SOERE National Networks of Environmental Research Observatories

ACTIVITY REPORT 2010-2014 (or 2011-2014) and PROJECT for the next 5 years

H+ international network of hydrogeological observatories

Contents

I. Description of the Observation or Experimentation System

I.1 Name of the infrastructure and website

- Name: *H+ international*, international network of hydrogeological sites for measuring and modeling flow, transport and reaction in heterogeneous subsurface environments
- Web site : http://hplus.ore.fr/en

I.2 Contact details of managers

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- **Tanguy Le Borgne,** associate professor (physicien adjoint CNAP), Observatoire des Sciences de l'Univers de Rennes, 35042 Rennes, 0223236702, tanguy.le-borgne@univ-rennes1.fr

I.3 Supporting institutions

- Coordination Laboratory : Observatoire des Sciences de l'Univers de Rennes (OSUR), UMS 3343 CNRS
- Participating institutions **:**
    - *Departments :* Géosciences Rennes (UMR 6118 CNRS), IC2MP (UMR 7285), Géosciences Montpellier (UMR 5243), EMMAH (UMR INRA-UAPV 114), Geosciences Azur (UMR 6526), BRGM, LSBB (UMS 3538 INSU/UAPV/UNS)
    - *Observatories :* Observatoire des Sciences de l'Univers de Rennes (OSUR), Observatoire de Recherche Méditerranéen en Environnement de Montpellier (OREME), Observatoire de la Côte d'Azur (OCA)
    - *Institutions :* CNRS / INSU, BRGM, INRA, Université Rennes I, Université de Poitiers, Université de Montpellier II, Université d'Avignon, Université de Nice, Laboratoire Souterrain à Bas Bruit LSBB
    - *Partner institutions :* NGRI (India), CSIC (Spain), Forschungszentrum Jülich (Germany)

I.4 Summary

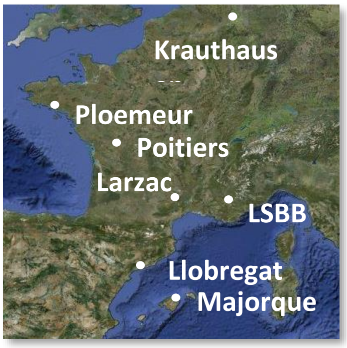
H+ international is a network of hydrogeological experimental sites. Its primary objective is to produce high quality observations and experimental data on subsurface flow and processes from instrumented sites. Recent years have witnessed the emergence of sophisticated Earth observation systems in response to societal and institutional demands (i.e., water framework directive) and to increasing anthropic pressures (climate change, water abstraction and storage, geothermal energy exploitation, mining, oil and gas activities, waste storage or CO2 sequestration). However, our knowledge of these environments, which control the long-term evolution of our water resources and sustain a large part of our energy resources, quickly decreases with depth. H+ offers a unique opportunity for breakthroughs in this domain by gathering well-established field infrastructures, pioneering academic teams and emerging companies that develop innovative sensors and hydrogeophysical inversion methods, and experts in subsurface modelling. The H+ experimental sites all represent unique infrastructures that require i) maintaining the quality of measurements and the efficient dissemination of the datasets, ii) ensuring continuous exchanges between teams managing experimental sites to share technical developments and new tools, iii) fostering site attractiveness by promoting international collaborations. The obtained datasets are disseminated through a common database (http://hplus.ore.fr/en/database/acces-database).

II Scientific and technical report on the activities of the SOERE with regard to the initial criteria

II.1 Scientific contributions

II.1.a Reminder of the missions, defined objectives and positioning of the SOERE within a strategic theme and/or programme for the partners in the AllEnvi alliance.

The H+ international network of hydrogeological experimental sites (figure 1), created in 2012, includes the H+ national network (Ploemeur, Poitiers, Mallorca, Larzac), and 4 sites managed by French partners (LSBB, Hyderabad) and European partners (Llobregat, Krauthausen). The challenge addressed by the H+ observatory is the exploration and modelling of subsurface heterogeneity, fluxes and biochemical reactions (figure 2). Acquiring reliable data in the field is critical in environmental science to fill the gap between modelling concepts or lab analogues on the one hand and the field truth on the other hand. The strategies developed for field experimentations over the last ten years largely differ from state to state in Europe, either project-based or sustained by long-term programs. Thus, in some cases, instrumental sites developed through intense efforts funded by specific projects, have faced difficulties to be maintained beyond the life span of the initial project. Data archiving methods also vary greatly, ranging from simple hard disks to dedicated databases with web interfaces. **H+ international represents a first step to pooling resources, instruments, data archiving and dissemination tools, and harmonize field strategies** in the perspective of the construction of common research infrastructures in Europe. The aggregation of French and European partners in the H+ international network has promoted scientific exchanges between teams that were previously developing experimental sites independently. The present proposal proposes to consolidate this international network.



Ploemeur (France)	Poitiers (France)	Mallorca (Spain)	Larzac (France)
O. Bour (Rennes)	G.Porel (Poitiers)	P. Pezard (Montpellier)	C. Champollion (Montpellier)
MONITORING OF A PUMPED FRACTURED AQUIFER	ADAPTED WELL ARRANGEMENT FOR EXPERIMENTS AND MODELLING	MONITORING OF THE FRESHWATER-SALINE WATER INTERFACE	CAPACITIVE BEHAVIOR OF A KARSTIC AQUIFER

LSBB (France)	Hyderabad (India)	Krauthausen (Germany)	Llobregat (Spain)
C. Danquigny (Avignon)	J.C. Maréchal (Montpellier)	J. Vandreborght (Jülich)	J. Carrera (Barcelona)
LARGE SCALE TUNNEL FACILITIES IN THE UNSATURATED ZONE	TROPICAL FRACTURED AQUIFER UNDER OVEREXPLOITATION	HYDROGEOPHYSICAL EXPERIMENTAL SITE	MONITORING OF A SEA WATER INTRUSION BARRIER

Figure 1: 2011-2014 H+ international network (hplus.ore.fr/en)

II.1.b Summary of the main scientific advances and outcomes achieved

The scientific activities developed in the H+ observatory are organized around three main Research Objectives:

- **develop innovative technologies and methodologies for imaging of subsurface systems**, in particular within the national equipex project managed jointly with the catchment network RBV (CRITEX 2012-2019 7 million €, challenging equipment for the temporal and spatial exploration of the critical zone at the catchment scale)
- **test, compare and validate these novel methods in highly instrumented experimental research sites** (Figure 2), where the new results, data are made available to academia and industry through a common on-line database,
- **integrate the produced datasets into predictive simulation tools** to enhance process understanding and improve operational simulations for subsurface operations.

Complementary scientific objectives are defined on the different instrumented sites: the impact of groundwater abstraction on the water cycle in fractured media (Ploemeur and Hyderabad), coupled transfers in highly localized flowpaths and a porous matrix (Poitiers), recharge pathways and storage distribution in karstified systems (Larzac), the monitoring of saline intrusions in coastal aquifers located in semi-arid regions (Mallorca and Llobregat), the study and imaging of intermittent flow and transport processes in the unsaturated zone (LSBB tunnel), the development of hydrogeophysical imaging techniques in heterogeneous media (Krauthausen).

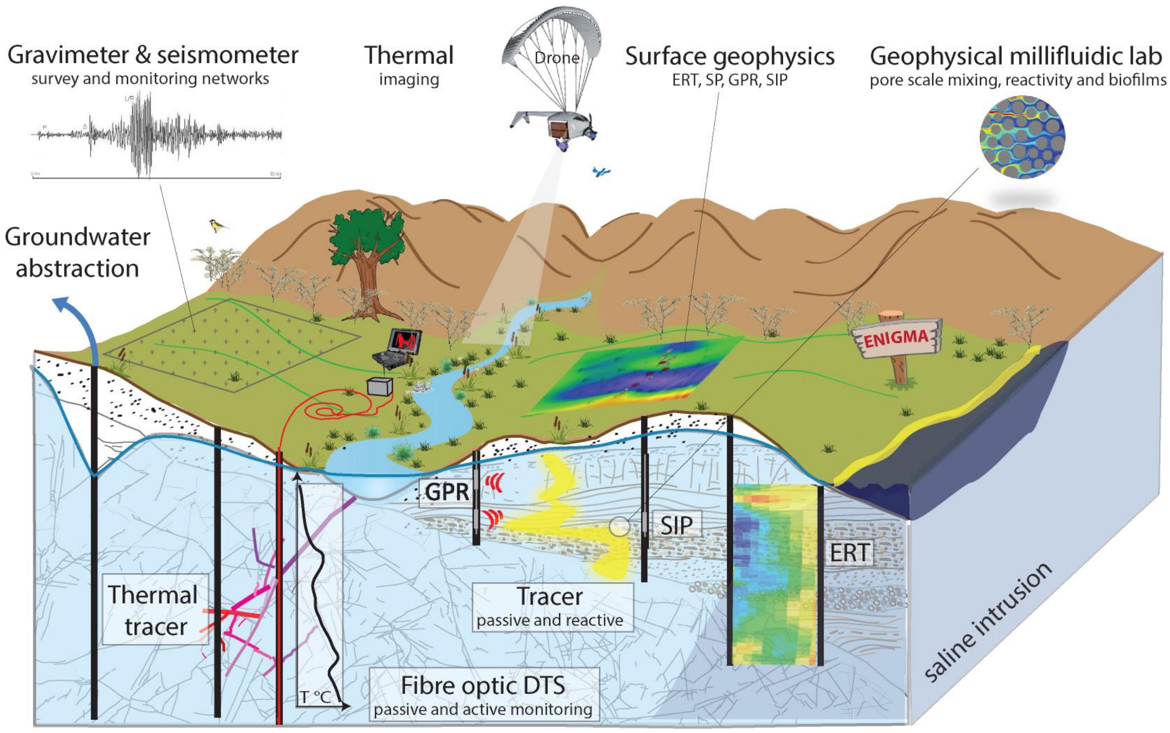


Figure 2: *co-location of different imaging techniques on densely monitored experimental sites to quantify subsurface spatial structures, fluxes, heat transfer and reactive transport phenomena.*

II.1.c Achievement of the scientific objectives fixed and progress made by the SOERE in this context thanks to its activities.

Scientific progresses achieved during the first period of the SOERE network H+ (2011-2014) are reflected in the publication list (annex 2). They include experimental innovations (see section

II.2.a) and progresses in the characterization and modelling of flow and transport processes in heterogeneous media. Emblematic results include:

- **The confrontation of models to in situ data and the inverse problem in hydrogeology**: the production of high quality data, driven by modeling questions, is one of the major challenges addressed by the H+ observatory. The objective is i) to design key experiments to test the model hypothesis and predictive capacities, ii) to develop appropriate inverse modeling approaches for imaging techniques adapted to the high level of heterogeneity of subsurface environments. This objective has been at the root of the creation of the H+ observatory and modeling teams have been closely associated to the development of the experimental sites. Hence the H+ datasets are used to test models at different scales by teams much beyond the network. The modeling benchmark perform on the Poitiers experimental site illustrates this approach (Bodin et al. 2012). Controlled tracer test data, obtained on the Ploemeur and Hyderabad fractured rock sites, were used to test and validate recently developed non-Fickian transport model, including the CTRW model (Kang et al., 2015, collaboration with MIT) and the stochastic stream tube model (Guiheneuf et al. submitted, collaboration with the university of California at Long Beach). A long-term collaboration has been developed with the University of Lausanne for the development of inversion algorithms that account for multiple data types in a probabilistic framework for fractured media (figure 2, Dorn et al., 2011, 2012, 2013).

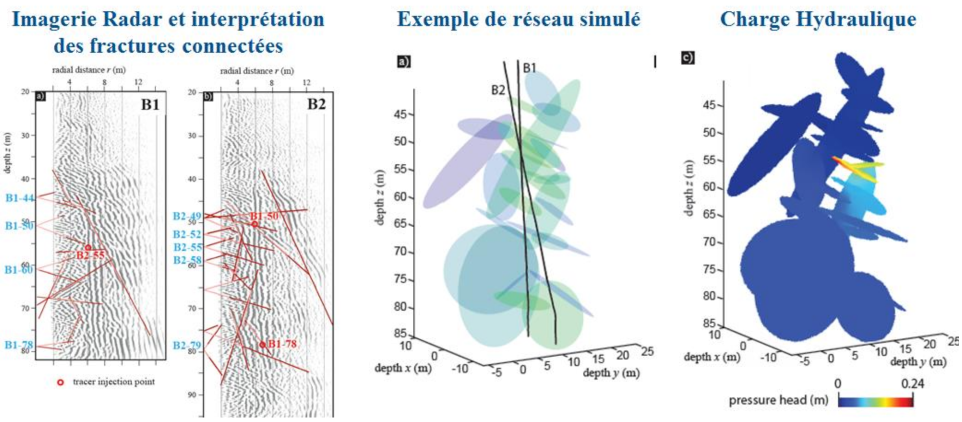


Figure 3: *radar imaging of fractures on the Ploemeur site in collaboration with the University of Lausanne, example of inverted fracture network and distribution of hydraulic head in fractures (Dorn et al. Geophys. Res. Lett. 2011, Dorn et al., Water Resour. Res. 2012)*

- **The characterization of transport processes and biogeochemical transformations** in the subsurface and through interfaces with other compartments. The progress obtained on the imaging of subsurface structures, flow distributions and residence time distributions on the H+ sites have set good conditions for the in situ characterization of reactive transport properties in these highly heterogeneous environments. This constitutes an important challenge of the H+ network in the coming years. Collaborations have been initiated with the catchment network RBV for the quantification of the contribution of groundwater to geochemical fluxes, which is currently a largely open question. Field campaigns have been launched on the H+ sites to study fluid solid interactions (e.g. analysis of selenium dissolution on the Poitiers site), the role of micro-organisms in reactive transport (e.g. denitrification on the Ploemeur site), the influence of mixing processes on biochemical reactions in the saline wedge on the Mallorca site (see figure 4, Hery et al., 2014). Furthermore, the H+ network has been the basis of thorough and innovative investigations of microbial communities' structure

(RNA and DNA sequencing, metagenomic analysis) in relation to groundwater residence-time, in collaboration with the Ecobio laboratory (Microbial ecologists).

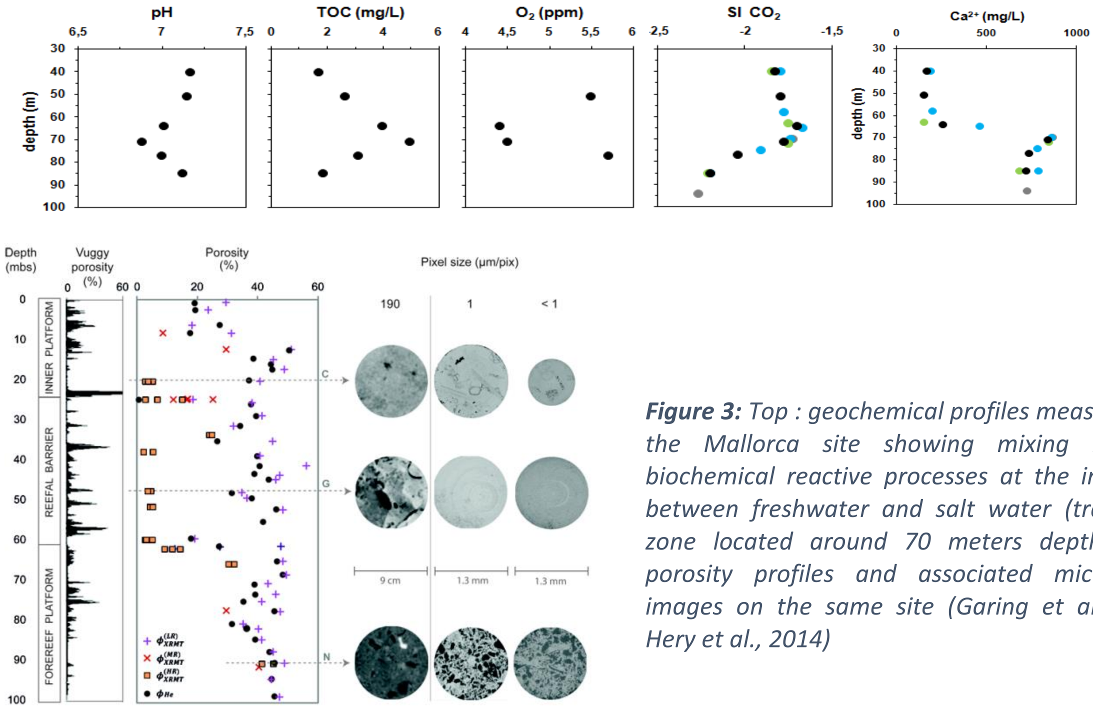


Figure 3: Top : geochemical profiles measured on the Mallorca site showing mixing induced biochemical reactive processes at the interface between freshwater and salt water (transition zone located around 70 meters depth), left: porosity profiles and associated microscope images on the same site (Garing et al. 2013, Hery et al., 2014)

- **The quantification of recharge fluxes in heterogeneous media**: Recharge fluxes are known to be highly heterogeneous and characterized by a wide range of characteristic temporal scales in heterogeneous soils and aquifers (figure 5 and 6). New experimental methods combining direct flow measurements and geophysical imaging have been recently tested on the H+ sites to characterize the spatial variability, the scale dependency and the temporal dynamics of recharge fluxes (Deville et al. In review, Meauxsome et al., in review, Roques et al., 2014, Guihéneuf et al., 2014, Dewandel et al. 2014, Jimenez-Martinez et al., 2013, Carrière et al., 2013).

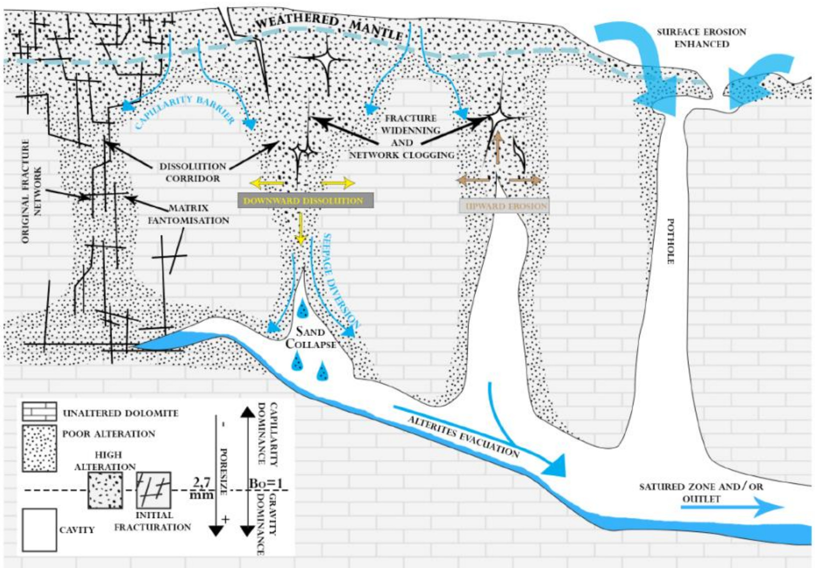


Figure 5: Conceptual representation of recharge in the karstic dolomite site of Larzac (from A. Meauxsoone).

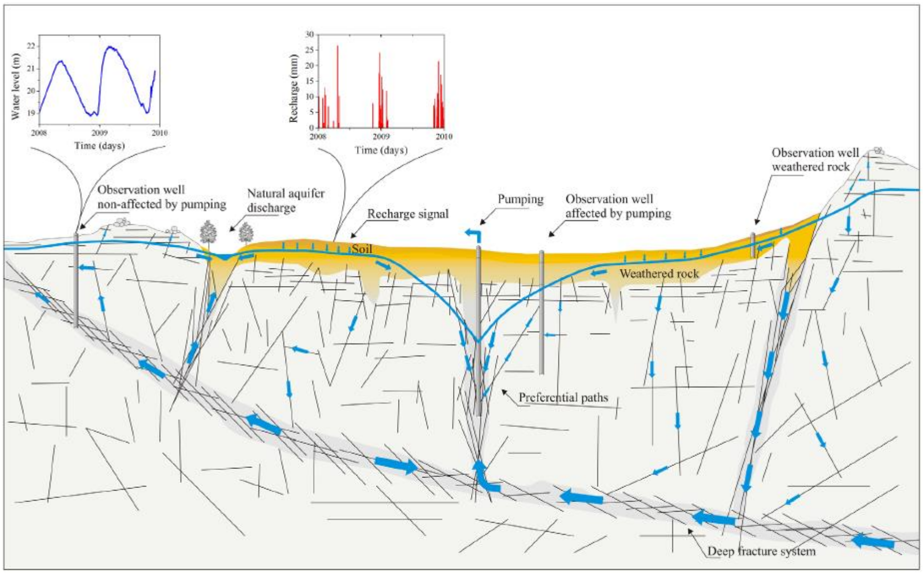


Figure 6: *Conceptual representation of recharge in fractured crystalline rocks (Jimenez Martinez et al., 2013)*

II.1.c Research collaborations initiated (specify the research groups or units concerned).

The H+ network promotes actively the development of scientific collaborations on its experimental sites (see annex 1). Exchanges are either directly funded by the network or through scientific projects (national and European) that make use of the sites. Hence, the experimental sites host every year experimental campaigns involving external scientists from France and abroad. The two international partners (figure 1) do not receive direct funding for the sites, which are supported by their projects. For these partners, H+ funds scientific exchanges and meetings. For instance, H+ funded the participation of CSIC scientists to experimental campaigns on the Ploemeur sites and the shipping of tools (fluorimeters) to the Llobregat site. The Rennes fiber optic DTS unit will be soon used by the Barcelona team on their site. A H+ meeting was organized in 2013 in Julich that gathered the main teams developing experimental sites in Europe. This meeting led to the submission of a European training network proposal, currently under evaluation. The ENIGMA proposal (European training Network in Innovative imaGing Methods for heterogeneous Aquifers) was first submitted in 2014 an obtained a favorable review with a grade of 87,6% just below the funding threshold at 91%. The project was resubmitted in January 2015 after improving the project and taking into account carefully the reviewers' comments.

II.2 Parameters measured, Data, Information System

II.2.a Inventory of objectives and critical assessment of the SOERE

- diversity of the parameters measured and their relevance to national strategy; data generated and their archiving;

The parameters measured on the H+ sites managed by the French partners are given in table 1.

Frequency	Parameters	H+ sites
Year, semester	Hydrochemistry, residence times, borehole temperature profiles	Ploemeur, Mallorca, Larzac, Hyderabad
Month	Hydrochemistry unsaturated zone	Ploemeur, LSBB
Day	Electrical resistivity	Mallorca, Larzac
Hour	Weather data, point measurement of temperature and electrical conductivity	Larzac, Poitiers, Ploemeur, Hyderabad, Mallorca
Minute	Piezometric levels, GPS, unsaturated zone monitoring (water content, pressure, temperature)	Larzac, Poitiers, Ploemeur, Mallorca, Hyderabad
Seconde	Absolute gravimeter, high precision inclinometers, flux tower, GPS	Larzac, Ploemeur, LSBB
Milliseconde	Seismometer	Ploemeur
Experimental campaigns	Borehole geophysics (multi-parameter probe, gamma ray, optical logs, resistivity, PS, flowmeter) and surface geophysics (electrical, electromagnetic, seismic). Pumping tests, flow measurements, fiber optic DTS, tracer tests, time lapse hydrogeophysics	Ploemeur, Poitiers, Mallorca, Larzac, LSBB

Table 1: *Parameters measured on the H+ sites (for the sites coordinated by French partners directly funded by the SOERE)*

Data archiving and dissemination is a key objective of the H+ observatory. A significant effort has been done through the SOERE funding during the last years to ensure that the main datasets of all sites (in particular the new SOERE sites LSBB and Hyderabad integrated in 2012 to the network, see figure 7) are continuously inserted in the database. The latter contains currently about 380 million values and it progresses at a mean rate of 70 million values per year.

For certain types of data the insertion procedure is very efficient. This is the case in particular for monitoring data produced by permanent hydrological or geophysical sensors, for which a semi-automatic treatment and insertion procedures are defined. However, the insertion of datasets obtained from experimental campaigns are usually more challenging since they correspond to unique multi-sensors arrangement with different experimental protocols defined for each experiment. This experimental approach is one of the particularities of H+ compared to other observatories. **Our objective is not only to monitor natural evolutions but to study the response of the systems to induced controlled perturbations to probe conceptual and modelling representations.** The archiving and dissemination of these experimental data requires a close coordination between data providers, database experts and data end users. The objective is to define data insertion formats that are adapted for each new experiment. This works currently well for hydraulic and tracer test experiments, which are archived in the database. However, the insertion of hydrogeophysical datasets is a significant challenge due to the different nature and format of the hydrological (e.g. pressure evolution, tracer breakthrough curve) and geophysical data (e.g. ERT panels or GRP profiles…). This difficulty has been identified as a critical challenge to be addressed at international level (see section IV) in close collaboration between geophysicists and hydrologists.

The continuous improvement of the extraction interface of the online database is important for the H+ observatory to ensure an efficient access to new users (see website http ://hplus.ore.fr/connexion, login : hplus, password : hplus001). Significant progresses have been achieved in this direction during the first SOERE period. H+ data can be currently extracted in three different ways: i) through formulating requests in the advanced interface, ii) through consulting pre-defined requests (login : hplus, password : hplus001) that allow a direct download of the main datasets on each site, iii) through the google earth interface (login : hplus, password : hplus001) that allows a spatial visualization of sites and measurement locations.

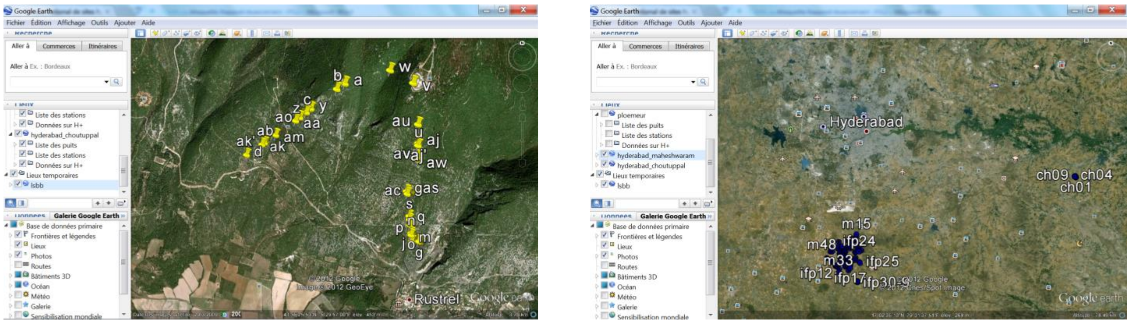


Figure 7: Illustration of the integration of the LSBB (left) and Hyderabad sites (right) in the H+ database and its google earth interface. Left: location of flow measurement stations in the LSBB tunnel, right : instrumented boreholes on the Hyderabad site.

- management and participation in data calibration and validation initiatives;

The H+ observatory organizes international intercomparison exercises for validating new measurement techniques or inverse modeling approaches. In particular H+ hosted in 2012 the first international intercomparison exercise for groundwater dating techniques (GDAT) coordinated by H+ scientists. Results were published in the special issue of the journal of applied geochemistry « Dissolved gases in groundwater and groundwater dating methods » (Labasque et al., 2014, Visser et al., 2014). In parallel, modeling studies were performed to evaluate the information content on groundwater age data for calibrating hydrogeological models (Aquilina et al., 2014, Massoudieh et al., 2014, Leray et al., 2014).

- development of innovative experimental or measurement methods.

H+ teams are strongly involved in the development of innovation experimental methods in particular through the equipex project CRITEX (2012-2019 Challenging equipment for the temporal and spatial exploration of the Critical Zone at the catchment scale), which was constructed jointly by the H+ and RBV networks. H+ teams are responsible of the following work packages: WP3 spatially distributed monitoring of temperature with fiber optic DTS, WP7.1 well equipment, WP7.2 well monitoring, WP 7.3 reactive tracer test experiments, WP 8.1 Gas tracing. Innovative experimental developments achieved in the last years in the H+ network include:

- **The measurement of flux and travel time distributions**: the characterization of the flow heterogeneity and its influence on the transport of dissolved elements is at the heart of the scientific challenges addressed by the H+ network. Flow measurements are performed for this purpose at different scales (boreholes, tunnels, soils). In particular, tomographic approaches that employ repeated measurements using multiple hydrologic perturbations and monitoring points offer enhanced spatial resolution (Klepikova et al. 2013). The combined use of different artificial and environmental tracers, including heat or reactive tracers is a promising approach to reduce characterization uncertainty of transport processes and conceptual models (Read et al. 2013, Klepikova et al. 2014, Roques et al. 2014, Aquilina et al., 2014). Furthermore, the development of new sensor technologies has enabled the measurement of variables, fluxes and properties that were not achievable before. Fiber-optic distributed temperature sensing yields new opportunities for direct spatially distributed measurements of fluxes, in particular at interfaces between surface and subsurface hydrological systems (Read et al., 2014). Furthermore dissolved gases measurements (CFC) can be inverted to infer the distribution of groundwater residence time with significant reduction of uncertainty for the calibration of groundwater models (Leray et al. 2014, Massoudieh et al., 2014, Marcais et al. 2015).

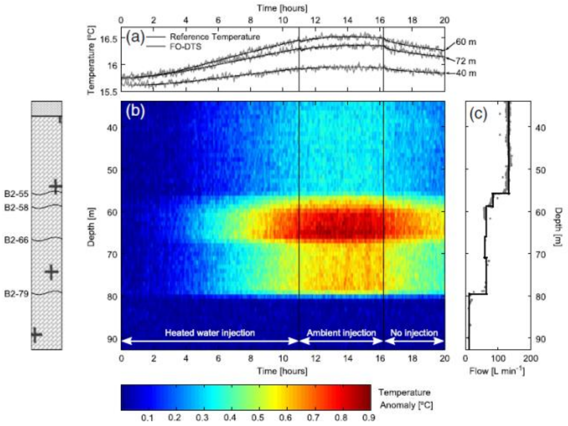


__Figure 8:__ Temperature profiles measured at different times during a heat tracer tests performed on the Ploemeur site. The spatially distributed sensing offered by the fiber optic technology allows detecting the arrival of the hot tracer at different depths corresponding to permeable fractures (Read et al., Geophys. Res. Lett., 2013).

- **The development and validation of hydrogeophysical imaging methods**: to (1) image hydrologically relevant subsurface structures, (2) estimate the spatial distribution of subsurface properties controlling flow and transport, and (3) monitor subsurface processes associated with natural or engineered in situ perturbations. H+ sites have contributed to test new strategies to combine hydrological and geophysical data to enhance resolution and reduce characterization uncertainty (Dorn et al. 2011, Biessy et al. 2011, Mazzilli et al. 2012, Deville et al. 2012, Garing et al., 2013, Carriere et al. 2013, Moreau et al. 2013). Geophysical measurements performed on the site include geophysical campaigns (seismic and electrical surveys, borehole geophysics, magnetic resonance imaging, ground penetrating radar), hydro-geodesic monitoring (long base tiltmeters, borehole tiltmeters, GPS) and gravimetric (absolute and relative). All these measurements represent a unique database to progress towards the field application of hydro-geophysical characterization concepts (see figures 9 and 10). This activity will be strongly developed in the next years within the CRITEX project.

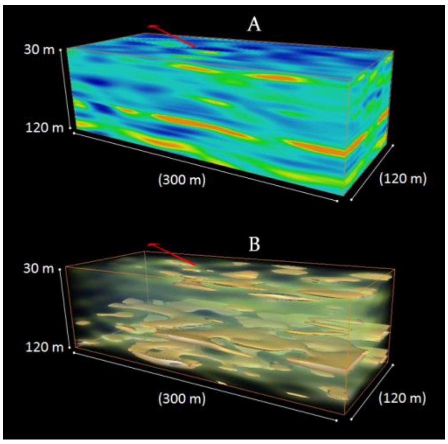


__Figure 9:__ (A) 3D pseudo seismic velocity distribution at the Poitiers experimental site; (B) extraction of the low seismic velocity zones correlated with karstic conduits.

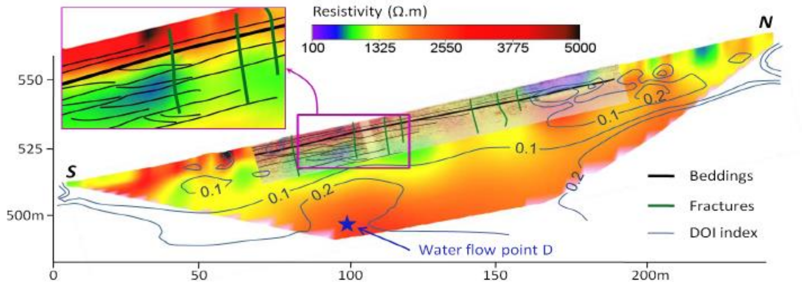


Figure 10.a: *Superposition of GPR and ERT profiles on the LSBB site (Carriere. et al. Journal of Applied Geophysics -2013)*

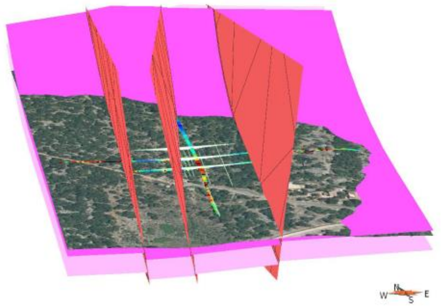


Figure 10.b: *3D view of the main fractured zones imaged by geophysics on the LSBB site (Ollivier, C. master thesis, UMR EMMAH, 2013)*

- situation concerning the exploitation and evaluation of data, and in particular: progress achieved regarding an open information system, its interoperability with those of the other SOERE, its potential integration in a national or an international environmental information system.

H+ is directly involved in the long term work to define common data archiving tools for environmental sciences. Progress has been achieved for the interoperability of the H+ database with the databases of the Rennes (OSUR) and Montpellier (OREME) observatories that regroup all the environmental databases managed by these structures (e.g. ecological databases). Hence H+ metadata have been evolving towards the ISO 19115 norm (inspire European directive 2007) and are being integrated in a geo-referenced open portal. Discussions are on-going with BRGM, INRA and the catchment network (RBV) to use and develop common data archiving and dissemination tools. At international level, the current SOERE program has trigger discussions with European partners developing experimental sites, highlighting the lack of international coordination for hydrogeophysical data archiving. The creation of common tools is one of the key objectives of this SOERE proposal.

- assessment of the availability of data to the scientific community, any use of the data in models; lists of teams exploiting the data and those which plan to use them.

The H+ sites offer particularly attractive conditions for teams to test new methods since they are already well instrumented and documented from large datasets. This aspect will be reinforced with the current proposal. The list of teams currently using the H+ data is given in annex 1. The external teams are given below:

14 teams in France : UPMC Paris, UBO Brest, Université de Nantes, Lhyges Strasbourg, LSCE Paris, Sisyphe Paris, IFP Paris, UPPA Pau, CEREGE Aix, LTHE Grenoble, CEFE Montpellier, Ecole des Mines de Paris, LTHE Grenoble, Université de Chambery

17 teams abroad : University of Lausanne (Switzerland), MIT (USA), Université of East Anglia (UK), Oregon State University (USA), University of Liège (Belgium), Université of Bochum (Germany), Politecnico di Milano (Italy), European Center for Geodynamics and Seismology (Luxembourg), Virginia Tech (USA), University of Neuchatel (Switzerland), Charles University of Prague (Czech Republic), University of Oxford (UK), University of California at Long Beach (USA), University of Balearic Islands (Spain), University of Mons (Belgium), Los Alamos National Lab (USA National) Geophysical Research Institute (India),

- assessment of the supply of data to other potential users with, when necessary, a time-line regarding exclusivity, for scientific communities.

H+ monitoring data are continuously inserted in the database, data from experimental campaigns are inserted after a period of treatment if possible less than a year after the experiment.

II.2.b Implementation of quality management:

- relative to the life cycle of the data: processing, long-term archiving and distribution of the data, in compliance with the standards of European and/or international protocols;

H+ is committed to ensure a high quality long term archiving and distribution. This aspect is discussed systematically at annual meetings and throughout the year through continuous exchanges between the coordinators, data providers, database engineers, and end-users. The H+ database engineers are involved, through the Rennes and Montpellier observatories, in the evolution towards the Inspire directive for metadata standards. The objective of the H+ data quality management strategy is to ensure:

- the accuracy and reliability of measurements through the use of equipment that are regularly calibrated with reference standards
- that measurement performed at different times are comparable
- that the sources of uncertainty are identified and quantified

- traceability of the data acquired (identification of the source of data throughout their processing or use).

The data formats for insertion in the H+ database include a description of the measurement conditions and context (human, material, methodological, environmental).

II.2.c Current positioning of the SOERE relative to long-term observation objectives.

Long term observations of subsurface environments, typically superior to ten years, are motivated by slow evolution of these systems that provide resilience to hydrological systems to environmental changes. The main objectives of the long term monitoring are i) to analyze the hydraulic and chemical response of aquifers to perturbations (e.g. pumping), ii) to quantify the impact of climatic or land-use changes, and iii) to obtain measurements of fluxes and element transport in the hydrological cycle over time scales representative of these systems that are characterized by a broad range of response times.

These long term observations are complemented by experimental campaigns to characterize physical and chemical heterogeneity, and parametrize hydrological models. A specificity of H+ is to develop this field experimental approach to push forward the coupling of data and models. The database is at the center of this approach to accumulate a mass of information on these complex natural objects, and use it in predictive models.

II.3 Openness and integration of the SOERE in the national landscape

II.3.a Assessment of the actions implemented to set up the SOERE

- openness to teams outside the scope of the SOERE

National and international collaborations developed by the H+ network are detailed in annex 1.

- interactions with other observatories and other SOERE

The development of exchanges with the catchment network RBV has been initiated at the start of the SOERE H+ since it represents a major interest for: i) addressing scientific questions at the interface between the subsurface and surface components of flow that are critical for quantifying fluxes of chemical elements in the water cycle, ii) pooling investments in equipment to ensure an access of both networks to the latest instruments, iii) structuring the scientific community on critical zone in France to participate to the European structuration. This collaboration led to the critical zone projects equipex CRITEX (see next section) and eLTER European infrastructure (see section IV.7).

- openness to other related themes in the field of the environmental sciences

The equipex CRITEX project (2012-2019) represents **a significant advance to develop exchanges on the long-term between the hydrological, hydrogeological and geophysics communities**, hence bringing across traditional fields. The instruments proposed in the project have been collectively discussed and have been selected primarily for being able to generate significant scientific **breakthrough** in the CZ sciences, either because they are new and have not been used in catchments before (ex. chemical sensors) or because they are proposed to be used in a network perspective (mobile laboratory). The different communities involved in the proposal (geophysicists, geochemists, hydrologists, hydrogeologists, geomorphologists) have also proposed instruments that are susceptible to connect disciplines and bridge the instrumental gaps between temporal and spatial scales. In this later case, breakthrough is not in the instrument itself but in the synergistic approach.

Links with biologist are also developed by the H+ team to investigate the role of micro-organisms in reactive transport processes (see section II.1.c). In the next years, this collaboration will extend to larger scale hydro-ecological processes, through the participation in the European eLTER infrastructure (see section IV.7)

II.3.b Review of current integration in the French, European and international infrastructure roadmap and notably:

- possible positioning relative to the French Investments for the Future (PIA) programme,

With the network of catchments (RBV), H+ is coordinating the equipex CRITEX that aims at improving the monitoring and characterization of fluxes and processes in the critical zone (2012-2019 7 million euros). The goal of the instrumental program proposed in the project is to build a measurement facility open to the RBV and H+ SOERE communities to work synergically on first-order cutting-edge research questions on the Critical Zone. H+ teams are responsible of the following work packages: WP3 spatially distributed monitoring of temperature with fiber optic DTS, WP7.1 well equipment, WP7.2 well monitoring, WP 7.3 reactive tracer test experiments, WP 8.1 Gas tracing.

- use of the SOERE in research projects (ANR, Europe or others).

The national and international research projects that use the H+ sites are given in annex 1.

- potential for the organisation of a network or account to be taken of recommendations by the AllEnvi Council regarding possible partnerships,

H+ has been defined as a network since its creation. As such it contributed to the structuration of experimental hydrogeology in France. The SOERE funding allowed the development new interactions with two important actors of hydrogeological science in France: the French geological survey BRGM and the underground laboratory LSBB. These new collaborations have led to several recent common publications. The development of closer collaborations with the main teams developing experimental hydrogeological sites in Europe has been an important achievement of this first SOERE period, with the submission of the ENIGMA European training network proposal.

- contacts and partnerships with other infrastructures or other services already accredited by organisations or establishments (CNRS-INSU SNO, ORE operated by other institutions, other arrangements).

H+ and RBV teams develop close interactions in the framework of the CRITEX project.

II.3.c Relationship with the operational environmental observatories (managed by ministries, agencies, communities, etc.) and with "civilian society".

The integration of the French geological survey BRGM in the H+ network during the first SOERE period is clearly consolidating the link of H+ science with operational applications. Furthermore, scientific programs are on-going with the French Environment and Energy agency ADEME and companies such as Antea group to transfer the experimental and modeling methods developed in H+ to applications such as geothermal systems or soil remediation. In India, the sites are used for testing decision support tools dedicated to a sustainable management of groundwater resource to be used by local ground water departments and Central GroundWater Board.

II.4 Productions related to the SOERE

II.4.a Scientific production (including PhD theses) and technical production of the SOERE concerning the common network or infrastructure, within the framework of its specific scientific objectives (over the past 5 years).

The list of publications using the H+ data is given in annex 2.

II.4.b Assessment of production specific to the SOERE

The H+ teams are strongly involved in experimental and technological developments for imaging heterogeneous subsurface structures, fluxes and processes. These techniques are often developed in collaboration with companies developing new technologies. Instrumental development include: spatially distributed measurement of temperature and fluxes by DTS fiber optic (with industrial partner SILIXA), the development of a new absolute quantum gravimeter that can be used for field surveys (with industrial partner MuQuans), the development of fractured rock characterization methods for geothermal energy systems (with industrial partner Antea group). The H+ sites are particularly useful to demonstrate the interest of novel instruments and methodologies. A large scale demonstration will be organized in 2015 for the fiber optic monitoring of 3D subsurface temperature at the Poitiers site.

II.4.c Contractual arrangements resulting directly from the activities of the SOERE.

The list of research and industrial contracts resulting from the SOERE activity is given in annex 1.

II.5 Governance

II.5.a A reminder of the organization chart of the scientific and technical teams managing the SOERE and any changes or developments.

The organization chart of H+ is presented in figure 11.

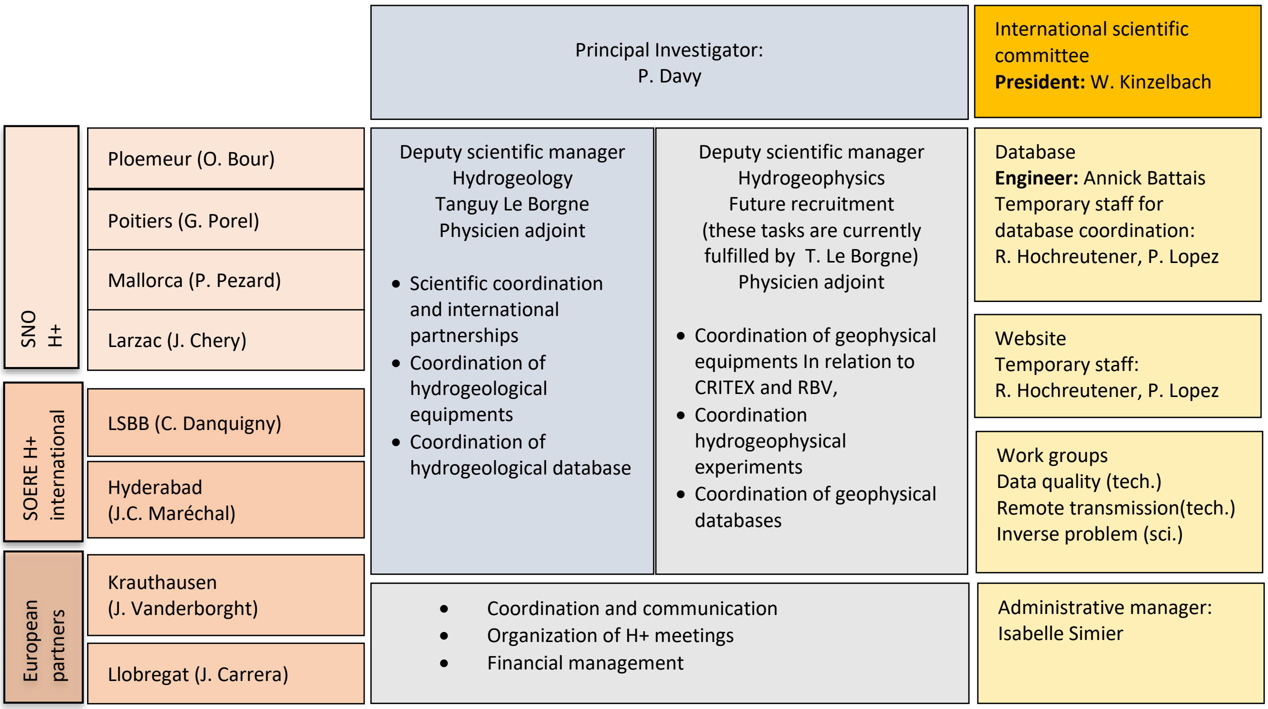


Figure 11: *organization chart of the H+ network*

II.5.b Current situation regarding the effective implementation and operation of committees (management board, scientific committee, users' committee).

The management committee, which includes the PI, the deputy scientific manager, and the site managers, coordinates the network and ensures that it reaches its objectives in terms of site operation, scientific progresses and data storage and dissemination.

Since 2008, the H+ observatory has an international scientific committee, whose role is to provide an independent evaluation of the management and results of the network and proposals for its future evolution. In the framework of the new SOERE period 2015-2020, we propose to organize a meeting of the scientific committee in 2015 to evaluate the results of the network and validate a prospective presenting new directions (evaluation of current sites, validation of new sites, national and European structuring).

II.5.c Current situation regarding internal management of the SOERE.

Decisions regarding budget, network management and prospective are taken during H+ meetings that take place on an average bi-annual frequency. The management committee encourages new instrumental developments on the sites to improve measurement and stimulate scientific activity. The management committee has also the responsibility to develop new scientific partnerships with the teams with a potential to bring scientific contributions for on the experimental or modelling sides. The international teams participate to the network but do not receive direct funding except for travel costs to meetings and joint experiments.

II.5.d Communication strategy

The H+ scientific activities are well represented in **international scientific conferences** including the EGU meeting in Vienna, the AGU meeting in San Francisco, the goldschimdt conference and the Geochemistry of Earth's Surface meeting. Synthetic presentations of site activities are also regularly done (ex. invited presentations Bour et al., GSA Metting in October 2013 and Bour et al., AGU Fall meeting in December 2014). The H+ website was entirely revised with a new design in 2013 for improving the visibility of the information.

The H+ teams are also strongly involved in **public engagement activities** to explain the scientific results (by means of videos and simple schemes) to the general public. In order to carry out these activities, the H+ scientists regular contact with civil servants, local authorities and journalists and take advantage of relevant public events to expose scientific results and to understand public requirements, such as The Feast of Science', which gives researchers the opportunity to have a direct interaction with the local public. In addition, field visits are organized for the general public as well as geo-environmental consultancies on the H+ field infrastructures to explain the principles and interests of the developed imaging techniques.

H+ is also contributing to outreach to the policy community. The challenge for policy makers is to take appropriate decisions for developing appropriate subsurface exploration strategies and monitoring networks, as well as to better understand the risks and opportunities associated with subsurface heterogeneity. Thus, a special emphasis is placed on the dissemination of the results of the project to policy agencies (e.g. regional councils and water and soil agencies). A direct link with the policy community is established through associate partner BRGM, which is the main referent for groundwater policy in France.

Training actions are regularly organized on the H+ sites. In particular, field courses take place each year for master students of the universities of Poitiers, Rennes, Montpellier and IFP school. In the field of professional training, a partnership was signed in February 2014 between IFP training, CNRS and the University of Poitiers for the use of the Poitiers site as an analogue reservoir for training on geophysics, geology and reservoir engineering in IFP training.

II.5.e Agreement of foreign partners relative to SOERE where all or part of the member observatories are located outside France and international waters.

BRGM and University of Montpellier have developed a long term partnership respectively with the National Geophysical Research Institute of India (NGRI) and with the Balearic governments for the development of the Hyderabad and Mallorca sites.

III Financial report

A financial synthesis is provided in table 1 and 2 for the period 2012-2014 over which the SOERE H+ received 305 500€. The table indicates an estimation of the global network budget including all co-funding (and PhD fellowships). The infrastructure funding of the Krauthausen and Llobregat sites are covered by the institutions of their respective countries. H+ funds meetings, scientific and instrumental exchanges with the associated partners. The CRITEX budget is indicated in a dedicated column. The budget was used for three main tasks:

- **consolidate the infrastructures of the H+ sites** in particular to host the new CRITEX instruments,
- **improve the efficiency of the H+ database** to integrate and disseminate data and renovate the web site to improve the visibility of the H+ network; a part time staff was hired for specifically for this purpose, which allowed considerable progresses in this domain,
- **develop exchanges with European partners**; in particular the H+ meeting organized in Julich in 2013 hosted most of the European scientists developing experimental sites in Europe, which lead to the submission of the ENIGMA European training proposal

2011-2014 Budget	Total (k€)
travel costs	298,5
consumables	431,5
expatriated permanent staff	270
temporary staff	858
equipment	772
TOTAL	2630
INSU SO	135
Universities, OSU, BRGM	840
Programs (Europe, ANR, INSU, ADEME, region)	669,5
CRITEX	680
SOERE	305,5

Table 2: Financial plan 2011-2014

The financial plan 2011-2014 was established from the detailed budgets and the contributions of the different partners: INSU, universities and the observatories who contribute to the investments in their observation services, the national and international scientific projects that use the H+ sites, and the CRITEX equipment program.

2011-2014 Budget	coordination and meetings	Database	Ploemeur (Rennes)	SEH (Poitiers)	Larzac (Montpellier)	Majorque (Montpellier)	LSBB (Avignon)	Hyderabad (BRGM)	Common equipments (CRITEX)	Total (k€)
travel costs	46	10	39	6	30	25	7,5	75	60	298,5
consumables	0	17	90	27	50	35	43,5	129	40	431,5
expatriated permanent staff			(1)	(1)	(1)	(1)	(1)	270		270
temporary staff (including PhD thesis)	15	48	195	48	99	102	105	96	150	858
Equipment	0	0	85	33	62	40	80	42	430	772
TOTAL	61	75	409	114	241	202	236	612	680	2630

Table 3: global budget 2011-2014 for the network coordination and the investments in French sites

(1) expatriated permanent staff is included only for BRGM.

IV SOERE project for 2015-2020

IV.1 Context

While the surface components of continental waters, such as streams, lakes and glaciers, are a very familiar part of our landscapes, **the vast majority of continental water resources resides and flows in the subsurface, and is thus broadly inaccessible to direct observation**. The growing societal needs for freshwater, energy and waste management imply that **subsurface environments are increasingly subject to multiple (possibly competing) uses of water resources** (e.g. groundwater abstraction, artificial recharge, contamination) **and energy** (e.g. geothermal energy, CO_2 sequestration, oil and gas extraction) while being **endangered by anthropogenic contamination**. In some parts of the world, subsurface hydrological systems are experiencing profound modifications, such as large-scale groundwater level depletion in response to increasing water consumption and massive CO_2 injection or fracking activities in enhanced geothermal systems and shale gas exploration, with debated effects on the environment. Intensification of agriculture, industrial activity, and urbanisation leads to a growing input of chemicals and pathogens to soils that subsequently endanger the quality and potential use of groundwater resources.

Society has responded to this challenge by demanding an increase in observation (e.g., EU water framework directive). These efforts have been successful in monitoring surface dynamics or documenting the state of aquatic systems, but have not been matched by an increase in our ability to quantify fluxes and processes in the subsurface. Despite progress made, uncertainties associated with subsurface flow and transport predictions still span orders of magnitude, and interpretation capabilities still remain often based on a mistaken view of homogeneous subsurface. **The degree of uncertainty associated with predictions and the need to fund costly exploration campaigns and to develop monitoring networks are particularly difficult to perceive by policy makers**. Hence, decisions regarding the development of new subsurface operations (e.g. groundwater pumping, artificial recharge, fracking operations, remediation of contaminated sites…) are often taken based on sparse data and simplified representations.

The critical need for *in situ* data on subsurface heterogeneities and processes: The last decade has seen great advances on stochastic hydrology, on 2D and 3D microscale imaging, and on geophysical methods. These advances have made it clear that (1) the subsurface is highly heterogeneous, (2) heterogeneity controls most flow, transport and biochemical processes. However, there still exists a wide gap between modelling hypotheses and field reality (e.g. common homogeneous or multi-gaussian representations of field parameters). Worse, **there are very few experimental datasets documenting *in situ* spatial patterns in hydraulic properties and processes at scales relevant to applications.** This deficiency is particularly critical for solving current scientific questions of strong societal and industrial relevance, including anomalous dispersion of dissolved compounds, impact of mixing on chemical reactivity, coupling of flow and microbiological activity, hydro-mechanical processes in porous and fractured media, fluxes and processes at boundaries between surface and subsurface compartments including unsaturated, river-groundwater and saline intrusion systems.

A unique opportunity for a breakthrough currently exists in Europe through the conjunction of:

- pioneering academic teams and emerging companies that develop innovative sensors and hydrogeophysical methods and inversion tools, including time-lapse and tomographic approaches to track temporal changes and assess fine-scale spatial distributions, in-situ experiments using novel tracers that go beyond passive observation, as well as innovative technologies and remote sensing techniques to derive spatially distributed information on temperature, water content and flow at multiple scales.

- **densely-monitored national field infrastructures** designed to host both long-term monitoring and experimental campaigns, building on cumulative knowledge through on-line databases,
- **world-leading experts in subsurface modelling** of coupled flow and transport processes in heterogeneous porous and fractured media, developing simulation platforms, upscaling theories, and stochastic models.

IV.2 SOERE H+ project 2015-2020

The objective of the SOERE H+ project 2015-2020 is **to consolidate the international dynamics created during the initial 2012-2014 SOERE H+ period**. The main European teams developing field experimental sites (see annex 3) have shown interest in joining a network organization, such as proposed in France in H+. A particularly critical aspect is data archiving and dissemination for these experimental sites that generate very diverse data, which are difficult to integrate routinely in a database. High quality hydrogeological sites have been developed over the last years, which large investments in different European countries, but often without well-established data storage and dissemination strategy. Hence, in this proposal H+ international will take a new dimension in consolidating its association with the partners managing the reference hydrogeological sites in Europe, with whom H+ has been developing close interactions since the H+ meeting in Julich in 2013. These exchanges have led to the submission of the ENIGMA European training network proposal (under evaluation) which will fund if successful 15 PhD thesis and scientific collaborations on the in situ investigation of subsurface flow and transport processes. The SOERE H+ 2015-2020 project will consolidate these emerging collaborations and provide the means to develop common experimental strategies and database infrastructures. It will also allow the development of new links between H+ and the TERENO critical zone network in Germany in which the associated sites of Julich and Leipzig are involved.

The teams involved in the 2015-2020 SOERE H+ international (annex 3) are: CNRS (H+), BRGM (H+), University of Montpellier (H+), University of Poitiers (H+), University of Avignon (H+), Helmholtz research center Julich (Germany), CSIC Barcelona (Spain), Helmholtz research center Leipzig (Germany), Tubingen University (Germany), Liege University (Belgium), Copenhagen University (Denmark), Lausanne University (Switzerland), Neuchatel University (Switzerland). These teams are the leading European groups for the in situ characterization of subsurface flow and transport processes (Annex 3). Note that Niklas Linde from Lausanne university does not manage an experimental site but brings world-leading expertise in hydrogeophysical imaging.

IV.3 Scientific and technical project

IV.3.1 Key challenges and main projects

The key challenges of the H+ international network are the following.

Strengthening innovation capacity: The H+ international network will strengthen the position of France and Europe at the forefront of environmental science and technology, through the development of innovative imaging techniques and the integration of these new data into predictive models. The original structuring of H+ international that combines innovative sensors, long term field infrastructures, and state-of-the-art modelling, will provide the scope for new opportunities for technological and scientific breakthroughs in this domain. The close interactions developed between 12 European research institutions and 1 national geological survey will create ideal conditions for efficient science and technology transfer.

***In situ* experimental data to answer critical modelling questions:** The joint development of field and modelling approaches will ensure that the produced data will be directly relevant for developing predictive models. The latter can provide answers to key questions related to environmental impacts, resource assessment or industrial design and planning. For this purpose, a central concern is that the models are well constrained by relevant field data. Hence, H+ will contribute to reduce the large uncertainty of modelling hypothesis on subsurface heterogeneity and processes. Furthermore, one important goal of H+ will be to transfer the inversion methods developed in academic research to the companies, including joint inversion techniques that exploit the complementary nature of different data types, stochastic inversion approaches that provide formal estimates of uncertainty, and multiple point statistics inversion approaches that rely on realistic geological representations. This will be done in particular through the development of user-friendly open-source inversion codes that will be disseminated through the H+ database together with the new datasets. This open code policy, which follows recent initiatives in the oil & gas industry (e.g. seiscope2 project http://seiscope2.osug.fr/?lang=en), will promote scientific progresses through enhanced exchanges of ideas and algorithms, as well as technology transfer to the industry and consulting companies.

Groundwater systems under changing conditions. Groundwater is a critical and strategic resource for both humans and ecosystems that is experiencing major changes due to long or short-term surface perturbations. Groundwater systems are often ignored from environmental change scenarios because of their complexity, and of their long response time. Currently, when predicting the impact of climate change on water resources, uncertainties arising from hydrological models are outweighing by far uncertainties from global circulation models and emission scenario (Wada et al., 2013). A key challenge for H+ is to decipher how groundwater circulation is affected by surface perturbations. H+ will be involved in a few natural and/or anthropic experiences under controlled conditions: i) new pumping to be started in a fractured aquifer (Guidel), ii) removal of 2 dams (40-m total height) on the Selune river, (iii) drilling of a new tunnel in the underground LSBB facilities. The monitoring of these “experiments” with a wide range of geophysical methods, geodetic (deformation), thermic (optic fibers) and geochemical methods (anthropic gases, radon) is a unique opportunity to characterize how water paths and exchanges are affected by short or long-term environmental changes.

Structuring of hydrogeological observatories at European level: H+ aims at contributing to structure hydrogeological research at European level. The main European teams developing field experimental sites have shown interest in joining a network organization, such as proposed in France in H+. A critical issue, which has been pointed out by all European partners of the ENIGMA teams, is data archiving and dissemination of hydrogeophysical methods. Up to now, there is no database capable of collating data from the different hydrogeophysical methods. In addition to developing scientific exchanges with European partners, the ambition of H+ for the next years is to coordinate the development of a reference database for hydrogeophysics.

Structuring of Critical Zone observatories at national and European level: The hydrogeological community is quite small and addresses only part of the scientific issues related to the Critical Zones. In France, H+ is associated to the RBV SOERE to coordinate the CRITEX equipment project, which was awarded in 2011 by an international committee. CRITEX is an instrumented shared analytical platform constituted of innovative sensors for the exploration of the Critical Zone. H+ is also involved in the project of Critical Zone Observatory Infrastructure, which is leaded by the

CNRS INSU and under study by the national alliance for environment (AllEnvi). The French Critical Zone infrastructure is intended to be part of a European Research Infrastructure.

IV.3.2 Main innovations

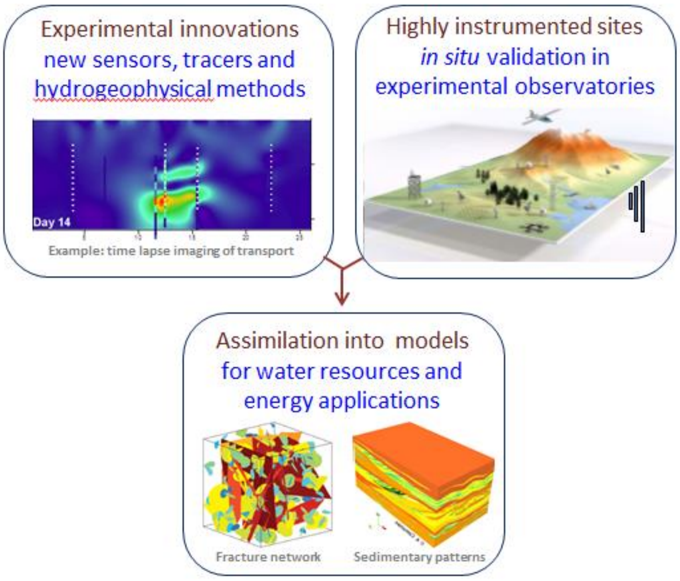
The SOERE H+ 2015-2020 project is based on four types of innovations:

The development of cutting-edge and prospective imaging technologies including full-waveform GPR inversion, tracer tomography, biogeophysical methods for reactive transport assessment, distributed flow measurements with fiber-optics, multiscale thermal imaging with drone and fiber optics, P and S wave monitoring of hydraulic properties and absolute quantum gravimeter surveys.

The co-location of data acquisitions with different experimental methods at highly instrumented experimental sites in order to provide *in situ* benchmarks for a range of hydrogeological conditions and for all relevant interfaces between the subsurface hydrosystem and its neighboring compartments. For this purpose, the network relies on the most advanced European infrastructures in hydrogeological experimentation (see Figure 12)

The integration of the produced datasets into predictive simulation tools aiming at providing predictions over spatial scales relevant to the management of water resources, assist in the design of contaminant remediation methods or enhance the understanding of complex thermo-mechanical processes. This will be accomplished by taking advantage of the strong consortium expertise in developing joint inversion, stochastic inversion, time-lapse inverse modelling, and upscaling methods.

The establishment of an international database for storing and disseminating results, open source codes and experimental datasets combining data of different nature for imaging subsurface hydrological systems. The basic tools required for this have already been developed within the databases of the national long term observatories involved in the network (see e.g. http://hplus.ore.fr/en/database or http://teodoor.icg.kfa-juelich.de/overview-en). Thus, the main tasks will be to develop exchanges between the pool of engineers that currently operate these databases and the researchers that develop new instruments and methods in order to establish common protocols for data storage and dissemination.



Field infrastructures	Unique attributes
Krauthausen site (FZJ) Hermalle site (ULG) Lauswiesen site (TU)	Hydrogeophysical test sites with high borehole density and large hydrogeophysical databases
H+ Ploemeur (CNRS) http://hplus.ore.fr/en/ploemeur H+ Hyderabad (BRGM) http://hplus.ore.fr/en/india	Fractured rock observatories for long term monitoring and in situ experiments
TERENO- Selke (UFZ) River Selke website HOBE obs. (UCPH) http://www.hobecenter.dk/ Emme (UNINE)	Nested observatories in highly instrumented catchments
Llobregat-Argentona (CSIC)	Saline intrusion monitoring and experimentation
H+ Larzac (UM) http://hplus.ore.fr/en/larzac H+ Low Noise Lab. (CNRS) http://hplus.ore.fr/en/lsbb	Unsaturated zone observatories for long term monitoring and in situ experiments

***Figure 12: Left**: Illustration of approach that will be followed by H+ in the next years, **Right**: The most advanced European*

infrastructures for in situ hydrogeological investigations will form the basis of collaborative field campaigns for testing and comparing imaging methods in a range of environments.

IV.3.3 Research methodology

The scientific methodology that will be developed in SOERE H+ 2015-2020 is based on five complementary research directions. The first three research line focus on the key aspects of subsurface hydro-system imaging through the development of novel techniques and methods for spatially distributed sensing of flow properties, for the hydrogeophysical imaging of transport and biochemical reaction processes and the quantification of fluxes at subsurface boundaries. The fourth scientific topic aims at developing overarching methodological approaches including data assimilation, joint inversion strategies and uncertainty assessment. The knowledge and models obtained in the four first topics will be integrated in the fifth research line to investigate the impact of subsurface flow and processes on larger scale hydrological systems (in relation with other scientific communities).

A central objective of the research program is to ensure an efficient integration of different imaging and modelling approaches. This will be done through the organization of joint experiments on the experimental infrastructures, where the different methods will be tested and synergies will be developed between the individual projects. The five main scientific topics that will be addressed in the next five years are:

1. **Characterizing the spatial distribution of flow, storage and hydraulic properties in the subsurface:** This research topic will be based on promising techniques that have recently emerged, including prototype instruments, novel inversion methods and the coupling of multiple datasets. The objectives are to
   - develop improved hydrogeophysical surveying techniques including full-waveform ground-penetrating radar (GPR), spectral induced polarization (SIP), time-lapse electrical resistivity tomography (ERT), airborne TDEM coupled with ground geophysics, ground-surface deformation monitoring, seismic noise correlation and Vp/Vs seismic tomography methods (figure 13)
   - design distributed flow-sensing methods based on heated DTS fiber-optic sensing
   - perform a large scale inter-comparison exercise on different reference field sites of the H+ network to assess the added value obtained from the different techniques

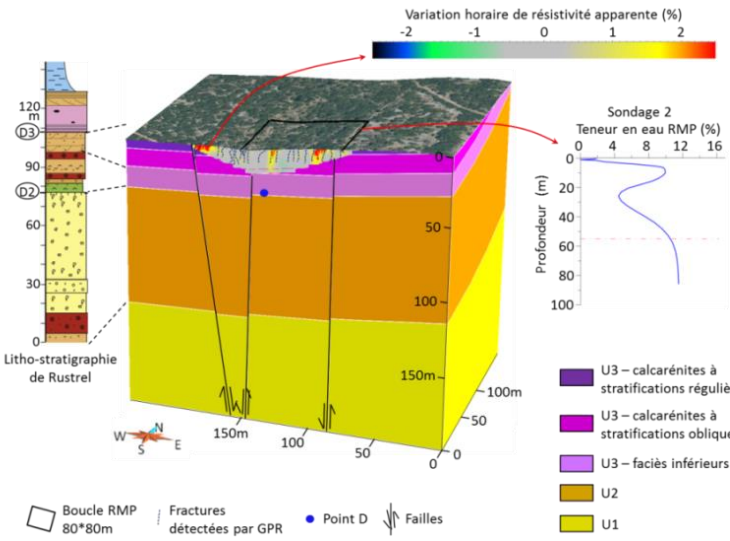


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Figure 13: *Illustration of multiple geophysical methods used to investigate the spatial heterogeneity and temporal dynamic of flow in the unsaturated zone overlying the LSBB tunnel: local scale monitoring of*

localized recharge with time lapse ERT, large scale characterization of water content with RMP, permeable fractures identified with GPR imaging (Carrière, 2014)

2. **Dispersion, mixing and reaction processes in fractured and porous aquifers:** the in situ characterization of these fundamental processes is extremely challenging because the classical interpretation of tracer tests relies on the advection dispersion equation that equate mixing and spreading. Field methods to distinguish these two processes (e.g., sampling without mixing) are yet to be developed. To overcome this problem, methods that fully exploit GPR signals and broad-band polarization spectra and that use heat and other tracers will be developed. Field reactive tracer tests will be monitored with the new chemical lab developed in the CRITEX project (figure 14). The specific objectives are to:
    - develop an upscaling framework for quantifying the impact of incomplete mixing and chemical reactions on geophysical signals
    - perform field tracer tests combining different tracers (conservative, reactive, heat) and geophysical monitoring (GPR, SIP, ERT)
    - in situ monitoring of dissolved gases for passive or reactive tracing (mass spectrometry)
    - fully characterize the microbial communities' structure and activity in relation to groundwater velocity and nutrients supply through coupled geochemical tracing and genomic sequencing.

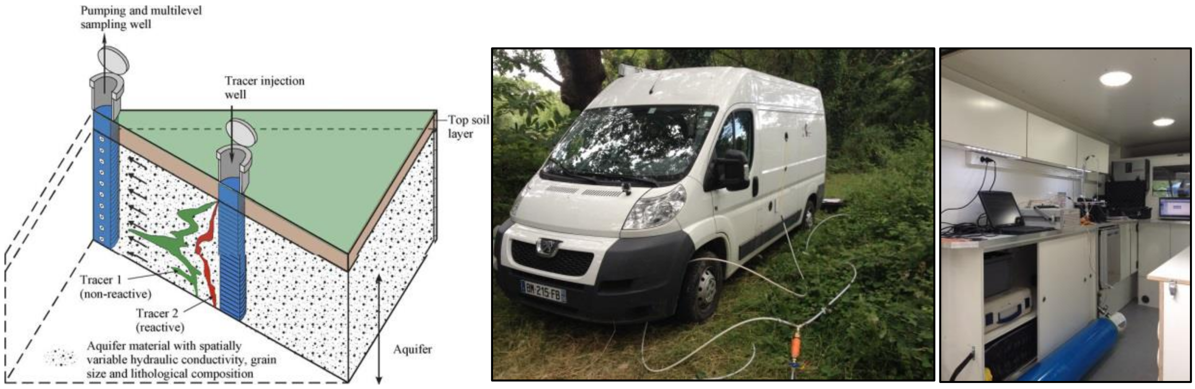

Figure 14: *Left: illustration of the reactive tracer test principle, right: mobile chemical laboratory developed in the CRITEX project to monitor continuously biochemical properties during reactive tracer tests.*

3. **Quantification of fluxes and reactive transport processes at the boundaries of subsurface hydrological systems** (soil - groundwater, surface water - groundwater), which represent critical zones driving subsurface flows and focusing a large part of the reactivity of hydrological systems. Research projects on this topic will combine absolute gravimeters prototype development, multiscale thermal imaging, and advanced tracing, imaging, and modelling techniques (figure 15). The specific objectives are to:
    - Test the potential of thermal imaging of spatio-temporal changes in surface water - groundwater exchanges (DTS fiber-optic, drones, satellites)
    - Develop and validate absolute quantum gravity instruments for assessing water content at 10 to 100 m scales
    - Investigate the interest of hydro-magnetic coupling to quantify large scale water content variations (LSBB tunnel)
    - Apply new imaging and inversion methods for characterizing spatial patterns, fluxes and reactive transport processes in river-alluvial and saline intrusion systems

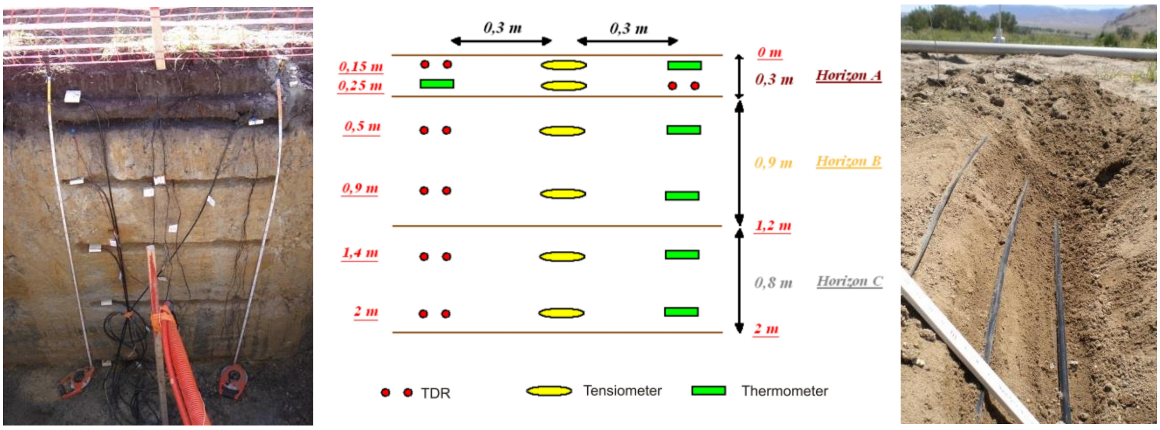

Figure 15: Unsaturated zone monitoring on the Ploemeur site with TDR, tensiometers, temperature sensors. This monitoring set up will be complemented by fiber optics installed at different depths to quantify the spatial distribution of temperature and fluxes (photo on the right from Amherst, University of Massachusetts).

4. **Joint inversion methods, upscaling, data assimilation and uncertainty assessment.** This scientific topic aims at i) developing a common reflection about the data inversion strategies, ii) treating comprehensively the theoretical issues related to averaging effects on the scale of resolution of imaging methods, iii) evaluating the value of the new datasets for constraining predictive models that aim at understanding undergoing processes and making predictions about the future evolution of these processes and their associated uncertainty.
   - Develop novel and efficient methods for the joint inversion of multiple datasets with different characteristic spatial resolution (e.g. hydraulic, geophysics, artificial and environmental tracers, temperature, ERT data…)
   - Integrate the new datasets into predictive models, estimate the associated uncertainties and derive conclusions on the validity of current representations of flow and transport processes in the subsurface and their possible revision in the light of new field data

5. **Large-scale hydrological impacts of sub-surface flow and processes**: This integrative line of research will investigate the role of the sub-surface flow component at the large scale, in relation with the hydrological community, the ecological community and the social science community. Groundwater fluxes in water and chemical elements are expected to play a key role in the long term evolution of eco-hydrological systems and in the global cycle of chemical elements. However, this contribution is often ignored from the "Critical zone". One of the main difficulties is linked on the complexity of hydrogeological systems and their long response time. Together with the new collaboration with the catchment networks RBV, the knowledge of subsurface fluxes and processes acquired on the H+ site and the capacity to monitor the impact of large scale hydrological perturbations (e.g. start of a new abstraction well on the Ploemeur site, large scale over-abstraction on the Hyderabad site see figure 16, new gallery on LSBB) offer a unique opportunity to link subsurface processes to the other compartments of the environment. This line of research will investigate:
   - the role of the sub-surface flows in catchments geochemical fluxes and reactivity (Residence times distributions, groundwater-surface interactions, importance of streambed and hyporheic zone reactivity,…)
   - the impact of large-scale groundwater abstractions in arid (Hyderabad site) and temperate (Ploemeur site) climates and the consequences on ecosystemic environment, wetlands functioning, contaminants transport, social impacts and adaptations of practices…

- the hydro-mechanical response of an aquifer to the excavation of a tunnel (Monitor project on the LSBB site) from a joint hydrogeological, geophysical and deformation monitoring using a unique set of measurements (pressure, fluxes, water content, seismic, electrical, electromagnetic, gravimetric, tiltmeter and acoustic sensors)

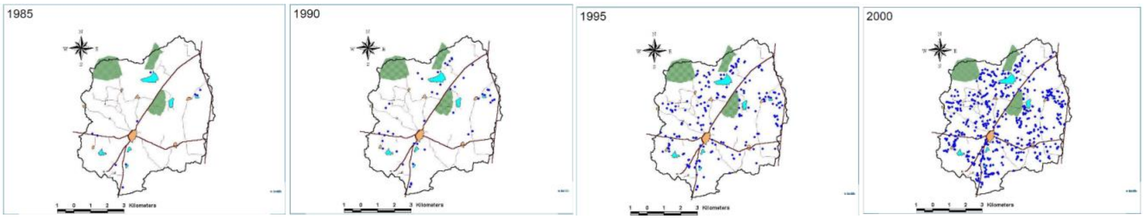

Figure 16: illustration of the increase of the number of boreholes on the Maheshwaram catchment (Hyderabad). In 15 years, the number of boreholes increased from 2 to 929 causing a major drop of water level.

IV.4 Parameters and data

The current and future parameters and data measured on the H+ sites for the French and international partners are detailed in annex 3.

IV.5 Information systems

Storing and disseminating hydrogeophysical datasets is a significant issue since they involve data of different nature, including hydrological data (e.g. hydraulic heads, pumping rates, river discharge), chemical data (e.g. concentrations of natural and introduced compounds and derived quantities such as groundwater age), geophysical data, categorical data (e.g. geological logs description), spatially distributed data (e.g. fiber optic distributed sensing of temperature, infrared camera, satellite images,...) and a variety of metadata (e.g. experimental time schedule, location of instruments, analytical techniques). Most published datasets are not easily accessible which limits the impact and added value for the scientific community of often costly experimental campaigns. The H+ network will gather teams developing novel imaging instruments and methods as well as groups coordinating long-term experimental field sites, hence providing **a unique opportunity to build up an international database for storing and disseminating data and metadata in subsurface imagery.** The database will be an essential tool for knowledge dissemination and scientific exchanges.

The establishment of an international database on subsurface experimental imaging for exploring and modelling subsurface structures, fluxes and processes is a key objective of the next five years. Large scale experimental efforts are very valuable to the scientific community as in-situ observations are typical more difficult to develop and less common than numerical models or lab experiments. Based on its strong field experimental capacities and group of high level young scientists, H+ international will provide critically lacking data to the scientific community, including in-situ assessment of subsurface flow velocities and hydraulic properties, geophysical monitoring of transport and reaction properties, and multi-scale characterization of surface-groundwater fluxes. H+ international will answer to the current lack of international database for experimental subsurface imaging data of multiple natures. Hence, the new datasets will establish reference benchmarks for validating prototype techniques, thereby providing stakeholders with trustworthy, fully validated methods.

H+ will develop a partnership with Neuchatel university, who is associate partner in this proposal, to link the H+ and the wwhypda web data base (http://wwhypda.org). While the H+ database provides monitoring and experimental data, wwhypda archives interpreted parameters (e.g.

permeability) derived from experimental data. Hence the two databases are very complementary. The objective will be to link these two platforms to provide both raw data and interpreted parameters. The latter can be used to generate analog geological simulations or as prior in inversion or for uncertainty analysis.

IV.6 Openness towards other scientific communities

A constitutive goal of the H+ observatory is to enhance the modelling of subsurface heterogeneity, fluxes and biochemical reactions. Making the link with the modelling community is thus a continued concern of the observatory.

Connections between the community of scientists working on groundwater (and in particular the reactive transport modelers) and the community of scientists interested by mass and energy budgets at the catchment and watershed scale has been established through the CRITEX program. These interactions between RBV and H+ are expected to grow in the future and be extended at European level with the associated partners of the current proposal. Furthermore, the development of collaboration with new sites that investigate flow and processes at the interface between the subsurface compartments (see annex 3) will foster the links of H+ scientists with the hydrological and ecological communities.

Collaborations also exist on eco-hydrology between H+ and the "Zone Atelier" network. In particular, the fiber optic tools developed in the H+ Ploemeur site are currently being tested on the "Zone Atelier Armorique" to quantify groundwater inputs into rivers. These collaborations will grow in the future in the framework of the eLTER European project ("advancing the European network of Long-Term Ecosystem Research Sites and socio-ecological platforms to provide highest quality services for multiple use enabling European Scale investigation of major ecosystems and socio-ecological systems, and targeted to support knowledge based decision making at various levels" see section IV.7).

In the future, the H+ observatory intends to develop partnership with social and human sciences about groundwater vulnerability and policy. Contacts have been established for instance with the LASCAUX project (law, food, land: http://lascaux.hypotheses.org/) to develop new interdisciplinary research on water resource management.

IV.7 Integration in national, European and international infrastructures

At national level. H+ is one of the French Networks monitoring the Critical zone of the Earth. It is very closely associated to the RBV SOERE. Both have designed the Equipex CRITEX, which was awarded in 2011 by an international committee. Critex is an instrumented shared analytical platform constituted of innovative sensors for the exploration of the Critical Zone. Furthermore, a project is presently under study by Allenvi on the design of a national research infrastructure (RI), overarching all the national observatories funded by the different research institutions for the study of the Earth's Critical Zone.

At European level, RBV and H+ have successfully integrated a European project called eLTER awarded in response to the H2020 call on European Infrastructures. eLTER aims at "advancing the European network of Long-Term Ecosystem Research Sites and socio-ecological platforms to provide highest quality services for multiple use enabling European Scale investigation of major ecosystems and socio-ecological systems, and targeted to support knowledge based decision making at various levels" As stated in the proposal « eLTER will combine the **European LTER-Network** and the most important **Critical Zone** projects and initiatives (CRITEX in France, the European project SoilTrEC/FP7 and the German TERENO network). This is well reflected in the composition of the consortium and the division of tasks. The **instrumentation** of sites ranges from extensive to highly instrumented master sites. Detailed site metadata are available on-line (DEIMS) ». Jérôme Gaillardet, coordinator of RBV, is leading the task NA 2.1 in eLTER that is "the analysis of the state of art of ecosystem infrastructures including critical zone observatories and LTSER platforms". Several sites of RBV and H+ have been included into the eLTER project in order to provide virtual access (BVET, Ploemeur, OHGE, Agrhys, Omere, Orgeval amongst the 162 European sites). The eLTER project is expected to foster CZ and LTER community to exchange and support interdisciplinary research. We think that there is a great opportunity for RBV and H+ to join the LTER-CZ ESFRI project that have been pushed forward by the German, UK and Austrian colleagues in 2015. This will need that France will be not only an "observer" but a true member of the consortium.

Furthermore, the European training network proposal ENIGMA coordinated by H+ (currently under evaluation) represents an important step for the structuration of experimental research in hydrogeology in Europe. If successful it will fund 15 PhD students that will work on the sites with a strong cooperation among partners. The SOERE H+ 2015-2020 will consolidate this international dynamics on the long term by providing means of coordination and database structures. The ultimate goal is to construct a long term European infrastructure on the basis of the links established in this network.

At international level, H+ and RBV (and the program CRITEX) have the possibility to be plenty engaged in the organization of an international critical zone network. Several members of RBV and H+ have been invited to the 3 international meetings organized in Delaware (in 2011), in Beijing (may 2014) and San Francisco aiming at bringing together a small group of funders and high-level international science leaders from China, France, Germany, United Kingdom and The United States. The goal of these meeting is to « advance in the implementation of a coordinated, jointly funded, international program of research on Critical Zone science that addresses pressing interdisciplinary scientific questions that can inform human decisions". In the next 5 years, H+ and RBV scientists would like to conserve a key role in the organization of a global network and the associated possibility of funding (Belmont Forum, Future Earth organization).

IV.8 Management structure

The management structure will be similar to that of the current SOERE (figure 11), integrating the new associated European partners: Helmholtz research center Leipzig (Germany), Tubingen University (Germany), Liege University (Belgium), Copenhagen University (Denmark), Lausanne University (Switzerland), Neuchatel University (Switzerland). The coordination team will be reinforced with one temporary staff to manage the increase in associated partners and to support the development of the hydrogeophysical database. A new committee will be created to drive the development of the international hydrogeophysical database.

V Budget for the SOERE 2015-2020

The estimated budget of the H+ international network is given in table 4 and detailed in table 5. As for the 2011-2014, the SOERE budget will not fund directly the experimental infrastructures of the associated European partners that will be supported by their own institutions and projects. It will fund international exchanges and database development. This budget includes the different on-going national and European funding, as well as the European training network proposal ENIGMA currently under evaluation. The estimation of the number of permanent and temporary staff (FTE) involved is given in annex 4. The French sites, whose activity is directly funded by H+, will involve a total of 18 FTE permanent staff, 2 temporary staff for technical support on field instrumentation, coordination and databases, and about 12 PhD students over the considered period. If successful the ENIGMA proposal will fund 15 PhD students that will work on the experimental sites in close collaboration with the different European partners.

The estimated budget for the SOERE H+ 2015-2020 is 180 k€/year. It will be dedicated to the follow main actions:

- **Site monitoring and instrumentation for the French sites**, which is the basic task of the H+ observatory, requires regular on-site visits and the maintenance of instruments. The objective is that the hydrological, geophysical and geochemical monitoring is ensured on the long-term without data loss.
- **In situ experimentation, innovative sensors and methods development**, to obtain representative measurements of flow and transport processes in the subsurface, in particular taking full advantage of the new instruments developed in the CRITEX project.
- **Network coordination**: the organization of annual meetings with the main European partners developing hydrogeological sites in Europe contributes greatly to the visibility of field experimental science in hydrogeology. It also allows positioning the H+ network in the construction of European infrastructures within the H2020 program.
- **The development of the H+ database as international database in experimental hydrogeology and hydrogeophysics** is a great challenge that will be addressed in the 2015-2020 in coordination with the associated European partners. A full time database manager will be hired for this period to coordinate this effort. He/she will ensure an efficient link between database developers, data providers and data users to obtain a user friendly database, adapted to the diversity of relevant data and frequently updated.

2015-2020 Budget	Total (k€)
travel costs	1235
consumables	1567
expatriated permanent staff	750
temporary staff	4133
equipment	2413
TOTAL	10098
INSU SO	225
Universities, OSU, BRGM	1400
Programs (UE, ANR, INSU, ADEME, region)	2743
ENIGMA	4830
SOERE	900

Table 4: Funding plan for the period 2015-2020

2015-2020 Budget (k€)	Coordination and meetings	Database	Ploemeur (Rennes)	SEH (Poitiers)	Larzac (Montpellier)	Majorque (Montpellier)	LSBB (Avignon)	Hyderabad (BRGM)	Common equipment (CRITEX)	ENIGMA (under evaluation)	Total
travel costs	125	0	50	10	40	38	13	150	59	750	1235
consumables	0	40	110	35	95	50	220	150	37	830	1567
expatriated permanent staff			(1)	(1)	(1)	(1)	(1)	500			750
temporary staff (including PhD thesis)	80	125	250	180	150	150	320	225	153	2500	4133
Equipment	0	0	100	60	70	50	900	100	383	750	2413
TOTAL	205	165	510	285	355	288	1453	1125	632	4830	10098

Table 5: Estimated global budget for 2015-2020

(1) Cost of expatriated permanent staff is included only for BRGM

VI Experts suggested

- **Suggested French experts:**
  - **Nicolas Florsch**, Sysiphe, Université Paris Jussieu, expert in hydrogeophysics, email : nicolas.florsch@upmc.fr, website : http://www.sisyphe.jussieu.fr/~florsch/
  - **Michel Quintard**, IMFT, CNRS, expert in hydrogeology, email : Michel.Quintard@imft.fr

- **Suggested International experts:**
  - **Alberto Guadagnini,** Politecnico de Milano, expert in hydrogeology, email: alberto.guadagnini@polimi.it
  - **Paul A. Ty Ferre**, University of Arizona, expert in hydrology, hydrogeophysics, field instrumentation and modelling, involved in the US critical zone observatories, email: ty@hwr.arizona.edu, website : https://sites.google.com/site/tyferre/

Annex 1 List of teams and projects using the H+ data

Ploemeur site

Partners	Research projects	Period
UMR 6118 Géosciences Rennes	PhD fellowships, European projects (ITN IMVUL, Interreg Climawat, ERC ReactiveFronts), ANR Hydrogeodesy, ANR Mohini, regional projects (DATEAU..), ANR Stock en Socle, Equipex CRITEX	2002-present
Université Pierre et Marie Curie	Geophysical imaging and S wave tomography	2007-2015
University of Montpellier	tiltmeter monitoring of ground surface deformation	2006-present
Virginia Tech (USA)	Hydro-geodesy and hydromechanical modelisation	2010-present
Bochum University (Allemagne)	Flow velocity measurements	2010-present
Université de Lausanne (Suisse)	Radar imaging of tracer motion in fractures (PhD thesis C. Dorn, Lausanne, Alexis Chakas 2014-2017)	2010-present
East-Anglia University (UK)	Monitoring of heat tracer tests and flux measurements with DTS fiber optics (PhD thesis T. Read)	2011-present
Oregon State University (USA)	Instrumental development for the spatially distributed of flow in boreholes with fiber optics	2013-present
MIT (Boston USA)	Characterization of anomalous transport in fractures (PhD thesis P. Kang, MIT)	2011-present
CSIC Barcelona (Espagne)	Characterization of anomalous transport in fractures	2011-present
Université de Liège (Belgique)	Measurement of in situ fracture flow velocities (PhD thesis P. Janin)	2011-present
Université de Nantes	EquipEx RESIF	2009-present
University of California	Use of groundwater age data in models	2013-present
California State University (USA)	Characterization of fractured media from sinusoidal pumping tests	2014-present

Poitiers site

Partners	Research projects	Period
IC2MP UMR 7285	SO H+, CPER EAUX-SOLS	2002-present
LHyGeS UMR 7517	ANR Resain	2011-present
LCABIE UMR 5254	PhD thesis J. Bassil / Sélénium	2011-present
LIAS EA 6315	Modelling pumping and tracer tests	2013-present
IFP School	Initial training	2008-present
IFP Training	Professional training	2009-present

Mallorca site

Partners	Research projects	Period
Géosciences Montpellier UMR 5243	PhD theses	2003-2013
UPPA Pau	High resolution characterization of complex reservoirs	2006-present
Université des Baléares (Espagne)	Temporal evolution of the saline intrusion	2012-present
HSM Montpellier	Role of bacteria at the freshwater/saline water interface in carbonate rocks	2012-present
BRGM Orléans	Groundwater geochemistry	2014-present

Larzac site

Partners	Research projects	Period
UMR 5243 Géosciences Montpellier	SO H+, SO RENAG, PhD thesis, RESIF	2009 - present
Université Pierre et Marie Curie	Hydrogeophysics (ANR HydroKarst G²)	2009-2013
UMR Hydrosciences Montpellier	Tracer tests, modelling (ANR / Stages	2009-present

	Master), Hydrochemistry	
Université Avignon	Hydrogeophysics (ANR HydroKarst G²)	2009-present
UMR Géosciences Rennes	Hydrochemistry , residence times (groundwater age) ANR HydroKarst G²	2009-2013

Hyderabad site

Partners	Research projects	Period
BRGM	CEFIRES/ European projects 7PCRD (SARASWATI, SAPH PANI,) ANR MOHINI, Asia Pro ECO Sustwater	1999 - present
NGRI (National Geophysical Institute)	European projects 7PCRD (SARASWATI, SAPH PANI,) ANR MOHINI, Asia Pro ECO Sustwater	1999 - present
Charles University of Prague	Asia Pro ECO Sustwater	2005-2008
International Water Management Institute	Asia Pro ECO Sustwater	2005-2008
Université Paris VI	IFCPAR project	1999-2003
Ecole des mines de Paris	IFCPAR project	1999-2003
Université de Neuchâtel	Stages Master	2002-present
UMR 6118 Géosciences Rennes	Transport in fractured media, jointly supervised PhD thesis	2010 - present
UMR 5563 GET Toulouse	ANR Shiva, hydrological modelling	2009-2014
SIRS SME	ANR Shiva, Remote sensing	2009-2014
Institut Français de Pondicherry	ANR Shiva, Remote sensing	2009-2014

LSBB

Partners	Research projects	Period
UMR EMMAH	Hydrogeophysical imaging and monitoring of unsaturated flow	2011- present
Geosciences Montpellier	Hydro-mechanical deformation monitoring with tiltmeters	2011- present
Paris VI University (METIS)	Vp/Vs seismic wave imaging	2013-present
Oxford University	Large scale hydro-magnetic coupling	2013-present
University of Chambery	Large scale hydro-magnetic coupling	2013-present
University of Pau / TOTAL Laboratoire des fluides complexes et de leurs reservoirs IPRA	Monitor project: Multi-sensor monitoring of a tunnel excavation	2014-present
University of Grenoble ISTERRE	Monitor project: Multi-sensor monitoring of a tunnel excavation	2014-present
Paris Sud University GEOPS, UMR8148	Monitor project: Multi-sensor monitoring of a tunnel excavation	2014-present
University of Nice GEOAZUR	Monitor project: Multi-sensor monitoring of a tunnel excavation	2014-present

Annex 2: H+ publications 2011-2015

2015

Alazard, M., Boisson, A., Pettenati M., Picot-Colbeaux, G., Perrin, J., Dewandel, B., Maréchal J.C., Ahmed, S., Kloppmann, W. Flow structure in crystalline aquifer investigated through borehole logging: Implications for Managed aquifer recharge. Submitted to Hydrogeology journal

Boisson, A., Alazard, M., Picot-Colbeaux, G., Pettenati, M., Perrin, J., Chandra, S., Dewandel, B., Ahmed, S., Maréchal, J.C and Kloppmann, W. Percolation tanks as Managed Aquifer Recharge structures in crystalline aquifers – An example from the Maheshwaram watershed. SaphPani Handbook – Chapter 7 – Submitted

Boisson A., N. Guihéneuf, J. Perrin, O. Bour, B. Dewandel, A. Dausse, M. Viossanges, S. Ahmed and JC. Maréchal, Estimation of the vertical evolution of hydrodynamic parameters in weathered and fractured crystalline rock aquifers: insights from a detailed study on an instrumented site, Hydrogeology Journal, in review

Boisson A., Perrin J., Dausse A., Riotte J., Ahmed S. (2015) Paddy field hydrodynamics revealed by a tracer test, South India, Submitted to Jour. Hydrology.

Boisson, A., Marechal, J.C., Perrin, J., Dewandel, B. and Ahmed, S. (2015) Impact of vertical geological structure and water table deplition on Indian crystalline aquifers, Engineering Geology for Society and Territory, Vol 3:583-587.Boisson, A.,

Guiheneuf, N., J. Perrin, O. Bour, B. Dewandel, A. Dausse, M. Viossanges, S. Ahmed and J.C. Marechal (2015), Determining the vertical evolution of hydrodynamic parameters in weathered and fractured South Indian crystalline-rock aquifers: insights from a study on an instrumented site, Hydrogeology Journal, DOI 10.1007/s10040-014-1226-x.

Deville S., C. Champollion, J. Chery, E. Doerflinger, N. Le Moigne, R. Bayer, P. Vernant (2014): Estimating epikarst water storage by time-lapse surface to depth gravity measurements, in review

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Marçais, J., J.-R. de Dreuzy, T.R. Ginn, P. Rousseau-Gueutin, S. Leray, Inferring transit time distributions from atmospheric tracer data: Assessment of the predictive capacities of Lumped Parameter Models on a 3D crystalline aquifer model Journal of Hydrology, Volume 525, June 2015, Pages 619-631

Meauxsoone A., C. Champollion, J. Chery, H. Jourde, S. Deville (2014) : cave flux and gravity for hydrogeological modelling in dolomite karst, soumis à Vadose Zone Journal, in review

Pasquet, S., Bodet, L., Longuevergne, L., Dhemaied, A., Camerlynck, C., Rejiba, F., Guérin, R. (2014) : 2D characterization of near-surface Vp/Vs : surface-wave dispersion inversion versus refraction tomography, submitted to Near Surface Geophysics

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Nicolas Guiheneuf, « Caractérisation des propriétés d'écoulement et de transport des aquifères de socle sous climat tropical ». Financement BRGM, thèse soutenue à l'Université Rennes 1 au 08/07/2014. Après sa thèse, N Guihéneuf a obtenu un poste d'ATER à l'Université Rennes 1.

Joseph Bassil, « Origine et processus de libération du sélénium dans l'aquifère carbonaté du Site Expérimental Hydrogéologique de Poitiers ». Thèse de Doctorat en co-tutelle Université de Poitiers – Université Libanaise, soutenue à L'Université de Poitiers le 18/12/2014.

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Maria Klepikova « Utilisation de la température pour caractériser les propriétés d'écoulement et de transport des milieux hétérogènes ». Financement CEE, projet IMVUL. Thèse soutenue à l'Université Rennes 1 le 16/05/2013.

Sarah Leray « Caractérisation des aquifères de socle cristallin et de leur ressource en eau - Apport des données d'âge de l'eau ». Thèse soutenue à l'Université Rennes 1 le 12 décembre 2012.

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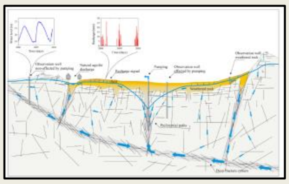
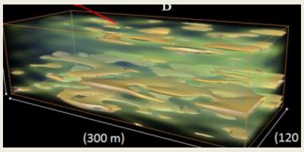
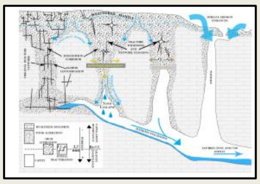
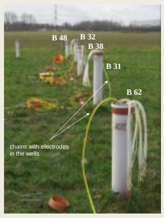
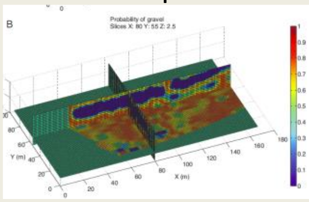
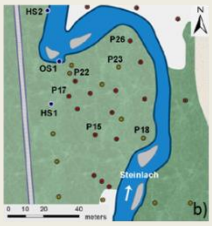
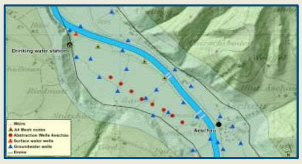
Annex 3: synthesis of scientific objectives, parameters and data on the H+ international sites

Field site **Scientists in charge**	**Ploemeur (France)** Olivier Bour (Rennes)	**S.E.H. Poitiers (France)** Gilles Porel (Poitiers)	**Campos, Mallorca (España)** Philippe Pezard (Montpellier)	**Durzon, Larzac (France)** Cédric Champolion (Montpellier)
MAIN SCIENTIFIC TOPICS	**MONITORING OF A PUMPED FRACTURED AQUIFER**	**ADAPTED WELL ARRANGEMENT FOR EXPERIMENTS AND MODELLING**	**MONITORING OF THE FRESHWATER-SALINE WATER INTERFACE**	**CAPACITIVE BEHAVIOR OF A KARSTIC AQUIFER**
Aquifer type	**fractured, weathered crystalline rocks** 	**Fractured, karstified limestone aquifer** 	**Karstic reefal carbonates** 	**Karstic carbonates** 
Characteristics	10 km^2, 60 wells (30-150 m depth), 2 vertical cored boreholes. Ground instrumentation : GPS, tiltmeters, seismometer ..	40000 m^2, In-situ instrumentation: 32 wells (125 m depth), 2 vertical cored boreholes, 2 oblique cored boreholes.	10 000 m^2, In-situ instrumentation: 18 piezometers (100 m depth for 13 of them, one 250 m deep)	100 km^2, In-situ instrumentation: tiltmeters, flowmeters, gravimeters, infiltration
Specific interest	– Strong signal and fast flow due to groundwater abstraction – Extensive database – Long term evolution, after twenty years of pumping the system has not reached equilibrium	– Dense and regular borehole grid, – Possibility to test and validate groundwater flow and transport models, – Biochemical reactivity with in-situ experiments	– Testing of hydro-geophysical methods for monitoring saline intrusion. – Detailed characterization at different scales, from µm to hecto meter scale (oil reservoir analog).	– Hydrogeodetic instrumentation (gravimetry, tilt) – geophysical imagery of structures and water content, vadose zone investigation, water budget closure
		Monitoring, experimentation and modeling		
Monitoring	Hydrology: piezometric levels, pumping flow rate, climatic variables, chemistry : major ions and traces, water ages with CFC, isotopes, Radon geophysics :GPS, tiltimeter, sismic,	Hydrology: piezometric levels, groundwater temperature, climatic variables	Hydrology : piezometric levels, from Hydreka and WestBay completion (p, T, Cw, pH) Chemistry : major ions with WestBay multi-packer completion Geophysics : resistivity with permanent array	Hydrology : Pluviometry, Spring discharge Flow meter and infiltration as a function of depth, EVT measurement (2011) Geodesy : long base tiltmetry, SG gravimetry
Experimentation	Pumping tests, flowmeter tests, ground surface deformation response to pumping tests, tracer tests: dipole and reactive push pull, time lapse geophysical imagery	Borehole flowmeter tests, imagery, and geophysics, Monopole and dipole pumping tests, Single- and cross-borehole slug tests, 3D seismic imaging, Tracer tests.	Pumping tests Tracer tests	MRS, electric imagery, Absolute gravity, relative gravity network, surface to depth gravity
Modeling	3D aquifer flow and transport model, effective model for pressure diffusion, inverse modeling of radar data	Benchmark of flow and transport models (2D/3D, EPM/DFN, forward/inverse) against experimental field data.		Inverse modeling of gravity time series using local reservoir models of the vadose zone
Deliverables, and associated tasks	– Test of new methods for characterizing the flow heterogeneity – Hydrogeodetic methods – Modeling approaches for fractured media – Chemical reactivity in relation to pumping – Distribution of residence and transfer times – Aquifer vulnerability to climatic and anthropic changes	– Development of new experimental and theoretical approaches for the characterization of multi-porosity aquifers, – Hydraulic and geometric characterization of high-permeability flow paths, – Test of new tracing techniques, – Coupled inverse modelling using flow, tracer and seismic data.	– Test of new methods for characterizing the flow heterogeneity. – Development of hydrogeophysical methods for permanent, on-line salt-water intrusion monitoring. – Detailed structural description from µm to 100 m scale.	– time gravity series associated to capacitive function of the aquifer – vertical and horizontal quantification storage variation – hydromechanical behavior associated to water storage in the vadose zone – aquifer storage variation over decadal periods

Field site Scientists in charge	LSBB (France) C. Danquigny (Avignon)	Hyderabad (Inde) J.C. Maréchal (BRGM)	Krauthausen (Deutschland) J. Vanderborght (Jülich)	Argentona saline wedge site (España) J. Carrera (Barcelona)
MAIN SCIENTIFIC TOPICS	**LARGE SCALE TUNNEL FACILITIES WITHIN THE UNSATURATED ZONE**	**TROPICAL FRACTURED AQUIFER UNDER OVEREXPLOITATION**	**HYDROGEOPHYSICAL EXPERIMENTAL SITE**	**MONITORING OF FLOW, MIXING AND REACTION PROCESSES IN THE SALINE WEDGE**
Aquifer type	**Fractured, karstic carbonates** 	**Fractured, weathered crystalline rocks** 	**Alluvial terrace** 	**Alluvial deposits** 
Characteristics	12 000m², 60 flow points (30-500 m depth) Ground instrumentation : GPS, tiltmeter, seismometer, ..	Choutuppal (430000 m², 19 piezometers) Maheshwaram (55 km², 250 piezometers)	1500 m², 80 piezo (10 m depth)	4000 m², 25 wells (10-25 m depth)
Specific interest	– Direct access inside the Unsaturated Zone. – Detailed characterization of structure, fluxes and chemistry in the unsaturated zone. – Spatial and Temporal long term monitoring of fluxes and chemistry	– Long term evolution of piezometry and chemistry in response to overexploitation, climatic and anthropogenic changes – Long term collaboration with National Geophysical Research Institute	– Heterogeneous sedimentary deposits – Very dense network of piezometers in the near surface (easy to access) – Large database of hydrogeophysical data (including tracer tests),	– High resolution and multi-method characterization of flow, mixing and reactive processes in the freshwater saline water interface – Characterization of radon transport and adsorption
Monitoring, experimentation and modeling				
Monitoring	Hydrology : rainfall, flow rates, physical parameters Hydrochemistry : major ions ; Total Organic carbon, isotopes Geophysics : seismic, electric, electromagnetic, gravimetry, and magnetometry	Hydrology: piezometric levels, pumping flow rate, climatic variables Chemistry : major ions and traces, isotopes Geophysics : electrical resistivity tomography Landuse change	Hydrology: Piezometric levels (automatic pressure sensors + manual)	Hydrology: Piezometric levels, fiber optic temperature and flow monitoring Hydrochemistry : major ions, Ph, conductivity, redox potential, temperature Geophysics: repeated ERT profiles
Experimentation	System dynamics under constraint Geophysical imagery methodological and instrumental development	pumping tests, flowmeter tests, tracer tests, time lapse geophysical imagery, artificial recharge, monitoring of recharge	Long term tracer tests hydrogeophysical imaging of tracer tests (electrical resistivity, Induced Polarization, GPR), direct flow measurements, cone penetration tests	Pumping tests sith ERT monitoring Heat and reactive tracer tests
Modeling	3D to 4D karst aquifer model development	2D regional groundwater flow modeling 1D geochemical modeling of water-rock interactions	Stochastic analysis of flow and transport, Inverse modeling of Electrical Resistivity Tomography	3D Hydrogeological model, effective model validation for saline wedge dynamics and for reactive transport
Deliverables, date and associated tasks	– Bimensuel hydrodynamic and hydrochemical data. – Petrophysical characterisation – Dynamic thermo-hydro-mechanical coupling at different scales. – Hydrogeophysical imaging of the hydrogeological dynamics of a deep unsaturated zone – Multi-sensor monitoring of a tunnel excavation	– Heterogeneity of weathering profile at catchment scale – Relationships between hydrodynamic characteristics and transport parameters – Origin and fate of geogenic contaminants, – Water quality vulnerability to anthropic and climate change.	– Hydrogeophysical measurement techniques for improved characterization of the subsurface environment and flow and transport processes – Development and validation of flow and transport models in heterogeneous media	– Hydrogeophysical measurement techniques for the characterization of the saline intrusion environments and associated flow and transport processes – Validation of modeling concepts for flow and transport in heterogeneous media

Field site Scientists in charge	Hermalle-sous-Argenteau site Alain Dassargues (Liège University)	The hydrological observatory HOBE Karsten Jensen (Copenhagen Unviversity)	Lauswiesen Site Carsten Leven (Tubingen University)	TERENO and CZO site River Selke Jan Fleckenstein (UFZ)
MAIN SCIENTIFIC TOPICS	**HYDROGEOPHYSICAL EXPERIMENTAL SITE**	**INSTRUMENTED CATCHMENT FOR MULTI-SCALE SURFACE WATER GROUNDWATER EXCHANGE MONITORING**	**HYDROGEOLOGICAL EXPERIMENTAL SITE**	**HYPORHEIC ZONE EXPERIMENTAL SITE**
Aquifer type	**Alluvial plain** 	**Alluvial plain deposits underlain by Miocene sand and clay** 	**Alluvial deposit** 	**Meandering, gravelbed river reach with adjoining alluvial aquifer** 
Characteristics	15 000 m², over 20 piezometers (12 m deep)	The total catchment size is 2500 km² however several subcatchments and local field observatories are placed within the overall catchment (nested observation approach)	>40000 m2, 1 water supply well, 1 large diameter well, >15 monitoring wells, several multichannel wells, typical depths 8-9 m, 1 horizontal well,	2 km long river reach Network of nested piezometers, streambed installations for hyporheic processes
Specific interest	– Heterogeneous alluvial deposits with thick clean gravels acting as preferential flowpath/channeling – Dense network of piezometers – Large database of geological, geophysical, hydrogeological and geotechnical data – Existing geostatistical integration framework – Existing Flow and transport model (including heat transfer) – Advanced characterization through cooperative inversion	– To obtain a better understanding of the hydrology at catchment scale and particularly to come closer to closure of the water balance. – To test innovative methods including hydrogeophysical imaging, Multi-scale thermal imagery of groundwater upwelling, cosmic ray characterization of soil moisture, stable isotopes of water as tracers for hydrological fluxes	– Heterogeneous sedimentary deposits – Very dense network of monitoring wells and a horizontal well – Large database of hydro-geological data (tracer tests, pumping tests, hydraulic tomography, Direct Push drillings) – Availability of Direct Push rig, 96 channel ERT unit with borehole electrodes, flow through heater for heat tracing	– Unique instrumentation to quantify the links and feedbacks between physical controls such as stream stage variability, streambed hydraulic conductivity and subsurface heterogeneity on the one hand and biogeochemical process patterns such as hot spots and hot moments of reactivity on the other hand
Monitoring, experimentation and modeling				
Monitoring	Manual monitoring of piezometric levels, water quality. Easy access.	Direct observation and indirect estimation of hydrological fluxes (precipitation, ET, groundwater flow to streams and lakes, submarine groundwater discharge, stream flow) and hydrological states (soil moisture, pressure, isotope concentration)	Hydrology: Piezometric levels (automatic pressure sensors including temperature, EC) Hydrochemistry : major ions	Stream bed pressure, temperature, EC, O2, , high-frequency monitoring of river stage, discharge, stream water nitrate (using UV-VIS probes) and O2, geophysical subsurface characterization, differential gauging,
Experimen-tation	Solute and heat tracer tests, FVDPM, hydrogeophysical monitoring (ERT, SP and DTS) and characterization, Geoprobe and drilling.	Tracer test and hydrogeophysical monitoring	Hydrogeology: Mulitlevel pumping test with fiber-optic pressure transducer, salt and dye tracer tests, heat tracer testing, Direct Push investigations Geophysics : ERT, refraction seismics, electromagnetics	instream tracer tests using reactive tracers, heat tracing,
Modeling	Existing Flow and transport model (including heat transfer) at the regional scale and at the site scale. Geostatistical integration of multiple datasets.	Hydrological modeling at different temporal and spatial scales	Larger scale stochastic model, smaller scale (inverse) model for flow and transport, ERT models	Coupled SW-GW model (Hydrogeosphere), reactive transport model (MIN3P), instream CFD model (OpenFOAM), conceptual rainfall runoff models for entire catchment + nutrient transport (mHM, Hype)
Deliverables, and associated	– Framework for integrating multiple datasets in	– Extensive database of hydrological observations and	– Hydrogeophysical measurement techniques for	– Identify and characterize space and time patterns of

tasks	heterogeneous aquifers characterization Development and validation of solute and heat flow and transport/transfer models	experimentation – New model developments – Calibration and validation of hydrological models	improved characterization of the subsurface environment – Development and validation of flow and transport models	reactivity and to quantify the resulting solute fluxes by jointly using novel and advanced tracing, imaging, and modeling techniques

Field site **Scientists in charge**	**Emme site** Philip Brunner (Neuchatel University			
MAIN SCIENTIFIC TOPICS	**SURFACE WATER GROUNDWATER EXCHANGE EXPERIMENTAL SITE**			
Aquifer type				
Characteristics	200 km² Network of nested piezometers steep hydraulic gradients with rapid groundwater flow rates (up 100 m/d). Long time series of: Stream flow (since 1974), pumping rates, temperature, groundwater levels (since 1976) Weather data close to catchment			
Specific interest	– Highly instrumented site at hyporheic and meander scale in a highly dynamic river – High transience of the natural forcing functions will allow probing the systems dynamics for a very large range of stream aquifer conditions			
Monitoring	Temperature measurements with a DTS system (2013) Groundwater heads and temperature Isotope measurements (rain, river, groundwater pump) Improved meteorological network, additional flow gauging stations (2010) High resolution aerial photography and streambed topography natural tracer Argon 37			
Experimen-tation	Tracer tests, hydrogeophysical imaging;			
Modeling	Numerical models simulating both the hyporheic and meander scale based on a high-resolution characterization of the streambed and calibrated with the tracer data.			
Deliverables, and associated tasks	– Provide and integrate field and modelling approaches that overcome the conceptual and observational gaps between the hyporheic and meander scale.			

Annex 4: Staff list for the French sites

Ploemeur site

NOM	STATUT	AFFECTATION (UMR, UMS…)	RESPONSABILITE	% implication
Chercheurs				
Olivier Bour	PR UR1	UMR 6118 Géosciences Rennes	Responsable du site, coordination des expériences	75%
Tanguy Le Borgne	Phys.adj. CNAP	UMR 6118 Géosciences Rennes - OSUR	Expérimentation hydrogéophysique, traçages et modélisation	100%
Luc Aquilina	Pr UR1	UMR 6118 Géosciences Rennes	Hydrochimie et temps de résidence	30%
Olivier Dauteuil	DR CNRS	UMR 6118 Géosciences Rennes	Mesure par GPS de la déformation hydro-mécanique	25%
Philippe Davy	DR CNRS	UMR 6118 Géosciences Rennes	Problème inverse et modélisation	20%
Frédérique Moreau	MC UR1	UMR 6118 Géosciences Rennes	Mesure par GPS de la déformation hydro-mécanique	25%
Laurent Longuevergne	CR CNRS	UMR 6118 Géosciences Rennes	Responsable des moyens géophysiques	50%
Personnel technique				
Nicolas Lavenant	AI CNRS	UMR 6118 Géosciences Rennes	suivi piézométrique, suivi non saturé	100%
Thierry Labasque	IR CNRS	UMR 6118 Géosciences Rennes	Base de données chimie, temps de résidence, traçages gazeux	50%
Frédéric Boudin	IR CNRS	Géosciences Montpellier	Mesure par inclinométrie de la déformation hydro-mécanique	10%
Annick Battais	IE CNRS	UMR 6118 Géosciences Rennes	Base de données H+	30%
Paulina Lopez	IE (CDD)	UMR 6118 Géosciences Rennes	Base de données H+, réunions H+	50%
Christophe Petton	Technicien	OSUR	Maintenance des installations, des instruments et logistique des campagnes expérimentales	30%

Poitiers site

NOM	STATUT	AFFECTATION (UMR, UMS…)	RESPONSABILITE	% implication
Chercheurs				
Gilles POREL	MCE	IC2MP UMR 7285	Responsable du site, Hydrogéologie	50%
Jacques BODIN	MC	IC2MP UMR 7285	Hydrogéologie	50%
Aude NAVEAU	MC	IC2MP UMR 7285	Hydrogéochimie	40%
Mathieu LE COZ	MC	IC2MP UMR 7285	Hydrogéologie	40%
Personnel technique				
Benoît NAULEAU	IE CNRS	IC2MP UMR 7285	Base de données H+, Instrumentation	100%
Denis PAQUET	AI CNRS	IC2MP UMR 7285	Instrumentation	30%

Mallorca site

NOM	STATUT	AFFECTATION (UMR, UMS…)	RESPONSABILITE	% implication
Chercheurs				
Philippe PEZARD	DR CNRS	UMR 5243	Responsable du site, monitoring en forage	30%
Stéphanie GAUTIER	MdC UM2	UMR 5243	Géophysique en forage	10%
Philippe GOUZE	CR CNRS	UMR 5243	Dispersion dans les carbonates	10%
Hervé PERROUD	Pr UPPA	UMR 5243	Géophysique en surface (sismique, ERT, radar)	20%
Personnel technique				
Muriel GEERAERT	T CNRS	UMR 5243	Monitoring hydrogéochimique	50%
Richards LEPROVOST	IE CNRS	UMR 5243	Instrumentation hydrogéologique	20%
Gérard LODS	IR CNRS	UMR 5243	Hydrogéologie et modélisation	10%
Gilles HENRY	IE CNRS	UMR 5243	Monitoring géophysique	20%

Larzac site

NOM	STATUT	AFFECTATION (UMR, UMS…)	RESPONSABILITE	% implication
Chercheurs				
Cédric Champollion	MCF	UMR5243 / Géosciences Montpellier	Responsable du site	50 %
Jean Chéry	DR	UMR5243 / Géosciences Montpellier	Modélisation	20 %
Hervé Jourde	MCF	UMP5569 / hydrosciences Montpellier	Hydrogéologie	10 %
Philippe Vernant	MCF	UMR5243 / Géosciences Montpellier	Géodésie	5 %
Personnel technique				
Nicolas Lemoigne	IE	UMR5243 / Géosciences Montpellier	Responsable technique observatoire	40 %
Frédéric Boudin	IR	UMR5243 / Géosciences Montpellier	Inclinométrie	30 %
Erik Doerflinger	IR	UMR5243 / Géosciences Montpellier	Géodésie	20 %
Philippe Collard	AI	UMR5243 / Géosciences Montpellier	Géodésie	5 %

Hyderabad site

NOM	STATUT	AFFECTATION (UMR, UMS…)	RESPONSABILITE	% implication
Chercheurs				
Adrien Selles	Chercheur	BRGM	Hydrogéologie	100%
Nicolas Guihéneuf	Doctorant	Univ Rennes 1/ BRGM	Hydrogéologie	100%
Shakeel Ahmed	Chercheur	NGRI	Hydrogéologie, géostatistique	50%
Subash Chandra	Chercheur	NGRI	Géophysique	50%
Jean-Christophe Maréchal	Ch. Responsable de site	BRGM	Responsable de site Hydrogéologie et modélisation	20%
Alexandre Boisson	Chercheur	BRGM	Hydrogéologie	10%
Hélène Pauwels	Chercheur	BRGM	Géochimie	10%
Jérôme Perrin	Chercheur	BRGM	Hydrogéologie	10%
Benoît Dewandel	Chercheur	BRGM	Essaishydrauliques	10%
Personnel technique				
Mohamed Wajiddudin	Technicien	NGRI	Hydrogéologie	100%
Thomas Schwarz	Ingénieur VIE	BRGM	Hydrogéologie	100%

LSBB site

NOM	STATUT	AFFECTATION (UMR, UMS…)	RESPONSABILITE	%
Chercheurs				
Charles Danquigny	MC	UAPV	Responsable de site	40%
Konstantinos Chalikakis	MC	UAPV	Géophysique	30%
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