought and learned more via the Vee map method and had a better understanding of the purpose of the laboratory investigation. The authors suggest Novak and Gowins (1984) as a useful reference to Vee map teaching.

With respect to web-enhanced course delivery, Hagen (2002) describes a graduate course on numerical modelling of water resources systems at the Department of Civil and Environmental Engineering, University of Central Florida. He incorporated web-based assignments, online bulletin boards, chat rooms, and E-mail onto an existing remotely delivered course. These web techniques successfully encouraged student interaction and peer review, especially for remote off-campus students.

Some teaching aspects involve material for specific hydrological topics. For example, a one-week module on stochastic groundwater modeling has been included in a University of Colorado graduate course since 2006. Teaching materials and further information are given by Mays (2010).

Even apparently trivial simulation games can potentially be aids in hydrology teaching. The components of *SimCity 4,* for example, include hydrology, air pollution, sanitation, and toxic waste spills. D'Artista and Hellweger (2007) reviewed the game's hydrological aspect inside this game and recommended to use it to teach urban hydrology in higher level undergraduate or even graduate courses. Specific games date quickly and it would be worth spending some time seeking recent versions of the *SimCity* genre.

Increased computer power means that quite sophisticated visualisation tools can be utilised to teach more difficult concepts. For example, Schwenk et al (2009) introduced a computer-aided visualization tool for stochastic theory education in water resources engineering at the Department of Civil and Environmental Engineering, Tennessee Technological University. Again, new visualization software will be developed as an on-going process and a search of the web will reveal current developments.

A different form of resource to be utilized in teaching relates to linkages and support from local organizations. For example, The Indiana University Center for Earth and Environmental Science (CEES) facilitates the Environmental Service Learning Program to engage students in urban water quality education (Tedesco & Salazar, 2006). This is done in partnership with The City of Indianapolis Department of Parks and Recreation, providing course material of contemporary environmental water problems.

There appears to be less literature addressing hydrology course planning, especially for whole semester courses. Neupauer (2008) integrated many topics to design a semester-long hydraulic containment project with various activities for a class of senior-level undergraduate and graduate students at University of Colorado, USA. This project effectively enhanced student learning in an introductory hydrogeology course. Teaching materials are available from the author.

Whatever the course structure and teaching mode, it can be helpful to find prior what may be major weaknesses in student knowledge. Sibley et al (2007) described an approach using box diagrams to evaluate students' systems thinking about rock, water and carbon cycles. They found by this method that many of their students lacked a critical ability to recognise parts of a system that were not readily apparent or visible.

4. THE SPECIAL CASE OF FIELD AND LABORATORY TEACHING

A two-year survey of hydrology course content in North American universities conducted between 1989 and 1991 showed a lack of field or experiment work in teaching hydrology in North American universities (Groves & Moody, 1992). The importance of field and laboratory experience at the undergraduate level was also been highlighted by Nash et al (1990) and Eagleson et al (1991). They warned that the lack of experience in field and laboratory created a crisis in hydrology education.

Trying to change the poor situation of field hydrology education in the early 1990s, MacDonald (1993) describes a Colorado State University course comprising a 13-unit field component of watershed measurements. The course details are still useful today and the point is made that field courses need not be costly or difficult, but the instructor must be able to adapt to the uncertainties and problems associated with field measurement in an educational situation.

More recently, Dunnivant and Olsen (2007) critiqued that pollutant transport was extensively covered in groundwater modelling lectures but it was absent in published laboratory exercises.
These authors describe their own design of a simple and inexpensive sand column to simulate the transport of pollutants in real-world groundwater systems. The first-hand working knowledge of conservative and non-conservative tracers and pore interactions gave students appreciation of the detail required for doing research experiments in the future. At a simpler level, Singha (2008) describes use of a juice container to help students visualize the interplay between stresses and fluid pressure when pumping a confined aquifer.

Outdoor physical teaching facilities such as in-campus wells can enhance student learning and fill the gap between classroom learning of concepts and its application at the watershed level. Hudak (1999) describes a field module for undergraduate hydrogeology course at the University of North

Texas. The characteristic of the module was four groundwater wells placed on university property to ensure long-term access and control of the site. Students expressed strong support for the teaching module and felt that the field work and measurement exercises were a worthwhile addition to the course. Iqbal and Chowdhury (2007) also reported their using on-campus monitoring wells to effectively enhance student learning in geo-hydrology courses at the University of Northern Iowa and the State University of New York. Many hands-on activities conducted via the wells were proved to effectively improve students' critical thinking and reasoning skills.

Nicholl et al (2008), at the University of Nevada, describe a new approach for teaching water level contour mapping based on artificial wells combined with synthetic data. When learning water level measurement techniques, the wells allow students to avoid most of the logistical and financial constraints associated with field measurements. A synthetic data set provides a reference solution to let students understand the manner and degree to which their interpretation differs from the known solution and all the discrepancies resulting from interpretation errors.

Even indoor classroom experiment experience can make a difference when teaching hydrology. Passey et al (2006) describe a simple and inexpensive sand model classroom experiment at the University of Utah, suited for teaching undergraduate students concepts of permeability and other aquifer characteristics using colored dye. This experiment was universally well received by students and teachers and has successfully left lasting visual impressions of processes in hydrology and environmentally relevant water issues. Another example is Neupauer and Dennis's (2010) in-class demonstrations to illustrate concepts of Darcy's Law and hydraulic conductivity. These authors introduce the use of a "Darcy bottle" as a teaching aid.

Many geology field camps presently include hydrogeology into field exercises. For example, the University of Missouri's well-known Branson Geology Field Camp has included hydrogeology since in the early 1990s (Lautz et al, 2007). A dye tracing experiment done in 2006 along with their advanced hydrogeology instruction relates stream discharge to groundwater flow dynamics. All students in the course gave the dye tracing project the highest rate for interest' and value. However, while geology field camps are a traditional part of the subject, there seems much less information on equivalent hydrology field camps to compliment and focus hydrology teaching courses.

5. CONCLUSION AND THE FUTURE

It is almost inevitable that any attempt to achieve an overview of an extensive and rapidly-changing field like university hydrology education resources will be seen as both incomplete and subject to becoming quickly dated. Some web references may become inoperative as time advances, and we acknowledge that many aspects of hydrology teaching are not referenced here. This will be due to some extent to simple omissions, decisions on our part not to reference certain material on the periphery of the field, or simply to keep this review within reasonable size. It may be that going into the future consideration should be given to establishing a "Journal of Hydrological Education" to provide a convenient and updated resource for those involved in this important subject area. In the meantime, we hope at least some parts of the review here will be of value for educators in hydrology in their quest for relevant course resources.

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