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Summer School – Cargèse, June 25th to July 7th 2018 - Report

Enigma ITN

Summer School – Cargèse, France:

Sensing and modelling of flow and transport process dynamics in heterogeneous subsurface environments

The Enigma ITN Summer School took place in Cargèse, France from Monday June 25 to Friday July 06 2018.

Support

Information about the summer school were communicated with the website, created for this occasion: https://cargese2018.sciencesconf.org/. This website was updated with the presentations done by the lecturers and with photos.

Main organizers of the workshop: CNRS and ETHZ, with:

Jougnot Damien, CNRS, France.
Roques Clément, ETH Zürich, Switzerland.
Davy Philippe, CNRS, France
Le Borgne Tanguy, CNRS, France
Gerard Marie-Françoise, CNRS, France

Participants to the workshop:

All 15 ESRs participated in the Summer School:

1	ESR1	Kevin de Vriendt
2	ESR2	Guilherme Nogueira
3	ESR3	Alvaro Pardo Alvarez
4	ESR4	Justine Molron
5	ESR5	Lara Blazevic
6	ESR6	Behzad Pouladi
7	ESR7	Joel Tirado Conde
8	ESR8	Anne Karin Cooke
9	ESR9	Alejandro Fernandez Visentini
10	ESR10	Peleg Haruzi
11	ESR11	Richard Hoffmann
12	ESR12	Satoshi Izumoto
13	ESR13	Veronika Rieckh
14	ESR14	Andrea Palacios
15	ESR15	Jorge Lopez Alvis

In addition, there were also 67 other students, mainly PhDs but also some Postdocs and Masters. *See the complete list of participants in Annex 2.*

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There were 40 lecturers from all over the world. There is the list of lecturers with the corresponding institutions in Table 1.

Table 1: Lecturers - Cargèse 2018 - Flow and transport in porous and fractured media

Binley	Andrew	Lancaster University Advisory Board member
Niemi	Auli	Uppsala University, Sweden.
Parker	Beth	University of Guelph, Canada. Advisory Board member
Darcel	Caroline	Itasca, France. Itasca representative (industrial beneficiary)
Soulaine	Cyprien	Stanford University, USA.
Villermaux	Emmanuel	Université Aix-Marseille, France
Nguyen	Frederic	Université de Liège
Neuweiler	Insa	University of Hannover, Germany.
Fleckenstein	Jan	Helmholtz Center for Environmental Research, UFZ, Germany.
Gaillardet	Jerôme	Institut de Physique du Globe de Paris, France.
Carrera	Jesus	Spanish National Research Council, Spain.
Jimenez Martinez	Joaquin	EAWAG, ETH Zürich, Switzerland.
Selker	John	Oregon State University, USA. OSU representative (partner)
Or	Dani	ETH Zürich, Switzerland.
Dentz	Marco	Spanish National Research Council, Spain.
Pool	Maria	Spanish National Research Council, Spain.
Manga	Michael	University of California, Berkeley, USA.
Cirpka	Olaf	University of Tübingen, Germany.
Tabeling	Patrick	ESPCI ParisTech, France.
Davy	Philippe	Université Rennes 1, France.
Van Cappellen	Philippe	University of Waterloo, Canada.
Van Genuchten	Rien	Utrecht University, Netherlands.
Ferre	Ty	University of Arizona, USA. Advisory Board member
Méheust	Yves	Université Rennes 1, France.
Bour	Olivier	Université Rennes 1, France.
M. Maxwell	Reed	Colorado School of Mines
Pio Rinaldi	Antonio	ETH Zürich, Switzerland.
Scanlon	Bridget	The University of Texas at Austin, USA. Advisory Board member
Olof Selroos	Jan	SKB, Sweden. SKB representative (partner)
Caers	Jeff	Standford University, USA. STAN representative (partner)
Druhan	Jennifer	Standford University, USA.
Singha	Kamini	Colorado School of Mines, USA. Advisory Board member
Blunt	Martin	Imperial College of London, UK.
Quintard	Michel	Institut de Mécanique des Fluides de Toulouse, France.
Linde	Niklas	Université de Lausanne, Switzerland.
Bayer	Peter	Technische Hochschule Ingolstadt, Germany.
Tecon	Robin	ETH Zürich, Switzerland.
Dassargue	Alain	Universite de Liege
Huisman	Sander	Forschungszentrum Julich
Bjanjic	Branko	Imperial college

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Photo 1: Lecture in one amphitheater of the IESC Center

Objectives

The summer school was open both to international experts in specific topics and to PhD students and researchers external to the consortium. It gathered highly qualified international experts to provide a broad view of key scientific questions as well as current societal issues and emerging applications in subsurface hydrology. The Cargèse summer school provided participants with a high-level interdisciplinary training on the fundamental processes and recent theoretical and methodological advances that have emerged in the study of flow, transport and biogeochemical processes in the subsurface.

There were also presentations about critical zones processes and about the state of the art in actual applications, including global water management, eco-hydrology, geothermal energy, CO2 storage, induced sismicity, seawater intrusion, underground remediation, risk assessment for nuclear waste storage and shale gas exploitation (presentations done by industrial partners).

The school has been specifically designed to provide participants with a common background on the fundamental concepts before attending cutting-edge research seminars (see an overview of the lecture room on Photo 1). Each day, the program included 2 or 3 lectures (Photo 3) focusing on fundamental processes (1 hour each) and 2 or 3 research seminars presenting recent advances on frontier research (45 minutes each). Hands-on were also organized on i) numerical methods, ii) laboratory imaging, and iii) innovative field sensing and monitoring in hydrogeophysics (Photo 2).

The detailed program is presented in Table 2 and all the lectures abstracts are in Annex 1.

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Program

Program Cargese 2018	Flow in Saturated Media	Unsaturated and multiphase flow	Geophysics	Transport Phenomena	Reactive transport		Microbiology and Ecohydrology	Large scale Hydrology	Modelling	Energy transport and storage	Hydromechanics
June 25th arrival at the IESC center	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday
Time	26-Jun	27-Jun	28-Jun	29-Jun	30-Jun	1-Jul	2-Jul	3-Jul	4-Jul	5-Jul	6-Jul
09:00 - 10:00	Introduction and presentation of the summer school **Organizing committee chairs**	Vadose Zone Hydrologic Processes - **R. van Genuchten**	Fundamentals of environmental geophysics **N. Linde**	Transport Phenomena - stochastic modeling and upscaling **M. Dentz**	Using travel times in reactive transport **O. Cirpka**		Microbiology and Ecohydrology **P. Van Cappellen**	Geochemistry of the Critical Zone **J. Gaillardet**	Simulation techniques to model flow and transport at the pore-scale **C. Soulaine**	Geothermal energy **P. Bayer**	Stress and strain in fractured rock masses **C. Darcel**
10:00 - 10:30											
10:30 - 11:30	How to do innovative science **J.Selker**	**Workshop - Practical courses**	**Workshop - Practical courses**	**Workshop - Practical courses**	Reactive transport **J. Carrera**		**Workshop - Practical courses**	**Workshop - Practical courses**	**Workshop - Practical courses**	**Workshop - Practical courses**	Hydromechanics **M. Manga**
11:30 - 12:30	Flow in Saturated Media **J. Carrera**				The Quest of the bottleneck **O. Cirpka**						Modeling fractured rock mass properties with DFN: concepts, theories and issues **P. Davy**
12:30 - 14:00											
14:00 - 15:00	Flow in High Permeability Porous Media **M. Quintard**	Capillary processes in porous media – an overview **D. Or**	Inverse problems – A Bayesian perspective **N. Linde**	Transport Phenomena - Mixing **T. Le Borgne**	Paper microfluidics **P. Tabeling**		Biophysical processes affecting microbial activity in soil environments **R. Tecon**	Reactive transport approaches to unraveling biogeochemical processes in groundwater systems **J. Druhan**	Large Scale Modelling **R. M. Maxwell**	Heat transport in fractured rocks - **O. Bour**	Earthquakes and water **M. Manga**
15:00 - 15:30											
15:30 - 16:15	Complex Fluids **M. Quintard**	Multiphase flow at Darcy scale **I. Neuweiler**	Imaging critical zone processes **K. Singha**	Saline intrusion **M. Pool**	**Workshop - Practical courses / ENIGMA meeting**		Subsurface microbiology and link with biogeochemical cycles **P. Van Cappellen**	Scientific discovery through computational hydrology: Elucidating connections between groundwater flow and transpiration partitioning **R. M. Maxwell**	Modeling Like It Matters - How to Use Hydrologic Models to Make Better Decisions **T. Ferré**	Underground nuclear waste storage **J-O. Selroos**	Induced seismicity and GeoEnergies: lesson learned from coupled hydro-mechanical modeling **A. Pio Rinaldi**
16:15 - 17:00	Foam flow in porous media **Y. Méheust**	Peering into the pore space: wettability, roughness and fluid flow **M. Blunt**	Process-based hydrogeophysics / Hydrogeophysics over multiple scales **A. Binley**	Mixtures in Porous Media - **E. Villermaux**			Contaminated Transport and Natural Attenuation in Sedimentary Rock: Insights from Field Research **B. Parker**	Applications of Remote Sensing and Models for Global Water Resource Assessments **B. Scanlon**	Inversion methods - Deterministic approach **F. Nguyen**	Groundwater vulnerability: from empirism to process-based assessments **A. Dassargues**	Discussion on induced seismicity **M. Manga and A. Pio Rinaldi**
17:00 - 17:15											
17:15 - 18:00	**Presentations Practical courses**	Pore-scale imaging and Modelling of Reactive Transport **B. Bijeljic**	Vadose Zone Hydrogeophysics **S. Huisman**	Mixing and reactions in multiphase systems: insights from microfluidics **J. Jimenez-Martinez**			**Pop-Up & Poster**	Groundwater-surface water interactions and hyporheic zone processes **J. Fleckenstein**	Uncertainty quantification **J. Caers**	CO2 geological storage **A. Niemi**	
18:00-19:00	**Poster & Apero**		**Pop-Up & Poster**				**Pop-Up & Poster**		**Pop-Up & Poster**		

Lecture (1h)
Research Seminar (35 min + 10 min questions)

Table 2: Program of the Cargèse 2018 Summer School on Flow and Transport in Fractured and Porous media

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Photo 2:Geophysics workshop by Damien Jougnot, CNRS

Photo 3: Lecture by Michael Manga, University of California, Berkeley, USA

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Photo 4: overview of the Institute Cargèse site

During the Summer School, the posters were displayed in the CNRS Institute (Photo 4) and there were several poster sessions (Photo 5) with pop-up presentations.

Photo 5: poster session and discussions

One poster session was especially dedicated to discussions between the Enigma ESRs and the Enigma Advisory Board members; see for instance, Ty Ferré on Photo 6, Beth Parker on Photo 7, Kamini Singha on Photo 8, Andrew Binley on Photo 9.

The Enigma Advisory Board sent after this session a review of each poster and discussion. The reviews were personally forwarded to each ESR.

These posters sessions were also the opportunity for the ESRs to interact with scientists from other institutions of the network (Photo 11 &Photo 10).

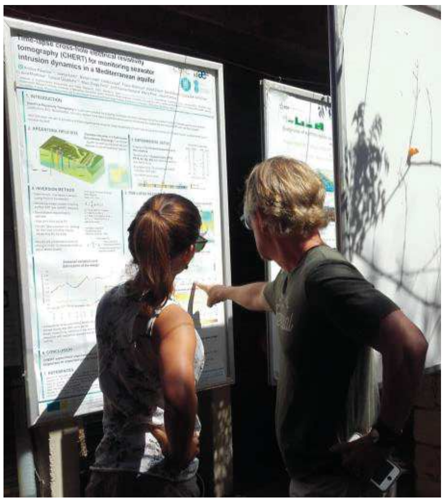

Photo 6: discussion between Ty Ferre (Enigma Advisory Board member) and ESR14 Andrea Palacios

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Photo 8: Kamini Singha, Enigma Advisory Board member discussing with ESR9 Alejandro Fernandez

Photo 7: Beth Parker, Enigma Advisory Board member discussing with ESR10 Peleg Haruzi

Photo 9: Andrew Binley, Enigma Advisory Board member discussing with ESR1 Kevin de Vriendt

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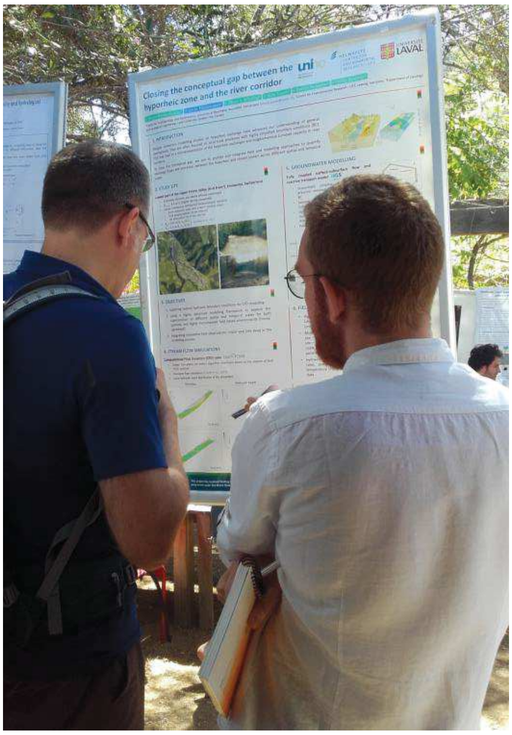

Photo 11: Jan Fleckenstein, Enigma ESR2 supervisor discussing with ESR3 Alvaro Pardo Alvarez

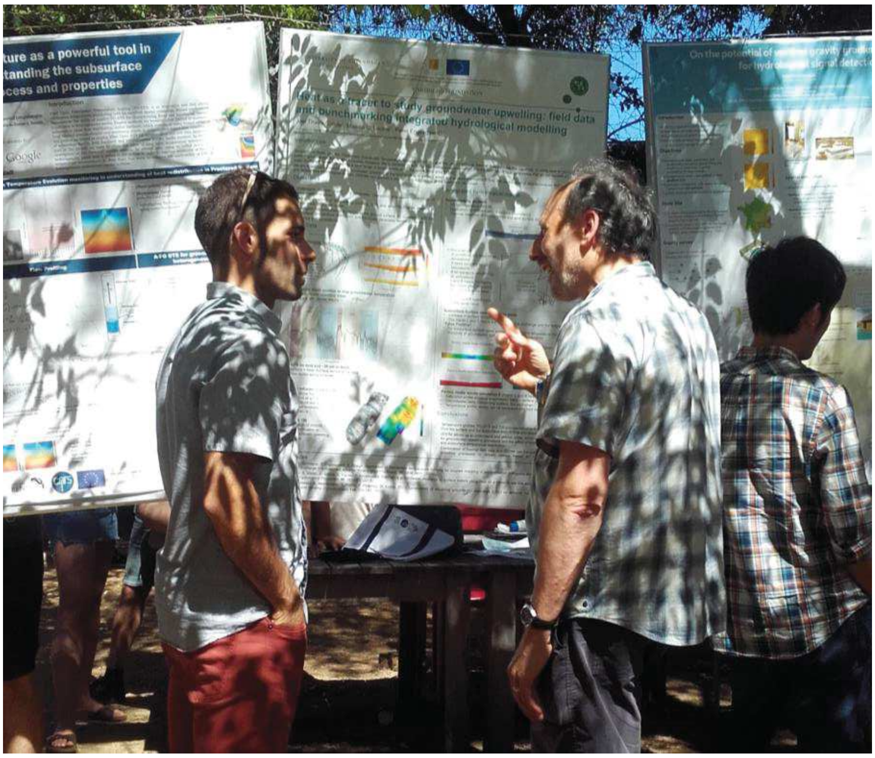

Photo 10: John Selker, partner scientist of Enigma (Oregon State University) discussing with ESR7 Joel Tirado Conde

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4th Enigma meeting in Cargèse

On Saturday July 30th, there was the Enigma meeting with all ESRs, the Enigma Advisory Board members and the Enigma committees (Photo 12 & Photo 13).
See the minutes of this meeting for more details.

Photo 12: lecture room of the Enigma meeting and participants

Photo 13: presentation of a work package ongoing works by ESRs

At the end of the Summer School, the Enigma advisory Board and the network had an informal short meeting to discuss about the Summer School, the network, advice from the Advisory Board…

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Dissemination

On Wednesday July 4th, Alain Dassargues, member of Enigma network as supervisor (University of Liège) presented a public lecture (in French). It was open to everybody and previously there have been posters about it in the Cargèse village, there was also a radio interview on a local FM. There is an article about this lecture on the Corsica university website : https://studia.universita.corsica/plugins/actu/actu-front.php?id=5641

The topic was : Use of groundwaters in water supply and the groundwater salinisation/soil compaction risks (Photo 14).

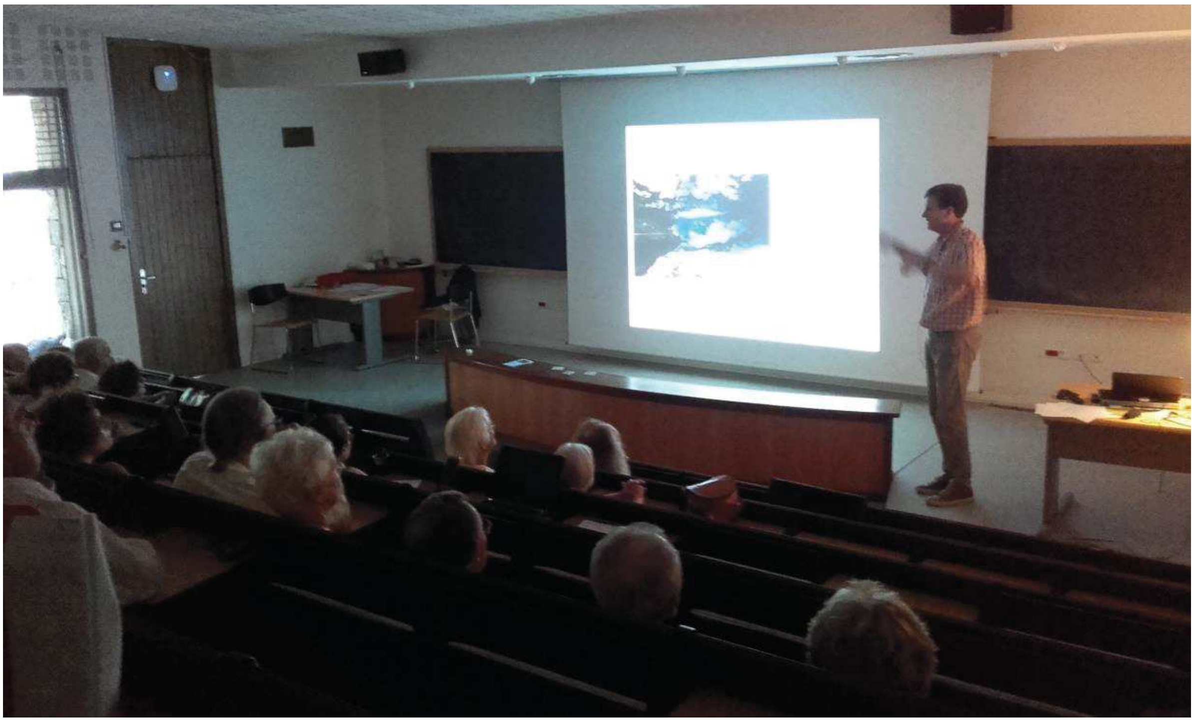

Photo 14: Public lecture by Alain Dassargues, University of Liège

The partners from Oregon State University recorded all presentations and some posters pop-ups. These videos will be made accessible in open access later on the OSU/NSF/summer school websites and there would also be links to some ESRs videos on the Enigma website too.

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Students' results and feedback

At the end of the Summer School, the students presented the results of their practical works done during the two weeks (Photo 15 & Photo 16) and discussed about them.

Photo 15: students' presentation at the end of the Summer School

Photo 16: students' presentation at the end of the Summer School

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Annexes

Annex 1: Abstracts of the presentations

Annex 2: Complete list of the participants to the summer school

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SUMMER SCHOOL CARGESE 2018: FLOW AND TRANSPORT IN POROUS AND FRACTURED MEDIA – Subsurface Processes In The Critical Zone: Observation, Experimentation and Modelling

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Abstracts Lectures and research seminars

<table>
<tr><td>John S. Selker</td><td>How to do innovative Science</td></tr>
<tr><td></td><td>The Cargese workshop is dedicated to helping young scientists launch successful careers in Hydrogeophysics. The lectures will rightly devote much of their attention to the fundamental scientific understanding and representations of processes in natural media. This will add to your foundation of a successful scientific career, but leaves open how to be successful in scientific exploration. In this lecture we will address how to frame and attack a fruitful scientific question with the “WUMPT” approach. The process begins with “wonderment,” proposing that the key to discovery is fascination with the world: creativity arises from this curiosity. The next step is to assess if the subject of your wonder is truly unknown, or just something of which you are unaware. This is the identification a gap in understanding (the literature) is an essential element of a scientific venture. Having established that a problem is open, we must then assess if the question matters. Life is too short to work on insignificant problems, even if they are poorly understood. Supposing that the problem is important, then we must assess if there is potential for a successful resolution of the problem. There are many problems that would be wonderful to solve, but for which we lack the tools to address. Finally, to solve the complex problems facing us in hydrogeology, we generally need to assemble a team spanning the disciplines and methods needed to succeed in resolving the open question. For a PhD student this may just be your academic committee, but often we need to reach beyond our home institutions to construct a team who communicate well, and are at the cutting edge of science. We will present several examples of WUMPT projects to illustrate these points.</td></tr>
<tr><td>Jesus Carrera</td><td>Flow in Saturated Media</td></tr>
<tr><td></td><td>I will briefly review the basic concepts necessary to understand flow through permeable media:
- Darcy’s Law, which expresses momentum conservation, will motivate introducing head, permeability and hydraulic conductivity.
- The flow equation, which expresses the mass conservation of a fluid phase, will motivate introducing specific storage.
If time permits, I will integrate the flow equation along the vertical to obtain the form normally used in practice and to introduce transmissivity and storage coefficient.</td></tr>
</table>

Michel Quintard	**Flow in High Permeability Porous Media (lecture)**
	Highly permeable media have the potential for triggering inertia effects in the case of saturated or unsaturated flows. They also lead to specific effects in the case of unsaturated flows due to the increased viscous interaction at the pore-scale, the potential effects of high capillary numbers and Bond numbers. Theoretical, experimental and numerical results will be given in this lecture concerning saturated flows with inertia effects. The, now classical, discussion about the various regimes observed when increasing the Reynolds number close to the Darcy regime will be reviewed. Indications will be given on the still open problem of the phenomenology at high Reynolds numbers, and theoretical aspects such as the upscaling RANS turbulence models and the development of macro-scale turbulent models. Brief indications will be given on the case of two-phase flows: new evidence about viscous interaction effects, the introduction of inertia terms in macro-scale models.
Michel Quintard	**Complex Fluids (non-Newtonian)**
	Complex fluids do not represent a single class of upscaling problems in porous media. This seminar does not address all cases, but, instead, focuses on some similar and generic problems encountered when non-Newtonian fluids are considered. In particular, it is emphasized how the non-linearity affects the upscaling process: transition from Darcy-regime to non-linear regime, anisotropy effects induced by the non-linear fluid behavior, impact of the non-linear effects on the REV concept. The lecture is based on theoretical considerations and HPC numerical results obtained for various 2D and 3D media, including 3D reconstructed images of typical reservoir rocks for flows of a typical non-Newtonian fluid featuring a Newtonian plateau and a power-law behavior.
Yves Méheust	**The flow of aqueous foams in porous media**
	Aqueous foams are used in subsurface applications such as enhanced oil recovery and subsurface remediation, which take advantage of their physico-chemical properties, but also of their peculiar mechanical/flow properties. We study the latter using a two-dimensional setup in which the foam structure can be monitored in time. We measure the velocities of individual bubbles as well as their fragmentation into smaller bubbles, and uncover a rich phenomenology, where the local foam structure controls the distribution of bubble velocities between different channels, and larger bubbles follow preferential paths of higher velocities; these preferential paths are themselves made intermittent by capillary fluctuations. Bubble fragmentation is mostly controlled by the foam's water content and initial mean size of the bubbles, and is responsible for an irreversible evolution of the foam's bubble size distribution as it travels through the medium. Relating quantitatively that evolution to the statistics of individual fragmentation events, we show that the distribution of properly-rescaled bubble sizes, at a given properly-rescaled

	distance from the flow inlet, is fully controlled by the geometry of the medium, and is thus independent from the structural parameters of the foam and mean flow velocity. * Main references: Jones et al., PoF (2013) Dollet et al., PRE (2014) Géraud et al, WRR (2016) Géraud et al, PRL (2018)
Martinus Th van Genuchten	**Vadose Zone Hydrologic Processes**
	A brief overview is provided of the processes controlling water, heat and solute transport in the vadose zone between the soil surface and groundwater. The overview is provided within the context of the HYDRUS software packages based on one- and multidimensional numerical solutions of the various processes involved. Special attention is given to the highly nonlinear nature of the governing flow equations. Among the topics being reviewed are numerical solutions of the Richards equation for flow in variably-saturated media, advection-dispersion typic equations for heat and solute transport, water uptake by plant roots as a function of water and salinity stress, nonequilibrium and multicomponent contaminant transport (including the use of solute decay chains), diffusion in the gas phase, preferential flow processes operative in macroporous or fractured media, attachment/detachment processes affecting colloid transport, and parameter estimation applications. The overview provides an introduction for a subsequent workshop about the windows-based HDRUS and STANMD software packages. *Federal University of Rio de Janeiro, Brazil; Utrecht University, Netherlands https://www.pc-progress.com/en/Default.aspx?rien-van-genuchten; rvangenuchten@hotmail.com
Dani Or	**Capillary processes in porous media – an overview**
	Dani Or - Department of Environmental Systems Science, Swiss Federal Institute of Technology (ETH) Zürich, Switzerland The coexistence of gaseous, liquid, and solid phases in unsaturated porous media gives rise to a variety of interfacial phenomena that induces spreading and liquid rise in pores, or retention of liquid by capillary forces against gravity. These phenomena, partially attributed to capillarity, determine the retention and movement of water and solutes through unsaturated porous media, define aqueous habitats for biological agents, and are important for the mechanical behavior of granular and unsaturated porous media. The presentation will systematically derive fundamental aspects that underlie capillarity in porous media and provide description of static and dynamic aspects of fluid arrangement affected by porous media pore spaces and capillarity. We will review established concepts and modeling of capillary properties (soil water

	characteristic curves and hydraulic properties of unsaturated media) and provide an outlook at recent advances related to motion of interfacial fronts and phase entrapment and mechanical aspects of unsaturated porous media. **Reference**: Or. D. and M. Tuller,2004, Capillarity, in: Encyclopedia of Soils in the Environment, Ed.: D. Hillel, pp.155-163 DOI: 10.1016/B0-12-348530-4/00339-8 **Outline:** • Review of fundamental aspects of surface tension and liquid-solid interfacial interactions • Aspects of wettability on surfaces with chemical and geometrical properties • Aspects of capillarity in angular pores – snap-off/jump processes • Origins of capillary rise in cylindrical and angular tubes • Dynamics of capillary rise giving rise to Washburn-Lucas equation • Motion of interfacial displacement fronts • Concepts of water retention and pore size distribution - models • Water films and adsorption SWC dry-end ; the role of specific surface area • Hysteresis – mechanisms and description • Capillarity and mechanical properties of unsaturated soil • Take home messages
Insa Neuweiler	**Modeling of water and oxygen transport in electrolyzers with multi-phase flow models on the Darcy scale**
	Hydrogen can be produced with proton exchange membrane (PEM) water electrolyzer cells, where water is split into hydrogen and oxygen. The production happens in a membrane electrode assembly. Water is transported to the membrane and oxygen is transported away from it through a porous transport layer. Often the porous transport layer is attached on the side opposite to the membrane to a channel system for transport of the fluids through the cell. A part of the losses in the cell are attributed to the transport processes through the porous transport layer. In order to optimize efficiency and stability of the cells, the transport of water and oxygen through the porous transport layer is modeled. Standard Darcy scale two-phase flow models could be used for this purpose. The modeling concepts and flow equations will be explained in the presentation. Standard parametrization of the model, based on information about the pore structure of a porous medium, will also be explained. Modeling results will then be compared to observations made in real electrolyzer cells, where different materials were used for the porous transport layer. Based on the comparison, assumptions of the model concept and its limitations will be

	discussed.
Martin Blunt	**Peering into the pore space: wettability, roughness and fluid flow**
	Micron-resolution X-ray imaging has allowed us to see inside rocks and other permeable media, and to observe fluid configurations at reservoir temperatures and pressures. One fundamental control on fluid flow is wettability, or the distribution of contact angle. We use direct measurements of contact angle in pore-space images to define a mixed-wet state where there is a wide distribution of effective contact angle with values above and below 90 degrees: the amount of variation is correlated with local measures of the surface curvature. We discuss how such a wetting state can emerge from thermodynamic considerations and then explore implications for fluid flow. We suggest how an ideal wetting state may be engineered to optimize either recovery or trapping. We hypothesize that a similar mixed-wet state may be observed in biological materials, from leaves to lungs, since it allows the simultaneous flow of two fluids over a wide saturation range.
Branko Bijeljic	**Pore-scale Imaging and Modelling of Reactive Transport in Porous Media**
	Understanding reactive transport phenomena in porous media has been transformed by the advances in both X-ray imaging and pore-scale modelling. Spatially resolved experimental description of solid and fluid(s) in the pore space and the ability to study dynamics inspired new concepts for quantifying signatures of flow, transport and reaction. Analysis of flow, transport (spreading and mixing) and reactive transport (fluid/fluid and fluid/solid) based on distribution functions will be introduced and demonstrated in a range of porous media with increasing degree of pore complexity. We will discuss new approaches including using multiple functions describing flow in complex media with separation of scales, intrinsic transit time distributions and flow propagators describing non-Fickian transport, and applying the similar concepts to the next level of complexity by examining reactive transport in chemically heterogeneous media. Critical assessment of the current state of thinking on effective reaction rate dependence of scales, and reactive transport regimes, will be discussed.
Niklas Linde	**Fundamentals of environmental geophysics**
	A wide variety of geophysical methods are used to provide insights about near-surface properties and processes of relevance. This talk introduces the physics underlying the most common geophysical techniques (seismics, electromagnetic induction, electrical resistivity tomography, induced polarization, self-potential, gravity, magnetics). I explain how attributes of physical fields can be measured, how the underlying physics can be modelled, and how information about physical properties can inform us about subsurface properties of interest. Finally, issues relating to experimental design, scale and

	dimensionality are touched upon followed by a recommendation of using multiple investigation techniques when addressing environmental problems with geophysics.
Niklas Linde	**Inverse problems – A Bayesian perspective**
	Indirect data (e.g., drawdown data, tracer breakthrough curves, electrical resistances or seismic traces) acquired at a given site are best combined within a formal framework to provide subsurface models or process descriptions that honour known physics and prior knowledge while acknowledging non-linearity as well as experimental and modelling uncertainties. Bayes theorem offers a general framework to achieve this. As soon as the physical response is responding non-linearly to model parameter values (i.e., most physics of interest), then a general solution to the inverse problem must be sought using computationally expensive global search algorithms (e.g., Monte Carlo, Markov chain Monte Carlo). This lecture introduces basic theory and algorithms used to sample from posterior density functions. After this, case studies with focus on complex spatial priors are presented. Finally, I share my experience on how to make this beautiful theory work in practice when confronted with discontinuous spatial fields and large data sets with high signal-to-noise ratios.
Kamini Singha	**Imaging critical zone processes**
	Earth's "critical zone", the zone of the planet from treetops to base of groundwater, is critical because it is a sensitive region, open to impacts from human activities, while providing water necessary for human consumption and food production. Quantifying water movement in the subsurface is critical to predicting how water-driven critical zone processes respond to changes in climate and human perturbation of the natural system. While shallow soils and above-ground parts of the critical zone can be easy to instrument and explore, the deeper parts of the critical zone—through the soils and into rock—are harder to access, leaving many open questions about the role of water in this environment. Here, we will explore a number of key subsurface properties and processes in the critical zone where geophysics may be able to help serve as a "macroscope", including developing linkages between changes in evapotranspiration and subsurface water stores, mapping water movement in 3-D over large areas, determining connections between geophysical changes and geochemical processes, and testing hypotheses about subsurface weathering and the subsequent controls on hydrogeology. Geophysical tools are central to the quantitative study of these problems in the deeper subsurface where we don't have easy access for observation.
Andrew Binley	**Process-based hydrogeophysics / Hydrogeophysics over multiple scales**
	Geophysics provides a multi-dimensional suite of investigative methods that are transforming our ability to see into the very fabric of the subsurface environment, and monitor the dynamics of its fluids and the biogeochemical

	reactions that occur within it. The need for greater quantitative characterization of the subsurface has stimulated a wealth of new investigations into petrophysical relationships that link hydrologically relevant properties to measurable geophysical parameters. The development of time-lapse approaches has provided a new suite of tools for hydrological investigation, and improvements in inversion techniques allow us to better quantify properties and states of the subsurface environment. Early hydrogeophysical studies often concentrated on relatively small 'plot-scale' experiments. More recently, however, the translation to larger-scale characterization has been the focus of a number of studies. We illustrate, through a number of case studies, how geophysical techniques can give greater insight into the fabric of the subsurface and processes that exist within it. We also discuss current challenges and future opportunities. Hydrogeophysics continue to develop driven by the increasing need to understand and quantify key processes controlling sustainable water resources and ecosystem services.
Sander Huisman	**Vadose Zone Hydrogeophysics**
	Hydrogeophysical measurements are useful to investigate the interaction between structural heterogeneity of vadose zone properties and water flow and transport processes. Structural characterization will be illustrated using results of a 1 km2 survey with electromagnetic induction measurements within the context of precision agriculture. Vadose zone processes can be investigated using time-lapse geophysical measurements. Although it is attractive to integrate such time-lapse measurements of varying origin, scale, and uncertainty into hydrological models, this is a far from straightforward task. After an introduction of the challenges of such model-data integration, the possibilities and limitations of coupled inversion approaches will be discussed. The presentation will end with my personal opinion on future research needs for hydrogeophysics.
Marco Dentz	**Transport phenomena – stochastic modeling and upscaling**
	The lecture will give an overview of scale effects and phenomena of non-Fickian transport in heterogeneous porous media. It deals with transport upscaling from the pore to the regional scale and introduces into stochastic modeling approaches to bridge the scales.
Tanguy Le Borgne	**Transport Phenomena – mixing**
	The lecture will give an overview of solute mixing processes in porous and fractured media and their consequences for biogeochemical reactions. It will first present field observations and applications. It will then explain basic theoretical concepts, including fluid stretching, aggregation and disaggregation, concentration statistics, mixing measures and reactive front kinetics.

Maria Pool	**Seewater Intrusion**
	About 41% of the world population lives in coastal areas where the main source of freshwater for urban supply, industry and agriculture is groundwater. In the past five decades, intensive groundwater exploitation in coastal areas have caused bore and soil salinization due to seawater intrusion. The seawater intrusion problem is a three-dimensional phenomenon where freshwater tends to float on top of seawater and a mixing zone develops between them. Seawater disperses across this mixing zone and is subsequently returned to the sea by freshwater discharge, thus forming a convection cell. The mixing process is governed by coupled nonlinear equations that describe density-dependent groundwater flow and solute transport. We will review the main analytical solutions to calculate the freshwater-saltwater interface depth and penetration (the sharp interface approximation), as well as the critical pumping rates in coastal aquifers (i.e., the maximum permissible discharge without salinizing the well). We will quantify the impact of mixing on the interface and the error introduced by using the existing analytical solutions. We will also analyze the impact of temporal fluctuations and heterogeneity on the mixing dynamics and chemical reactions in coastal aquifers.
Emmanuel Villermaux	**Mixtures in Porous Media**
	On hand of a technique allowing for in-situ measurements of concentrations fields, the evolution of scalar mixtures flowing within a porous medium made of a three-dimensional random stack of solid spheres, is addressed. Two distinct fluorescent dyes are injected from separate sources. Their evolution as they disperse and mix through the medium is directly observed and quantified, this being made possible by matching the refractive indices of the spheres and of the flowing interstitial liquid. We decipher the nature of the interaction rule between the scalar sources, explaining the phenomenon altering the concentration distribution of the overall mixture as it decays towards uniformity. Any residual correlation of the initially merged sources is progressively hidden, leading to an effective fully random interaction rule of the two distinct sub-fields.
J. Jimenez-Martinez	**Mixing and reactions in multiphase systems: insights from microfluidics**
	Multiphase flows are ubiquitous in environmental and industrial applications. We currently lack a comprehensive understanding of the coupling of multiphase flows and both fluid-fluid and fluid-solid reactions in porous media. Microfluidics offers the possibility to study the coupling of hydrodynamics and mixing and reactive phenomena in such complex systems, which in many cases are numerically intractable. In this talk, different experimental approaches will be presented, including ambient and reservoir conditions, two and three phases, continuous and pulse line injection, and engineering and geological material. I will discuss the increasing heterogeneity in the fluid flow velocity as the volume fraction of the immiscible phase increases. For fluid-fluid systems,

	velocity heterogeneity generates greater concentration gradients, enhancing mixing and chemical reactions. In fluid-solid systems, the presence of liquid films does not necessarily reduce the specific surface in contact with the solid; however, they reduce the rate of renewal of one of the reactants, reducing the dissolution rate. The presence of an immiscible phase enhances precipitation through the creation of low velocity regions and the presence of supersaturated solution. Finally, for the particular case in which the reaction between two chemicals results in a solid product, I will show the propagation of the reaction wave by overcoming the mechanical resistance offered by the solid product and the formation of a new solid interface, i.e., self-sealing.
Olaf Cirpka	**Using travel times in reactive transport (lecture)**
	Breakthrough curves in multi-component reactive transport scale in time with advective travel times of a conservative solute if the reactive properties of the medium are uniform and dispersive mixing can be neglected. The lecture will start with idealized cases where travel times are prefect predictors and discuss how multiple fronts evolve from a single perturbation in concentration due to multi-component coupling in reactive transport. I will continue with cases where the approach is not suitable at all because the reactions are controlled by other processes than aging of water parcels. Finally, I will introduce extensions for cases with spatially non-uniform reactive properties of the medium, in which travel times are replaced by other easy-to-compute metrics with units of a time (exposure time, cumulative relative reactivity, hypothetical breakthrough times derived from electron balances). If possible, let’s get rid of the nabla operator without introducing too much of an error!
Jesus Carrera	**Reactive transport**
	I will briefly review the basic concepts necessary to understand reactive transport. Reactive transport simply involves solute transport and chemical reactions, which act as sink-source terms and which alter the appearance and nature of transport. Therefore, I will outline the how different types of reactions affect transport: - Adsorption reactions, which will allow me to introduce the concept of retardation. - Exchange reactions - Kinetic reactions, which will motivate introducing the Damkholer number concept and why it is a poor concept. - Equilibrium reactions, which will motivate introducing components, chemical zonation and mixing as a concept different from spreading. If time permits, I will introduce the general reactive transport equation, which is facilitated by the concept of stoichiometric matrix.

Olaf Cirpka	**The quest of the bottleneck**
	This one is kept secret…
Patrick Tabeling	**Paper microfluidics**
	Over the last years, paper has been taken as a subtsrate for creating microfluidic devices. Here, fluids are driven by capillarity in porous media. This low-cost technology is used for on-field diagnostics of contagious diseases, in developing countries. I will present the subject, for which my group has made, recently, several contributions.
P. van Cappellen	**Bioenergetics in Geomicrobiology**
	Biomass-explicit reaction-transport models of subsurface environments use microbial growth yields (*Y*) measured in the laboratory or predicted with thermodynamics-based methods. However, *Y* values are rarely measured under the low energy conditions that often prevail in the subsurface, and existing predictive methods for calculating *Y* values when metabolic energy supply is limited remain poorly tested. Here, I introduce a new method for calculating *Y* values that extends to low energy conditions: the Gibbs Energy Dynamic Yield Method (GEDYM). Method validation relies on a compilation of 132 observed *Y* values from the literature, comprising predominantly (60%) low energy (< 25 kJ (mol e^{-})$^{-1}$) metabolisms. GEDYM is based on estimating the Gibbs energy change of the metabolic reaction (ΔG_{met}), which links the Gibbs energy changes of the catabolic (ΔG_{cat}) and anabolic (ΔG_{an}) reactions of a given microorganism through its growth yield. Because the values of ΔG_{met}, ΔG_{cat} and ΔG_{an} all depend on their respective reaction quotients, the resulting *Y* values account for changes in the chemical environment of the cell. GEDYM incorporates an empirical relationship that accurately estimates the extent to which ΔG_{met} deviates from its standard state value from the relative difference between ΔG_{cat} and its corresponding standard state value. GEDYM yields *Y* values with lower relative errors than existing empirical and semi-theoretical methods, including the linear free energy relationship (LFER) and the Gibbs energy dissipation (GEDM) methods. Using dissimilatory iron reduction, sulfate reduction and methanogenesis as examples, I illustrate the importance of considering variations in catabolic energy supply when predicting *Y* values for individual metabolisms.
Robin Tecon	**Biophysical processes affecting microbial activity in soil environments**
	Robin Tecon and Dani Or Department of Environmental Systems Science, Swiss Federal Institute of Technology (ETH) Zürich, Switzerland Soil hosts unequalled diversity of microorganisms that play a central role in its function and key cycles (carbon, nitrogen) and in long term soil formation and

	structure. In this lecture, we will examine the interplay between soil physical and microbial processes ('biophysical processes') and discuss how porous media properties and hydration conditions affect the organization and activity of soil microbes (focusing on bacteria and the microscale). We will first review some elements of microbial diversity and distribution in soil, as well as some general traits of soil bacteria. We then examine the physical nature of soil as a microbial habitat, with an emphasis on the organization and dynamics of the aqueous phase. Terrestrial environments often show patchy distribution of resources and fragmented aquatic habitats, which strongly influences microbial interactions among soil communities. In particular, we will highlight the consequences for bacterial dispersion ranges, species coexistence, spatial organization and respiration, with examples from recent modeling advances in these fields, and point at current challenges and opportunities. Finally, we will summarize the importance of microbial activity in soil formation and physical properties (especially the role of biopolymers). Reference: Tecon R. and D. Or. Biophysical processes supporting the diversity of microbial life in soil. FEMS Microbiology Reviews. 2017 Aug 16; 41(5):599-623. http://dx.doi.org/10.1093/femsre/fux039 **Outline** • Intro on soil microbial diversity and abundance: key figures and taxa; drivers of diversity and abundance; distribution at microscale • General traits of soil bacteria: genomes; life strategies; hgt • Soil as a microbial habitat: solid/aqueous/gas phases ; dynamic aqueous phase; soil water potential vs. microbial activity; cell motility and dispersion • Biophysical processes controlling microbial life: species coexistence and diversity; self-organization and aerobic/anaerobic respiration • Soil formation and structure: EPS; soil-EPS hydraulic properties • Summary/Take-home messages
P. van Cappellen	**Global Changes to Carbon and Nutrient Cycles by River Damming**
	The damming of rivers represents one of the major anthropogenic disturbances of the natural cycles of water, carbon and nutrient elements on the continents. The associated changes in the environmental flows of nutrients have far-reaching ecohydrological consequences, from individual ecosystems to the global biosphere. While dam reservoirs usually act as sinks of macronutrients in river systems, their effects on riverine fluxes and chemical speciation differ markedly from one nutrient element to another. Dams thus fundamentally

	alter nutrient limitation patterns, trophic conditions and water quality in river ecosystems and receiving water bodies, including lakes, floodplains, wetlands and coastal marine areas. Regional and global assessments of the changes in riverine nutrient fluxes caused by the construction of dams have so far relied on empirical correction factors with limited predictive capability. By contrast, we developed a knowledge-based upscaling framework, which integrates available data on elemental budgets for individual reservoirs, mechanistic models of nutrient cycling in surface water bodies, and a stochastic analysis of model outcomes. The approach enables us to simulate the temporal changes in nutrient elimination by damming in all the major river basins of the world. Here, we illustrate the use of the modeling approach to estimate the global modifications of the riverine fluxes of organic carbon (C), phosphorus (P), nitrogen (N) and silicon (Si) by dams. Next, the results for the individual elements are brought together to assess the historical and future changes in the relative riverine delivery of P, N and Si to the world's coastal zone. A key conclusion is that damming has, and will continue, to cause global shifts in nutrient ratios discharged to the oceans, thereby changing the structure of coastal plankton communities.
Beth Parker	**Contaminated Transport and Natural Attenuation in Sedimentary Rock: Insights from Field Research**
	High-resolution field investigations at selected industrial properties contaminated with chlorinate solvents for several decades serve as long term, natural gradient tracer experiments. Their concentrations can be measured over many orders of magnitude for delineating and understanding plume behavior. In fractured sedimentary rocks the effects of diffusion cause two strong and useful effects: 1) complete dissolution of the DNAPL phase from fractures in the source zone and 2) strong plume front retardation due to transverse diffusion into the matrix. This results in nearly all the contaminant mass residing in the low permeability matrix where measurable diffusion halos identify hydraulically active fractures; many more than are found by conventional borehole measurements. The ability to distinguish the fractures important for contaminant transport are used to inform DFN numerical models for groundwater flow and transport and show concentration distributions that match observations at the field sites when informed with site-derived parameters. Given that the time and distance scales for plume attenuation is site specific, improved field methods for informing DFN numerical models will improve science-based decisions for bedrock aquifer vulnerability assessments and wellhead protection zone delineations specific to various contaminant types that threaten groundwater resources.
Jérôme Gaillardet	**Geochemistry of the Critical Zone**
	In this lecture, we aim to give an idea of the main developments that have been

	achieved over the last decades for constraining critical zone processes using geochemical tools. The critical zone initiative was mostly promoted by lab geochemists that had observed that the rates of weathering (the flux of dissolved matter released by the chemical interaction between water and minerals)are orders of magnitude higher in laboratory experiments than they were in the field. The solution of this conundrum has many very different aspects but more interestingly, it basically initiated new approaches coupling geochemical rates and processes to physical and biological processes. She paved the way to integrated approaches. Through the use of concentrations, of elemental ratios and isotopic ratios we will give examples of the principal advances as well as an overview of where this research field is moving forward.
Jennifer Druhan	**Reactive transport approaches to unraveling biogeochemical processes in groundwater systems**
	Water is a basic necessity for life, and exerts a primary control on virtually all geological, chemical and biological processes occurring at or near the Earth's surface. Because these water-rock-life interactions take place at interfaces, both fluid composition and the physical and chemical structure of porous media must be treated as coevolving phenomena. Such complex and interrelated processes can hinder both interpretation and prediction of key environmental processes. One avenue of addressing this complexity is the use of multicomponent numerical methods that combine the governing equations of flow, transport and reactivity. In this presentation I will demonstrate the construction and application of multi-component reactive transport models to address key hydrogeochemical problems, with an emphasis on the balance between simulations of complex reactivity versus highly heterogeneous hydrologic conditions. Examples include stable isotope fractionations during microbially-mediated redox cycling and reactivity in highly resolved permeability structures. The goal is to demonstrate how simulations can be used to interrogate complex field data and thus provide new insights into the processes governing hydrogeochemical systems.
Reed Maxwell	**Scientific discovery through computational hydrology: Elucidating connections between groundwater flow and transpiration partitioning**
	Understanding freshwater fluxes at continental scales will help us better predict hydrologic response and manage our terrestrial water resources. For example, better understanding partitioning of evapotranspiration into bare soil evaporation and plant transpiration, the role of warming on snowmelt dominated headwaters catchments, and the response to the residence time of water from geology and climate are examples of key questions in the terrestrial water cycle. Computational Hydrology is an additional tool to study interactions water fluxes and stores across the critical zone. We used integrated hydrologic simulations that couple vegetation and land energy processes with surface and subsurface hydrology to advance these topics with a focus on transpiration partitioning at the continental scale. These high resolution,

	transient simulations encompass the major watersheds of the United States and demonstrate great complexity in hydrologic and land energy states. Results demonstrate a novel connection between lateral groundwater flow and terrestrial water budgets. This work reconciles systematic differences between global observations and global land surface models. This suggests that lateral groundwater flow, which is generally simplified or excluded in earth system models, may provide a missing link to reconciling observations and global models of terrestrial water fluxes.
Bridget R. Scanlon	**Applications of Remote Sensing and Models for Global Water Resource Assessments**
	Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, USA. There is increasing interest in evaluating trends in global water resources in response to climate variability/change and human intervention. Here, we evaluate the reliability of water storage trends based on a comprehensive comparison of decadal trends (2002–2014) in land water storage from seven global models (WGHM, PCR-GLOBWB, GLDAS NOAH, MOSAIC, VIC, CLM, and CLSM) to trends from three Gravity Recovery and Climate Experiment (GRACE) satellite solutions in 186 river basins (∼60% of global land area). GRACE satellites have been likened to giant weighing scales in the sky. The models underestimate the large decadal (2002–2014) trends in water storage relative to GRACE satellites, both decreasing trends related to human intervention and climate and increasing trends related primarily to climate variations. For example, in the Amazon, GRACE estimates a large increasing trend of ∼43 km3/y, whereas most models estimate decreasing trends (−71 to 11 km3/y). Land water storage trends, summed over all basins, are positive for GRACE (∼71–82 km3/y) but negative for models (−450 to −12 km3/y), contributing opposing trends to global mean sea level change. Impacts of climate forcing on decadal land water storage trends exceed those of modeled human intervention by about a factor of 2. The model-GRACE comparison highlights potential areas of future model development, particularly simulated water storage. The inability of models to capture large decadal water storage trends based on GRACE indicates that model projections of climate and human induced water storage changes may be underestimated.
Jan Fleckenstein	**Groundwater-surface water interactions and hyporheic zone processes**
	Groundwater (GW) and surface water (SW) are two interconnected components of one single resource and impacts on either of the two will inevitably affect the quantity or quality of the other. Although early hydrological research had already emphasized these linkages GW and SW resources have long been perceived and managed as two separate entities. However, with growing demands on water resources, uncertainties in water supply associated with climate change and the deterioration of aquatic

	ecosystems, the awareness for the need to manage GW and SW as a single resource has steadily grown. In the seminar a brief history of research on GW-SW interactions as well as an overview of general concepts and ideas will be given. We will discuss different field methods to characterize and quantify GW-SW interactions including their merits and limitations. A specific emphasis will be on modeling GW-SW interactions, hyporheic exchange and links between hydrologic dynamics and biogeochemical processes that affect water quality. All topics will be discussed in the light of the latest research in the field and with an outlook to future research directions.
Cyprien Soulaine	**Simulation techniques to model flow and transport at the pore-scale**
	Recent interests in CO2 sequestration or in unconventional oil recovery rose new challenges for porous media research as the systems to be modeled evolve in time and may exhibit strong coupling between mass and heat transfer, and eventually rock mechanics. To characterize or to get new insights on large scale physics, a general strategy consists in going to the pore-scale where the physics is wellestablished and then upscale the results. At that scale, the geometry of the complex pore space enclosed by the solid skeleton is described in complete detail, boundary conditions at the fluid/solid interface are specified and the equations of fluid mechanics are solved, namely Navier-Stokes equations. With the recent improvements in imaging techniques such as X-ray computed microtomography combined with modern High Performance Computing techniques it is now possible to have access to the exact three dimensional (3D) structure of a rock sample and to solve the flow in the void space. In this lecture, we review different Navier-Stokes-based simulation techniques to model fluid flow and transport in porous media at the pore-scale.
Reed Maxwell	**Large Scale Hydrologic Modeling**
	Questions critical to human water use and environmental change increasingly require modelling approaches that incorporate interconnected hydrologic processes from the subsurface to the atmosphere, include human-water interactions and bridge a wide range of spatial scales. These needs have pushed models forward in both process complexity and spatial extent. The lecture will focus on large scale hydrologic modeling. I will discuss hydrology models that include connections between groundwater, surface water, land surface processes, human water use and land-atmosphere interactions at high resolution over continents and across the globe. Despite significant advances in model realism and accuracy, there are still many technical challenges and data gaps (such as subsurface datasets) that that must be addressed by the hydrologic community as we work towards computationally efficient and realistic global modeling platforms.
Ty Ferré	**Modeling Like It Matters - How to Use Hydrologic Models to Make Better Decisions**

	This lecture will summarize an approach to hydrologic modeling that is focused on making better decisions. The premise is that most water-resources related problems involve multiple groups who commonly have very different objectives. I will outline an approach to harnessing the power of self interest of these groups, through 'advocacy modeling'. The goals are: 1) to explore uncertainty more meaningfully; 2) to promote collaborative decision-making under conflict; and 3) to improve the effectiveness of hydrologic data collection. The material will review a semester-long course that I have taught on the subject that pitted a proposed agricultural facility against a local town and an environmental group.
Fred Nguyen	**Inversion methods in Geophysics - deterministic approach**
	How does one obtain a model representative of the subsurface from a finite set of noisy observations? If I have sparse but direct observations, how can I include them in the inverse modeling? Once obtained, how do you assess the quality of the model and its uncertainty? The course covers the main algorithms used to solve linear and non-linear inverse problems in a deterministic framework together with image appraisal. Particular attention will be paid to numerical, mathematical and statistical aspects in relation with geophysical applications but is not restricted to them.
Jeff Caers	**Uncertainty quantification**
	The future of humanity depends on the successful and sustainable exploitation of critical geological resources such as oil/gas, minerals, heat, storage & fresh water, as well as the transition out of hydro-carbons. Managing such resources will require the integration of a large amount of disciplines such as geological sciences, geophysics, data science, engineering and decision science. Engineering the subsurface is challenging because of the large uncertainties, large costs and hence risks involved. Practical approaches will have to address all uncertainties jointly, deal with large computation times in both data processing and model building, integrate the vast and heterogeneous data sources and manage properly geological heterogeneity. In this lecture, I will outline the challenges of engineering the subsurface, the gaps in our knowledge, the most pressing needs, and, based on those observations, a new data science-based framework that integrates all these disciplines into a manageable decision model. This new framework has been applied to several cases involving oil & gas production, contaminant remediation, heat extraction & subsurface storage. I will present the application to managing groundwater in Denmark. Denmark provides a unique case because of a clear formulation of governmental objectives, the appropriate definition and involvement of the various stakeholders, the collection of high quality data such as Airborne EM data, the specific nature of geological heterogeneity, and the general desire to do it the “right” way: leveraging science and community involvement into a sustainable future water supply. The purpose of this lecture is not to provide the details of each component, but to present the synthesis required to solve problems in practice

Olivier Bour	**Heat transport in fractured rock**
	Although heat is often used as a groundwater tracer in fractured media to identify permeable fractures, locate recharge or discharge zones, the modelling and prediction of heat transport in fractured media is particularly challenging due to i) the heterogeneity of fracture networks at all scales, ii) fracture-matrix thermal exchanges which lead to thermal retardation and attenuation that are often difficult to interpret. Here, we will first show through different examples how heat can be efficiently used at different scales to identify active permeable fractures, karst conduits, identify source of groundwater or estimate borehole flows. In a second step, we will present the main challenges associated to heat transport in fractured rock. We will also present a theoretical framework for interpreting joint solute and thermal tracer tests, which allows to infer information on flow topology and heat transfer in fractured media from the analysis of thermal tracer tests.
Peter Bayer	**Geothermal Energy**
	Do rocks burn? No, but they can warm us! This lecture gives an incomplete introduction to geothermal energy use with a focus on the conditions in Central Europe. This includes an overview of different direct and indirect use types covering the broad range from deep enhanced geothermal systems to very shallow geothermal collectors. We will learn about the technologies used in practice as well as about concepts that are more the emphasis of current research activities. There will be a focus on the thermal conditions in the subsurface, in cities and rural areas, highlighting the major heat transport mechanisms, conduction and convection. Special interest is set on the role of groundwater, which carries and stores heat. As in related fields of applied geosciences, to assess the role of governing processes, knowledge of ground properties and structural heterogeneity is essential for guiding appropriate technological design and management. With this geoscientific perspective, we will envisage the potential of optimal geothermal energy harvesting as well as storage of heat and cold beneath our feet.
Jan Olof Selroos	**Underground nuclear waste storage**
	The lecture will briefly introduce the concept of and motivations for geological disposal of nuclear waste. Focus will then be on groundwater flow and solute transport modelling relevant for site-descriptive understanding and safety assessment of such repositories. Examples will be drawn from recent studies performed within the Swedish and Finnish nuclear waste programs. Specifically, the use of discrete fracture network (DFN) models to understand flow and solute transport characteristics in sparsely fractured rock will be introduced. Furthermore, safety assessment applications for the different time periods studied such as open repository, temperate, permafrost and glacial conditions will be

	exemplified. Also analogue field studies recently performed at the Greenland ice sheet supporting assumptions made for glacial and permafrost simulations will be discussed. Finally a few examples will be provided on geological and hydrogeological measurements that can be made in tunnels and boreholes in order to locally condition stochastic DFN models. The purpose of such conditioning will be described, and the resulting reduction in uncertainty illustrated. The relevance of some of the ENIGMA experiments to be conducted at the Äspö Hard Rock laboratory will be put in context of the goals of increased process understanding and increased prediction confidence.
Alain Dassargues	**Groundwater vulnerability: from empirism to process-based assessments**
	Various groundwater vulnerability definitions and methods have been developed. Considering groundwater quality issues, the most common and traditional techniques are unfortunately based on empirical calculation of an index supposed to represent the protective effect of underground formations overlying or containing the groundwater resource. The subjective and empirical nature of these methods created their poor scientific reputation. There is thus a strong need for giving more emphasis on processes-based vulnerability indicators. According to the chosen definition of groundwater vulnerability/sensitivity to different stress-factors, different alternatives may be proposed, based on the use of unsaturated and saturated flow and solute transport simulations. Conceptual choices must be chosen progamatically in relation with the objectives. Different process-based vulnerability assessment methods are illustrated. In a Pressure-State-Impact causal chain, it is also possible to calculate sensitivity coefficients for a user-defined groundwater state for which several physically-based indicators are proposed. They reflect the easiness with which the groundwater state transmits pressures into impacts. They can be converted in vulnerability, using the concept of 'transgressing a given threshold' (Luers et al., 2003). While the methodology is general and can be applied for quantity as quality issues, the vulnerability is related to a damaged state and to the 'distance' between the current state and a given threshold. These methods allow a clear distinction between conventional choices (threshold) and scientific work.
Auli Niemi	**CO2 geological storage**
	Geological storage of carbon dioxide in deep geological formations is widely recognized as a key transitional technique for reducing atmospheric emissions of CO_2 and thereby its inverse effects on climate. Worldwide, a number of projects are already in operation while others are under construction and planning. This lecture will start with a short overview of the status of CCS and the key geoscientific challenges related to it. We then proceed to discuss the geohydrological flow, transport and trapping processes of the injected CO_2, along

	with the related coupled processes. Different modeling approaches are reviewed next and exemplified through case studies. We finally conclude with an in-depth look into one of the key trapping processes, namely the residual trapping, and its characterization through experimental and model studies over the range of scales, from core and pore network scale to the scale of field scale CO_2 injection, based on data from Heletz pilot site.
C. Darcel	**Stress and strain in fractured rock masses**
	Assessing the effective mechanical properties of rock masses is a prerequisite to many geotechnical applications, and a still major scientific issue about the way to take account of the heterogeneities of rock mass. Amongst all potential heterogeneities, fractures are those whose impact on rock strength and stiffness is prevalent with the difficulty that the distribution of fractures is complex with a wide range of spatial scales involved, and highly variable densities in space. In this lecture, we derive the relationships that link the general elastic properties of rock masses to the geometrical properties of fracture networks, with a special emphasis to the case of frictional crack surfaces. We extend the well-known elastic solutions for free-slipping cracks to fractures whose plane resistance is defined by an elastic fracture (shear) stiffnes and a stick-slip Coulomb threshold. The application of these theories to actual rock masses raises two main issues. The first is about the role of frictional stresses in the damaged elastic modulus, since friction is likely prevailing on large geological fractures; the second is the intrinsic complexity of fracture networks, which results in a wide range of fracture sizes from micrometer to kilometer scales.
Michael Manga	**Hydromechanics - Lecture**
	Deformation of rocks changes the pore space and hence properties of the fluids within those pores. At the same time fluids moving through pore change pressure which in turn causes deformation. I will review the theory of linear poroelasticity and the time-dependent coupling between rock deformation and fluid flow within the rock. The basic theory is described by Biot's linear constitutive laws coupled with Darcy's law for flow in porous materials.
Philippe Davy	**Modeling fractured rock mass properties with DFN: concepts, theories and issues**
	DFN – Discrete Fracture Network – is primarily a modeling framework for fractured geological systems that aims to integrate field data into simulations of flow and/or deformation. It is complementary to, or competing with, continuum methods with both advantages of easily integrating the statistical properties of fracture networks, and of not assuming any homogenization scale. The conference aims to take stock of the recent work on DFN modeling and

	applications in hydrogeology or rock mechanics. We present the complete workflow from integrating and extrapolating fracture data into DFN models, to predicting transfer and mechanical properties of fractured rock masses. We discuss some fundamental issues about the DFN modeling framework – e.g., upscaling and critical scales, determinism and intrinsic variability, statistical and model uncertainties, critical structures for flow (HYDRO-DFN) of for geomechanics (MECHA-DFN). We illustrate these issues with theoretical concepts, numerical experiments and case studies. We discuss in particular the minimum complexity of models required to stay consistent with data.
Michael Manga	**Earthquakes and water**
	Distant earthquakes are well known to induce a wide range of responses in surface water and groundwater. These responses are often viewed as mere curiosities as their occurrence is limited in space and time. The observed phenomena, however, probe the interaction between hydrogeological processes and mechanical deformation in the shallow crust. Hence they provide insight into the interaction between the water cycle, tectonics, and properties of the crust. In this talk I will review observations and explanations for hydrologic responses to earthquakes.
Antonio Pio Rinaldi	**Induced seismicity and GeoEnergies: lesson learned from coupled hydro-mechanical modeling**
	Pressure changes caused by the direct injection/extraction of fluid at depth may produce variation in the state of stress, inducing seismicity and enhancing fluid circulation, consequently have an impact on the sealing capabilities for storage projects. The importance of geomechanics including the potential for reactivating faults associated with large-scale underground operations has recently become more widely recognized. In this context, here we review and summarize some recent modeling efforts, aimed at understanding the so-called induced seismicity. The simulations were conducted using simulators for coupled multiphase flow and geomechanical modeling. We account for stress/strain-dependent permeability and study both the fault reactivation and enhanced permeability, as well as possible leakage through the fault zone during storage activities. Several scenarios are investigated to study seismicity associated with CO_2 storage, hydraulic fracturing for shale gas, enhanced geothermal exploitation, and gas production. Results of the numerical analysis aims at discriminating the several physical processes occurring during exploitation of deep underground resources.

Annex 2: Complete list of participants to the summer school

Name	Surname	Institution
Pasquet	Sylvain	IPGP
Borhany	Hojjat	Géosciences Rennes
Heyman	Joris	Université Rennes 1
Palacios	Andrea	CSIC-IDAEA
Lemmens	Laurent	SCK-CEN / KU Leuven
Hoffmann	Richard	Hydrogeology & Environmental Geology
Lincker	Manon	MINES ParisTech
De Vriendt	Kevin	IDAEA - CSIC
Molron	Justine	Itasca Consultants sas
Miranda	Mafalda	Institut national de la recherche scientifique
Orucoglu	Esra	CNRS
Pardo Álvarez	Álvaro	Université de Neuchâtel
Avery	Elizabeth	University of Kentucky
Mehr	Nicole	Oregon State University
Kurz	Dorothee	ETH Zürich
Tirado Conde	Joel	University of Copenhagen
Nicolas	Madeleine	Univ Rennes
Goyetche	Tybaud	GHS-UPC-CSIC
Rembert	Flore	Sorbonne Université METIS UMR 7619
Patino	Janis	University of California Davis
Mendieta	Aida	Sorbonne Universités
Ashworth	Mark	Heriot-Watt University
Haruzi	Peleg	Forschungszentrum Jülich
Hamlat	Bastien	IFPEN - INRIA Rennes
Rieckh	Veronika	University of Tübingen
Hakoun	Vivien	IDAEA-CSIC
Aquino	Tomas	IDAEA-CSIC
Azzaino	Zain	University of California Davis
Bjerre	Elisa	University of Copenhagen
Goirand	Florian	CNRS
Pouladi	Behzad	CNRS
Thiros	Nicholas	University of Montana
Doolaeghe	Diane	Géosciences Rennes
Gonze	Kevin	UMONS
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