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Incorporating student-centered approaches into catchment hydrology teaching: a review and synthesis

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Abstract. As hydrologists confront the future of water resources on a globalized, resource-scarce and human-impacted planet, the educational preparation of future generations of water scientists becomes increasingly important. Although hydrology inherits a tradition of teacher-centered direct instruction – based on lecture, reading and assignment formats – a growing body of knowledge derived from engineering education research suggests that modifications to these methods could firstly improve the quality of instruction from a student perspective, and secondly contribute to better professional preparation of hydrologists, in terms of their abilities to transfer knowledge to new contexts, to frame and solve novel problems, and to work collaboratively in uncertain environments. Here we review the theoretical background and empirical literature relating to adopting student-centered and inductive models of teaching and learning. Models of student-centered learning and their applications in engineering education are introduced by outlining the approaches used by several of the authors to introduce student-centered and inductive educational strategies into their university classrooms. Finally, the relative novelty of research on engineering instruction in general and hydrology in particular creates opportunities for new partnerships between education researchers and hydrologists to explore the discipline-specific needs of hydrology students and develop new approaches for instruction and professional preparation of hydrologists.

1 Introduction

There is an increasing need to understand the dynamics of water resources as key determinants of development, human and environmental health, and conflict and sustainability (Gleick and Palaniappan, 2010; Postel and Wolf, 2001; United Nations Development Program, 2011). The context of the global water crisis provides a strong motivation for universities to train cohorts of hydrological professionals who can provide expertise in interpreting, predicting and managing the dynamics of water in the 21st century. Sustainable management of water resources is challenging for many reasons: the global nature of water scarcity, the complex interconnections between hydrologic dynamics and a myriad of physical, biological, social and economic processes that take place in catchments (Rockstrom et al., 2009; Vorosmarty et al., 2010; Crutzen and Stoemer, 2000), and the difficulties that global changes in climate and land use pose for prediction (Milly et al., 2008). In this context, the hydrologic community needs to critically appraise the teaching of hydrology, not only in terms of the content of hydrologic courses, but also in terms of the way that the subject is taught as it impacts the professional development of future hydrologists (Uhlenbrook and de Jong, 2012; Wagener et al., 2012).

The science of education research expanded significantly during the latter half of the 20th century (Piaget, 1954; Smock, 1981; Zimmerman, 1981), with a specific focus on engineering education emerging in the past 10 yr (Shulman, 2005). This body of research into how students learn, and into the kinds of educational efforts that can promote desirable educational outcomes offers a valuable resource to hydrologists as they confront the challenge of evaluating and reforming hydrology education. The revolution in hydrology teaching demanded by practitioners and commentators is broadly reflected in discussions surrounding the future of science and engineering education (Rugarcia et al., 2000).

The aim of this paper is to provide a summary of some of the theoretical developments in educational research that are pertinent to the teaching of hydrology, to illustrate these concepts with hydrological examples, and to review our attempts to apply these developments in our own classrooms and within targeted hydrology summer schools. Despite the expansion of engineering education research, there remains a dearth of research specifically targeting hydrology education, meaning that we have relied largely on anecdotal accounts when discussing hydrological examples, and on examples from the broader literature to provide empirical data. The only clear way to overcome these limitations is to engage upon a program of educational research within hydrology, and the paper concludes with a discussion of where the opportunities for such research might lie.

To avoid confusion between different disciplinary foci within hydrology, the paper primarily addresses educational issues associated with teaching catchment hydrology at an upper undergraduate–graduate level. The arguments may therefore reflect the perspectives of catchment hydrologists, but we hope that they will prove relevant to teaching and learning across multiple hydrological sub-disciplines.

2 Hydrology graduates: traditional requirements and modern challenges

Lying at the interfaces of many disciplines and perspectives, there are multiple dimensions to knowing and understanding catchment hydrology (Wagener et al., 2010; Vogel, 2011). The working definition of a catchment hydrologist for our purposes is someone who is engaged in the quantitative study of the terrestrial water cycle at the scale of individual catchments (Wagener et al., 2004). Two opposing approaches to conceiving catchment hydrology can be outlined: the first based on the application of fundamental physical laws – specifically the conservation of energy, mass and momentum – within boundary conditions set by the natural environment. Dooge (1981) referred to this reductionist, process-based approach as providing the "internal descriptions" of the catchment. Alternatively, hydrologists may study the dynamics of the overall catchment system without references to the detailed structure of its components. The nature of the functioning of the system is inferred from the input and output observations. Despite the process complexity at small scales, catchment responses at large scale are often rather simple (Sivapalan, 2003). Dooge (1981) calls this macroscopic approach the "external description" of the catchment. Both approaches have strengths and limitations: the internal description perspective is challenging to apply at large spatial scales, because natural systems are heterogeneous, contain complex forms of spatial and temporal organization, and are usually impossible to completely observe; while methods based on external descriptions are difficult to extrapolate to different places or different times.

There are many traditional tools that are used to make hydrological predictions from both perspectives (e.g., flood frequency analysis, rational method, US-SCS curve numbers, unit hydrograph approaches, Green and Ampt infiltration equation). These tools have strengths and are often embedded in standard approaches for hydrological prediction, but are also subject to limitations (Wagener, 2007; Beven, 1993), which may be exaggerated under scenarios of land use and climate change (Sivapalan et al., 2003; Milly et al., 2008). As human activity increasingly drives hydrological dynamics, hydrologists are also forced to confront the interaction of natural and engineered systems, and of water resource management decisions on the dynamics of the hydrological cycle, in effect expanding the domain of the discipline as a whole (Gupta et al., 2000). Numerous calls have been made to the hydrology community to alter its perspectives from a "business as usual" model to one which can respond to the challenges posed by global change (Gupta et al., 2000; Dooge, 1986, 1988; Torgersen, 2006; Hooper, 2009; Uhlenbrook and de Jong, 2012; Wagener et al., 2012).

This emerging perspective in many ways requires a unification of the internal and external approaches. It challenges students to generate new knowledge, expertise and experiences that represent a synthesis of process knowledge and knowledge gained from interpreting data relating to hydrological response directly at the catchment scale.

Hydrology education must provide students with the ability to approach the hydrological prediction problem from both perspectives, and provide experiences to gain the depth of understanding to synthesize the knowledge derived from each one. Comprehending this level of complexity, and the duality of the ways to conceptualize hydrological processes, requires higher-order, reflective, metacognitive and critical thinking skills – skills that are increasingly identified across multiple scientific and engineering disciplines as the core elements of professional competence (Lenschow, 1998).

Future hydrological scenarios are characterized by uncertainty, associated with non-stationarity, human influences, climate change and an increased appreciation of the non-local and complex interactions between hydrological processes and other environmental processes. Future hydrologists must undertake their work in the face of this uncertainty. In these contexts, scientists who make decisions based on didactic rules are unlikely to produce useful contributions. Interpreting data, formulating, developing and testing conceptual models, and critically evaluating ideas, however, will be essential, as will the ability to work across disciplines and across geographic areas (Gupta et al., 2000; Dooge, 1986, 1988; Torgersen, 2006; Hooper, 2009). Core elements of such interdisciplinarity are increasingly reflected in the formal curricula for hydrological specialists – hydroinformaticians for instance are expected to have an education that spans "physics, mathematics, ecology, geography and computer and software engineering" (Popescu et al., 2012).

The challenge for the modern education of hydrologists, then, is to firstly provide graduates with a strong understanding of the fundamental theories, tools, methods and approaches of contemporary hydrology, and also, hopefully, with positive feelings about hydrology (educational outcomes in the affective or emotional domain) (Bloom, 1956).

Beyond knowledge, however, hydrology education is now challenged to prepare creative graduates with skills in critical thinking, collaboration, interdisciplinary communication, with the intellectual confidence to proceed in an uncertain environment, and with an ethical framework to address complex issues responsibly (Stouffer et al., 2004). Not only, therefore, do we need to teach hydrologists well, and to leave them with positive responses to hydrology as a discipline; but we need to adopt ways of teaching that can foster these intangible skills. The lecture and homework-problem based teaching that applies material covered in class and emphasizes getting the "right answer" (Mills and Treagust, 2003), typical of most hydrology courses (Aghakouchak and Habib, 2010; Elshorbagy, 2005; Mohtar and Engel, 2000), seems almost antithetical to the implicit skills hydrology graduates need, and often fails to provide opportunities for students to exercise and develop skills in problem solving, writing or teamwork (Woods et al., 2000). Education research suggests that didactic, "chalk and talk" approaches to teaching are often ineffective helping students develop an appropriate understanding of content (Goris and Dyrenfurth, 2012; Duit, 2004). To understand this point of view, it is necessary to review educational theory.

3 Framework, vocabulary, and an overview of educational theory

3.1 The four components of education

There are four essential elements in education – the learner; the subject matter and syllabus, which comprises the skills and knowledge the learner is to master; the methods of teaching and learning activities used to bridge the two, known as the *pedagogy*; and the assessment used to measure outcomes of learning and to guide ongoing pedagogical activities (Shuell, 1986; Smith et al., 2005; Pellegrino, 2006). To be effective, a pedagogical method must be appropriate to both the nature of the learner and the content being covered (Bransford et al., 2004; Svinicki, 2004; Catalano and Catalano, 1999). While we recognize the importance of the assessment of learning outcomes, this discussion focuses on the intersection of the learner, the content and the pedagogy.

3.2 Pedagogical content knowledge

What enables a good teacher to teach well? It is clearly not just an expert command of the subject matter – we have all known experts who teach poorly. Similarly, it must be more than mastering pedagogical skills: we would not expect an English professor to teach hydrology well, no matter how good an English teacher they were.

Good teachers, therefore, must have knowledge about how to teach particular kinds of subject matter to facilitate learning (Bodner, 1986; Ward and Bodner, 1993). This understanding of how to link pedagogy with the subject matter is known as Pedagogical Content Knowledge, or PCK. PCK tends to be an idiosyncratic notion of what is appropriate to teach, at what point, through what method. It is content specific: in the context of catchment hydrology, PCK relates to the understanding of which concepts are difficult to understand, and why, and how teaching strategies can explicitly cater to those challenges (Shulman, 1986; Shulman and Shulman, 2007). As teachers develop their expertise, their PCK will also grow and develop. PCK can have many forms, but might be best defined as "the most powerful analogies, illustrations, examples, explanations, and demonstrations- in a word, the ways of representing and formulating the subject that makes it comprehensible for others" (Berry et al., 2008). To illustrate the concept of PCK, consider the use of the "leaky-bucket" or "flowerpot" analogy of a catchment, illustrated in Fig. 1.

The leaky-bucket or flowerpot analogy invites students to think about a catchment as a more elaborate form of a flowerpot. Water is introduced into the flowerpot system by irrigation or rainfall, is partitioned into infiltrated water and runoff at the surface, is transpired by the plants in the flower pot, and drains from the flower pot as it reaches its base (the "leaks" in the "leaky bucket"). Like real catchments, the flowerpot contains soil, water and vegetation, and represents a fluctuating, vertically inhomogeneous moisture store. Many of the simple process descriptions that can be applied at catchment scales are made intelligible by developing "leaky-bucket" models of the flowerpot.

Why is the flowerpot or leaky bucket an effective element of PCK? It has several strong points: it draws on student familiarity with potted plants, it allows simple experiments to be performed, the processes in the flowerpot bear reasonably good correspondence to those in real catchments, and the mathematical and theoretical descriptions derived from the model form a reasonable bridge to more complex process descriptions, or to forming scaled-up models that are suitable for representing catchment processes. As with all conceptual models of real world processes, it may result in the generation of misconceptions (for instance it is a poor representation of heterogeneity and of the relative scale of vegetation

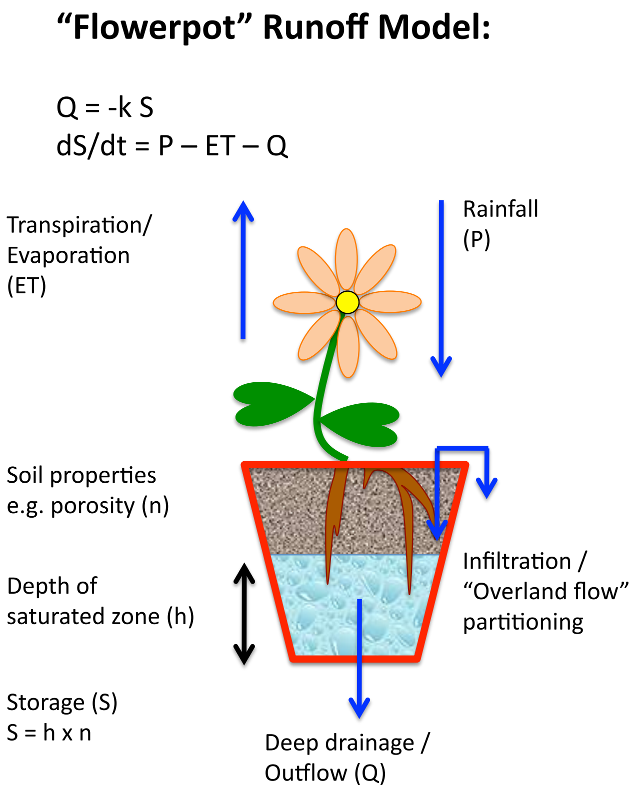

Fig. 1. Cartoon illustration of the flowerpot analogy for a catchment used in teaching catchment hydrologists. Containing vegetation, a root zone, a vadose zone, a saturated zone and soil; and modeling processes of rainfall, infiltration, surface flow partitioning, drainage, outflow, evapotranspiration and water storage in the soil, the flowerpot is an effective example of PCK commonly employed by catchment hydrologists. By employing simple parameterizations of the fluxes and a water balance over the flowerpot, a simple runoff model can be made and explored.

to catchment size). Effective PCK in this case would also involve highlighting the ways in which a flowerpot's water balance behavior differs from reality, and the limitations of the usefulness of thinking about catchments in this way.

3.3 Varying teaching and PCK to reflect the way that people learn

Because PCK arises from an idiosyncratic relationship between instructor, content and the context of the students, there is never only a single "right" way to teach particular content. In fact, research on the development of disciplinary specific expertise has demonstrated that the suitability of instructional methods differs according to the nature of the discipline, concepts and topics taught within the discipline (Donald, 2002; Clough and Kauffman, 1999). However, higher quality teaching, and thus good PCK, likely arises when the pedagogy and the content both work together to enhance student learning. To evaluate or design teaching approaches, it is therefore important to understand how students learn.

There are two broad kinds of learning that hydrology students will be engaged with – the learning of facts and principles, and the learning of skills and procedures (Svinicki, 2004). Both are important for catchment hydrologists; however, there is less controversy over procedural learning. There is a general consensus that procedures are largely learned through the observation of others, practice, trial and error (Bandura, 1975, 1986).

As illustrated in cartoon form in Fig. 2, however, there are several theories regarding how facts and principles are learned. Information processing theories focus upon how information is communicated to learners and is transformed into knowledge (Svinicki, 2004; Shuell, 1986). This theory proposes that a learner receives information through their senses (e.g., by reading, listening, touching, etc.), which is transmitted into their long-term memory. Information processing suggests that the quality of learning is primarily a function of the quality of the information presented by the instructor. These theories are helpful in explaining common observations of students, for instance "information overload", unconscious selection of input stimuli, and reduction of knowledge to rote memory (Johnstone, 1997). While information processing theories explain how learners deal with sensory stimuli in the classroom, the dominant theory regarding the transformation of these stimuli into knowledge is now constructivism.

Constructivism posits that information is taken in from the environment through the senses and selectively stored in working memory. Learners then make connections between the new information and their prior knowledge, and memories. This process results in the "construction" of new understanding or conceptualizations, which are stored in the long-term memory. Learners therefore play an active role in determining what is learned from particular information sources. Knowledge is constructed in the mind of the learner, rather than being imparted by the teacher and absorbed directly by the student (Bodner, 1986; Smock, 1981). Constructivism implies that new knowledge is evaluated, manipulated, and connected using prior knowledge, preconceptions, values, and beliefs in order to make sense of experiences (Piaget, 1954; Smock, 1981; Zimmerman, 1981; Bodner, 1986). Prior knowledge is not necessarily derived from the classroom, and may reflect self-consistent mental models of the natural world derived from students' previous experience. Even where these mental models are incompatible with scientific theory, they may prove very resilient. Understanding and working with these prior conceptions thus becomes a core challenge for teachers (Ward and Bodner, 1993). A more recent theory argues that perception and long term memory are socially constructed by a group of learners through a process of discussion and collaboration, a theory known as socio-constructivism (Greeno et al., 1996). Socio-constructivism helps explain the empirical findings that student learning

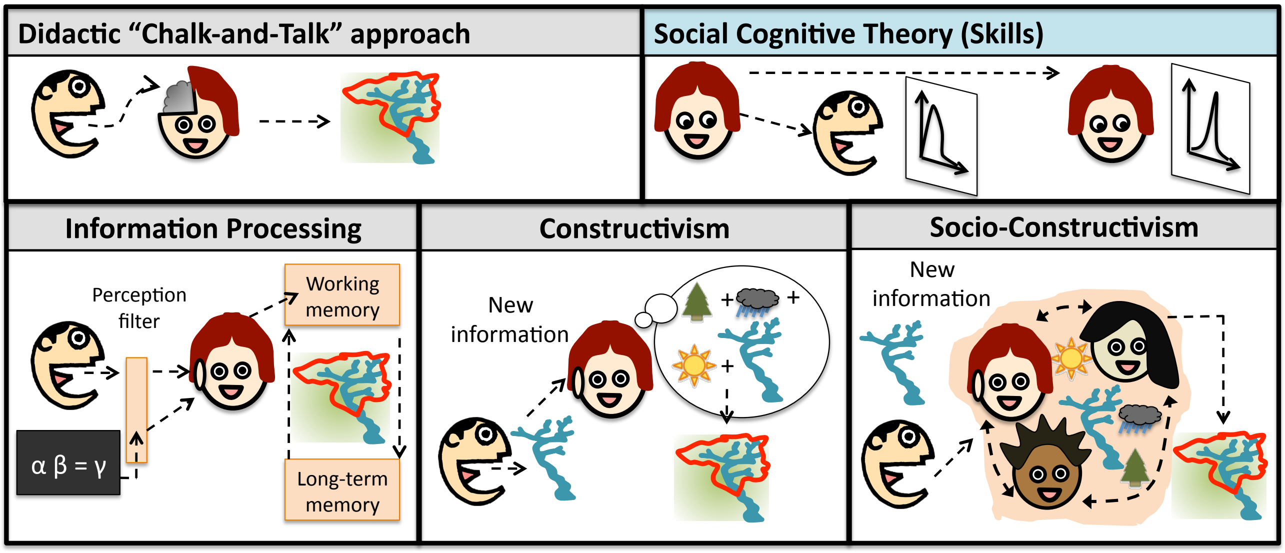

Fig. 2. Cartoon illustration of the major categories of learning theory in contrast with the assumptions implicit in a didactic or "chalk-and-talk" approach to teaching. Information processing accounts for the challenges associated with communication in a learning context. Students unconsciously filter the sensory inputs from ears and eyes, so that what the students "hear" is not necessarily what the instructor said. Once received, students must do mental work on information held in their short-term, working memory, in order to generate long-term knowledge. There are physiological and mental limits to memory capacity and to the rate of mental work. Information overload, selective retention and a resorting to rote memorization can be understood in terms of the cost of this mental effort. Constructivism posits that learners integrate new information with their existing knowledge to construct understanding of new principles: students would link the teacher's explanation with their own understanding and experience of energy balance, rainfall, vegetation water use etc. as they refined their mental model of a catchment. Socio-constructivism emphasizes the role of social interactions between learners in facilitating the construction of knowledge. Learning of skills and procedures is thought to occur by learners observing, mimicking and practicing skills as modeled by a teacher, and then successfully applying the skill in a new context, as described by social cognitive theory. In contrast to the implicit assumption that students will learn the information transmitted by the instructor, these learning theories highlight the active role that students must play as learners.

outcomes are often enhanced when they are given opportunities to learn collaboratively (Felder, 1995). The constructivist and socio-constructivist theories have several implications for teachers and for successful teaching:

1. Constructivism suggests that the way students learn from new information and facts is context dependent. Teaching approaches that build on familiarity and intuition will help support students in understanding new topics. Conversely, it may be important to highlight areas where previous experiences or intuition might lead students astray, in order to make difficult subjects easier to understand, or to avoid generating misconceptions.

   For example, the flowerpot analogy described above "works" because it draws on processes and objects that are familiar and intuitively understood by students, while allowing them to extend that familiarity to a new setting. However, the analogy has limitations – for instance its simplistic 1-D form may lead students to draw erroneous conclusions about the physics of subsurface flow and its links to runoff generation.

2. Constructivist ideas suggest that learning is not a passive process, but one in which learners are actively engaged. Creating opportunities for two-way communication between instructor and student can therefore assist instructors in adapting their teaching to student needs.

   For instance, following the introduction of the flowerpot analogy, instructors might pose homework problems that ask students to critique the model in terms of its applicability to real catchments, and to comment on (i) what was easy to understand about the model, and why, and (ii) what was difficult to understand about the model, and why. This homework problem firstly attempts to assess conceptual understanding, but also asks students to reflect on their learning, their comprehension, and areas of concern, giving instructors an opportunity to adapt their teaching.

3. Two-way communication between a single instructor and tens or hundreds of students in a class is logistically challenging. However, students can learn from each other and engage in learning as a collaborative exercise – establishing 2-way communication with their peers, and constructing understanding together. New educational technologies are now available to assist

Table 1. Examples of inductive teaching and learning approaches for hydrology teachers.

Technique	Example hydrology problems/projects	Classroom activities
Problem-based learning/ inquiry-based learning	How will predicted changes in rainfall and population growth affect urban water security? What are the implications (safety, social, economic, ecological) of dam removal? Why has continental runoff declined globally?	Group work plans Group discussion Task execution Targeted lectures (brief)
Project-based learning	Design a flow-measurement system to be implemented in a deep, flash flood prone canyon. Develop design criteria for stormwater management at a proposed mine site in an environmentally sensitive area. Design a water-harvesting system and water management plan for a remote, unpowered, desert community.	Group work plans Group discussion Task execution Targeted lectures (brief) Prototype construction/ design drafting Class presentations
Case-based learning	What were the hydrological implications of water diversion from Owens Lake to San Francisco? How predictable were these? What commonalities arise when comparing the water use and water policy trajectories of different cities (e.g., Los Angeles versus Atlanta)?	Case review Targeted lectures Group work and discussion
Discovery learning	Multiple problems are suitable.	Self-directed by students

instructors with obtaining rapid feedback from students in large classes, including electronic “clickers”, web or mobile-phone based polling tools, or even comprehensive delivery of content through online media (Popescu et al., 2012). Increased use of these technologies to facilitate constructivist teaching and learning has been championed in other disciplines, for instance via the Process-Oriented Guided Inquiry Learning (POGIL) movement in chemistry (Moog and Spencer, 2008).

For instance, student groups could be given an in-class task to predict the behavior of a leaky-bucket model. A web-based poll could be used to give immediate feedback to the instructor in terms of the response the students expect to see. Small group discussions can then be used to allow students to explain their thinking to each other. The students could then be polled again in order to evaluate the outcome of this group activity. Thus, small group settings can be used to reinforce teaching, to develop a collaborative approach to inquiry, and to advance conceptual and theoretical understanding. Collaborative learning does raise obvious challenges in terms of assessment, but several models, including group homework assignments complemented by individual tests (Felder, 1995), self assessment, assigned team roles, and even collaborative components on tests or examinations have also been suggested (Yezierski et al., 2008).

Regardless of specific theories of learning, two further important principles must be emphasized. The first is that learning is not purely a cognitive undertaking; motivational and affective processes contribute significantly to the enterprise. Students must be active participants in their learning (Greeno et al., 1996; Smith et al., 2005). Empirical studies broadly confirm that student engagement is one of the determining factors in undergraduate students’ academic success (Astin, 1993; Light, 2001; Pascarella and Terenzini, 1991).

The second principle is that learning more knowledge and facts is not sufficient for the development of expertise. Mastering a subject also requires that students can rank knowledge in terms of its importance, and organize it around conceptual hierarchies that enable knowledge to be used (Alexander, 1997; Shuell, 1986). Students therefore need opportunities to apply information in new contexts, to deconstruct concepts to reveal their underlying structure, and to integrate new and prior knowledge (Fink, 2003; Anderson et al., 2001). For example it is not sufficient to present hydrology students with interpretations from a hydrograph recession analysis: for students to really learn the concepts they would also need opportunities to fit recession curves to measured data, to derive the theory that links the hydrograph recession to catchment function (e.g., Brutsaert and Neiber, 1977), to integrate the recession analysis with their existing understanding of runoff generation, stream stage and flow variation, flow measurement techniques and other watershed-scale processes, and to question traditional theoretical interpretation of recession dynamics in light of new findings (Harman et al., 2009). Exercises that require students to commit to a hypothesis before exploring its validity (by data analysis, model implementation or observation), create opportunities to highlight conflict between previously held assumptions and physical reality, creating opportunities for learning (Bodner, 1986; Smock, 1981).

3.4 From instructor-centered to learner-centered teaching models

The shift towards instructional methods that support constructivist models of student learning implies an accompanying focus on the role of student engagement and cognitive effort. This necessitates a change in pedagogy that can support these important student roles: specifically from instructor-centered to more student-centered forms of instruction (Felder et al., 2000).

The typical techniques of hydrological teaching, such as lecturing, reading, and structured problem sets, are instructor-centered. Instructors actively deliver material, taking on the role of an “expert teacher” (Pathirana et al., 2012) while students take notes, read, and apply that material via problem sets. In contrast, learner-centered approaches offer students a degree of autonomy in directing their learning, and require students to share responsibility for building knowledge with the instructor (Bransford et al., 2004), with the teacher taking on the role of a guide, i.e., “facilitator” and “delegator” styles of teaching (Pathirana et al., 2012). Learner-centered methods generally begin with a specific realistic problem, e.g., experimental data, or a real world problem, enabling the student to see the relevance of the problem, and providing a clearer context for the student to connect to their own prior knowledge (Prince and Felder, 2006; Lombardi, 2007; Herrington and Oliver, 2000). Many instructional strategies can be categorized as learner-centered, including problem-based learning, project-based learning, inquiry-based learning, case-based learning, and discovery learning, as illustrated in Table 1 and elaborated on in Sect. 4 .(Herrington and Oliver, 2000; Thomas, 2000; de Graaff and Kolmos, 2003).

Both methods have benefits: instructor-centered methods can be highly effective in the acquisition of factual knowledge and the application of that knowledge to a defined range of contexts (Robinson, 1996; Costin, 1972), while student-centered approaches improve student engagement, motivation and transferability of knowledge from classroom settings to new problems (Chickering and Gamson, 1987; Astin, 1993; Light, 1992, 2001). The methods also have drawbacks, with instructor-centered approaches generally failing to provide opportunities for deconstruction, integration, and transfer of knowledge to novel contexts (Clough and Kauffman, 1999; Prince and Felder, 2006). Conversely, learner-centered approaches may be inefficient for teaching factual knowledge and conceptual understanding, are time and resource intensive, and, depending on the degree of autonomy offered the students, may also result in the development of misconceptions (Yadav et al., 2011). Student-centered approaches place a large onus of responsibility for learning on students, and often require a change in student attitude, and may meet strong resistance from students (Felder, 1995). To a large degree, however, student- and instructor-centered approaches are complementary, and if employed together, offer a way to broaden students’ learning experiences and develop expertise, without sacrificing the core components of a traditional education (Smith et al., 2005; Prince and Felder, 2006).

For hydrology instructors, who inherit a strongly instructor-centered educational tradition, constructivism and the success of POGIL and collaborative learning models in other scientific disciplines (Felder, 1995; Moog and Spencer, 2008; Yezierski et al., 2008) provide a motive to explore the forms of learner-centered methods that could be melded into a traditional “chalk-and-talk” based course. Studies in civil engineering students found that student learning was greater when a combination of both learner- and instructor-centered methods, including homework problems, group projects, experimentation, model building, conversing with experts, and real world projects, were combined (Bernold et al., 2000). A closer analysis matching specific pedagogical activities with student learning styles found that the learner-centered methods were particularly effective for students who characterized their learning styles as “abstract and concrete experimenters” – over 50 % of the engineering student population (Bernold et al., 2000). Not only do empirical studies support improvements in content-related educational outcomes, but many studies support the value of learner-centered pedagogies for improving critical thinking skills (Litzinger et al., 2005), self-directed learning, research skills, and expression (Jiusto and DiBiasio, 2006), and confidence (Mahendran, 1995). These kinds of outcomes strongly reflect the need for creative, confident, independent and flexible hydrology graduates outlined in Sect. 2.

A common critique of student-centered approaches to engineering education is that these approaches require considerable investment of time and resources, which can prove to be a significant barrier to teachers adopting them (Jiusto and

Table 2. Summary curriculum adopted by Troch and Sivapalan uniting deductive and inductive teaching methods for graduate catchment hydrology education.

Desired outcomes	Modes of teaching
Empirical basis for catchment form: – Morphology (drainage area, shape, network structure, slope, aspect) – Climate and vegetation (aridity index, land use, eco-region, LAI, phenology) – Soils and geology (soil texture distribution, soil hydraulic properties)	Instructor-centered: – Lecture format (concepts, links to hydraulics, physics, chemistry, mathematics etc.) – Homework (give students opportunity to apply knowledge to well-posed problems) – Tests and quizzes (assessment) – Discussion of landmark papers (peer-to-peer learning, critical thinking, communication)
Link between form and dynamics: – Point scale water and energy balance – Plant hydraulics (stomatal regulation, xylem, root structure, cavitation) – Runoff generation (fill and spill, connectivity, infiltration excess, saturation excess, variable source areas, macropores, preferential flow paths) – Runoff routing and baseflow (rill and gully flow, sheet flow, kinematic wave, dynamic wave, Muskingum, de St.-Venant, Dupuit-Forcheimer, Boussinesq, riparian aquifer, baseflow recession, master recession curve) – Spatial variability and heterogeneity (remote sensing, representative volumes, effective parameters) – Process Interactions (hillslope-stream connectivity, vegetation organization)	Student-centered: – Analysis of real-world data (confront students with complexity, guide analysis and reporting, patterns of behavior, develop and test hypotheses) – Comparative hydrology (move from individual sites to many places, hypothesize about patterns of similarity and difference) – Case studies (discussion, interest, context for fundamentals)
Water balance at catchment scales: – Patterns of behavior across multiple catchments (Budyko, L'vovich, regime curve, dominant process concept) – Vegetation dynamics (phenology, drought, climate change, disturbance) – Effects of human intervention (urbanization, drainage, reservoirs) – Top-down and bottom-up modeling (data based v. process based)	Synthesis and applications: – Top-down / bottom-up modeling (synthesize knowledge, study process interactions, learn from patterns of behavior) – Design and management (apply knowledge to generate products)

DiBiasio, 2006; Mahendran, 1995; Prince and Felder, 2006). Given the lack of literature regarding learner-centered teaching approaches in catchment hydrology, resource related concerns might be particularly challenging in this field. To offer a potential way forward, the following section presents two examples from the authors' experiences. We note immediately that these examples have not been formally evaluated through an engineering education study, and therefore remain anecdotal. However, we can use the frameworks presented above to analyze the different kinds of student-centered pedagogy in each of the examples, highlight aspects of PCK in the examples, and compare them to published studies addressing similar teaching strategies in other engineering disciplines.

4 Student-centered catchment hydrology education in action

Two different examples are presented in this section. The first example relates to the teaching methods employed by two of the authors of the article (MS and PT) in their graduate and upper-undergraduate catchment hydrology courses. The courses contain many standard elements of lecture, reading and problem sets, but are supplemented by case studies, and elements of problem and discovery based learning. The second example relates to the Hydrological Synthesis Summer Schools, held in Vancouver, British Columbia in the summers of 2009 and 2010. These Summer Schools had a research focus and a strong basis in discovery learning.

4.1 A curriculum based approach

4.1.1 Outline of the approach

MS and PT have taught catchment hydrology at undergraduate and graduate levels in Australia, Belgium, The Netherlands and USA (Illinois and Arizona), adapting their teaching methods over the years. At present, both instructors use a mix of student- and instructor-based teaching strategies. The curriculum for their contemporary catchment hydrology courses is shown in Table 2, and consists of three major components: catchment morphology, the link between morphology and hydrologic dynamics in the catchment, and a comparative and synthesis component that considers spatially and temporally lumped dynamics of the water balance at catchment scales.

Fundamental material in the course (for example, the observational basis for catchment morphology, soils/geology and vegetation, and the process basis for linking catchment form with catchment dynamics) is introduced to students through typical lecture formats. This lecture course ensures that the core aspects of a traditional hydrologic education are covered, and also provides the “scaffolding” that students draw on in the student-centered components of the course. The student-centered components of the course primarily address the synthesis of process (“internal descriptors” of Sect. 2) and catchment response (“external descriptors” of Sect. 2) across multiple locations.

The hydrological theory used in the student-centered course component draws on the idea of “catchment function” (Black, 1997; Wagener, 2007; McDonnell et al., 2007). Wagener et al. (2007) presented the idea of hydrological signatures as holistic representations of catchment function that can be observed in the variables of dynamic catchment behavior (e.g., streamflow or soil moisture). Signatures are outward manifestations of the internal catchment dynamics. The nature of the signatures changes with temporal and spatial scales at which they are observed or analyzed (Atkinson et al., 2003; Biggs et al., 2005; Farmer et al., 2003; Kirchner et al., 2004; Thoms and Parsons, 2003). Examples of signatures include, but are not limited to, those characterizing inter-annual variability (e.g., runoff coefficient, baseflow index), mean within-year variability (regime curve), random variability of daily flows within the year (i.e., the flow duration curve), the recession curve and the flood frequency curve.

These signatures provide an elegant, holistic representation of catchment responses, and provide vehicles to explore the underlying process controls. Exploring the nature of a given signature creates a “real world problem” for students to engage with. Starting with data from one to several catchments in different climatic or landscape settings, students can extract one or more signatures from the data. They draw on their knowledge of the underlying process controls and deconstruct these to interpret the signatures. Students then compare and contrast the properties of the signatures of several catchments, requiring synthetic, analytical and evaluative/interpretive thinking skills.

The problem-based task was introduced into the course as a term project. Support for its implementation was provided by a graduate teaching assistant, who acted as a resource for the students at the detailed level of code development and data analysis. In practice the mathematics needed to generate these signatures is not onerous, and the students readily understood the value of signatures for interpreting catchment behavior. The support of the teaching assistant was critical to the success of the term project: the teaching assistant provided technical support to students (in terms of making available the needed data and the data analysis tools). This support helped the students complete their analyses efficiently, and allowed the professor to focus their interactions with students on the hydrological questions that emerged as they engaged with their data.

In more advanced classes, students were encouraged to do class projects involving group efforts that focused on a single signature, where students would approach these signatures from several perspectives, and gain both holistic and in-depth process knowledge, or on applying process-based models to link climate and landscape properties to hydrological response. For example, as part of the advanced hydrologic and hydoclimatic variability class at Illinois, a group of four students focused on the flow duration curve (FDC) as a signature. One group of students worked on statistical analysis of over 200 catchments and extracting regional patterns. Another group of students approached the flow duration curve from a process modeling perspective. Starting with simple models, they systematically analyzed the process controls on the FDC, and increased model complexity until the model predictions matched the observations in a majority of catchments. This offered them deep insights on the functioning of the catchments. In another example, as part of the advanced catchment hydrology class at Arizona, a group of six students studied similarities and differences between catchments along a climate gradient using a process-based model developed by Carrillo et al. (2011).

Through these projects, the students gained insight into the relative controls of climate, geomorphology, soils, and vegetation on hydrological response. The analysis gave students the opportunity to explore the effects of heterogeneity of climate and landscape on catchment function, and illustrates that there are forms of understanding in catchment hydrology that can only be derived from insightful exploration of data and patterns extracted from data. By comparing patterns that emerged across time, space and through the deployment of different methodologies, students gained insight into the generalities and limitations of standard analyses and rules of thumb (Shaw and Walter, 2012). Qualitatively, the problem-based approach appeared to increase student motivation (as inferred from the relative quality of the term-project presentations when compared to standard problem sets during the course), to enhance team-work skills and create opportunities for students to learn from each other, and seemed to improve student recall and understanding of the topics covered in the course.

4.1.2 Student-centered teaching strategies employed

Several components of the course outlined by MS and PT rely on student-centered teaching strategies: specifically the use of case studies to motivate the topic, and problem-based learning approaches to address comparative and synthesis aspects of the curriculum. These approaches have unique characteristics, challenges and benefits for engineering education.

Case studies

Case studies are a flexible teaching method, that can be implemented in both instructor- and learner-centered ways (Prince and Felder, 2006). When the case is well defined and solutions are presented, case studies are usually instructor-centered; when no or limited solutions are presented, providing opportunity for critical thinking; information seeking; analysis; transfer; and creativity, case studies offer an opportunity for student-centered learning.

Case-based learning draws on realistic situations to motivate analysis and problem solving. In the courses taught by MS and PT, case studies include analysis of historical dam-break and flood scenarios, analysis of paired catchment experiments, or historical or contemporary water resources management problems. By studying the cases, students familiarize themselves with real-world problems and the skills needed to address them.

Case-based learning is fairly common in engineering education (Yadav et al., 2010). Several studies of case-based learning have found that it increases student engagement with the material (Hoag et al., 2005), their critical thinking, and their problem solving skills (Dochy et al., 2003; Yadav and Beckerman, 2009; Henderson et al., 1983). However, students have indicated that case studies do not necessarily improve their conceptual understanding (Yadav et al., 2011).

Problem-based learning

The exploration of signatures of catchment function using analysis of real-world data in PT and MS's classes is an excellent example of how problem-based learning (PBL) can be adapted to the hydrology classroom. In PBL, student effort is focused on an open-ended real world problem (de Graaff and Kolmos, 2003). Suitable problems should have moderate complexity and limited structure, with a few plausible solution paths and alternative solutions (Jonassen and Hung, 2008). Teams of students work on the problem, identifying areas of learning that they need in order to achieve a solution. They then pursue various means to acquire the necessary knowledge (Albanese and Mitchell, 1993). PBL classroom activities can be structured around groups creating and executing work plans, within and between group discussions, and brief lectures (Duch, 2001; Mills and Treagust, 2003). The instructor acts as a guide and a resource rather than the primary source of information.

PBL is uncommon in engineering, and there is no consensus on the benefit of PBL for engineering teaching and learning. From a theoretical standpoint, PBL provides extensive opportunities for students to develop questioning and critical thinking skills (Hmelo-Silver, 2004), and encourages engagement through the use of real world problems. PBL promotes knowledge transfer by allowing students to learn skills in a fluid situation, which is transferable to novel contexts (Lombardi, 2007). However, the results of the few studies that have been undertaken are contradictory. PBL was shown to increase motivation and critical thinking in industrial engineers in the Netherlands (Litzinger et al., 2005), and in engineering management students in Brazil (Ribero and Mizukami, 2003). A study in Sweden found that computer engineers emphasized the importance of cooperative learning in PBL and were more comfortable with PBL approaches than cohorts of psychology and physiotheraphy students investigated with the same methods (Dahlgren and Dahlgren, 2002). Conversely, a study in the Netherlands concluded that PBL was not suited to engineering instruction (Perrenet et al., 2000). One example of the successful implementation of PBL is in the biomedical engineering program at the Georgia Institute of Technology (Newstetter, 2005). This program implements elements of the PBL approach from the beginning to the end of the curriculum asking students to undertake such tasks as: designing a device to rapidly identify types of mold present in a room or using biomechanics to determine the probability that a deceased infant died from a brain injury received from shaking (see Newstetter, 2005, for a detailed description of this program). PBL is well suited for the investigations of comparisons between places, techniques, methods and times: approaches which may offer students insights into contemporary issues of non-stationarity, empirical versus process-based approaches, and the challenges of generalization and upscaling from small-scale examples (Shaw and Walter, 2012).

4.2 A discovery based approach

In 2009 and 2010, several of the authors of this paper were involved in the Vancouver Hydrological Synthesis Summer Institutes: novel educational and research enterprises in which students took the lead in outlining, planning and implementing research around four consecutive topics over a 6 week period (Thompson et al., 2011; Wilson et al., 2010). A group of 8–12 students was confronted with four general research topics and provided with supporting datasets. The students were challenged to (i) develop research questions and hypotheses that were relevant to the research topic and which could be addressed using the available data; (ii) to develop a research strategy by which the team could answer these research questions and investigate the hypotheses; (iii) implement that research strategy, adapting it as necessary; and (iv) to present their results at a "capstone" symposium consisting of other young earth scientists. For instance, in one project students developed hypotheses and research plans to explore the determinants of catchment water balance partitioning using data from 430 US Watersheds, and a combination of data analysis, analytical modeling and GIS based methods. The details of the Summer Institutes are reported in several papers regarding hydrological synthesis (Thompson et al., 2011; Wilson et al., 2010), the research outcomes of the 2009 Institute are published in a special issue of Water Resources Research, and the 2010 Institute outcomes are currently being submitted to a special issue of the Journal of Geophysical Research. There are several aspects of the Summer Institutes that are worth emphasizing in terms of their implications for student-centered learning.

For example, the role of mentors as resources and guides was critical, given that students' followed a research and discovery path that was set by their curiosity and their questions, rather than their existing skill base. Because of this, students required considerable support. The ratio of faculty mentors to students was approximately 1 : 4. Thus, the teacher to student ratios required to successfully implement this kind of model in the engineering classroom may prove unrealistically high for many classes. The student group, however, also relied strongly on peer-to-peer support, allowing more experienced students to supplement the role of faculty in mentoring and guiding their peers. Students regular shared knowledge and skills with each other, and collaborated as a group to determine hypotheses and the overall research direction. The Summer Institutes thus seem to have been quite successful in building a community of learners (Brown and Campione, 1990, 1994; Shuell, 1986; Shulman and Sherin, 2004), and fostering a social environment in which students could learn.

A second observation was that this discovery-based approach was most successful when students drew on data and observations in order to formulate hypotheses and propose analyses. While a modeling-based project was attempted, model development and testing were challenging to implement amongst a diverse group of students. The lack of success in implementing models likely reflects practicalities of group work, the nature of model development, and the time constraints of the summer school. Conversely, the multiplicity of analyses that could be applied to a large dataset, the ability to frame these analyses at varying levels of detail, and the need to interpret data to frame hypotheses proved suitable to group work and to self-directed discovery learning. Comparative analyses formed an integral component of this research (Shaw and Walter, 2012).

At the conclusion of the Summer Institute, our qualitative impressions were that the student outcomes from this experience were different from those of "typical" hydrological course work. The students hadn't necessarily learned every aspect of formal theory relating to their research topics, and most students acknowledged that gaps in this formal knowledge remained. Their confidence, critical thinking, and teamwork skills, however, were strengthened – consistently with research showing that practice in problem solving, communication and teamwork, and the opportunity to reflect on performance in these areas contribute to the development of these critical skills (Woods et al., 2000)

4.2.1 Student-centered teaching strategies employed

The teaching approach adopted in the Summer Institutes could be viewed as an extremely unstructured form of problem-based learning as discussed above, or as an example of discovery learning.

Discovery learning

Discovery learning is arguably the most self-directed student-centered method. In the most extreme instance, students are given a problem and work largely alone to solve the problem, with little guidance from the instructor. Most current implementations of discovery learning come under the rubric of "guided discovery", in which instructors play the role of a resource and mentor as students explore information, seek patterns and commonalities, generate hypotheses and ultimately test their ideas. Discovery learning is implemented in several engineering contexts, such as the capstone laboratory course in mechanical engineering program at the University of South Carolina. In this course, the final design laboratory task is a self-developed and directed research project (Lyons and Young, 2001). Discovery learning is also used in innovative computer interfaces, service learning projects, and museums. The limited use of this method in engineering coursework, particularly at undergraduate level, reflects its time-consuming nature, the requirement for high levels of student engagement and motivation, and the risk of misconceptions developing in the absence of detailed faculty guidance (Mayer, 2004). Its successful deployment at the Summer Institutes relied on a high level of faculty and mentor support, on the fact that students could dedicate 6 solid weeks to the discovery-learning program, and to the high levels of student engagement and motivation, which were secured by the competitive application process to the Summer Institute.

As was the case for problem-based learning, students not only pursued the solutions to problems but also learned the tools they needed to solve those problems as they went. This was exemplified by one student learning wavelet and Fourier analysis techniques during the 2009 institute in order to explore the coupling between flow and chemical concentration timeseries from an agricultural watershed (Guan et al., 2011). Despite the logistical challenges and demanding nature of discovery learning, the Summer Institutes indicate that with motivated students, a focus on learning from data, and sufficient faculty support, discovery learning can be highly enriching, particularly for advanced students.

4.3 Other student-centered learning techniques

The other major form of student-centered learning available to hydrology instructors include project or design based learning. Being product oriented (Thomas, 2000), project based learning familiarizes students with professional practices, while its relatively constrained scope minimizes the possibilities of incorporating incorrect information and forming misconceptions (Mills and Treagust, 2003).

Project-based learning is relatively widely implemented in engineering education.

Studies indicate that it increases engagement, critical thinking, self-direction and research skills, again at the expense of a significant time and resource commitment (1995) (Jiusto and DiBiasio, 2006), while the emphasis on creating a product rather than on the learning process itself can be a disadvantage (Mills and Treagust, 2003). Because hydrology is often more concerned with process understanding and representation than with a specific product, the value of project- versus problem-based learning might be more limited in this field.

5 Conclusions

The expansion of research into education in the latter half of the 20th Century has led to a revolution in thinking about pedagogy. This revolution can be characterized by shifts: from didactic approaches towards constructivist models of learning, from instructor-centered to more student-centered models of teaching, and towards a broad recognition of the significance of specialized knowledge about how to teach particular content in determining teacher expertise and student success. Engineering has been a relative latecomer to this research domain, and hydrology remains almost entirely unexplored from the perspective of education research. As hydrologists critically reflect on teaching, learning and student outcomes, however, there is scope both to draw on the experience in other branches of science and engineering, and to initiate hydrology education research programs to develop discipline-specific knowledge.

As outlined here, engineering education research suggests that students are more likely to acquire the higher order analytical, evaluative, and synthesis skills needed to handle the uncertainties of hydrological prediction and interpretation when student-centered approaches to teaching and learning are adopted as a complement to traditional direct instruction. We have argued that hydrology education therefore needs to incorporate learning experiences that will foster such higher-order skills. We have provided examples from our own experience, including upper-level university instruction to focused hydrological institutes, and shown how student-centered approaches that focus on learning from data can be incorporated into these educational settings. However, significant questions remain. What content in hydrology are student-centered methods best suited to – and is our thesis that they apply best when synthesizing Dooge's internal and external approaches valid? Can student-centered approaches be applied to lower-level hydrology teaching, for example in first-year engineering survey courses? Which student-centered strategies are most suitable for which subject matter? What is the role of novel modes of content delivery – for example through the use of computer games (Hoekstra, 2012; Seibert and Vis, 2012) – in bridging the gap between student- and teacher-centered learning? How can teaching programs and student outcomes be evaluated to measure the success of different educational approaches? And can we find ways to document the outcomes of this research and use it to educate the next generation of hydrology teachers, avoiding the problem of recurrent professional amnesia that otherwise assails engineering educators at the college level, who are rarely taught how to teach (Stice et al., 2000)?

While we can draw on broader engineering education research to inform our approach in hydrology, there is a need to initiate education research initiatives that are specific to hydrology education. These initiatives should include the development of a taxonomy of pedagogical content knowledge for hydrology that includes a set of the most important topics in the various sub-specialties and the various ways in which these can be represented, explained and demonstrated. This includes an understanding of which of these topics are easy or difficult for students, where misconceptions commonly occur and what makes topics difficult. Research in teaching and learning hydrology should evaluate the effectiveness of both learner- and instructor-centered approaches as applied to specific content knowledge, and how these vary with students' learning styles and prior experiences. Promising research indicates that formal hydrology teacher training can help shift teaching styles from those more aligned with instructor-centric methods to those that would promote learner-centric methods (Pathirana et al., 2012). Increasingly, content support for hydrologic teaching offers opportunities to free instructors from traditional lecture formats and to expose students to a broad range of expertise (Wagener et al., 2012). These research initiatives could contribute to the broader endeavor of teaching and learning research by providing examples of PCK and learning strategies in hydrology, allowing comparisons with other fields (Abell, 2008; Viiri, 2007).

By supporting and evaluating the use of student-centered teaching and learning in hydrology, such a program would benefit educators and hydrologists alike. Given the many open questions about teaching and learning in hydrology, the challenges facing the next generation of hydrologists, and the expanding effort in engineering education, initiating collaborative research efforts between engineering education specialists and hydrology teachers is opportune, vital to endeavors to reform hydrology teaching, and likely to add value to student and learning outcomes in both disciplines.

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