Possibilities of geophysical survey for groundwater contamination and subsurface pollution determination and monitoring in the coastal zone

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Abstract One of the important challenges facing coastal zone managers today is how to identify, measure and monitor submarine groundwater discharge and seawater intrusion, and how to evaluate its influence on cumulative impacts of coastal land-use decisions over distance and time. A new geophysical technique can help to solve the problem and provide direct monitoring of groundwater–seawater interactions in coastal aquifers. The Transient Electromagnetic Method, TEM, allows subsurface sounding to 300 m depth.

Key words coastal geophysics; hydrogeology; oceanography; groundwater–seawater interaction

INTRODUCTION

The focus of this report is to describe the current understanding of groundwater in freshwater–saltwater environments using a new geophysical method. One of the important challenges facing coastal zone managers today is how to identify, measure and monitor submarine groundwater discharge (SGD) and seawater intrusion (SWI) and how to evaluate its influence on cumulative impacts of coastal land-use decisions over distance and time (Burnett *et al*., 2002, 2003; Kontar, 2002; Kontar *et al*., 2002; Kontar & Ozorovich, 2006; Taniguchi *et al*., 2006). Numerous field studies have yielded a wealth of information on the occurrence and intrusion of saltwater into coastal–zone freshwater aquifers. Several geochemical and geophysical techniques are used to directly or indirectly monitor saltwater in coastal aquifers. Because of the very high concentration of chloride in seawater (typically about 19 000 mg/L) the chloride concentration of groundwater samples has been the most commonly used indicator of saltwater occurrence and intrusion in coastal aquifers. However, other indicators of groundwater salinity, such as the total dissolved-solids concentration or specific conductance of groundwater samples, are also used. Understanding of the multi-variable dimensions of groundwater management in coastal zones can be improved through the application of innovative information technologies (the application of neural networks to data analysis, optimization, pattern recognition, image identification, etc.), and by using new generations of non-invasive techniques for groundwater exploration, which can be successfully combined with nuclear and isotopic techniques (Burnett *et al*., 2002) and will help to understand the results obtained using these techniques (Kontar & Ozorovich, 2006).

This report is a result of research conducted by a team of Russian scientists (E. A. Kontar, L. I. Lobkvsky, I. A. Garagash, I. Ya. Rakitin, Yu. R. Ozorovich and

F. A. Babkin). It is the opinion of the team that further development of electromagnetic sounding as a geophysical method (Kontar & Ozorovich, 2006) in conjunction with nuclear and isotopic techniques for investigation of SGD (Burnett *et al*., 2002) is useful for this type of research. This method can provide a clear understanding of the fluctuation of the interface between freshwater and groundwater in the coastal zone over time and its spatial dimensions.

The new operational monitoring system, MARSES TEM, has capabilities and advantages that can be used for water search tasks (groundwater table), the definition of waste levels, monitoring changes in subsurface horizons, etc. The system is based on the transient electromagnetic method (TEM) sounding technology, which enables one to conduct subsurface soundings to a depth of 300–500 m. This system can also be applied to solve long-term tasks for monitoring natural subsurface ecosystems, subsurface horizons, soil salinity levels, salinity gradients, and groundwater levels. All of these parameters can be used to track seasonal and climatic changes in selected coastal areas. The distinctive difference in the proposed coastal monitoring system is the measurement of soil humidity along the coast at all depths down to the groundwater level. It is not possible to detect these subsurface horizon humidity parameters by any other monitoring means, such as observation wells or digging pits, etc.

The goal of this contribution is to obtain a fundamental understanding of the physical and chemical processes taking place at the dynamic subsurface freshwater–seawater interface by carrying out detailed studies on a small-scale, at one or two sites in a coastal area. This should provide a conceptual framework for understanding the effects of these processes on a larger scale and over longer periods of time. Insight into the controlling processes and the development and testing of a coupled variable-density flow, multi-species transport, and reaction code will increase the possibilities for sustainable management of coastal aquifers.

At present, a stand-alone portable non-invasive subsurface research instrument based on TEM measurement is available. It is capable of measuring the resistivity of subsurface slices of up to 100–150 metres and works with a stock IBM compatible portable computer using a serial interface. Brief technical details of the instrument are as follows:

- weight: 1.5 kg
- size (mm): 103 × 27 × 310
- working temperature: –20°C to +65°C
- power consumption: more that 50 measurements at maximum depth.

During IAEA SGD CRP (2002–2006) two successful field tests of the MARSES TEM system were conducted: in Sicily, Italy and on Long Island, USA. Only the results obtained during the experiment in Sicily are reproduced here.

RESEARCH BACKGROUND

In the course of Russian space research missions to Mars, soil conditions were found to be similar to the Earth's arid and semi-arid lands. The MARSES TEM was developed for subsurface sounding and mapping applications. More specifically, these instruments relate to methods for the mapping, tracking, and monitoring of: groundwater, groundwater channels, groundwater structures, subsurface pollution plumes, mapping interconnected fracture or porous zones, leaks in earthen dams, leaks in drain fields, monitoring changes in subsurface water flow, changes in ion concentration in the groundwater, monitoring *in situ* leaching of solutions, changes in subsurface redox or reaction fronts, underground chemical reactions, subterranean bio-reactions, or other subsurface water and related geological structures. Recent research has been devoted to the development of new technologies for monitoring the subsurface processes in coastal zones and has revealed significant comparative advantages.

These include:

1. Flexible software development gives an opportunity to adapt this monitoring system to solve different tasks: monitoring of groundwater discharge, identification of saltwater intrusion at the groundwater level, etc.
2. At present the geophysical equipment and instrumentation market does not have a similar system for non-invasive exploration of subsurface ecosystems. The system has been developed for space missions and has met stringent requirements for both hardware and software.
3. A flexible architecture gives an opportunity to build a system by using unified instrumentation and specialized software for resolving particular monitoring tasks.
4. These advantages in system monitoring make possible the development of integrated monitoring systems for different urban, dry land, arid and semi-arid coastal-zone lands.
5. Simplicity of use and maintenance, with the possibility of exchanging working modules during service procedures provides an opportunity to apply this system in any region for up to five years, with no need to develop a service and maintenance station network.
6. The property of TEM at the late stages of transience determines the maximum depth of sounding, which together with its good resolution and high degree of accuracy is the main advantage of the method, as well as the physical and geological parameters acquired during measurements of geo-electric sections, makes the MARSES TEM monitoring system one of the most competitive and innovative for further development and use for monitoring and studying SGD and SWI in coastal zones.

MODERNIZATION AND TESTING OF THE MARSES TEM SYSTEM

Theory

The physical and mathematical bases of TEM are described fully and sufficiently in the literature (e.g. F. Kamenetsky (in Russian) “Electromagnetic geophysical researches” Moscow, GEOS, 1997). Here we shall state only the basic aspects of the theory having direct relation to the technology of soundings with TEM-FAST.

One of the few models of media, for which the formulae are simple and accessible for the analysis of received TEM signals, is the model of the homogeneous half-space. To exemplify the opportunities with TEM, we shall consider asymptotic estimation of signals for late and early stages. The late stages of transient $t = t/\mu\,(R^2/\rho) >> 1$ for one-turn, round antennas R and r, lying above the homogeneous half-space with resistivity ρ and magnetic permeability of vacuum μ, are described by the formula:

$$E(t)/I = 0.05 \times (\pi^{1/2}\mu^{5/2})/\rho^{3/2}(r^2R^2)\ t^{-5/2} \quad (1)$$

The registered signal is proportional to conductivity $\sigma^{3/2} = 1/\rho^{3/2}$ and to the product R^2r^2. Thus, in TEM the amplitude of signals at late stages is sensitive to changes of conductivity of the section in comparison, for example, with methods of direct current. The signals $E(t)/I$ at $t/\mu(R^2/\rho) >> 1$ do not depend on a site of receiving loop $r < R$. The formula (1) is also true at a height h above the surface of the half-space of the antennae. In late stages of transience, the signal registered in the receiving antenna, is caused by currents induced in the current's ring inside section with effective radius R_{eff} and "attitude" depth $H_{eff} \sim R_{eff}$. $R_{eff} = (t\rho/\mu)^{1/2}$, some times exceeding the radius of the transmitting loop $R_{eff} >> R$.

The vertical magnetic field created by this contour is practically homogeneous within the limits of its area at $h < R_{eff}$, therefore the registered signals are proportional to the derivative of the magnetic field over time, and do not depend on the site of reception. The property of TEM at late stages of transience determines the maximum depth of sounding, which in a combination with good resolution of the method ($\dot{E} \sim \sigma^{3/2}$) and high degree of accuracy is the main advantage of the method. Early stages of transient $t_0 << 1$ for the coincident antennas $R = r$ do not depend on the resistivity of media:

$$E(t)/I = \mu R/(2t) \quad (2)$$

At early stages ($t_0 << 1$) for small receiving antennas $r/R << 1$ the signals are proportional to the specific resistivity of media ρ and do not depend on time, t:

$$E(t)/I = 3\pi\rho\,(r^2/R^3) \quad (3)$$

Monitoring

MARSES TEM sounding instruments are based on time domain electromagnetic sounding. MARSES TEM is a portable, reliable geo-electrical sounding instruments made to satisfy small space requirements and simple, intuitive usage.

TEM allows subsurface sounding at depths of 300–500 metres. Applications include: groundwater, prospecting deposits, hydrogeological research, geological surveys required before the construction of buildings, ecological research, archeological and subterranean objects search, monitoring of high risk industrial and engineering objects, research and testing of rock samples.

A number of MARSES instruments should be placed in coastal zones with ecological hazards to provide measurements in the areas of interest. Using a radio system (Fig. 1) it will be possible to transmit data to headquarters, where the data will be processed and stored for future use and reference. Using modelling and visual presentation software it will be possible to create graphs, charts, time variation and other easy to understand representations of the monitored area.

The significant advantage of this system in comparison to known ecological hazard monitoring systems is its cost effectiveness. It does not require expensive satellite monitoring of the coastal zone or employment of satellites in data transfer. Another advantage is its compact and ready to use nature that allows rapid measurements at any required area. Moreover, it is significantly cheaper than competitors.

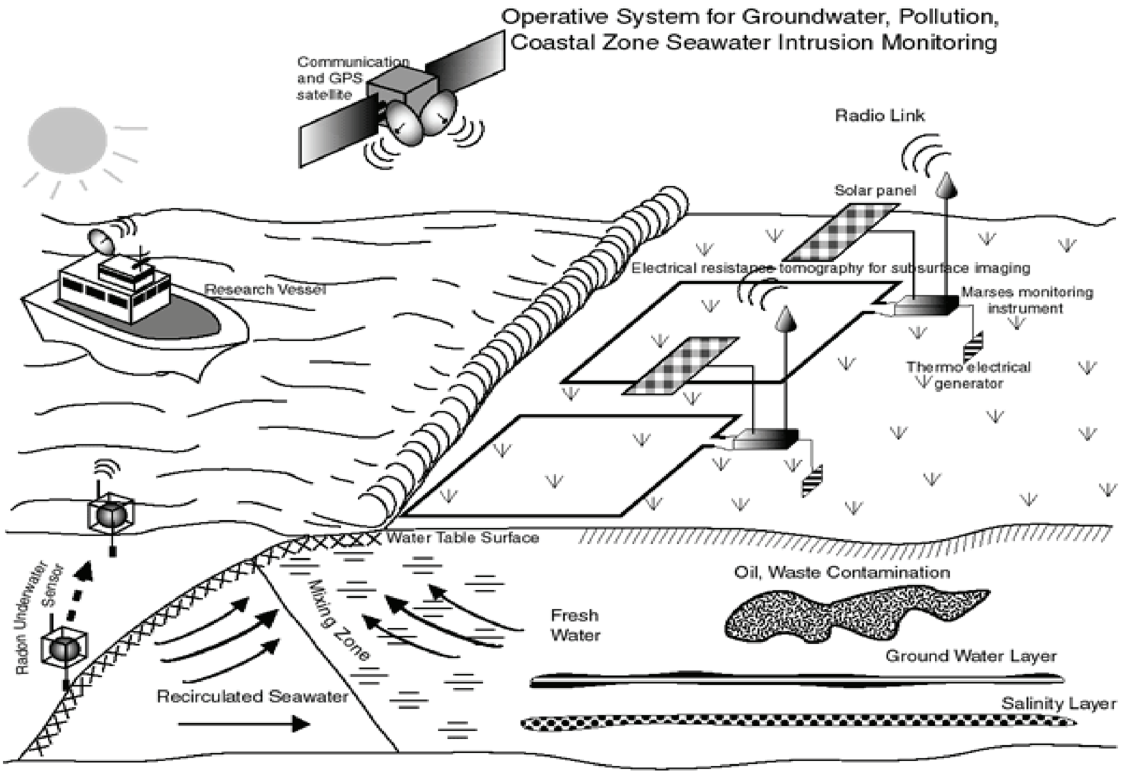

Fig. 1 The coastal zone subsurface monitoring system organization structure.

In contrast with many of the competitors' instruments MARSES TEM has exceptional advantages among small depth sounding devices. Because the MARSES TEM hardware was developed to be employed in space research missions it possesses a unique portability and is dramatically lighter. It fits inside a suitcase, with the antenna, supporting notebook, and batteries. Use of a notebook PC for data processing makes it easier to view the results, process them, prepare reports and send them to headquarters. MARSES TEM supplies reliable data in areas with high EM distortions (about 1 volt and higher), such as in industrial zones and on urban streets. Sounding parameters can be easily adjusted from a PC.

At present there is no mobile operational monitoring system based on non-invasive technology and methodology. Thus development of these innovative monitoring systems has great potential and widespread application.

As this system was developed within the framework of space research missions, it possesses unique methodological and technological features and advantages in comparison to other monitoring systems based on different principles and methods.

RESULTS OF TESTS

We conducted two field tests of the MARSES TEM system: in Sicily, Italy and on Long Island, USA. A distinctive feature of the experiments with sounding of the subsurface horizons was the realization of simultaneous measurements of the geo-electrical sections at two points 70 metres apart for the various cycles of a tidal wave over a period of several days. These measurements have, for the first time, revealed the spatial and time variability of the saltwater–freshwater interface, and show the effect of complex transformation of the salt and fresh water interface in the coastal zone. The analysis of the time variation of the geo-electrical section shows high correlation with the daily tide and nonlinear transformation of the boundary of the saltwater–freshwater interface in the process of its spreading offshore.

GEOHYSICAL SURVEY OF THE SALT–FRESH WATER INTERFACE AND SEA SPRING ZONE IN THE MARINA DI RAGUSA AREA, SICILY

Hydrogeology of the Marina Di Ragusa beach study area

The Marina di Ragusa beach study area is located in the south of Sicily. The study of the geological characteristics of the territory has allowed us to exactly identify the aquifer that supplies the discharge into the sea along this stretch of Sicilian coastline. It is a carbonate aquifer in which karstic phenomena have taken on a determining function in conditioning the underground water circulation that locally assumes artesian characteristics. A second alluvial aquifer has also been identified that is partly supplied through lateral contact and through artesian flow, by a deeper aquifer.

The links between the tectonic morphology and underground circulation are then evident. The supply of the main deep aquifer occurs on the Hyblaean relief. Calculations were performed to assess the effective infiltration in the region's different areas according to the nature of the terrain and the climatic conditions and the river waterbed interchanges, which were revealed to be a determining factor in quantifying the supply volume of the aquifers.

Measurements of the spatial distribution of geoelectrical sections of the saltwater–freshwater interface

Although overuse and contamination of groundwater are not uncommon throughout Sicily the proximity of coastal aquifers to saltwater creates unique issues with respect to groundwater sustainability in the coastal region of Donnalucata. These issues are primarily those of possible saltwater intrusion into freshwater aquifers and changes in the amount and quality of fresh groundwater discharging to coastal saltwater eco-systems.

Further development of electromagnetic sounding as a geophysical method in combination with nuclear and isotopic techniques for investigation of SGD is useful for this type of research. Potential directions for field geophysical methods include the development of improved interpretation techniques, particularly for three-dimensional interpretation and integration with other data sets, and the development of survey techniques for high-resolution measurements of geoelectrical slices of small study areas using simultaneous measurements with four sounding loops for spatial and temporal surveys in 3-D geoelectrical section.

Additional methodical measurements are necessary for the reception of complex geoelectrical data in study areas with physical and chemical parameters of subsurface horizon in the field sites, which include:

1. Chloride content based on water sample measurements at the field sites.
2. Measurements of resistivity in the upper level of the sounding area and the conductivity directly on induction logs measured in the well.
3. Laboratory measurements of resistivity of soil samples from the sounding area.

After implementation of all the requirements stated above it is possible to construct closed measures in the saltwater interface, which will allow connection between data from *in situ* isotope and geophysical measurements.

This method will allow for the expansion of information on spatial and temporal variations in the saltwater interface, and its structural and geological properties, which cannot be obtained by alternative methods.

At the present time there is no method for adequate and direct *in situ* measurement of porosity, salinity and resistivity of soil in subsurface horizons. For this reason methodical and experimental investigations for the exploration of the saltwater interface using different field instrumentation represent an important direction for future research for comparative studies in SGD and saltwater interaction, and vadose zone flow processes, pollution determination and monitoring of the coastal zone.

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