http://coastal-alert.bgs.ac.uk

Project no. GOCE-CT-2004-505329

Project acronym: ALERT

Sustainable Management of Water Resources by Automated Real-Time Monitoring

Instrument: Specific Targeted Project

Thematic Priority: Global Change and Ecosystems

Publishable Final Activity Report

Period covered: from 1st June 2004 to 31st December 2007

Date of preparation: February 2008

Duration: 3.5 years

Project coordinator name: Dr R D Ogilvy

Project coordinator organisation: British Geological Survey (NERC)

Revision: Draft v.1

1. Project execution

The ALERT project has developed a radically different strategy for monitoring and managing the impact of climatic change and land-use practice on scarce water resources. Innovative ALERT technology has been designed which allows the near real-time measurement of geoelectric, hydrologic and other physical properties "*on demand*", thereby giving early warning of potential threats to vulnerable water systems.

The principal objectives of the project were:

- to use proven and new sensors which could be permanently deployed *in-situ* and then interrogated using novel GSM, GPRS wireless telemetry and satellite telecommunications to provide snap-shots of the subsurface at regular intervals, thereby obviating the need for expensive repeat surveys.
- to relate time-lapse geoelectric measurements to hydrogeological and hydrogeochemical properties and processes.
- to develop a predictive numerical modelling capability that can link all components in the hydrologic continuum (climate, soil, surface water, groundwater recharge-discharge, and seawater intrusion-extrusion).
- to develop new data fusion techniques, risk analysis and decision support tools within a web-based GIS database for the sustainable management of water resources.

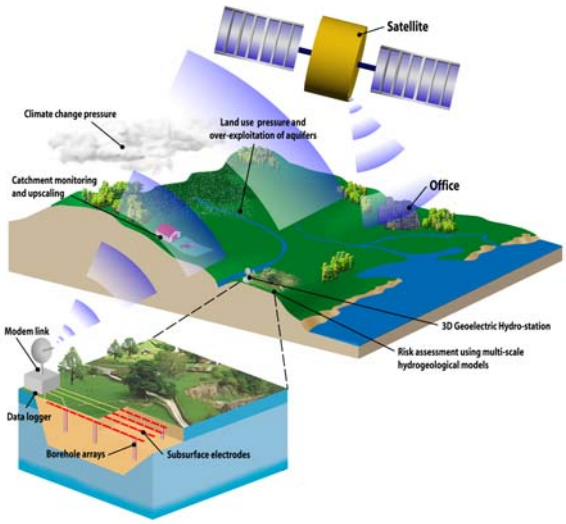

Fig. 1 Schematic diagram of ALERT system.

The consortium participants were:

Partic. No.	Participant name	Participant short name	Country
1	British Geological Survey (NERC)*	BGS	UK
2	Forschungszentrum Jülich GmbH	FZJ	Germany
3	University of Copenhagen	KU	Denmark
4	University of Almeria	UAL	Spain
5	Catholic University of Louvain	UCL	Belgium
6	Aristotle University of Thessaloniki	AUTH	Greece
7	Industrial Research Institute for Automation and Measurements	IRIAM	Poland
8	ESCO Sp.zo.o	ESCO	Poland
9	Geotomographie	GeoT	Germany
10	Cadi Ayyad University of Marrakech	UCAM	Morocco

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Work performed and end results

An intelligent prototype ALERT (Automated time-Lapse Electrical Resistivity Tomography) system has been designed which allows, for the first time, the near real-time measurement of *in-situ* geoelectric properties. These properties are used to provide surrogate indicators of hydrochemical and hydrogeological property variations associated with subsurface aquifer dynamics.

Technology: The ALERT survey concept makes use of electrode arrays, permanently buried in shallow trenches or attached to borehole casing. This network is then interrogated from the office by wireless telemetry (e.g: GSM, GPRS, satellite or wireless internet) to provide volumetric images of the subsurface at regular intervals. No manual intervention is required; data is transmitted automatically according to a pre-programmed schedule and for specific survey parameters, both of which may be varied remotely (Fig 5) as conditions change (i.e: an adaptive sampling approach).

The technology has been tested in the lower Andarax basin, Almeria, Spain, where the coastal aquifer is under threat from over-exploitation, rising sea levels, anthropogenic pollutants and seawater intrusion. Automated time-lapse electrical images have been captured daily to study changes in the seawater/freshwater interface. These data are automatically captured by the

fileserver in BGS and then uploaded to the office PC for databasing, processing, modelling and visualisation. The process from data capture to visualisation is seamless.

Fig. 2 Excavation of the ALERT trench and drilling

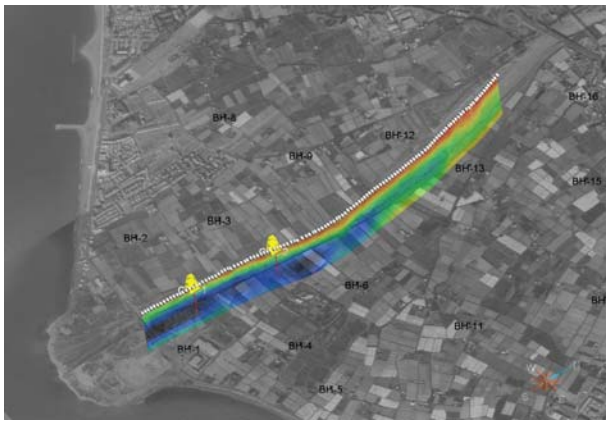

Fig. 3 Aerial photography with 2D ERT image overlay.

Fig. 4 Prototype ALERT instrument

Fig. 5 ALERT control interface software

Hydrologic properties: New algorithms and code have been developed to optimize geoelectric data collection and to invert time-lapse geoelectric data. Using these codes an innovative methodology has been proposed that combines electrical and hydrological inversions. The electrical images derived by the time-lapse ALERT data streams are converted, using calibrated and site specific petrophysical relationships, to mass fractions and then inverted to recover hydrological parameters (hydraulic conductivity and dispersivity). This methodology yielded positive results for different hydrological scenarios of seawater intrusions in homogeneous media. Inversion of hydrological parameters for heterogeneous media proved to be more difficult, due to the increased number of parameters, the nonlinearity of the imaging resolution/sensitivity, and the increasing number of petrophysical relationships to be established. However, the methodology was found to be applicable for layered media and salinity mass fraction was determined with a high degree of certainty.

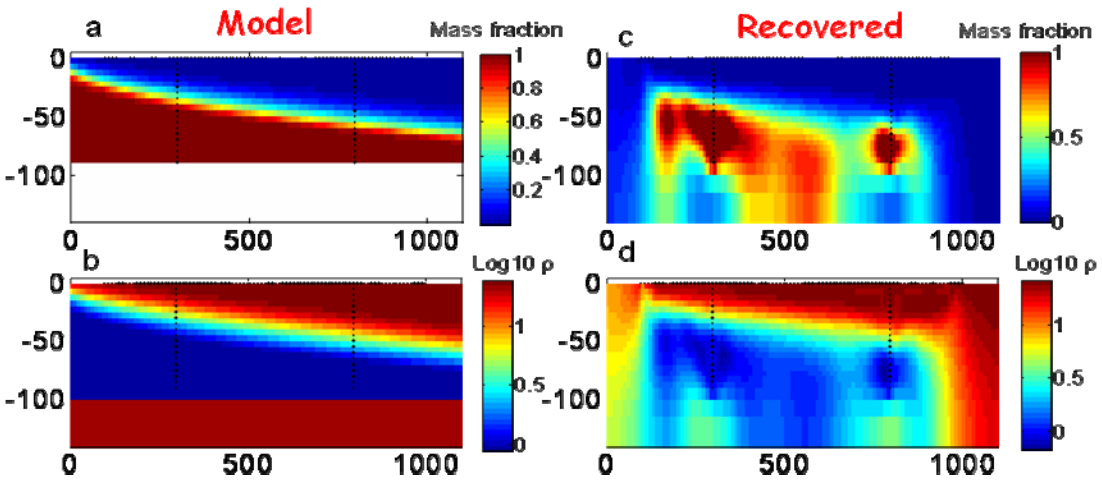

Fig. 6. Illustration of the electric-hydrologic conversion methodology. Mass fractions (a) are converted to electrical resistivity distributions (b) using established petrophysical relationships. These models are then inverted using electrical tomography (d) and converted back to mass fraction (c). The original and recovered mass fraction images are compared to find a representative model.

Hydrogeological modelling: A fully distributed MIKE SHE code was used to understand the behaviour of the water resources in the Andrax river basin. Evapotranspiration (ET) is a very large component of the water budget (95% of the precipitation evaporates). The MIKE SHE model was validated for two simulation scenarios based on traditional and a combination of traditional and remote sensing data respectively. However, the Andarax River Basin exhibits a rather unique hydrological behaviour because of the semi-arid Mediterranean climate and the complexity of the geological settings.

A 3D saltwater intrusion model of the Andarax delta gave good agreement between observed and modeled head values in the delta, indicating a robust flow model. Simulations of the saltwater intrusion model were satisfactory though not perfect. The simulation domain required discretization into grid cells of 50m x 50m x 2m, resulting in approximately 1 million nodes. The simulation studies required heavy computational loads but confirmed that the controlling components of the model were horizontal hydraulic conductivity, transverse dispersivity, the structure of the aquifer, and historical pumping. Flow and transport parameters were successfully estimated.

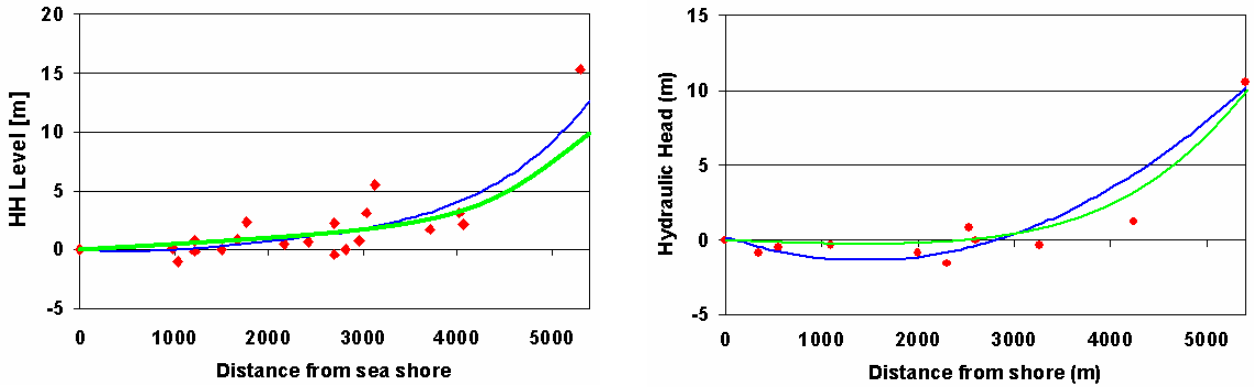

Fig. 7. Comparison of observed and simulated hydraulic head levels along a N-S transect in the delta area. Red dots are head measurements, blue line is a trend line (for measurements) and the green line is simulated head levels. Left: Observed and simulated hydraulic head at year 1972 (pre-pumping). Right: Observed and simulated hydraulic head at year 2006.

Once acceptable initial conditions had been established transient simulation runs were conducted to simulate the effect of groundwater pumping on flow in the aquifer and seawater intrusion. A fairly good match between measured and simulated hydraulic head levels was obtained, both for steady state and after 35 years of pumping.

However, the models confirmed that seasonal, annual or even hydraulic head changes over a few years had little effect on the hydraulic head in the delta area, indicating that the delta hydraulic head response is only weakly coupled to the inland hydraulic head response. Unfortunately this limited connection leads to a very small, if any, detectable, change in the saltwater intrusion front. The primary factor controlling the saltwater intrusion in the coastal zone, was found to be anthropogenic, i.e., groundwater pumping for agri- and horticulture. This finding explains why little or no movement was observed with the ALERT images. Although proof of the ALERT survey concept was established, the unusual hydrogeology of this test site proved to less than perfect for the purposes of the project.

GIS Database: A secure project website was developed to facilitate project communications, discussions, management, data exchange, and archiving of raw and processed data. An externally developed open-source web application portal framework (http://www.liferay.com) was adapted for this purpose. The Web GIS functionality was provided using ESRI ArcIMS software. Historical and new data, maps, models, logs, tables and references have been collated from a variety of sources for the entire Andarax catchment region. Many added value information products have been generated. This site will be maintained for 2 years beyond the lifetime of the project to assist future exploitation and use. A small set of publically accessible web pages are available to raise public awareness about the project and to list all publishable outputs.

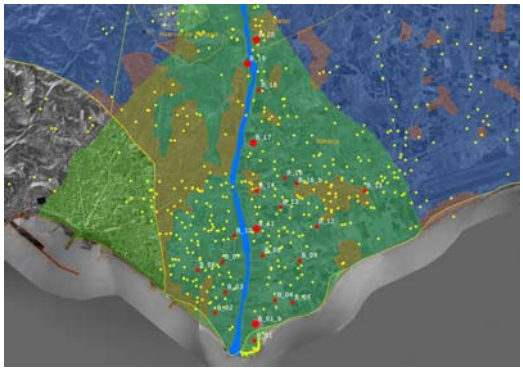

Fig. 8 GIS map of borehole locations

Scenario modelling: Based on extensive socio-economic surveys the project has identified the multiple objectives of the stakeholders in the Andarax catchment region, including the future water demand. The objectives were translated into criteria and indicators that can be treated in a decision support system (DSS) to allow informed debate on the different water management strategies and their likely impacts. A participatory, bottom-up approach was used to correctly identify the water management issues.

These issues and concepts were translated into a prototype DSS software package (the ALERT-DSS). The architecture of the DSS software is modular and consists of a scenario builder and evaluation tool. Operational decisions (pumping and water transfers) were determined by the optimization model. Then, broader environmental and socio-economic issues were dealt with through the soft operational tools embedded in the ALERT-DSS. The management model returns indicator results for aquifer cells at the different time steps of the planning period, and for different scenarios and alternatives. A GIS tool allows visualization of the indicator values over time and space. Tests with the DSS prototype scheme compared different management alternatives for a range of external scenarios, including climate change and higher macro-economic activity. Both scenarios will invariably lead to a decrease of

groundwater level and increase in water transfer costs. Recommendations have been made for further development of the DSS prototype using uncertainty/sensitivity analysis.

Achievements and expected impacts

- Prior to the commencement of this research, no geoelectric instrumentation system was commercially available which would allow the remote imaging of aquifers "on-demand" using wireless telemetry. A prototype ALERT system has now been designed and successfully deployed in the River Andarax, Spain to demonstrate this capability.
- Traditional groundwater management relies heavily on "spot" borehole sampling but this approach is time-consuming, often infrequent, and may not be representative in heterogeneous aquifers. Water resource managers are not getting timely or accurate information needed to conserve water bodies or instigate remedial strategies. The ALERT survey concept has shown, for the first time, that 2D or 3D volumetric and temporal hydrologic property distributions to be determined from time-lapse electrical resistivity tomography. Large areas and depths can be monitored remotely from the office PC without the need for manual repeat surveys or sampling.
- Relations between aquifer forcing functions and seawater intrusion have previously been developed but none of these solutions have been used to estimate the observed position of intrusions in pumped coastal aquifer systems. The ALERT images obtained from this project clearly delineated the seawater/freshwater interface in the Andarax delta region. The front was mapped at about 2.5km from the shoreline, well on excess of earlier estimates (~300m) based on isolated borehole observations. The proven ALERT technology could therefore be an invaluable tool for optimizing pumping for irrigation schemes and desalination plants. Over-pumping could be prevented, thereby significantly improving the sustainability (and longevity) of the water resource.
- A 3D saltwater intrusion model of the Andarax delta gave good agreement between observed and modeled head values in the delta, indicating a robust flow model. Flow and transport parameters have successfully been estimated. However, the model confirms that the coupling between the inland hydraulic head and that in the delta is weak and natural seasonal variations have little impact on the saline front. The primary factor controlling the saltwater interface in the coastal zone is due to groundwater pumping. Nevertheless, the model was capable of capturing the important flow processes in the catchment and as such will be a useful tool for predicting the available groundwater resources in the delta region. No robust hydrogeological model existed prior to the project. The results confirmed that negative hydraulic heads exist throughout the entire coastal aquifer, indicating an aquifer in a state of hydraulic imbalance, which will lead to the continuous intrusion of saltwater.
- The hydrogeological model results confirmed however that no lateral movement of the saline front could be expected in the ALERT images during the lifetime of the project. This disappointing result does not invalidate the ALERT monitoring concept. It is anticipated that application of this technology elsewhere (in a less complex setting) could significantly improve the sustainable management of scarce water resources.
- An Integrated Water Resource Management (IWRM) scheme was developed for the Andarax test site based on a participatory integrated planning approach. Although the implementation was invariably site specific (constrained by catchment functions, stakeholder usage and macro-economic activity) significant new generic procedures and methodologies have been developed which did not exist prior to project. A new Decision Support System (DSS) has been delivered for predicting the impact of future water demand, land use (tourism, horticulture), and climate change on existing water resources, within the context of the Water and Groundwater Framework Directives.

2. Dissemination and use

Publishable results

Product Description	Possible market applications	Stage of development	Collaboration sought	Intellectual Property Rights granted	Contact Details
Oral papers (1) on SIP petrophysics and (2) time-lapse inversion	Water resource modelling, hydrogeophysics	Papers presented, EAGE, Sept. 2005. In Proceedings.	None	FZJ	A Kemna, F Nguyen
Oral paper on ERT images in River Andarax	Water resource modelling, hydrogeophysics	Paper presented, EAGE, Sept. 2005. In Proceedings.	None	BGS, UAL	O Kuras, P I Meldrum, R D Ogilvy, J. Gisbert, J., Jorreto S and F. Sánchez Martos
Oral paper on borehole-to-surface time-lapse inversion	Water, pollution, hydrogeophysics, saltwater intrusion, aquifer monitoring	Paper presented, EAGE, Sept. 2005. In Proceedings.	None	AUTH, BGS	P Tsourlos, R Ogilvy
Oral paper,	Hydrogeophysics	Paper presented, AGU, Dec. 2005. In Proceedings?	None	FZJ	F Nguyen
Oral paper on recharge in semi-arid River Andarax basin	Aquifer modelling, hydrogeology, monitoring, water resource management	Paper presented at EGU, April 2006.	None	KU, UAL	F Andersen, A Pulido-Bosch
Oral papers (1) on hydrological modelling and (2) on constraining saltwater intrusion models by time-lapse ERT imaging	Aquifer management, hydrogeology, monitoring, saltwater intrusion modelling	Paper presented at CMWRXVI, June 2006.	None	KU, UAL, FZJ, BGS	A Antonsson, A Kemna, O Kuras, J Gisbert
Oral papers on (1) GIS Database for Andarax basin and (2) geophysical logging as a tool for pumping control	Aquifer management, hydrogeology, monitoring, saltwater intrusion modelling	Papers presented at AQUAinMED conference, April 2006	None	UAL	I Frances, S Jorreto
Oral paper on Decision Support System for Groundwater management	Aquifer management, planning, agriculture, tourism	Paper presented at AQUAinMED conference, April 2006	None	UCL, UAL	N Van Cauwenbergh , I Frances
Oral paper on hydrogeological modelling	hydrogeology, monitoring, water resource modelling	Paper presented at European Geophysical Union (EGU) Conference. 1 oral paper.	None	KU, UAL	F Andersen, S Jorreto
Oral papers on ALERT results	hydrogeology, monitoring, water resource modelling, hydrogeophysics	Papers presented at IAH Water Resource Congress & Exhibition, May 2006	None	BGS, UAL, FZJ, AUTH, IRIAM, UCL, KU	O Kuras, A Pulido-Bosch, A Kemna, M Vanclooster
Oral paper on hydrogeological modelling	hydrogeology, monitoring, water resource modelling	Paper presented at CMWRXVI, June 2006.	None	KU, UAL	F Andersen, S Jorreto
Oral paper on	Saltwater intrusion	Paper presented at	None	FZJ, KU,	A Kemna

hydrological –electrical imaging model simulations	and coastal aquifer management	SWIM-SWICA Salt Water Intrusion Conference, Sept 2006		AUTH	A Antonsson P Tsourlos
Oral paper on hydrogeological modelling	Saltwater intrusion and coastal aquifer management	Paper presented CWRXVI Conference, XVI International Conference on Computational Methods in Water Resources, Copenhagen, Denmark, June 2006. In Proceedings.	None	KU, UAL	F. Andersen, K.H. Jensen, I. Sandholt, S. Jorreto and A. Pulido-Bosch
Oral paper on hydrogeological modelling	Hydrological Modelling in a semi-arid region using remote sensing data.	Paper presented at Fall Meeting, American Geophysical Union, San Francisco, USA, December 2006	None	KU, UAL	F. Andersen, K.H. Jensen, I. Sandholt, S. Stisen, S. Jorreto and A. Pulido-Bosch,
Oral paper on scenario modelling and water resource management	Multi-objective, multi-participant decision support in natural resources management.	Nat Book Series. Submitted for publication. June 2006	None	UCL	N. Van Cauwenbergh and M. Vanclooster,
Oral paper on joint hydrogeophysical modelling	Constraining a 2D density-dependent saltwater intrusion model using electrical imaging	CMWR XVI – Computational Methods in Water Resources, XVI Int. Conf., Copenhagen, June 19-22, 2006	None	KU, FZJ	F. Antonsson, F. Nguyen, P. Engesgaard, and A. Kemna,
Oral paper on hydrogeophysical modelling	Potential of electrical imaging to constrain saltwater intrusion models: 2D numerical simulations:	Summer Research Workshop "Hydrogeophysics", Soc. Expl. Geophys., Vancouver, July 31-August 2. 2006	None	FZJ, KU	A Kemna, F Nguyen, A Antonsson, and P. Engesgaard,
Oral paper on hydrogeophysical modelling	A synthetic study on constraining a 2D density-dependent saltwater intrusion model using time-lapse electrical resistivity data:	1st SWIM-SWICA, First Int. Joint Salt Water Intrusion Conf., Cagliari, September 24-29, 2006	None	KU, FZJ	A. Antonsson, P., Engesgaard, A Kemna, and F Nguyen,
Oral paper on numerical algorithm for optimisation	Optimizing Resistivity Array Configurations by Using a Non-Homogeneous Background Model:	Extended Abstracts "Near Surface 2006" – 12th European Mtg. of Environmental and Engineering Geophysics, Eur. Assn. Geosci. Eng., P076.	None	AUTH	E Athanasiou, P Tsourlos, C.B. Papazachos, and G N Tsokas
Oral paper on ERT inversion	An Algorithm for Fast 3D Inversion of Parallel 2D ERT Data-Sets:	Extended Abstracts "Near Surface 2006" – 12th European Mtg. of Environmental and Engineering Geophysics, Eur. Assn.	None	AUTH	Papadopoulos , N.G., Tsourlos, P., Papazachos, C., Tsokas, G.N., and A

		Geosci. Eng., Sept 2006, B025.			Sarris.
Oral paper on ALERT monitoring technology	Automated Monitoring of Coastal Aquifers with Electrical Resistivity Tomography	In Proceedings TIAC'07 International Conference on Technology of Seawater Intrusion in Coastal Aquifers, Almeria, Spain, 16 Oct 2007.	None	BGS, UAL, FZJ, AUTH	R D Ogilvy, O Kuras, P I Meldrum, P B Wilkinson, J Gisbert, S Jorreto A Pulido Bosch, A, Kemna, F Nguyen and P Tsourlos.
Journal paper on ALERT monitoring system	Automated time-Lapse Electrical Resistivity Tomography (ALERT) for monitoring Coastal Aquifers	Near Surface Geophysics journal, 2008, Special issue on hydrogeophysics (Paper accepted)	None	BGS, UAL	R D Ogilvy, O Kuras, P I Meldrum, P B Wilkinson, J Gisbert, S Jorreto A, Frances, I., Pulido Bosch.

Contact details for these publications can be found on the public home page of the ALERT project website http://coastal-alert.bgs.ac.uk. A total of 35 oral and journal papers had been presented at international conferences and/or submitted to high-impact research journals. Other exploitable results (technology, software, databases) have been documented in the confidential Exploitation Plan. Appropriate protection is being sought for these products.