

This discussion paper is/has been under review for the journal Hydrology and Earth System Sciences (HESS). Please refer to the corresponding final paper in HESS if available.

Flowing with the changing needs of hydrogeology instruction

T. Gleeson¹, D. M. Allen², and G. Ferguson³

¹Department of Civil Engineering, McGill University, Montreal, Quebec, Canada

²Department of Earth Sciences, Simon Fraser University, Burnaby, BC, V5A 1S6, Canada

³Department of Civil and Geological Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

Received: 12 January 2012 – Accepted: 12 January 2012 – Published: 20 January 2012

Correspondence to: T. Gleeson (tom.gleeson@mcgill.ca)

Published by Copernicus Publications on behalf of the European Geosciences Union.

1115

Abstract

Hydrogeology is now taught in a broad spectrum of departments and institutions to students with diverse backgrounds. Successful instruction in hydrogeology thus requires a variety of pedagogical approaches depending on desired learning outcomes and the diverse background of students. We review the pedagogical literature in hydrogeology to highlight recent advances and analyze a 2005 survey of 68 hydrogeology instructors. The literature and survey results suggest there are ~15 topics that are considered crucial by most hydrogeologists and >100 other topics that are considered crucial by some hydrogeologists. The crucial topics focus on properties of aquifers and fundamentals of groundwater flow, and should likely be part of all undergraduate hydrogeology courses. Other topics can supplement and support these crucial topics, depending on desired learning outcomes. Classroom settings continue to provide a venue for emphasizing fundamental knowledge. However, recent pedagogical advances are biased towards field and laboratory instruction with a goal of bolstering experiential learning. Field methods build on the fundamentals taught in the classroom and emphasize the collection of data, data uncertainty, and the development of vocational skills. Laboratory and computer-based exercises similarly build on theory, and offer an opportunity for data analysis and integration. The literature suggests curricula at all levels should ideally balance field, laboratory, and classroom pedagogy into an iterative and integrative whole. An integrated approach leads to greater student motivation and advancement of theoretical and vocational knowledge.

1 Introduction

In the last thirty years, hydrogeology has emerged as a core course in geoscience departments as well as civil, geological and environmental engineering departments (Pederson, 1987; Tinker, 1989; Santi and Higgins, 2005). In addition to providing foundational training to geoscientists and engineers, core hydrogeology courses are often

1116

taken as electives by students from a variety of backgrounds including biology, environmental science, geography, urban planning and bioresource engineering (to name the backgrounds of students in the authors' classes in the last year). Hydrogeology is also taught as a component of courses in other departments such as forestry and catchment science as well as interdisciplinary centers examining water, sustainability, resources and climate change issues. In short, hydrogeology is now taught in a broad spectrum of departments to students with very diverse backgrounds. Demand for hydrogeology instruction has grown because of strong employment prospects for trained hydrogeologists and the growing recognition of groundwater in other disciplines. Data from the US Department of Labor and the American Geological Institute suggest the job market for hydrogeologists in the "green economy" (Bahr, 2009) is strong and will continue to be so in the future (Santi and Higgins, 2005). Hydrogeology has even been called "recession-proof" (Coontz, 2008). The growing recognition of the interactions of groundwater with surface water hydrology, ecology and other disciplines (Alley et al., 2002; Sophocleous, 2002) has also contributed to increased demand for hydrogeology instruction.

Hydrogeology is largely an applied science, and instructors grapple with the balance between teaching vocational skills which increase employability, and teaching theoretical knowledge which is essential for more complex problem solving. Teaching hydrogeology is further complicated by three additional issues. Hydrogeology necessitates great breadth of background knowledge. Learning outcomes have traditionally been narrowly targeted specific to hydrogeology, but students with a more diverse background may require these to be broader. Hydrogeology is taught in a variety of different departments and institutions as well as a variety of educational settings (field, laboratory, and classroom), each with its own complications.

This paper summarizes the challenges for teaching undergraduate hydrogeology in an experiential learning context and offers a pragmatic approach for adapting to changing demands while maintaining crucial learning outcomes. A review of the literature focuses both on crucial learning outcomes and different pedagogical approaches that

1117

have been successfully implemented for teaching hydrogeology in the classroom, the field and laboratory. Our objective is to qualitatively review, highlight and promote the diversity of pedagogical advances and applications that have occurred, largely in the last 15 years. We draw primarily from the *Journal of Geoscience Education* (previously called the *Journal of Geological Education* before 1996) because articles on hydrogeology are not common in engineering education journals. Figure 1 shows how the rate of publishing papers on hydrogeology pedagogy increased dramatically in the mid 1990s. We also analyze unpublished data from a survey of hydrogeology instructors ($n = 68$) that were asked what topics should be included in an undergraduate hydrogeology course. The voluntary survey was conducted online with pull-down tabs before a 2005 workshop entitled "Teaching Hydrogeology in the 21st Century" organised by the National Association of Geoscience Education (raw data available at <http://serc.carleton.edu/NAGTWorkshops/hydrogeo/index.html>). We conclude with ideas for integrating learning in the field, laboratory and classroom settings, emphasizing the importance of experiential learning, which in recent years has become a focus in pedagogy at all levels and across many disciplines.

We focus attention on introductory physical hydrogeology, recognizing that many institutions may only offer one course in this field while others may offer two or more such as aqueous geochemistry, contaminant transport, field school or modeling (Pederson, 1987). We acknowledge that hydrogeology is taught in a variety of departments and institutions which have a large range of ability and interest in supporting pedagogical advancement in hydrogeology. For simplicity we use the term "hydrogeology" which can be considered equivalent herein to groundwater hydrology, geohydrology or groundwater engineering for the purposes of this pedagogical article. We also use "geoscience" and 'engineering' as short forms, respectively, for earth science and geology or civil, geological and environmental engineering.

1118

2 Evolving student backgrounds

The growing diversity of students taking introductory hydrogeology requires instructors to carefully scrutinize (and perhaps relax) prerequisites to allow for broad student backgrounds. Understanding these various backgrounds will allow realistic learning outcomes to be set (see the next section) and help develop consistent expectations for both the instructor and the students. A greater student diversity may mean that specific course requirements may be met by incoming students yet their overall background can be vastly different. This presents a particular challenge because we commonly teach concepts using examples that relate to topics students may have covered in previous courses – oftentimes, not those courses listed as prerequisites. For example, students who have taken stratigraphy and sedimentology (i.e. geoscience majors) will associate hydrostratigraphy concepts readily, while engineering majors will likely have strong skills in partial differential equations. The physical geography major, however, may have a strong background in climatology and hydrology. This diversity of backgrounds means that the instructor must be adaptable and gauge expectations accordingly, particularly when setting exams, so that students are tested specifically on what they have learned in the course and how that knowledge relates to their individual background. This is the essence of experiential learning as will be discussed later.

Introductory hydrogeology courses are normally offered in the 3rd or 4th year of an undergraduate program. At a minimum, introductory physical hydrogeology requires students to have some basic knowledge and skills in three subject areas: (1) physical geology: basic rock types, basic structural features, stratigraphy, geological maps cross-sections; (2) Newtonian mechanics with well-developed physics-based problem solving skills; and (3) an appropriate level of mathematics including algebra, trigonometry, introductory calculus. For an introductory course in hydrogeology, these prerequisites need be no higher than a first year level. For those introductory courses including aspects of aqueous geochemistry and contamination, the fundamentals of chemistry should be well in hand.

1119

3 What are the crucial learning outcomes?

Hydrogeologists are required to possess a wide spectrum of knowledge and skills because the discipline itself is multidisciplinary. Aquifers are often studied using a variety of multidisciplinary tools (geological, geophysical, geochemical, mathematical, and computational) demanding some level of competency and knowledge in their application. However, all of these skills and topics cannot practically be taught in a single undergraduate course. Therefore, a challenge to teaching hydrogeology is choosing which topic or skill to include or emphasize in a given course or lecture. Additionally, hydrogeology instructors may find it challenging to design (or perhaps modify) a “one size fits all” course that provides foundational training to students with diverse backgrounds. Each instructor will have different desired learning outcomes depending in part on their background, department and institution. And each student will have a different learning style and background. This suggests that no singular, prescriptive pedagogy for hydrogeology is possible, useful or perhaps required.

The crucial topics or skills that should be taught in a hydrogeology class have been discussed in the literature (Table 1) as well as at workshops, conferences and symposia of the National Association of Geoscience Education and the Association of Engineering Geologists. Tinkler (1989), Santi and Higgins (2005), Siegel (2008) and Neuman (2009) list or discuss topics they consider crucial for a hydrogeology class based on their personal experience and discussions with other professionals (Table 1). Results of the 2005 survey at a workshop of the National Association of Geoscience Education indicate that few topics are considered crucial by most hydrogeologists while many other topics are considered crucial for only some hydrogeologists (Fig. 2). Participants were given three choices: (1) topic considered crucial, can't be missed; (2) topic covered, would consider shortening or eliminating; (3) not covered. Only fifteen topics are considered crucial by >75% of hydrogeology instructors. The crucial topics are listed in Fig. 3 and focus on properties of aquifers and fundamentals of groundwater flow. More than 100 other topics are considered crucial by some hydrogeologists

1120

(Fig. 2; Supplementary Fig. S1), suggesting a large variety of topics are taught in undergraduate hydrogeology classes. Overall, the topics considered crucial by >75 % of hydrogeologists are generally consistent topics and skills recommended by Tinkler (1989), Santi and Higgins (2005) and Siegel (2008). This suggests these 15 topics should likely be part of all undergraduate hydrogeology courses. Other topics can supplement and support these crucial topics, depending on desired learning outcomes. In the next section pedagogical advances in the class, field and laboratory that can cover the various topics are discussed.

4 Advances in pedagogical approaches

In this section, we review the literature on pedagogical approaches for hydrogeology. Web-based resources are also available. For example, the website “Teaching Hydrogeology in the 21st Century”, hosted by National Association of Geoscience Education and Carleton College (<http://serc.carleton.edu/NAGTWorkshops/hydrogeo/index.html>) is a significant resource for pedagogical ideas including activities and assignments, visualizations, internet resources, hydrogeology analogies and articles accessible to undergraduate hydrogeology students. There are also a number of online videos (e.g. YouTube or Vimeo) that are worth exploring for undergraduate hydrogeology courses.

Throughout this section, we refer to experiential learning, which, simply put, is learning by experience. Experiential learning is defined as “the process whereby knowledge is created through the transformation of experience. Knowledge results from the combination of grasping and transforming experience” (Kolb, 1984). In practice, experiential learning is characterized as inductive, learner centered, and activity oriented (Saskatoon Public Schools, 2009, from <http://olc.spsd.sk.ca/de/pd/instr/experi.html>). Inductive reasoning is a form of reasoning that makes generalizations based on individual instances. Personalized reflection about an experience (learner centered) and the formulation of plans to apply learning to other contexts (activity oriented) are critical factors in effective experiential learning.

1121

4.1 Teaching hydrogeology in the classroom

Field and laboratory pedagogy are important, but the essential theoretical underpinnings of hydrogeology are taught in the classroom. Amazingly, the literature discussing classroom pedagogy is limited (Fig. 1). A few recent articles have suggested specific active learning activities that could be useful. Siegel and McKenzie (2004) discuss a project of a fictional contamination incident that divides the class into three groups and culminates in a one-day mock trial. Singha (2008) presents a simple, inexpensive demonstration (using a juice container!), which can be used to help students visualize the interplay between stresses and fluid pressure when pumping a confined aquifer. Below we describe a semester-long design project developed by Neupauer (2008) that integrates classroom theory with weekly assignments. Mays (2010) introduces a one-week module on stochastic groundwater modelling.

In addition to providing a venue for emphasizing fundamental knowledge, a classroom setting allows for tackling multidisciplinary topics. Student discourse can enrich learning through the sharing of ideas, particularly when their backgrounds are diverse. This too is part of experiential learning, and often allows for more complex problem solving. For example, a discussion about watersheds will bring a variety of issues to light in a classroom that has mixed academic backgrounds, particularly when a few biologists in the room can add to topics encompassing aquatic ecology.

Since the number of papers focusing on classroom pedagogy is limited and the classroom is important for emphasizing fundamental knowledge, more papers could be written on classroom pedagogy. These could follow the example of Mays (2010) who explicitly discusses a lesson plan with a reading assignment and classroom presentation including terminology, key concepts, and modelling approach that will be used in the subsequent class meeting in the computer laboratory. More articles could be written that offer suggestions to engage students in active learning like Siegel and McKenzie (2004) and Singha (2008).

1122

4.2 Teaching hydrogeology in the field

Teaching hydrogeology and hydrogeology research skills in the field is crucial because this is the essential source of all data (Fletcher, 1994). Three avenues for teaching hydrogeology in the field are field trips, on- or near-campus sites, and dedicated field school sites. Each method is complicated by difficulties in data acquisition.

Field trips are generally considered sightseeing tours where students examine features, perhaps make a few measurements and take notes. Even a simple walk around campus can lead to discussion about local topography, geology and likely groundwater flow pathways, without the need for measurement. To give students a greater understanding of the entire aquifer, Trop et al. (2000) recommended a short field trip that was completed in the normal allotted classroom time. The stops included a local water processing plant and an outcrop of the local aquifer rock, followed by a traverse across the valley to examine the extent of this aquifer rock (Trop et al., 2000). This exercise was designed for pre-service teachers and first year students, and is an excellent introduction to the scale and concept of aquifers. Also, students felt ownership of their learning after collecting their field data.

On- or near-campus sites might include visiting geological exposures, hydrogeologic wells, and/or river systems that allow students to actively observe, test and monitor a groundwater system. Such sites can act as a focus for learning modules that strengthen independent research skills and vocational skills (Day-Lewis et al., 2006; Laton, 2006; Fryar et al., 2010; Fletcher, 1994; Mayer, 2001; Rimal and Stieglitz, 2000). Access to these types of facilities provides a venue for developing practical skills using sampling and monitoring instruments, such as water level tapes and simple surveying equipment, or pumps and field meters for conductivity, pH or dissolved oxygen (Allen, 1998; Rimal and Stieglitz, 2000). Students collect useful data, which can be used later for laboratory analysis to characterise the aquifer. Collecting data gives students ownership over their learning and is excellent vocational training; however, very little theoretical knowledge is gained (Sanders, 1998). Using on-campus wells assumes the

1123

fortuitous situation of a useful and accessible well on campus or nearby. If this is not the case, a new well can be justified by coupling education purposes with research programs, and/or providing a backup water supply or water quality testing site for the university (Fletcher, 1994; Rimal and Stieglitz, 2000).

Acquiring data necessitates having access to a suitable field site. This can be a challenge in areas with few wells or where well access is restricted (Sanders, 1998). Field schools occur at a dedicated location, and include active learning experiments and activities. An off-campus field school can offer a more complete and in-depth field methods course because of the greater time available (typically 7–14 days). Such a field school can be paired with a traditional geology field school (Halsor et al., 1998; McKay and Kammer, 1999) or offered as a stand-alone hydrogeology field school (Horner et al., 1998). Universities that offer these field schools include University of Waterloo, Western Michigan University, University of Minnesota, Clemson University, ETH Zürich and western Canadian universities, as described below. Field schools provide opportunities for active learning, with students collecting useful quantitative data that can be used in various calculations (Lee, 1998). McKay and Kammer (1999) described neophyte hydrogeologists producing useful data, and more importantly, data analysis and interpretation after a three day intensive field school. Creating a hydrogeology field site for education, however, is a significant financial and faculty investment (Laton, 2006; Halsor et al., 1998; McKay and Kammer, 1999; Mayer, 2001; Day-Lewis et al., 2006). The cost (\$10 000–\$100 000) of developing an off-campus hydrogeology site is prohibitive to most departments. However, these costs can be offset by borrowing testing equipment, using existing drilled wells, or partnering with a company at an existing site (McKay and Kammer, 1999). Alternatively, two or more universities may partner, as was done between the University of British Columbia and the University of Calgary in setting up a joint hydrogeology field school site. The site is equipped with several nested piezometers, three multi-level piezometers, and a pumping well. Currently, students and faculty from both these universities, as well as from Simon Fraser University participate in the field school. Students are given an opportunity not only to

1124

learn vocational skills, but to apply knowledge gained through prerequisite hydrogeology courses to tackle the analysis and interpretation of the data. In addition, they meet and work with students and faculty from other universities in western Canada.

5 Each method is useful depending on the desired instructional outcomes. Field trips are useful for introductory classes, whereas on- or near-campus sites and field schools are applicable to senior undergraduate classes because they are more actively student-led, and thus, inspire student involvement. However, development of such sites is more time intensive and possible expensive.

4.3 Teaching hydrogeology in the laboratory

10 Teaching hydrogeology in a laboratory using personal computers as well as physical and chemical experiments is essential, because it gives a broader and more systematic understanding of aquifers (Horner et al., 1998; Lee, 1998). Various apparatuses are useful for physical modelling and chemical experiments.

15 Personal computers assist laboratory teaching in computer-assisted instruction, data visualisation and analysis, and numerical or analytical modelling. Computer-assisted instruction is a broad category where software partially or wholly replaces human instruction, becoming a tireless tutor (Renshaw et al., 1998). Most software is little more than an electronic textbook, which tests and guides students through scripted questions. More recently, computer-assisted instruction “experiment simulators” have been
20 successfully applied to augment, but not replace, standard experiments, especially to prepare students before or summarize after the laboratory (Renshaw et al., 1998). Renshaw et al. (1998) showed that experiment simulators can be effective not only for increasing lower level cognitive skills but also higher order skills, such as cross-domain knowledge and critical thinking. Computer-assisted instruction software engages students
25 in a pseudo-active manner, but gives students little appreciation of aquifer heterogeneity or the limits of data acquisition.

Visualization and analysis software has revolutionised our spatial understanding of the chemical and physical variability of aquifers (Hudak, 1998). A wide variety of data

1125

from water quality to aquifer tests are easily computed, plotted or graphed on personal computers, allowing students time to concentrate on the data collection or interpretation (Horner et al., 1998; Lee, 1998; Dunnivant et al., 2002). Hand contouring can be a useful skill (Siegel, 2008) but an alternative for large datasets are software that
5 displays 2-D or 3-D plots instantaneously (Hudak, 1998). Although this plotting is not inherently more accurate, it is faster and easier for students to visualize. A first note of caution is that incorrect and incomplete data sets looks just as good, especially on 3-D plots, as do good, complete data sets (Burkhart, 1998). Computer derived plots can lull students into not inquiring about the data quality, which is a huge variable in any study.
10 A second note of caution is that geostatistical analysis techniques should accompany any computer-assisted contouring. Geostatistical analysis techniques are taught in Geographical Information Systems and/or Spatial Analysis courses, but are often neglected in undergraduate hydrogeology courses. Students need instruction on how to critically evaluate their data and the resulting contour maps. An exercise demonstrating
15 how one data set can be contoured to give quite different results is useful.

Analytical or numerical modeling can help students understand the process and controls of groundwater flow and or transport, and are useful vocational skills. Model complexity can range from highly simplified domains to complex models that integrate real field data (Rojstaczer, 1994; Haitjema, 2006). Macfarlane et al. (2006) develop contaminant transport software with a graphical user interface for a capstone educational
20 experience, in which students take on the role of an environmental consultant.

Physical models, such as a “sand tank” apparatus, have been used as scaled aquifer models (Lee, 1998; Trop et al., 2000). A sand tank is a simple, clear plastic tank with a water input on one side and output on the other. Sand and/or gravel are aquifer
25 materials, while silt or clay layers act as aquitards. Flow rate and style are controlled by altering the architecture of the layers. Introducing color dyes into the model aids in identifying the water table or visualizing contaminant transport. Physical models can be constrained by field trip observations and/or laboratory testing of physical parameters (Lee, 1998; Trop et al., 2000; Hudak, 2001). Students are most engaged when they

derive the boundary conditions for a scaled model from their own data (Trop et al., 2000). Scaled models are useful for introductory classes to gain an understanding of flow dynamics, but overly simplify the heterogeneity of aquifers.

5 Even though chemical characterization of aquifers is important to researchers, especially considering water quality and contamination issues, little is published on the pedagogy of this topic. Fletcher (1994) outlined the purposes and general design of chemical characterisation laboratories, but only Lee (1998) has provided concrete examples of chemical laboratory exercises. Dunnivant et al. (2002) briefly discussed pollutant fate, but primarily described a new computer-assisted instruction program, “Enviroland”.
10 Discussion on both the guiding principles and practical exercises for chemical hydrogeology laboratory exercises are needed.

The problems facing laboratory pedagogy are diverse, but are partially derived from the same problems as field pedagogy. First, aquifer heterogeneity and complexity wrecks havoc on analysis and modelling of any aquifer, especially if real data derived
15 from a field study are used in an introductory setting (Allen, 1998). Second, gigantic databases and the drive for three-dimensional visualization demands both diverse and complex software packages that are not easily learned (Hudak, 1998). Third, any scaling model is inherently inaccurate, and one must choose the variables which it hopes to model most accurately (Trop et al., 2000).

20 In conclusion, computer software and physical models are important and innovative learning tools in the hydrogeology laboratory. These can lead to greater understanding of the spatial limits and flow dynamics of aquifers. Ideally, computer software and physical models can use student-derived field data, which keeps students actively included and helps students remember the limitations of the data.

25 **5 Toward an integrated pedagogy**

To ensure the long-term sustainability of groundwater resources, we need to train a greater number of scientists and engineers who are versatile in both the theoretical

1127

and practical aspects of groundwater, and who can become responsible and knowledgeable scientists and citizens (Tinker, 1989; Fletcher, 1994). Many instructors of hydrogeology contend that field, laboratory and classroom components are all critical elements in a well-structured hydrogeology curriculum at all levels (Tinker, 1986;
5 Fletcher, 1994; Abate, 1998; Sanders, 1998). Many authors suggest that theory should be learned in the classroom and vocational skills should be taught in the field or laboratory (Abate, 1998; Lee, 1998). However, they offer few suggestions on classroom pedagogy or how to balance the components of field, laboratory and classroom. Learning of the three components ideally would be integrated into a cohesive, iterative whole
10 with data collection in the field and analysis in the laboratory balanced with advances in theory in the classroom (Fig. 4). The three components would be organized into an iterative loop, in which advances in each component encourages, supports and advances learning in the other two components. The allocation instructional time and faculty resources between the three components will vary drastically between different
15 instructors, departments and institutions depending of desired learning objectives and students. Furthermore, students should, as much as possible, derive their own data in the field, analyse these same data in the laboratory, and discuss the ramifications and meaning of their data and data analysis procedures in the classroom. In essence, we advocate that a balance be sought between theory and practical application, in which
20 students are included in all components as owners of their data and their learning. To this end, we discuss how such an integrated curriculum encourages active learning and critical thinking, and we introduce methods and questions meant to encourage an integrated curriculum. To illustrate our view we first discuss two examples of this type of integration:

25 1. Trop et al. (2000) presented a well-structured example of integrating field, laboratory and classroom components. As previously described, pre-service teachers were taken on a field trip to make descriptions of an aquifer. With their field descriptions as boundary conditions, they were asked to build a sand box model of their aquifer in the laboratory. Then these models were tested for accuracy, and

1128

findings. Such an exercise builds on much needed writing skills, which ultimately will help to prepare the student for consulting or industry jobs or for thesis research at a graduate level.

A few simple, but significant, questions are useful when trying to make hydrogeology courses more integrated and active. Is what we are learning in the classroom linked thematically and does it support what we are learning in the field or laboratory? Or are the two disassociated? Are the students deriving their own data and is this same data set being used in laboratories and being discussed in the classroom?

6 Conclusions

The above descriptions of field, laboratory and classroom pedagogy reveal that there is a bias towards advances in field and laboratory teaching (Fig. 1). This has been true since the first hydrogeological pedagogy articles were published on laboratory methods (Brice and Levin, 1962; Lehr, 1963; Blanchard, 1964). At this watershed moment in pedagogy of hydrogeology, there is limited discussion about classroom pedagogy or debate about content in hydrogeology classes at least in the peer-reviewed literature. The bias towards field and laboratory pedagogy may be due to the relative youth of hydrogeology pedagogy and/or due to the research and teaching interests of hydrogeologists, which lie predominantly in the field and laboratory.

The literature and survey results suggest there are ~15 topics that are considered crucial by most hydrogeologists and >100 other topics that are considered crucial by some hydrogeologists. The crucial topics focus on properties of aquifers and fundamentals of groundwater flow, and should likely be part of all undergraduate hydrogeology courses. Other topics can supplement and support these crucial topics, depending on desired learning outcomes. Students can learn these topics in a balanced and iterative loop of components of field, laboratory and classroom learning (Fig. 4). At the outset of this paper, we asked what form hydrogeology training should take and how to balance the need for theoretical knowledge and the need vocational skills. Students

1131

can be exposed to all facets of the groundwater science – field, laboratory and theory – and they can learn to apply their data collection skills to their interpretive skills in such a way that a balance is attained between theory and practical application. An integrated hydrogeology pedagogy encourages active and experiential learning, which leads to greater student motivation and advancement of theoretical and vocational knowledge.

Supplementary material related to this article is available online at:
<http://www.hydrol-earth-syst-sci-discuss.net/9/1115/2012/hessd-9-1115-2012-supplement.pdf>.

Acknowledgements. B. Teswksbury is thanked for encouraging us to analyse the unpublished survey data.

References

- Abate, C.: Techniques for successful graduate and undergraduate instruction in hydrogeology- Geological Association of America, Abstracts with Programs, 30, pp. 306, 1998.
- Allen, T.: Field laboratories in environmental geology and hydrogeology Geological Association of America, Abstracts with Programs, 30, pp. 306, 1998.
- Alley, W. M., Healy, R. W., LaBaugh, J. W., and Reilly, T. E.: Flow and storage in groundwater systems Science, 296, 1985–1990, doi:10.1126/science.1067123, 2002.
- Bahr, J.: O brave new world: geoscientists in an emerging green economy, GSA Today, 20, 12–14, 2009.
- Blanchard, F. N.: An electric analog model demonstrates ground-water flow, J. Geol. Educ., 12, 104–105, 1964.
- Brice, J. C. and Levin, H. L.: Porosity and permeability experiments for general geology laboratory, J. Geol. Educ., 10, 81–90, 1962.
- Burkhart, P. A.: Thinking like a drop of water and other tips for learning hydrogeology Geological Association of America, Abstracts with Programs, 30, pp. 306, 1998.

1132

- Coontz, R.: Hydrogeologists tap into demand for an irreplaceable resource, *Science*, available online at http://sciencecareers.sciencemag.org/career_magazine/previous_issues/articles/2008_08_08/caredit.a0800120, doi:10.1126/science.caredit.a0800120, 2008.
- Day-Lewis, F. D., Gray, M. B., Garfield, R. L., and Day-Lewis, A. D.: An On-Campus Well Field for Hydrogeophysics Education and Undergraduate Research, *J. Geoscience Education*, 54, 480–486, 2006.
- Dunnivant, F. M., Danowski, D., and Newman, M.: Teaching pollutant fate and transport concepts to undergraduate non-science majors, environmental scientists and hydrogeologists using Enviroland, *J. Geoscience Education*, 50, 553–558, 2002.
- Fletcher, F. W.: A hydrologic field laboratory for undergraduate instruction and research, *J. Geol. Educ.*, 42, 491–493, 1994.
- Fryar, A. E., Thompson, K. E., Hendricks, S. P., and White, D. S.: Incorporating a Watershed-Based Summary Field Exercise into an Introductory Hydrogeology Course, *J. Geoscience Education*, 58, 214–220, 2010.
- Haitjema, H.: The Role of Hand Calculations in Ground Water Flow Modeling, *Ground Water*, 44, 786–791, doi:10.1111/j.1745-6584.2006.00189.x, 2006.
- Halsor, S. P., Orem, B. F., and Rudenko, D.: A multi-media field laboratory and the development of an undergraduate methods course in subsurface hydrogeology, *Geological Association of America, Abstracts with Programs*, 30, pp. 307, 1998.
- Horner, T. C., Cornwell, K., and Kusnick, J.: Use of active learning modules in water quality and stream flow to enhance understanding of the scientific method, *Geological Association of America, Abstracts with Programs*, 33, A193, 1998.
- Hudak, P. F.: Visualising ground-water-flow fields and contaminant plumes in an undergraduate hydrogeology class, *J. Geoscience Education*, 46, 132–136, 1998.
- Hudak, P. F.: Creased-plastic rock permeameter for hydrogeology students, *J. Geoscience Education*, 49, 182–186, 2001.
- Kolb, D. A.: *Experiential learning: experience as the source of learning and development* Prentice-Hall, New Jersey, 1984.
- Laton, W. R.: Building Groundwater Monitoring Wells on Campus A Case Study and Primer, *J. Geoscience Education*, 54, 50–53, 2006.
- Lee, M.-K.: Hands-on laboratory exercises for an undergraduate hydrogeology course, *J. Geoscience Education*, 46, 433–438, 1998.
- Lehr, J. H.: Ground-water flow models simulating subsurface conditions, *J. Geol. Educ.*, 11, 124–132, 1963.

1133

- Macfarlane, P. A., Bohling, G., Thompson, K. W., and Townsend, M.: Helping Students Make the Transition from Novice Learner of Ground-water Concepts to Expert Using the Plume Busters Software, *J. Geoscience Education*, 54, 610–619, 2006.
- Mayer, J. R.: Teaching undergraduate hydrogeology using an on-campus well field; balancing theory and practical application, *Geological Association of America, Abstracts with Programs*, 33, pp. 241, 2001.
- Mays, D. C.: One-Week Module on Stochastic Groundwater Modeling, *J. Geoscience Education*, 58, 101–109, 2010.
- McKay, L. D. and Kammer, T. W.: Incorporating hydrogeology in a mapping-based geology field camp, *J. Geoscience Education*, 47, 124–130, 1999.
- Neuman, S. P.: Comment on “Siegel D. 2008. Reductionist hydrogeology: ten fundamental principles. *Hydrological Processes* 22: 4967–4970”, *Hydrol. Processes*, 23, 1676–1677, doi:10.1002/hyp.7280, 2009.
- Neupauer, R. M.: Integrating Topics in an Introductory Hydrogeology Course through a Semester-long Hydraulic Containment Design Project, *J. Geoscience Education*, 56, 225–234, 2008.
- Pederson, D.: Education and employment in hydrogeology, *J. Geol. Educ.*, 35, 16–21, 1987.
- Renshaw, C. E., Taylor, H. A., and Reynolds, C. H.: Impact of computer-assisted instruction in hydrogeology on critical-thinking skills, *J. Geoscience Education*, 46, 274–279, 1998.
- Rojstaczer, S.: The limitations of groundwater models, *J. Geol. Educ.*, 42, 362–368, 1994.
- Sanders, L. L.: Teaching hydrogeology to undergraduate and graduate students, *Geological Association of America, Abstracts with Programs*, 30, pp. 305, 1998.
- Santi, P. M. and Higgins, J. D.: Preparing Geologists for Careers in Engineering Geology and Hydrogeology, *J. Geoscience Education*, 53, 512–521, 2005.
- Siegel, D.: Reductionist hydrogeology: ten fundamental principles, *Hydrol. Processes*, 22, 4967–4970, 2008.
- Siegel, D. and McKenzie, J. M.: Contamination in Orangetown: A Mock Trial and Site Investigation Exercise, *J. Geoscience Education*, 52, 266–273, 2004.
- Singha, K.: An Active Learning Exercise for Introducing Ground-Water Extraction from Confined Aquifers, *J. Geoscience Education*, 56, 131–135, 2008.
- Sophocleous, M.: Interactions between groundwater and surface water: the state of the science, *Hydrogeology Journal*, 10, 52–67, 2002.

1134

- Tinker Jr., J. R.: Technical writing in hydrogeology, *J. Geol. Educ.*, 34, 25–27, 1986.
- Tinker, J. R. J.: Undergraduate education in hydrogeology, *J. Geol. Educ.*, 37, 20–23, 1989.
- Trop, J. M., Krockover, G. H., and Ridgway, K. D.: Integration of field observations with laboratory modeling for undergraduate hydrologic processes in an undergraduate earth-science course, *J. Geoscience Education*, 48, 514–520, 2000.

Table 1. Critical knowledge and skills for practicing hydrogeologists.

Santi and Higgins (2005)
<ul style="list-style-type: none"> – Design of subsurface investigations – Three-point problem solution – Flow net construction and analysis – Oral and written communication skills – Use of Darcy's law and calculation of groundwater velocity – Hydraulic conductivity and intrinsic permeability, calculation and measurement methods – Aquifer types and groundwater occurrence – Storativity and transmissivity, calculation and measurement methods – Vertical groundwater gradients and flow – Water budget and hydrologic cycle – Basic statistics and probabilistic methods – Geographic information systems – Aquifer testing and analysis
Siegel (2008)
<ul style="list-style-type: none"> – "Don't push the data farther than they can be pushed and be honest with respect to what can be done" – Darcy's law needs to be understood at the "gut" level – Potentiometric surfaces are different from the water table – Surface water is an "outcrop" of the water table – Groundwater occurs in nested flow systems, separated by hydraulic boundaries – Contour using your head, and not your computer – Explore simple bivariate plots as an analysis tool
And for courses including geochemistry
<ul style="list-style-type: none"> – Groundwater chemistry is predictable from first principles – Chemical oxidation and reduction control many important groundwater and contaminant chemical compositions – As a working approximation, contaminant plumes should be considered narrow and no wider than a few times the width of the source at their heads

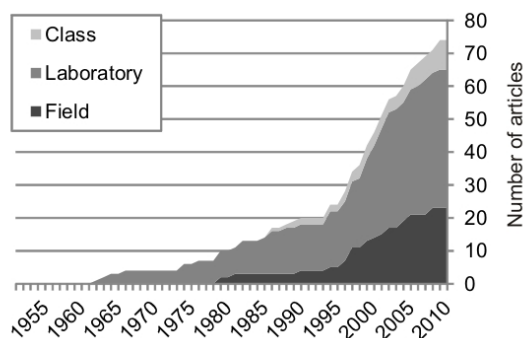


Fig. 1. Articles in the Journal of Geological Education (pre-1996) or Journal of Geoscience Education (post-1996) focusing on hydrogeology pedagogy either in the classroom, laboratory or field.

1137

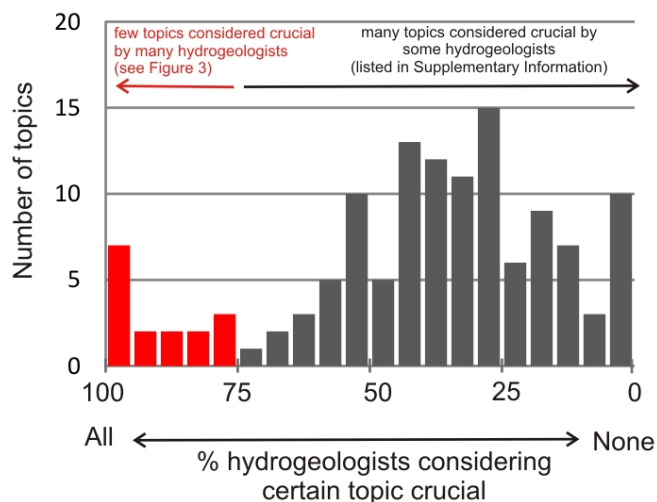


Fig. 2. Response of hydrogeology instructors ($n = 68$) asked what topics should be included in an undergraduate hydrogeology course. The voluntary survey is described in the Introduction. The 15 topics that >75% of hydrogeologists consider crucial are list in Fig. 3. The >100 other topics that some hydrogeologists consider crucial are listed in Supplementary Fig. S1.

1138

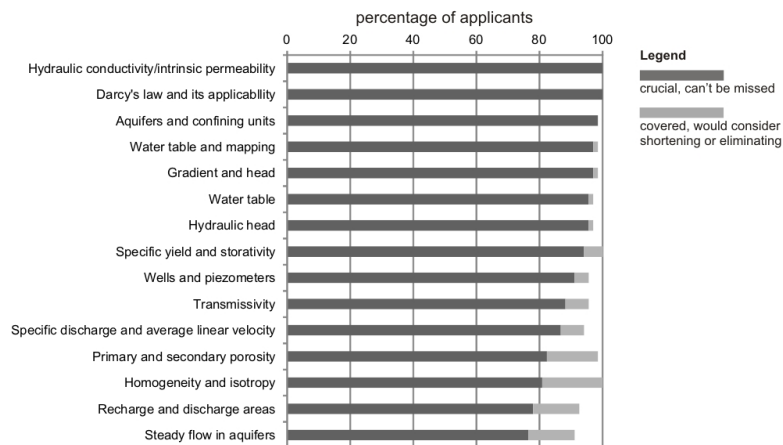


Fig. 3. The top fifteen most important topics for an undergraduate hydrogeology course according to a survey conducted in 2005 of academic hydrogeologists ($n = 68$). A graphic compilation of all topics on the survey can be found in the Supplementary Fig. S1.

1139

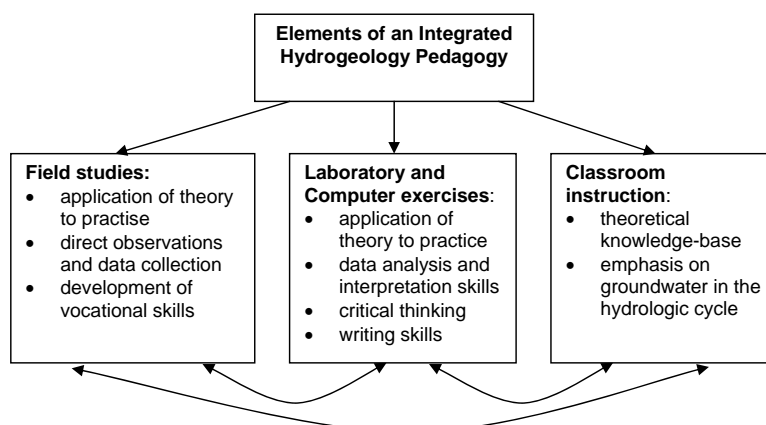


Fig. 4. The elements of an integrated hydrogeology pedagogy must be balanced in an iterative loop so that each element supports other elements.

1140