New slimline logging and testing tools for shallow hydrological investigation: the EC "ALIANCE" project

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ABSTRACT

Salt intrusion in coastal aquifers, either from natural or anthropogenic source, is often related to over-drafting due to agricultural use, a high density of population, or the effect of droughts in arid regions. While the physical processes associated with salt water intrusion are still being discussed, more field data are needed to assess the predictive models developed for long-term management and vulnerability assessment of groundwater resources in this context. This research focuses on the development of new geophysical logging, hydrological testing and long-term monitoring methods to describe and monitor saline intrusion processes.

Scientific objective and approach. In order to mitigate the risks of saline water intrusion in coastal aquifers, an integrated, multi-scalar hydrogeological characterisation of subsurface structures and dynamics is required. The objective of ALIANCE is to develop a strategy for the quantitative description of fluid flow and storage in the shallow subsurface. A site-specific protocol will be implemented, leading to a site modeling capability associated with long-term monitoring from pressure and electrical fields. This includes state-of-the-art geological, geochemical, petrophysical, geophysical logging and hydrological methods, and the design of 5 new downhole sensors yielding new data for model validation. Two end-member sites in terms of hydrogeological behavior will be set up for long-term experimentation, the testing of the new tools, and the validation of site-specific experimental and modelling protocols from µm- to 100 m-scale. Active in-situ testing from short- and longer-term injections with variable salinity fluids will simulate over-drafting or saline water intrusion. In addition to pressure and fluid electrical conductivity, the electro-hydraulic coupling principle will be used to characterise and monitor water/brine hydrodynamics.

Expected impact. ALIANCE aims to improve the long-term management of brine intrusion in coastal aquifers from detailed field description and hydro-electrical monitoring. The research will provide (1) a new geophysical and hydrological protocol to characterize shallow aquifers in an integrated manner, (2) new logging and testing sensors to investigate shallow aquifers, (3) geophysical and hydrological data at 2 end-member sites to validate existing numerical codes, (4) a test for new in-situ monitoring techniques of salt water intrusion in coastal aquifers.

Partnership. The ALIANCE project is funded by the European Community (EC) and assembles a group of academic institutions and small companies from 5 countries. The CNRS at the University of Montpellier 2 (France) is coordinating the project starting Jannuary 1, 2002. While the University of Birmingham (UK) will be coordinating efforts dealing with the granitic experimental site in Brittany (France), ETH-Zurich (Switzerland) will be in charge of the saline wedge site in Mallorca (Baleares, Spain). The University of Oviedo (Spain) is in charge of core and fluid analyses in the context of sites description and drilling. The new logging and testing tools will be built by ALT (Luxembourg), GeoEnergy (France) and the University of Montpellier 2 (France). The CNRS in Marseille (France) will be assisting ALT in the development of one of the logging sensors, developping research in the area of acoustic detection of fluid flow in boreholes from Doppler shift related to fluid movements through the borehole wall.

PROJECT

Over 50 % of the accessible water at or near the Earth surface is over-exploited due to human activities. Groundwater is particularly at risk in urban or semi-arid areas, with the maximum danger in coastal zones where more than 60% of the world population is concentrated. As the main source of drinking water, this strategic but vulnerable resource is of utmost importance. The overall objective of this research is to improve groundwater sustainability and quality in coastal and semi-arid environments. For this, the aim of ALIANCE is to develop, integrate and assess a set of new geophysical tools, methods and scientific approaches to obtain an improved description of aquifer and fluid parameters in the subsurface. The cornerstone of ALIANCE is the setting-up of in-situ facilities for experimentation and long-term monitoring.

The European community includes a large number of potentially exposed coastal aquifers due to over-exploiting and/or natural drought, especially in the Mediterranean region. The mitigation of seawater encroachment has thus become a key issue (*http://www.ce.udel.edu/faculty/cheng/saltnet/index.html*) as, for example, the salinity of groundwater often exceeds drinking water standards, and eventually threatens long-term agricultural use. We propose here to study an intruding saline wedge from changes in space and time of pressure and electrical fields.

The slow renewal of groundwater, especially in semi-arid regions, enhances the need for long-term management tools. In order to mitigate the risks of long-lasting pollution or over-abstracting in exposed aquifers, it is necessary to improve the exploration and monitoring methods to describe aquifer characteristics and fluid flow dynamics. Such improvements are also needed to develop, test and validate new theoretical and numerical models which are, in turn, necessary to assess aquifer vulnerability or groundwater sustainability and quality. For this, the development of integrated approaches is requested to link exploration, monitoring, modelling and management facilities. In conjunction with present efforts to improve theoretical approaches and quantitative modelling, ALIANCE intends to focus on the improvement of aquifer characterisation and long-term monitoring.

In short, ALIANCE will develop and assess for end-users an integrated set of geophysical and hydrogeological tools and methods. Groundwater resources management and mitigation of long-lasting pollution risks, with a special attention to saltwater intrusion issues will be the main objectives of the research. For this, ALIANCE proposes to create in-situ experimental facilities, new downhole sensors yielding a far more precise in-situ fluid flow and transport description, and to test a new monitoring set-up. A rapidly deployed expert approach usable by industry or districts will be produced to merge multi-scale, multi-methods, and site-specific data into modelling procedures.

APPROACH

When addressing the question of modelling groundwater flow and pollutant redistribution at catchment scale, the lack of data or the incoherency of datasets makes difficult the description and monitoring of the multi-scalar processes that control groundwater resource and quality. ALIANCE proposes to investigate, from µm- to 100-m scale, two hydrogeological « end-member » sites, with an emphasis on the quantitative description from surface and borehole measurements of the hydraulic and electrical processes in the aquifer. The ALIANCE strategy includes the following fundamental, methodological and applied aspects:

- design of a state-of-the-art but innovative, integrated and multi-scalar protocol for hydrological coastal site evaluation in the shallow subsurface (including : site reconnaissance, geophysical survey, coring, fluid sampling, conventional logging, monitoring and cross-hole experiments),
- development, testing, deployment, modelling and assessment of 5 new geophysical logging and testing sensors to contribute to the in-situ quantitative evaluation of hydraulic and

electrical transmissivity at the cm- to site-scale, leading to an improved subsurface characterisation,
- testing of a new long-term monitoring strategy based on the hydro-electrical principle for the assessment of fluids circulation and brine distribution in coastal aquifers,
- setting-up of a data bank so that measurements and results can be made available to the public and fellow researchers on the Internet.

- **Design of an innovative, integrated and multi-scalar protocol**

The management of natural groundwater reservoirs requires the definition of predictive relationships between fluid flow, fluid composition, flow structures, aquifer hydrostratigraphy and physical properties of the porous media. These relationships should be extracted from the combination of data collected from structural and dynamic analyses. Structural data relate to the measurement of fluid and rock properties, while dynamic data are obtained from the testing and monitoring of the aquifer behaviour. In most cases however, the datasets are not complete enough for direct modelling of the aquifer behaviour at catchment scale.

ALIANCE proposes to integrate state-of-the art and new surface, subsurface, borehole and laboratory investigation methods. A specific goal is to propose a methodology for integrating multi-scalar sources of data (flow and tracing experiment, electrical resistivity, acoustic characterisation, etc ...). In order to do so, the relationship between fluid flow and structures in the aquifer will be studied in details from core- to 100 m-scale. The physical basis for long-term groundwater and salt encroachment monitoring from the surface and in boreholes will be extracted from this multi-scalar investigation.

- **Design and assessment of new geophysical logging/testing tools**

ALIANCE proposes to develop 5 new slimline downhole tools for geophysical logging and hydrological testing.

Two of them are « **SOURCES** » used as the base for hydrological testing experiments, in single wells or between wells, in order to investigate the aquifer by the means of perturbations. For the more impermeable aquifers such as fractured granite, the **H_2E** (for « Harmonic Hydraulic Endoscopy ») device is based on the harmonic pressure perturbation principle to evaluate the in-situ hydraulic conductivity and fracture network connectivity. For the more permeable aquifers, the **CoFI** (for « Controlled Fluid Injection ») will be designed to perform controlled fluid injections in terms of pressure and salinity during **CoIn** (for « Controlled Injection ») Experiment. It is conceived as a versatile tool to perform either (i) single well flush in/out experiments to evaluate fracture network dispersivity near the well using water conductivity as a tracer, or (ii) to evaluate the clay component in the electrical conductivity of the aquifer from the injection of variable salinity fluids (*Waxman & Smits*, 1968), or (iii) to create an artificial brine plume to simulate salt intrusion. Specific numerical models will be implemented in order to simulate each of theses tools during the experiments.

The other three tools are « **RECEIVERS** » in the form of new geophysical logging sensors (respectively **DopTV** for « Doppler TeleViewer », **SHyFT** for « Slim Hydraulic Formation Tester », and **MuSET** for « Multi-Sensor Electrical Tool »). These new tools can be used either independently or, in a more appropriate manner, in conjunction with the SOURCES for cross-hole aquifer investigation. These tools are conceived to provide a complementary description of key parameters to improve our capacity to : (i) identify flowing fractures and quantify flow discharge from Doppler analysis during testing experiments (DopTV), (ii) determine the fluid flow velocity in the direction orthogonal to the borehole surface (DopTV), (iii) measure in-situ pore fluid pressure between packers or from a sealed pad (SHyFT), (iv) sample fluids from discrete horizons in the aquifer (SHyFT), (v) evaluate dm-scale permeability during testing and sampling (SHyFT), and (vi) measure downhole electrical spontaneous potential (MuSET) in conjunction with fluid pressure (p), temperature (T) and fluid electrical conductivity (C_w).

The SHyFT technique comes from oil and gas exploration. Permeability data obtained from this sensor are directly comparable to those measurable on core. This consequently provides an invaluable means to measure in-situ, micro-scale (or matrix) permeability when no core is available. For coastal environments, the SHyFT is designed to provide (i) continuous fluid conductivity measurements during testing, and (ii) a controlled fluid sampling procedure.

The DopTV imaging tool should provide the first means of measuring the horizontal component of flow in a borehole and their angular variations, hence to evaluate the contribution of each fractures during testing. Used in the course of pumping tests, the DopTV should also provide a means to characterise the evolution of the aquifer permeability as a function of the applied perturbation.

In order to improve long-term monitoring of water/brine hydrodynamics in coastal aquifers, a new method based on combined borehole and surface potential measurements will be evaluated. The design of the new slimline MuSET logging tool is a key for this development. Because it is fairly simple to deploy and cost effective, this monitoring method is promising. The proposed research program will allow to test this method in an upscaling direction, that is from core- to borehole- and finally site-scale measurements in relation to surface monitoring.

In all, depending on the nature of the experiment, the RECEIVERS will be used either in a standard logging mode or stationary, for short or long durations in a downhole observatory mode. During a given experiment, while the SOURCE condition can be maintained, the RECEIVERS may be used successively in nearby holes for an integrated description of aquifer characteristics. To ensure the development of several logging sensors, the ALIANCE structure has been based on a close cooperation between academia and industry.

- **Development of experimental and long-term monitoring facilities**

Depending upon geological context and reservoir structure, groundwater flow and brine dispersion can behave in widely varying manners. As a result, means for the characterization and monitoring of coastal aquifers must be tested at least at « end-member » sites. For simplicity and efficiency, **ALIANCE** proposes to investigate two end-member groundwater reservoirs with a set of 50 to 100 meters deep boreholes. As part of a clustering initiative, these two sites will be selected among those investigated in the context of the EC **SALTRANS** project.

The **EXPERIMENTAL SITE** (EXS) will be chosen as a support for developing and testing the new geophysical and hydrodynamic tools, including the modelling and monitoring methods. It will be chosen in granite as fresh as possible in order to minimize fluid-rock interactions, ignore matrix transmissivity, and for a simple characterisation of the fracture network. The Ploemeur site in Brittany (France) studied as part of SALTRANS appears as a potential experimental site for ALIANCE, with granite and schist in the subsurface. ALIANCE will provide additional data for modelling at this site. Depending on existing data and site development, two to four boreholes will be drilled (at least two will be cored) in order to obtain an pertinent array of 5 to 8 experimental holes.

The **SALINE WEDGE SITE (SWS)** will address directly the problem of brine intrusion. A set of 5 to 8 holes (three or four of them should be cored) will be located across a known saline/fresh groundwater transition in a sedimentary environment. The understanding of processes in such a system will be based on integrating geology, hydrogeology, geophysics, petrophysics and geochemistry at core- to site-scale. Here also, the most appropriate site will be chosen from the set of sites studied in the context of SALTRANS in the initial phase of the project. The Majorca site near Pollenca (Baleares, Spain), with fractured limestone and slight karstification possibly related to brine intrusion processes, is here the preferred candidate.