Grand Challenges for Hydrology Education in the 21st Century

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Abstract

A thorough understanding of the hydrosphere is crucial for the sustainable evolution of human society and our ecosystem in a rapidly changing world. This understanding can only come from well-trained professionals in the field of hydrology working in research and practice. In Civil and Environmental Engineering, this knowledge is the basis for the design of infrastructure and its management. Here we briefly review the historical development of engineering hydrology education from the middle of the 20th century. The 20th century was characterized by the establishment in the 1950's and 1960's of a clear, modern, and durable vision for hydrology education as a distinct formal program of study, and the consolidation in the 1990's of the original vision. In recent years a series of publications has expanded the traditional vision of hydrology education. This recent literature emphasizes formalized approaches to hydrology education including community-developed curricular resources, data and modeling based curricula, formally assessed pedagogies, and formalization of non-traditional pedagogies. Based on these findings, we present several challenges for hydrology education in the 21st century. Central themes of the challenges for hydrology education are the development of international hydrology education communities and networks, shared learning technologies – partially driven by the need for a more mechanistic approach to engineering hydrology, formalized and validated pedagogies, and adaptations of international best educational practices to regionally specific hydrology and socio-economic context.

"Knowledge required for understanding and solving complex water problems may be considered as a continuum extending from the basic physical and biological sciences, through the applied natural sciences, and a thrust into the behavioral sciences. The breadth of knowledge encompassed is greater than in any other field of study. A complete educational program in hydrology and water resources needs to provide the opportunity for students to specialize in any segment of the continuum as well as the opportunity for others to obtain a general education across the continuum. Historically, training in water science has been compartmented on campuses within several established disciplines, with little integration among these disciplines. Also, training in the behavioral sciences with emphasis on water resources administration has been very limited, especially in the political, social, and legal fields. Recently, there has been concerted effort on several campuses to integrate and broaden hydrology and water resources education by the development of inter-disciplinary programs."

Harshbarger and Evans (1967)

1. Introduction

"*If the apocalypse is still a little way off, it is only because the four horsemen and their steeds have stopped to search for something to drink*" (The Economist, May 22, 2010, issue featuring world water concerns). Today, society has clearly recognized that a thorough understanding of the hydrosphere is crucial for the sustainable evolution of human society and our ecosystem in a rapidly changing world. This understanding can only come from well-trained professionals in the field of hydrology working in research and practice. In Civil and Environmental Engineering, this knowledge is the basis for the design of infrastructure and its management.

Here we review the historical development of hydrology education from the middle of the last century to now. It is appropriate to begin in the second section by reviewing the broad history of hydrology education to understand the long-term trajectory of the field. This will help us to understand what has been accomplished, what has not been accomplished, and what new priorities should be established. In the third section we review the recent developments and accelerated interest in formal hydrology education since roughly the year 2000. In the fourth section we synthesize the literature to develop several grand challenges for engineering hydrology education in the 21st century.

We find that the hydrology education conversation in the (mainly) peer-reviewed international literature from the mid-20th century to present is dominated by U.S. and European institutional priorities, structures, and views, and by applications to engineering hydrology educational programs. This review will therefore be of greatest utility to those sub-communities. This bias is a natural result of the historical trajectory of academic science and education during the 20th century, and of the historically applied roots of hydrology. Although the foundations of the field remain a solid starting point for future developments, the existing formal literature is not fully representative of the needs of the rapidly globalizing and internationalizing hydrology community in the 21st century, or of the rapidly increasing socio-economic embedding of hydrology and water resources problems. Therefore, central themes of the grand challenges for hydrology education are the development of international hydrology education communities and networks, shared learning technologies, formalized and validated pedagogies, and adaptations of international best educational practices to regionally specific hydrology and socio-economic context.

2. The historical trajectory of hydrology education

W.B. Langbein (1958) traces the origins of hydrology education, at least in the United States, to early U.S. military hydrologic engineering textbooks in 1862, and internationally to the formalization of the academic field with the 1923 establishment of the International Association of Scientific Hydrology (now the International Association of Hydrological Sciences, IAHS), and the first modern hydrology textbooks in the 1920's. Langbein summarizes the state of hydrology education in 1958 as underdeveloped and in need of formalization, citing statistics that no formal hydrology degree programs existed in the U.S., that less than a third of U.S. institutions had a hydrology course, and that only 12% of practicing hydrologists had taken an undergraduate course in hydrology topics. Roughly half of practicing hydrologists had a Civil Engineering background, and the vast majority had received their hydrology training through field practice and applied apprenticeship, often within governmental resource management or military agencies, rather than through formal university study (e.g. Wilm 1957). Formalization of university undergraduate programs in hydrology was identified as a priority. These patterns were generally representative of the international situation at the time, at least within the ‘developed’ world (Gray, 1969).

Early efforts correctly recognized the inherent interdisciplinary nature of hydrology, and that defining hydrology was essential to the establishment of a coherent research and education agenda or focused hydrology education programs. Price and Heindl (1968) cited 31 different definitions of hydrology. Harshbarger and Evans (1967), as quoted, provided a remarkably timeless definition of the educational requirements for hydrological research and education that has been echoed for the last half century. They recognized the need for complex systems approaches, interdisciplinary integration of physical, biological, socio-economic, legal, and behavioral knowledge, a combination of professional breadth with deep technical specialization, and the practical problem of interdisciplinary training in a disciplinary university curricular structure.

The 1960’s were the first landmark period of development in formal hydrology education. For example, in 1961 the University of Arizona’s Hydrology and Water Resources program was established, joining a small number of formal international programs. The Technical University of Dresden in Germany, having offered a course in hydrology as early as 1899, established a formal degree program in hydrology in 1968 – interestingly within the Department of Physics. A second German hydrology degree program, offered through the Department of Geography, followed in the 1970s at the University of Freiburg. Similar efforts and time-scales can be found in other countries, e.g. the Netherlands started offering postgraduate education courses in water-related topics in 1957 through an organization now known as UNESCO-IHE Delft. This attention coincided with the 1965-1974 declaration of the International Hydrological Decade (IHD) by the United Nations Educational, Scientific and Cultural Organization (UNESCO), which initiated an intense period of focus in dozens of countries on the creation and standardization of a coherent research and education agenda (UNESCO-IHP 1991, UNESCO 1974, UCOWR 1971, USNC-IHD 1976).

The UNESCO International Hydrological Program (IHP) was established in 1975 to continue the work of the IHD. Gilbrich (1991) provides a 25-year summary of the IHP. Maniak

(1993) published an assessment of model hydrology curricula that implement the IHP's agenda. Kovar and Gilbrich (1995) explores emerging needs for postgraduate training and generally re-emphasizes the earlier IHP findings, adding the establishment of 'professional hydrologist' certifications for M.S. degrees and the need for Geographical Information Systems and modeling software training. The UNESCO-IHP continues to implement this evolving agenda with a variety of programs that have educational or community building components, such as Hydrology for the Environment, Life, and Policy (HELP, e.g. Camkin and Neto, 2013) and Flow Regimes from International Experimental and Network Data (FRIEND), with the UNESCO-IHP international training programs.

The period between the end of the IHD in 1974 and the 1991 publication of the so-called 'Blue Book' (Eagleson et al. 1991; so-called based on the blue color of the book cover) was marked building momentum in the international university community around the concept of hydrology as an independent science. The Blue Book is considered a landmark in hydrology science and education in the U.S., and perhaps embodies the moment in time when the consolidated ideas of the 1960's reached a degree of international 'critical mass' after three decades of work.

Several other cotemporaneous publications mark the early 1990's as the second landmark period for hydrology education. A survey assessment by an American Society of Civil Engineers (ASCE, 1990) found that the industry and academic communities were generally satisfied with the state of the educational practice, with the specific exception that professional industry practitioners were becoming critical of inadequate training in field practice methods, tools of the trade, professional and business skills, and engineering licensure prerequisites. MacDonald (1993) proposes specific field educational curricula as a remedy. Nash et al. (1990) identify other problems with the educational paradigm, including too much reliance of hydrologic science education on the empiricism of civil engineering programs, inadequate undergraduate training in the physical fundamentals of hydrologic science, and a growing divide between hydrology science and engineering that slows the translation of hydrology science into practice (see also UNESCO 1990). James (1993) favorably reviews the progress of the educational efforts of the prior three decades, but notes the potential danger of stagnation of the emerging core hydrology curriculum and the resulting need for the creation of a process of continuous improvement to keep water resources education programs up to date with the rapidly accelerating and diversifying development of theory, computer tools, models, and methods. Zojer (1996) echoes the trends of other studies from the 1990's: in the 1970's hydrology courses were general and qualitative, in the 1980's postgraduate courses became highly specialized and quantitative instrumentation and computer models were emphasized, and the 1990's saw emphasis on the practical applicability of hydrologic science, on interdisciplinarity and breadth, and on the incorporation of socio-economics. Elaboration and implementation of these priorities continues today with increasing emphasis on the human role in the water cycle (Miller and Gray, 2008).

Recent Developments

It may be observed that since the 1990's there has been simultaneously a concern, from the university hydrologic science perspective, over inadequate fundamental training in hydrologic theory, and, from the engineering practitioner's perspective, over inadequate engineering, professional, and practical training. There is a general perception that while formal training in hydrology has been improving, practical and field experience has not (Wagener et al., 2007), although efforts are being made (Wagener et al., 2012). In our opinion, this tension and diversity of opinion is a natural and healthy result of the successful establishment by the 1990's of hydrologic science as a distinct and diverse set of educational programs, both within and separately from Civil Engineering departments. However, recent surveys of the community of hydrology educators also suggest that the increasing demands for more holistic education, while appreciated by hydrology educators, are difficult to fulfill. Declining educational budgets, increasing student numbers, and the time-commitment needed to develop appropriate courses are barriers to investment of the needed time. Meanwhile, adverse incentives are present, such as an extremely competitive research and publication culture that fails to adequately reward pedagogical contributions (Wagener et al., 2007).

In the first decade of 2000, advances in research on Science, Technology, Engineering, and Mathematics education (STEM) began to benefit the hydrologic education community. These advances brought awareness that education is itself a science and a field of practice that can be improved through applied research, and that this research is a priority for the university community (Boyer, 1990). This literature is too broad to summarize, but specific examples are representative of the general trends pertaining to hydrology education. Much of this literature challenges the historical norms in the university classroom, and advances by way of theory and learning outcome assessment an emerging ‘constructivist’ or ‘student-centered’ pedagogy of ‘active’ exploration as opposed to the traditional ‘positivist’ or instructor-centered pedagogy of information conveyance (Felder 2012, Prince and Felder 2006, Prince 2004). Constructivist theories of knowledge assert that human learning occurs when new information interacts with a student’s existing experiences in the context of an activity or problem; it is experiential learning, as opposed to rote learning. Bransford et al. (2000) demonstrate that curiosity is necessary for learning, and that it can be motivated in the classroom by carefully crafted problems; hence the focus on ‘problem based learning’. Sheppard et al. (2008) argue for a ‘project-based’ and ‘practice-like’ curriculum that builds broad professional stills like teamwork, problem solving, and ethics. Much of this work has taken place in the specific context of undergraduate engineering education (Shulman, 2005), but has directly impacted the broader hydrology education community via its roots in undergraduate engineering programs. Research Experiences for Undergraduates (REU’s) and ‘summer institutes’ or ‘summer schools’ are examples of implementations of these STEM pedagogical concepts in the context of undergraduate and graduate research.

A shift in the emerging paradigm is facilitated by the near-universal availability by the 2000’s of the internet, which renders redundant the instructor’s traditional gatekeeper role as a conveyer of content, but re-emphasizes the instructor’s role as a guide to critical thinking and proper application of information to problems. Technology, notably for hydrology education including internet resources, modeling, visualization, GIS methods, and hydroinformatics, is an important part of many emerging pedagogies. However, technology is not a panacea and must be used carefully to enhance learning (Felder and Brent, 2000).

The focused public attention during the 2000’s on climate science, on the applied problems created by climate change, and on urban and natural resources sustainability issues has placed a new urgency on specific hydrologic science problem solving abilities and related educational priorities. The recognition that “stationarity is dead” (Milly et al., 2008), or at least that historical statistical norms are no longer a sufficient basis for planning the future, has been particularly transformative in hydrologic science. However, the methods need to overcome nonstationarity have been slow to enter the engineering hydrology classroom, especially at the undergraduate level. This new awareness is particularly relevant for motivating the use of mechanistic models (rather than statistical/empirical models), the use of holistic systems approaches, and the incorporation of human socio-economic systems (the ‘anthroposphere’) within coupled natural-human system models of the ‘hydrosphere’ as a direction for 21st century hydrologic science (Wagener et al., 2010). It is remarkable that these priorities have been closely held by the hydrologic science and education community for several decades, and that only recent events have brought focus and urgency to the implementation of these priorities within the university hydrologic science curriculum.

The appearance of the term ‘hydrophilanthropy’ during the 2000’s, describing “…*the altruistic efforts … to provide sustainable, clean water for people and ecosystems worldwide…”*, is notable as recognition by the community of hydrology education and practice of the increasing popularity of service-based, problem-based, and project-based approaches to university education (Kreamer, 2010). Such projects are by definition culturally embedded and often embody a combination of field work, use of instrumentation and observations, engineering, science, communication, teamwork, and sustainability thinking, in the context of problems with socio-economic implications. These hydrophilanthropic projects are an attractive way to motivate and engage students of diverse backgrounds in a context that teaches across most of the hydrology education agenda. The second ‘Blue Book’ (Hornberger et al., 2012) – an approach to revisit the state of hydrology 30 years after the first review was lead by Peter Eagleson – touches on hydrophilanthropy. Hydrophilanthropy is an important development for hydrology education because it may enhance student motivation and it provides context for constructivist learning, not to mention the real-world benefits of these projects.

Perhaps motivated by the developments in STEM education, climate science, and sustainability, or by the mainstreaming of the internet, the past few years have seen a remarkable amount of activity in the hydrologic education community, including numerous meetings (e.g. Showstack, 2010) and special issues focused on the topic (Seibert et al., 2013, Missingham and McIntosh, 2013). In no particular order, the common themes of recent publications include practical, professional, and field experience education especially as addressed using virtual trips and gaming (Kingston et al., 2012, Hoekstra, 2012, Rusca et al., 2012, Lyu et al., 2013, Leff et al., 2013), socio-hydrology, coupled natural-human systems, and the decision-making anthrosphere (Sivapalan et al., 2012, Sivakumar, 2012, King et al. 2012, Hoekstra, 2012; Wagener et al., 2010), emerging student-centered, case-based and problem-based pedagogies

(Shaw and Walter, 2012, Lyon et al., 2013, Popescu et al., 2012, Ngambeki et al., 2012, Dennison and Oliver, 2013, Missingham, 2013, Camkin and Neto, 2013, Elshorbagy, 2005, Lyon and Teutschbein, 2011, Wagener et al., 2010), formal assessment of pedagogy and learning outcomes (Merwade and Ruddell, 2012, Marshall et al., 2012, Pathirana et al., 2012, Lyon and Teutschbein, 2011, Majdi et al., 2012, Marshall et al., 2013), establishment of community-based core concepts and material for hydrology education (Aghakouchak and Habib, 2010, Wagener et al., 2007, Wagener et al., 2012), enhancement of the curriculum using models, data, and visualization (Data and Modeling Driven Geoscience Cybereducation, DMDGC, Merwade and Ruddell, 2012, Mohtar and Engel, 2000, Habib et al., 2012, Dolliver and Bell, 2006, Majdi et al., 2012, Popescu et al., 2012, Wagener et al., 2004, Seibart and Vis, 2012), regionally customized approaches (Jonker et al., 2012, Bol et al., 2011), and the training of the professionally broad but technically deep 'T-shaped' hydrologist (Uhlenbrook and de Jong, 2012, Pathirana et al., 2012, McIntosh and Taylor, 2013, Pinter et al., 2013, Cap-Net, 2008).

These and other recent publications indicate that a third landmark has been reached in the history of hydrology education. The first landmark was characterized by the establishment of a *vision* for formal university hydrology education, and was put into action during the IHD in 1965. It retrospect it is clear that the leadership provided during the 1950's and 1960's set an agenda for hydrology education that has proven durable and actionable in the past half-century. Great progress has been made on most, although not all, of this agenda, and active work continues today. The second landmark was characterized by a *consolidation* in the 1990's around the creation of an independent hydrologic science and formal university hydrologic education programs, and the implementation of most of the original vision. This emerging third landmark is characterized by *expansion* of the original vision beyond the horizon of the 1950's driven by the practical demands and opportunities of the 21st century. As of 2013, this expanded vision most notably adds modernization and innovation in the areas of community-developed and internet-based free hydrology curricular resources, interactive data, modeling, and visualization based curricular resources, formal pedagogical design and quantitative educational outcome assessment, and formal adoption of student-centered and other emerging non-traditional pedagogies.

Grand challenges in hydrology education for the 21st Century

The original visions for hydrology education articulated by Langbein (1958), Harshbarger (1967), and others, are remarkably timeless. Those early leaders envisioned a hydrology education that was interdisciplinary, systems-oriented, applied but rooted in science, both broad and specialized, and inter-departmental, with additional emphasis on political, social, legal, and economic aspects of water resources management. Meanwhile, as new technologies, new opportunities, and new problems continue to emerge, the potential for this vision to be realized continues to expand. Having reviewed the history and state of the practice in engineering hydrology education, and to a degree for global hydrology education in general, and with the benefit of many recent authors' views on the subject, we present an opinion on 'Grand Challenges' for hydrology education in the 21st century.

(1) Formalize the 'T-shaped' Hydrologist by Bringing Authentic, Student Centered, Practice-Like, Coupled Natural-Human System, and Field Experiences to the Classroom

The metaphor of a T-shaped educational profile expresses the need to combine the depths in training in a specific area (i.e. the vertical bar of the T), with the ability to work across disciplines in multi-disciplinary teams (i.e. the horizontal bar of the T). The T-shaped profile is described by Harshbarger and Evans (1967) in their original vision statement where, "…a complete educational program in hydrology and water resources needs to provide the opportunity for students to specialize in any segment of the continuum as well as the opportunity for others to obtain a general education across the continuum". Both broad and specialized skills have always been demanded from practicing hydrologists, and have often been taught informally in hydrology programs. The importance of these skills is increasing as hydrologists find themselves at the center of interdisciplinary projects – given the role water often plays as the connecting agent. Student-centered pedagogies including problem-based, project-based, case-based, hydrophilanthropic, and fieldwork content are ideally suited to provide the breadth required by professionals. Carefully designed projects and fieldwork with formalized T-shaped outcomes should have a place in the 21st century hydrology course. These pedagogies should incorporate socio-economic, sustainability, decision-making, legal, cultural, and other coupled natural-human system concepts that are difficult to teach using traditional lecture and theory (Sheppard et al., 2008). This type of pedagogy is also a natural fit for undergraduate and graduate research projects that interface with the classroom, but formal models and validated best practices for this pedagogy are lacking. Formal work is beginning to emerge to address this (Bloeschl et al., 2011).

(2) Translate Scientific Hydrology Advances into Practice via the Classroom

A criticism of hydrologic science is that recent advancement in modeling and instrumentation has not done enough to change the operational norms of applied engineering and hydrology practice and water resource management. In our opinion, the best way to remedy this issue is to bring the state of the art in hydrologic science and modeling into the upper-division undergraduate and M.S. postgraduate classroom, where the state of the art can be comparatively co-taught along with established and codified methods to the next generation of professionals. This is particularly true in the increasingly important area of urban water engineering, where the rational method is still standard practice despite long-understood recognition of its limitations and inadequacy for integrated urban socio-eco-hydrological design (Hawkins et al., 2008, Jones, 1971). Unfortunately, teaching both the state of the practice and the state of the art takes more time and energy from an instructor, and asks more of the curiosity and attention of the typical student of applied engineering hydrology. Efficient approaches that do more with less time and energy will therefore require additional development.

(3) Replace Historical Stationarity with Physics-based Dynamics, Feedback, Connectivity, and Variability in Engineering Hydrology Applications

The hydrology of physical dynamics, in combination with an understanding of system connectivity, feedback, variability regimes, and physically limiting boundaries, must urgently replace historical stationarity and statistical ‘error bars’ in the methods taught in the undergraduate engineering hydrology classroom (Milly et al., 2008, Kumar 2008). Most (if not all) engineering hydrology textbooks follow engineering practice in their heavy emphasis on the empirical and statistical applications of hydrology (e.g. flood frequency analysis). Connecting the process understanding of scientific hydrology with quantitative analysis and design applications required by engineers is a crucial challenge for hydrology education. If we are to succeed in transforming historical stationarity assumptions in engineering hydrology practice, our graduates must be able to apply physics-based quantitative methods to solve the same problems. The need for a better understanding of hydrologic variability in both space and time is part of this effort (e.g. Bloeschl et al., 2013). The applied engineering hydrologists of today are facing the challenges of land use transformation and climate change, and they need these skills in order to design the water supply and stormwater management solutions of the future.

(4) Develop an International Faculty Learning Community for Hydrology Education

Hydrology education is a challenging, complicated, and valid area of scholarship (Boyer, 1990). For example, hydrology textbooks will generally publish generic methods (e.g. Darcy's Law) that can more or less be applied anywhere as long as some basic criteria are met. However, hydrologic systems are not that simple and generic equations are not easily translated into local solutions. Hence, experience with specific hydrologic systems (e.g. semi-arid or mountainous) is crucial for hydrologic practice and research.

This might best be done as a part of a community approach to curriculum development and publication. This can for example be achieved through teaching notes, i.e. published guidelines on how to convey material to specific groups of students in specific places (Wagener et al., 2012). International communities of hydrology education specialists can form the core of the network that will develop, disseminate, and transfer best practices and resources across geographical and cultural boundaries.

Hydrologic science, in contrast to sciences such as physics and mathematics, depends heavily on tacit knowledge gained by working with many datasets and by analyzing many systems. This tacit knowledge is not easily shared between educators using textbooks, but can be transmitted by emphasizing and formalizing as educational methods field work, team teaching, integration of research with education, and workshops. These activities will often be organized around shared multi-university interests in a regional hydrological location.

(5) Develop Community-Published Core Curriculum and Materials

The Internet has transformed the marketplace of information, such that information is virtually free. The role of the hydrology educator is now to help students filter information, contextualize it, and apply it correctly. The textbook of the future is a customized collection of online resources. Owing to the extreme breadth and rapid pace of advancement of the field of hydrology, no single information source, including the best textbook, is adequate. The emergence of internet-based communities and social networks has created the potential for a new solution to this problem: a community of hydrology educators that collectively publishes, reviews, quality-controls, and updates modular curriculum materials. This is the idea behind the Modular Curriculum for Hydrologic Advancement (MOCHA, Wagener et al. 2012). We believe that this type of approach is the next logical step and is an appropriate 21st century approach to the development of core concepts and curriculum. It also satisfies arguments for the creation of a continuous-improvement process for the curriculum (James, 1993) that leverages the energy of the entire community for improvements. Incentives are a part of this challenge, because the prevailing academic publication culture fails to adequately reward those who invest in the formal development of high-quality and peer-reviewed curricula. The formalization of a sub-disciplinary hydrology education community will help to balance the incentive structure and speed dissemination and adoption of the results of the work.

(6) Augment Theoretical Instruction with Data and Modeling Driven Cybereducation (DMDC)

DMDC methods,including some ‘hydroinformatics’ methods, have been utilized since the 1980’s but are increasingly valuable as a natural form of formalized student-centered learning strategies. These approaches are believed to be most effective at the upper division undergraduate and postgraduate levels after theoretical concepts have been introduced to learners (Merwade and Ruddell, 2012, Habib et al., 2012), but may with effort be translated to lower levels of the curriculum. Crucially, DMDC including systems models, data analysis, and visualization, is arguably the best way to teach complex systems concepts, dynamics, feedback, connectivity, and uncertainty. This might best be done as a part of a community approach to the development and publication of up-to-date DMDC materials. A large number of hydrology DMDC resources are already available on the internet, but these are not organized in a coherent, updated, or quality-controlled venue. At the very least, the hydrology community should undertake to review and curate the best of these materials so that excellent resources can be highlighted and disseminated, and their creators rewarded and recognized.

(7) Continuing Education of Practicing Hydrologists

The rapidly changing world around us continues to reduce the time periods over which certain learned skills or knowledge could be considered state-of-the-art, or at least best practice. In this sense, hydrology is no different than other fields; on the contrary, it might even be more exposed due to heavy dependence of observational and computational capabilities. Providing opportunities to refine and update the tool-set a hydrologist once learned at University therefore has to be part of the hydrology education landscape. This can be in form of stand-alone online modules (see for example the NOAA COMET program), through summer schools or short courses now offered by many Universities, or by part-time courses that allow working hydrologists to gain additional qualifications. In some parts of the world, e.g. the UK, there is also an increasing focus on engineering doctoral centers that focus on applied science questions that a student investigates while working in a company, rather than being a full-time student.

(8) Education for Culturally Specific and International Hydrology Applications

In the developing world, hydrology and water resource is following a remarkably Western trajectory, emphasizing first the construction of centrally managed dams, canals, levees, and drainage networks to mitigate damaging drought and flood cycles and to provide water supply and flood protection, then second investment in water and wastewater treatment and environmental protection (e.g. China, Jun and Chen, 2002). This is perhaps an intended outcome of 50 years of UNESCO-IHP efforts to develop and standardize worldwide professional hydrology education. However, recent work suggests that alternative paradigms of hydrologic science and water resource engineering are possible and perhaps desirable, as an expression of the unique socio-economic, ethical, religious, or technological characteristics of the local culture (Chamberlain, 2008, Rongchao et al., 2004, Kreamer, 2010). India, for example, relies on a much more decentralized and distributed water storage system, and distributed approaches can be more effective in contexts with highly diverse legal, economic, or social contexts, or where centralized systems are impractical. To the extent that emerging research establishes actionable knowledge regarding local hydro-economics, socio-hydrology, and eco-hydrology, this knowledge should be translated into the hydrology curriculum at the undergraduate and professional levels, particularly in universities located within that cultural context. The global hydrology community should discover whether and how hydrology and hydrology education needs to be done differently in the Global South and beyond the scope of the historical mainstream of U.S. and European led engineering hydrology. To date, this type of hydrology education work is under-represented in the formal peer-reviewed literature.

(9) Hydro-Economics: Sustainably Managing Water with Markets

The Water-Energy Nexus is a popular talking point, but as pointed out by Zetland (2011) water is also connected to every aspect of the human and natural economy (the ‘water-everything nexus’). Even when public agencies provide regulatory control, future solutions to water resource challenges will increasingly involve businesses, water markets, water rights, private contracts for environmental services, conservation easements, and impact offsets. These arrangements are already transforming water supply, stormwater management, and water quality in many locations (e.g. Sunding, 2000, or McCrea and Niemi, 2007). Water professionals, including those destined for public service positions, need education on the economic side of water management and on market-based solutions to hydrological problems. In addition to formal economics, related methods such as Life Cycle Analysis, concepts of ‘embedding’ of water in goods and services, or of goods and services in water, and other methods can help us to understand how our decisions impact water resource sustainability via a web of connections in the complex coupled natural-human system.

(10) More University Students Learning Hydrology First

Perceptions of employability are one reason that engineering hydrology has historically been the dominant choice of degree program for students of hydrology. Most students have historically preferred to study hydrology as a specialization or focus from within engineering or broader geosciences degree programs. This is particularly true at the undergraduate level. This problem is as old as hydrology, but the increasing socio-economic importance of water issues in the 21st century presents an opportunity. A historical and ongoing challenge for the hydrology field is to create leadership roles outside academia for hydrologists, and also for organizations that primarily emphasize hydrology. This will drive demand for students that specialize in hydrology, and in turn subscription to hydrology courses and programs at all educational levels. As an exemplar, China's President Hu Jintao was a hydraulic engineer, reflecting the societal importance China places on water resource issues.

Additionally, the university educational system is currently struggling to adapt its model to serve an incoming student population with different abilities, interests, qualifications, and demographics than it did during the mid-20th century when the vision for hydrology education was first established. Promoting hydrology as a subject in the science curriculum in primary schools may be an important step toward attracting more students to undergraduate hydrology programs. Without an introduction to hydrology before University, students are less aware of the field and less likely to choose to enroll in Universities and degree programs that specialize in hydrology.

Conclusions

Hydrology education has become an increasing focus in recent years. This is driven by the realization that the current approach to hydrology education is inadequate for current and future societal challenges, and that opportunities created by new media and computational advancements remain underutilized. We review how hydrology education has evolved over the decades, and where the community appears to be headed. This review is written from the perspective of the U.S. and European engineering hydrology communities which have historically dominated the conversation, but with an attempt to understand the broader global hydrology education concerns. Based on the literature, we present a synthesis of the challenges for hydrology education in the 21st century. These challenges require the development of new disciplinary sub-communities, the development of formal pedagogies, new technologies, and a broadening and globalization of hydrology education to meet the unique needs of society beyond the historical scope of the hydrology education community's work.

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