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Teaching groundwater dynamics: connecting classroom to practical and field classes

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Abstract

Preparing future hydrogeologists to provide inputs in societal discussions in a changing world is a challenging task that induces a need for efficient teaching frameworks. The educational literature suggests that hydrogeology courses should consistently integrate classroom instruction with practical and field classes. However, most teaching examples still separate these three class components. This paper presents an introductory course to groundwater dynamics taught at the Université des Sciences de Montpellier, France. The adopted pedagogical scheme and the proposed activities are described in details. The key points of the proposed course are: (i) an educational scheme that iteratively links groundwater dynamics topics to the three class components, (ii) a course that is structured around a main thread (well testing) called in each class component, (iii) a pedagogical approach that promotes active learning strategies, in particular using original practical classes and field experiments. The experience indicates that the proposed scheme improves the learning process, as compared to a classical, teacher-centered approach.

1 Introduction

Hydrogeology is basically an applied science that lies at the boundaries of geology, hydrology, hydraulics, soil sciences, physics and chemistry. Hydrogeology education is directly and indirectly impacted by the actual environmental challenges (e.g. characterizing and predicting the impacts of global change). Besides the scientific challenge of quantifying the direct impacts of global change on the groundwater resource, future hydrogeologists will have to provide crucial inputs – to other actors of planetary fields that are not groundwater specialists – in discussions on e.g. food production, energy and metal resources (Gleeson et al., 2012). There is therefore a clear need for an efficient teaching framework in the hydrogeology field.

A recent review on pedagogy for hydrogeology education suggests that an efficient pedagogical scheme should: (i) integrate the three class settings (i.e. classroom, field and practical classes) within an iterative loop in which each would supports the others (see our interpretation on Fig. 1), and (ii) promote learner-centered teaching methods (Gleeson et al., 2012). Noll (2003) exemplifies the shift from a traditional lecture/laboratory format towards an integrated approach. Most educational publications in the area of hydrogeology still dissociate field experiments (e.g. Woltemade and Blewett, 2002) from laboratory activities (e.g. Lee, 1998; Singha and Loheide II, 2011; Renshaw et al., 1998). Learner-centered features such as active learning teaching are present in most common inductive instructional methods such as problem-based or project based methods (Prince and Felder, 2006) and collaborative learning (i.e. group work towards a common goal Millis and Cottell Jr., 1997). The introduction of learner-centered demonstrations such as small experiments conducted with Darcy bottles or a plexiglass tank to illustrate concepts in groundwater into lecture classes is reported to spark off sophisticated questions and discussions. Physical models may help to address quantitative aspects (e.g. order of magnitude of groundwater fluxes or hydrodynamic parameters) of hydrogeology education (Neupauer and Dennis, 2010; Rodhe, 2012). Numerical models may help to assess and visualize the influence of the parameters involved in hydrogeological processes (velocity and concentration fields e.g. Singha and Loheide II, 2011) or to address basic modeling concepts such as sensitivity analysis (Gates et al., 1996; Li and Liu, 2003). Practical classes with hands-on experiments activities proved to be appropriate to explain physical processes in aquifers (Lee, 1998; Gates et al., 1996; Noll, 2003). Field activities can either be oriented towards passive or active demonstrations and experiments. A strong difficulty encountered in constructing field trips is to integrate the available resources (i.e. site, instruments, etc...) to the student's learning outcomes.

To address the challenge of the evolving hydrology education, pooling the teaching material and strategies in an open like community platform such as the Modular

Curriculum for Hydrologic Advancement project seems particularly interesting for future education (Wagener et al., 2012).

This paper aims to provide an example course on the sub-topic of groundwater dynamics. The key points of the proposed pedagogical scheme are the following: (i) learner-centered activities are favored, whenever possible, (ii) the integration of classroom, practical classes and field work are maximized, within the university's time and material constraints, (iii) sustainable teaching material is promoted. The proposed course includes original material for the practical classes.

This paper is structured as follows. Section 2 sums up groundwater dynamics key topics along to possible learning activities. Section 3 presents an example of structure and material for a course on groundwater dynamics. Section 4 is devoted to the discussion and Sect. 5 to concluding remarks.

2 Groundwater dynamics for hydrogeologists

As a consequence of a broader background (i.e. diverse earth sciences backgrounds) of students attending a hydrogeology curriculum of higher degree (Gleeson et al., 2012), it is necessary to provide students with the appropriate basics in groundwater dynamics before subsequent specialty courses are taught. A voluntary survey conducted amongst academic hydrogeologists recently published indicates that the greater part of the crucial topics in a hydrogeology course were related to groundwater dynamics. These topics include for instance: *“hydraulic conductivity”*, *“Darcy's law”*, *“gradient and head”*, *“transmissivity”* (Gleeson et al., 2012). Based on both the pre-cited survey and our experience we present in Table 1 a non-exhaustive summary of the necessary basics in groundwater dynamics. The different topics are distinguished by the nature of the learning outcome (knowledge or vocational skills) and presented along with common teacher and learner-centered teaching strategies. These topics should be addressed iteratively during lecture, practical and field classes. The specific goals of each of the three class setting are as follows:

1. lecture classes (associated to exercises) aim to (i) set the course background and remind basic notions, (ii) develop the students' knowledge with advanced concepts, (iii) skim over technical field methods;

2. practical classes composed of "hands-on" experiments aim to (i) develop specific technical and vocational skills, (ii) introduce the learner to critical thinking, (iii) use the theoretical knowledge and concepts learned during lecture classes, (iv) use the data gathered in the field;

3. field work is meant to (i) develop specific vocational skills, (ii) call upon the knowledge and skills learned during lecture and practical classes.

Note that the different teaching activities presented in Table 1 are not specific to a single class setting. Indeed, active learning teaching strategies cannot be associated with a given category of knowledge (Prince and Felder, 2006). Promoting the involvement of the students in the different class components should improve their commitment to the overall course and thereby improve their learning ability. As regards groundwater dynamics, the theoretical aspects taught in lecture classes when using appropriate activities and material can efficiently be illustrated in practical class or in the field. The students can sequentially learn, build knowledge bridges, practice and understand groundwater dynamics key topics when they characterize phenomena at different scales (i.e. time and space), in different places (i.e. classroom, practical classes and field) and with different approaches (i.e. theoretical or experimental). Moreover in an iterative loop between the three kinds of classes, the theoretical concepts learned during lecture classes are supported by catching the students curiosity during practical classes and field work.

3 An adapted teaching loop for a groundwater dynamics course

3.1 Overall teaching approach

The course presented hereafter is part of the qualitative and quantitative hydrogeology Master's degree program taught since 2004 at the Université des Sciences de Montpellier. The course comes during the first spring session (i.e. second semester of the first year). The course represents an amount of 5 ETSC (i.e. credit points). In this course, the final evaluation test and the practical classes and field reports account respectively for 60 % and 40 % to the global student's mark. The number of students attending this course roughly varies between 20 and 50, depending on the years and the choice of students. Note that when a large number of students attend the course, the class is divided into small groups (i.e. 10 students) for the practical classes and the field activities. The students which follow this introductory course to groundwater dynamics come from both the geosciences curriculum taught at the Université des Sciences de Montpellier and other universities or schools. This teaching unit is also open to the students following the university's Master's program devoted to petroleum reservoirs. For this course, the students are expected to have at least basic pre-knowledge in Darcy's law, general geology, mathematics and physics, but small knowledge discrepancies are expected in particular from the new comers.

Active participation is promoted during the different classes either through open topic questions, exercises, or experiments (Exp.) in order to favors the students' knowledge construction and student-teacher discussions. As an example, during lecture in classroom short time windows are dedicated to interactively solve exercises with inputs from the students. The applied field case motivates the students through its professional aspect.

The efficient, iterative loop between the three class setting proposed by Gleeson et al. (2012) (see Fig. 1) is adapted to the university's time and material constrains as follows (see for comparison Fig. 2). First, within an iterative loop between classroom and practical classes, essentials basics and methodology of groundwater dynamics are taught and practiced. Then, in the field, an applied field case is conducted, it requires to use most of the topics spanned during the course.

Pedagogical activities and sustainable teaching activities are promoted in this course in order to stress the students upon groundwater scarcity and quality issues. Different approaches are used in the course to address this topic. For instance in practical classes, by noticing that water circulates in a closed system. The teacher can also emphasize the importance of saving water as the city of Montpellier is integrally supplied in drinkable water by groundwater. This topic seems efficient to increase the student awareness on groundwater pollution issues. The Université des Sciences de Montpellier is located in a region influenced by the Mediterranean climate. Introducing the precipitation regime topic associated to this climate offers an opportunity to address subjects such as aquifer recharge and groundwater scarcity issues. A specific topic of groundwater dynamics is recursively reminded during the course. Using a main thread is meant to ease the transition between the different topics tackled during the course, and to maintain the student's interest at a high level. The requirements for the selected topic are: (i) to cover a large range of theoretical concepts and vocational skills, (ii) to fit in lecture, practical and field classes, (iii) to answer the student need for professional skills. For this course, well testing was selected as the main thread based on the following considerations: (i) it is a key topic in groundwater dynamics with various complexity levels, (ii) it is at the meeting point between theory and field investigations, (iii) it is an essential/prerequisite tool for any hydrogeologist engineers and scientists.

3.2 Classroom

Classroom is the "ground" class component for groundwater dynamics teaching, and the starting point for our iterative learning/teaching loop (Fig. 2). The theoretical aspects tackled in the course are illustrated by short application exercises where the teacher can deploy the different learner-centered teaching methods presented in Sect. 2. The success here depends strongly on the students dynamics (i.e. number of students,

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

reaction) in class. A classical global assessment is conducted at the end of the semester, with exercises similar to the ones seen in classroom.

3.3 Practical classes

The practical class adopts an experiential learning context, based on three original hands-on experiments that we especially designed for educational purpose. The two physical models used by the students presented hereafter work in a closed system of water avoiding a waste of water. A group report (in a scientific form) is due in a delay of 15 days after the end of the course. For this report, the assessment criteria emphasize the students' interpretations and discussions.

The first hands-on experiment (circular tank) is meant to address the following groundwater dynamics topics: (i) the effect of a well pumping at a constant rate on the shape of the water table (head fields) in steady state conditions and its change over time in transient conditions, (ii) the use of analytical solutions with steady state data (e.g. Dupuit-Thiem) to assess the hydrodynamics parameters of the analogical aquifer, (iii) discussing the validity of using Theis' solution with transient state data in an unconfined aquifer to assess the hydrodynamics parameters of the analogical aquifer and, (iv) the use of the superposition principle to interpret the head field between two pumping wells. Figure 3 (top) presents the associated apparatus and the detail of both the material and the proposed activities is provided in Appendix A.

The second experiment (rectangular tank) addresses the following topics: (i) the use of Darcy's law in unconfined conditions, (ii) definition of a protection perimeter around a pumping well on the basis of the head and velocity fields measured on the analogue aquifer and, (iii) the pumping well's maximum flow rate. Figure 3 (middle) presents the associated apparatus and the detail of both the material and the proposed activities is provided in Appendix B.

The third experiment (numerical model) is closely related to the previous experiment (i.e. rectangular tank): when efficiently conceptualized similar results are obtained. This experiment is meant to address the following topics: (i) confined and unconfined aquifer settings, (ii) results comparisons of heterogeneous hydrodynamic properties and equivalent homogeneous medium, (iii) the influence of the boundary conditions on the well productivity. Unlike physical experiments numerical simulations have the attracting feature of fast flexibility and let explore the influence of both varying boundary conditions and aquifer settings. The results of the simulations are interpreted and compared with reference to those obtained with the second experiment (i.e. rectangular tank). Details of both the material and the proposed activities is provided in Appendix C.

We encourage the interested reader to contact the author for further informations on the construction of the pre-cited physical models.

3.4 Field class

The field class takes place in a well field facility that was initially designed for research purpose (see general settings in Fig. 3 bottom). The field experiment has a low impact on the groundwater resource as it is strongly influenced by the near flowing river (see details in Appendix C).

The aim of the field class is to: (i) assess the local hydraulic and chemical aquifer properties, (ii) characterize and interpret the local groundwater dynamics, (iii) identify the uncertainties related to the field methods.

The supervision consists in refining the students objectives, roles and tasks to address efficiently the field work. This management is meant to avoid time loss. A group report (with a professional form) is due, in a delay of 15 days after the end of the course, to assess the student's understanding of the local groundwater dynamics behavior. For this report, the evaluation focuses on the discussions related to the results and the students' interpretations of the pumping test.

The activities conducted on the field can be divided into three steps:

1. Data collection for the pre-pumping characterization of the local groundwater dynamics. This characterization includes: (i) pre-perturbation measurements of the piezometric heads in each observation well, (ii) deploying data-loggers

with help of a field technician, (iii) boreholes characterizations by means of depth/temperature and electrical conductivity logging, (iv) setting the pumping line in the pumping well.

2. The pump is started by the technical team. During the transient phase of the pumping test, the students perform: (i) manual piezometric heads measurements in observation wells (by group of two), (ii) flow measurements at the outlet of the pumping line, (iii) borehole logging with temperature and electric conductivity sensors.
3. The technical team stops the pump when a steady state (or pseudo-steady state) is reached. The transient recovery phase of the pumping test is manually monitored by the students until initial piezometric head values are reached.

4 Discussion

The key points of the adopted pedagogical scheme are: (i) an adapted iterative loop for an integrated pedagogy (Fig. 2), (ii) articulating the course around a main thread called in each class component, (iii) promoting active learning strategies and developing in particular, original practical classes and field experiments. Note that practical classes have been subject to gradual modifications since the beginning of this course in 2004 (i) addition of numerical modeling activities to the rectangular tank experiment, (ii) introduction of the circular tank experiment.

Yearly general assessments of the Master program are conducted by means of students feedback questionnaires. For this course, positive feedbacks are received from the students. Most students feedbacks stress that both lab-experiments and field experiments greatly improved their understanding of groundwater dynamics, owing to the link it provides between theory and practice. The students behavior (i.e. classroom discussions and exam results) also confirms the positive impact of the proposed pedagogical scheme. Individual student results at the final assessment are strongly correlated to practical classes group reports results which evidences the efficiency of collaborative learning for groundwater dynamics teaching. At first, group working acts as an ice breaker and helps the integration of students from abroad. Then, it supports direct help between the students. Writing group reports also develop students team management skills. Finally, the sustainable teaching materials increases the students awareness on critical groundwater issues such as water scarcity or pollution. These elements suggest that the proposed pedagogical scheme has a positive impact on the student learning outcome, as compared to a teacher-centered scheme. It also favors discussions between the students and the teachers and fosters the taste for academic research.

Possible improvements of the proposed pedagogical scheme are related to: (i) the introduction of physical models in lecture classes as exemplified by Rodhe (2012), (ii) improvements in the practical classes' apparatus. As regards students' participation to lecture classes, simple demonstrations assisted with physical models could be used to bring analogue aquifer/process models in classroom and help formulating deeper questions. An example of such demonstrations can be found in e.g. Neupauer and Dennis (2010); Rodhe (2012) as regards hydrological processes. Planned improvements in the practical classes' apparatus (Exp. 1 and 2) include: (i) adding a colorant to the liquid in the piezometer tubes in order to ease the water levels reading and thus increase the time for data analysis and process interpretation, (ii) designing a data logger with a sampling frequency and accuracy adapted to the fast processes of the physical models. The addition of new activities to the practical classes, using the existing apparatus is indeed possible: for example, activities related to diffuse recharge and mass transport could easily be added to Exp. 3 (numerical model). However within the actual course's time constrains, the investigation of additional topics remains difficult.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

5 Conclusions

The challenges in groundwater dynamics teaching are principally related to the multidisciplinary aspects of the topics taught and the diversity of the student's backgrounds, motivations and professional goals (e.g. research, industry). In this context, an efficient teaching framework has to promote learner-centered activities, whenever possible (Gleeson et al., 2012). The example provided herein illustrates the actual shift of educational methods (i.e. from teacher-centered to learner-centered). Its design induced building a course's structure with an integrated pedagogy between the three class setting (field, classroom and practical classes). In this paper, we presented a brief summary of the different key topics that should be addressed in a course dealing with the basics of groundwater dynamics, along with a detailed pedagogical scheme to address a course on the basics of groundwater dynamics.

The key points of the adopted pedagogical scheme are: (i) an adapted iterative loop for an integrated pedagogy (see Fig. 2), (ii) articulating the course around a main thread called in each class component, (iii) promoting active learning strategies and developing in particular, original practical classes and field experiments in a sustainable way. The integration of classroom, field and practical classes was performed taking into account the university's time and material constraints. In each class setting, the association of theoretical topics and learning activities either starts a new iteration of the learning loop or supports and link the current loop topics. All along the course, the learner's interest is stimulated with the recursive topic of well testing, which leads to the final, applied field problem. The large range of topics related to well testing allows the teacher to cover increasingly complex notions (e.g. from hydrodynamics parameters to the diffusion equation and finally the applicability of the superposition theorem).

Our experience indicates that this pedagogical scheme improves not only the learner's motivation but also its peer relation and learning ability as compared to more conventional teacher-centered lecture. The promotion of sustainable experiments in the practical classes and in the field, increases the students awareness on groundwater and climate issues. The introduction of new experiments dedicated to practical classes proved possible at a reduced cost. In the same way, developing new field activities needed only an access to a pumping field for a day. These new experiments could therefore be included in an adapted form to groundwater dynamics courses in developing countries in which groundwater issues are crucial.

Our hope is that the proposed course will bring useful elements to teachers addressing the groundwater dynamics teaching challenge.

Appendix A

Circular tank apparatus

A1 Material

A schematic representation of this physical model is presented on Fig. 3 (top). The presented circular tank ($H \times r = 100 \times 50\,\mathrm{cm}$) is made from stainless steel with waterproof joints. Stainless steel was chosen to avoid premature corrosion. Before assembling, we recommend the builder to drill and cut all the necessary holes on (i) the future bottom face (i.e. inflow, wells, pressure probes and inner circular railing fixation) and, (ii) the outer face (i.e. overflow exists). An inner circular railing of radius 35 cm with a large mesh is filled with a homogeneous medium size sand (hydraulic conductivity $\approx 10^{-5}\,\mathrm{m\,s^{-1}}$) over a height of about 50 cm. Three screened PVC pipes (diameter = 2.5 cm) screwed to the bottom of the tank integrally cross the sand layer. Each well is controlled by an individual faucet under the tank. Water inflow to the physical model is ensured with constant water level condition. The water is pumped from an independent water tank. Inflow occurs at the bottom of the circular tank in the free space between the inner railing and the outer tank. Three overflow outlets located at an equal distance from each others and at an identical height on the outer side allow to keep an homogeneous constant head in the tank ($h = 45\,\mathrm{cm}$) around the sand layer. Water flowing through the overflow outlets returns to the independent water tank. Outer flows from the wells or the overflow outlets are measured with help of a graduated cylinder and a chronograph. Water levels in the sand are monitored by a network of 52 small holes (diameter $= 0.7$ cm) drilled at the tank's bottom. Flexible transparent PVC pipes link each hole to vertical transparent glass tubes (diameter $= 0.7$ cm) placed on a board in front of the tank. These tubes serve as monitoring "piezometers". Note that this pressure probe system is sensible to trapped air bubbles. Transparent pipes ease tracking potentially trapped bubbles. We also advise to respect the indicated diameter to avoid capillarity effect in the vertical tubes. An actual piezometer is build out of a screened pipe (diameter $= 2.5$ cm) and placed in the sand between a well and the outer railing. It provides an access to the water table level (i.e. head) from the top of the physical model and can host a data logger sensor. To minimize sand spreading outside the inner railing, inside the wells or the pressure holes, we recommend to place a thin net around the wells, on the inner side of the railing and on the bottom of the tank. Of course the net should have a mesh aperture lower than the grain size. Synthetic net curtain bought by the meter perfectly fit the need.

Most of the cost of this apparatus is incurred in the stainless steel tank construction. The total cos of the apparatus depends on the facilities offered to the teachers aiming at constructing such lab-experiments. Indicative costs range from 500 € (furnitures only) up to 5000 € (lab-experiment completed by an external company). This indicative prices neither include the injecting pump nor the data logger sensor (approximatively 1000 €). Potential savings can be realized by self assembling the experiment components (i.e. railing, pipes, piezometer board) and using an other building material, for instance Polymethyl Methacrylate (PMMA).

A2 Activities

During practical class, the circular tank apparatus is used to mimic the following configurations: (i) one well producing at a constant rate in a porous aquifer bounded by a constant head boundary, (ii) two wells producing at a constant rate in a porous aquifer bounded by a constant head boundary, (iii) one injecting well close to a pumping well, both with the same injecting and pumping rate.

The tasks of observation, description and measurements of the flow at the wells and of the water levels in the sand in steady and transient state allow the students to explore groundwater flow theory. The theoretical quantitative aspects of groundwater dynamics are put in practice by using for instance the Dupuit-Thiem approximation to interpret steady-state measurements and derive the hydraulic conductivity of the well's surrounding sand.

Transient state flow dynamics is studied using the data gathered by the pressure sensor placed in the piezometer. The results of the steady state and transient state characterization of the sand medium are discussed and compared in the group report. The validity of the superposition theorem in unconfined aquifer conditions is also discussed based on the gathered data. The fact that for relatively small drawdowns as compared to the aquifer thickness, the errors induced by the use of pumping test interpretation methods developed for confined flow conditions or by the use of the superposition theorem may be deemed negligible is very apparent with the proposed activities.

Appendix B

Rectangular tank apparatus

B1 Material

The apparatus is a rectangular stainless steel sand box ($l \times L \times h = 120 \times 90 \times 20\,\mathrm{cm}$) (Fig. 3 middle). It is divided into five compartments means of internal railing. Two compartments are saved for the upstream and downstream reservoirs. The three compartments left are filled with distinct uniform grain-size sands (hydraulic conductivities $k_1 \approx 10^{-5}\,\mathrm{m\,s^{-1}}$, $k_2 \approx 10^{-4}\,\mathrm{m\,s^{-1}}$, $k_3 \approx 10^{-3}\,\mathrm{m\,s^{-1}}$). In order to avoid sand spreading

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

and mixing, a thin synthetic net is placed on the railing walls (the same technique is used for the circular tank apparatus, see Appendix A1). Water is flowing in a closed loop from a reserve water tank to the rectangular tank. A permanent inflow is maintained to the upstream reservoir and, constant head conditions in both upstream and downstream reservoirs are obtained using overflow outlets. Water flowing out from the tank returns to the reserve water tank.

The gradient between the upstream and the downstream reservoirs can be changed by adjusting the height of the overflow outlets. Steady state is reached within a few minutes. At mid length, the rectangular tank is drilled to receive two screened pipes (made from 1 cm diameter pipes of plumbing) screwed to the bottom face of the tank. These pipes are meant to stand for fully penetrating wells in the aquifer model and can be activated by opening a faucet located under the tank. Pressure heads are monitored at 34 locations using the methodology detailed in Appendix A1. Pressure measurements are in particular performed in the two wells and in the upstream and downstream reservoirs. Monitoring piezometers are placed on the tank's face, similarly to the circular tank apparatus. Flow measurements are performed manually at the wells outlets and at the outlet of the tank apparatus, using a graduated cylinder and a chronograph. The cost of this apparatus is similar to that of the circular tank (from 500 € up to 5000 €, see details in Appendix A1).

B2 Activities

With this physical model, the students are introduced to the influence of heterogeneities in the hydraulic conductivity on the groundwater flow dynamics, in steady state conditions. Water table level and flow rate measurements are measured at the different outlets for different flow settings: (i) regular flow through the sand layers (no producing well), (ii) one producing well, (iii) two producing wells.

With help of water table maps, cross-sectional views and water budget the students trains to perform: (i) an approximate outflow determination with use of an equivalent homogenous aquifer solution and Darcy's law, (ii) the determination of a potential protection perimeter around a pumping well, (iii) maximal flow rate determination for the pumping well.

Appendix C

Numerical model

C1 Material

Historically, to introduce the students to numerical simulation, the educational free software Aquifer Simulation Model for WINdows (ASMWIN) developed by Chiang et al. (1998) was used. Since the newest versions of MS-Windows™ are not supporting ASMWIN anymore, the other free software Processing Modflow for Windows (PMWIN) developed by Chiang and Kinzelbach (2001) is used. An executable file can be downloaded online at the following address: http://www.pmwin.net/. This model runs on most MS-Windows™ operating systems. PMWIN is a program which brings the various code related to MODFLOW together. MODFLOW is the 3-D finite difference groundwater flow developed by the US Geological Survey. Note that among the different programs developed along to MODFLOW exist PMPATH (advective transport and particle tracking code by Chiang and Kinzelbach, 1994) and MT3D (3-D transport model by Zheng and Wang , 1990). PMWIN also includes a graphical user-interface which facilitate pre- and post-processing for MODFLOW, thus making its use fairly straightforward. The results of the simulations can be exported in different file formats for later representation and interpretation with other numerical tools.

C2 Activities

First, the students are setting a numerical model of a homogenous aquifer with (i) similar dimensions of the rectangular box described in Appendix B and, (ii) the previously found equivalent average hydraulic conductivity value. They can check the consistency between numerical results and the measured hydraulic head in the sand tank. Additional simulations are run for configurations of increasing complexity: (i) confined and unconfined equivalent homogeneous aquifer, (ii) confined and unconfined heterogeneous aquifer, (iii) confined and unconfined heterogenous aquifer with a pumping well. That later configuration introduces the particle tracking. In the final group report, the simulation results have to be presented in a particular form (piezometric contour lines with a defined interval and water budgets), which forces the students to explore the software's functionalities.

The proposed activities aim to develop conceptualization skills. For example, setting up a numerical model of the rectangular sand box address the issue of acceptable boundary conditions. Note that these conceptualization skills and problem resolution techniques can then be used in a broader field than the groundwater dynamics topic.

Appendix D

Field class

D1 Geological setting and material

The well site is located nearby the university campus (accessible in less than 20 min) which save time for the student transfer. To avoid malicious acts, the well field facility is relatively protected. The well site is in an enclosed area and the head of the well and the piezometers are closed after each experiments. For this activity, most of the costs are related to the wells, their number and the geological context. A solution with numerous wells is preferable because it gives the opportunity to (i) split the group of students in subgroups over different wells for the monitoring activity and, (ii) explore broader the aquifer hydraulic properties. However this point also depends on the number of students. Also we recommend to target aquifers with simple hydrogeological context such as alluvial aquifers in relation to a river. This solution avoids deep drilling, if there is a perennial stream, the experiment can be conducted any time of the year and its impact on the groundwater resource can be neglected.

At the location, the geological context is constituted of Quaternary alluvial deposits and marine Neogene deposits. The local stratigraphy can be described as an alternation of sedimentary layers of sand, clays and gravels on a depth of about 30 m. This stratified sediments lies over a thick layer of Miocene marls. The site has two aquifers horizons: the upper, unconfined aquifer horizon is located within the top layers alternation of sand and clays and the lower confined or semi-confined aquifer horizon is located within the deeper gravel layer. The marly level is the bedrock of the gravel aquifer. The well field facility comprises a total of 15 boreholes (Fig. 3 bottom) over an area of approximatively 5000 m^2. The boreholes are integrally screened with plastic pipe and they all reach the aquitard at their bottom. Piezometric measurements indicate that both aquifers may be either drained or fed by the close flowing Lez River depending on the season. When conducting pumping tests, the pumped water can be expelled to the river through the city's rainwater network pipe.

D2 Activities

The proposed activities aim to investigate the local groundwater dynamics behavior. The field class starts with a quick reminder of the geological context of the site, of the sequence of activities and of the investigation methodology (ideally, this teacher's intervention would be avoided). Thereafter, data collection can be divided into three steps. First, the students set and dispatch pressure probes (data loggers) in the observation wells with the help of the technical team. Manual water level measurements are performed in each well for later characterization of the pre-pumping hydrodynamics. Conductivity and temperature borehole logs are conducted with a data logger in selected wells. For technical reasons, the pump is already set in the pumping well before they get on site but the pumping equipment is described by the group. Then, the pump is started by the technical team. The transient aquifer response to the pumping is monitored manually by the students (by groups of two), and by the dispatched data loggers. The measurement frequency is adequately set to the rate of change in the water levels. When the measurement frequency is low enough, the students start to perform conductivity and temperature logs in parallel to the water level measurements. Flow rate measurements at the outlet of the pumping line are performed throughout the pumping test using a 3×10^{-1} m^3 plastic tank and a chronograph. Last, the pump is stopped and the recovery phase is monitored manually. The students are asked to produce an interpretation report about the local groundwater dynamics' properties of the aquifer, based on the gathered data. On site, the pumping experiment indicates at early times that the well produces the gravel horizon. At late times, recorded data shows a drainance effect. This is interpreted as a contribution from the upper unconfined aquifer (sand and clays). Conducting the interpretation of this effect together with the students induce to call upon the concepts previously seen during the course in the classroom.

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Table 1. Summary table of groundwater dynamics topics associated to teaching strategies.

Learning outcomes	Teaching strategies
Theoretical knowledge: – basics in hydraulics – fluid dynamics equations – Darcy's law – steady state and transient solutions – hydraulic conductivity – well hydraulics – water table and hydraulic head – yield and specific yield – specific drawdown – aquifers and confining units – homogeneity and isotropy Vocational and technical skills: – field investigation methods – data analysis and uncertainties assessment – data interpretation – numerical investigation – water table mapping – piezometric head measurements – flow-rate measurements – pump functioning	Teacher-centered: – lecture – specific course exercises (direct application) Learner-centered: – guided inquiry (application exercises with teacher support) – discovery (autonomous student's exploration of course content) – just-in-time (teaching adjustments facing student's answers) – case-based (case study with discussion) – problem-based (open-ended real world problem) – project-based (project study and work)

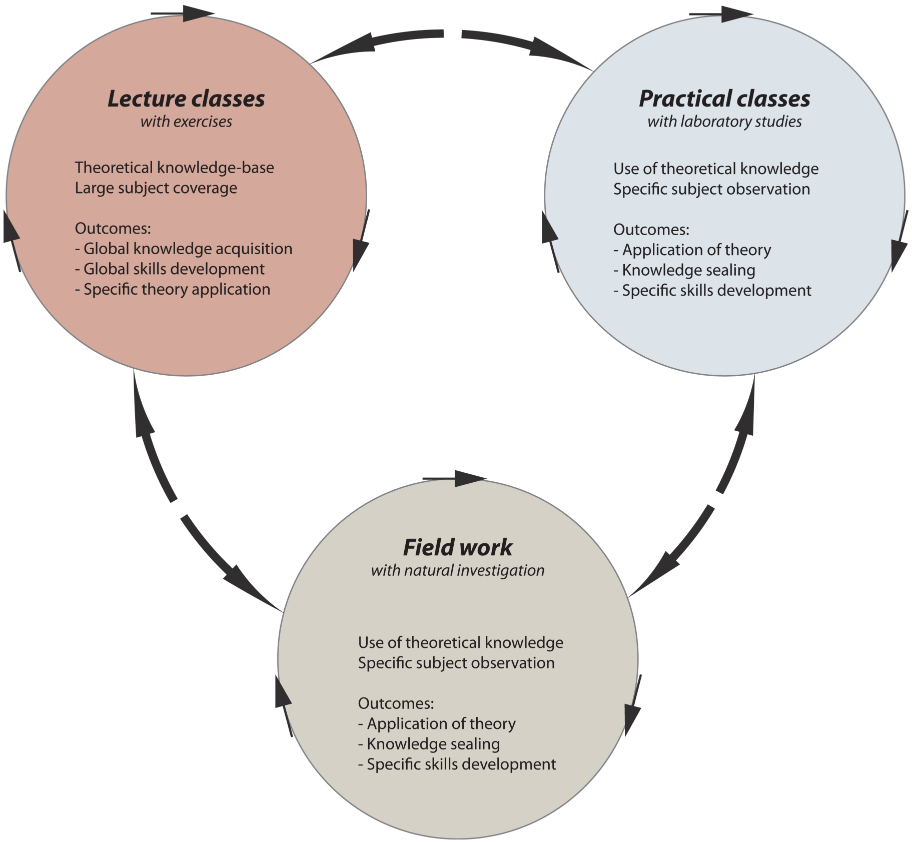

Fig. 1. Our interpretation of an integrated hydrogeology pedagogy associated to an iterative loop over three class setting elements, inspired from Gleeson et al. (2012).

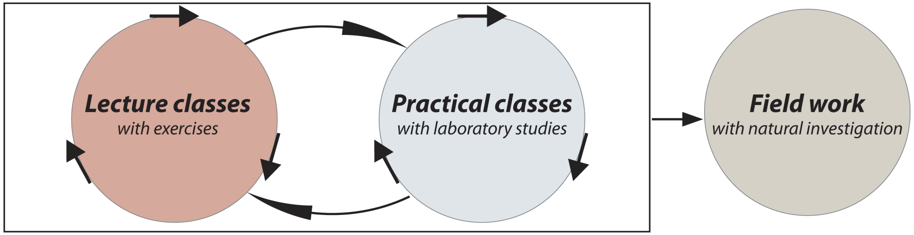

Fig. 2. The adapted structure of the iterative loop over the three class components for an integrated pedagogy in this course devoted to groundwater dynamics. At first, the students progress within a cycle between the classroom and practical class. Once this cycle ends, the students are taken in the field and investigate an applied case.

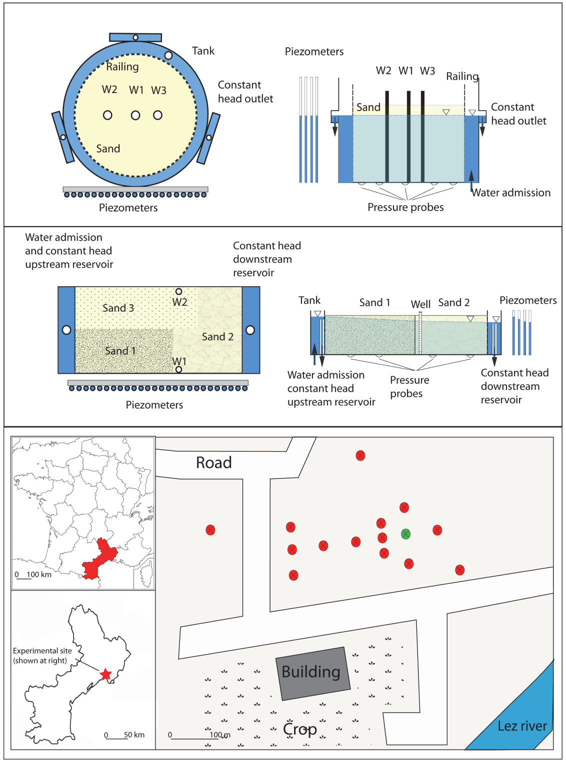

Fig. 3. Schematic view of physical models for practical classes (top and middle) and experimental field site (bottom). Top and middle: left and right sides are plan and cross-section views, W1, W2, W3 stand for the wells, the additional external tank that provides water is not represented. Bottom: experimental well test site (the red dots stand for the piezometers, the green dot stands for the pumping well).

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion