A NEW DOWNHOLE, REAL TIME AND NEAR FIELD HYDROGEOPHYSICAL OBSERVATORY OF GROUNDWATER QUALITY: SALT WATER INTRUSION AND TREATED WASTEWATER INFILTRATION

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ABSTRACT

This paper presents the petrophysical interpretation method allowing data inversion from the electrical resistivity into pore fluid conductivity/salinity with applications to salt water intrusions (Hossegor, SW France) and treated wastewater infiltrations (Coutières, W France).

***Key words** : conductivity, monitoring, salt water, treated wastewater.*

RESUME

Ce papier présente la méthode d'interprétation pétrophysique permettant l'inversion de données de la résistivité électrique à la conductivité/salinité du fluide de pore avec des applications à des intrusions d'eau salée (Hossegor, SO France) et les infiltrations d'eaux usées traitées (Coutières, O France).

UN NOUVEAU TYPE D'OBSERVATOIRE HYDROGEOPHYSIQUE TEMPS REEL ET A CHAMP PROCHE DE LA QUALITE DES EAUX SOUTERRAINES: INTRUSION D'EAU SALEE ET INFILTRATION D'EAUX USEES

***Mots clés** : conductivité, monitoring, intrusion d'eau salée, eaux usées traitées.*

.1 INTRODUCTION

The downhole imaGeau observatory (SMD – Subsurface Monitoring Device) provides an opportunity to deploy a vertical string of sensors probing outward into the reservoir in order to study changes over time of pore fluid electrical conductivity (hence salinity) and/or saturation. This in-situ set-up is based on near-field and high resolution (in space and time) measurements of formation electrical resistivity in aquifers.

.2 MATERIELS AND METHODOLOGY

The SMD is designed to measure the formation electrical resistivity in the near vicinity (at dm to meter scale) of a borehole, and to deduce the electrical conductivity of the pore fluid from petrophysical calibration. As much as possible, the downhole array is kept in direct contact with the formation, avoiding a possible bias coming from fluid circulation along the electrical array. The electrical array may be cemented with a bentonite grout, again to protect the hydrological integrity of the penetrated sequence.

The electrical profiles might be used to derive pore water electrical conductivity and, as a consequence, salinity for an equivalent pore fluid with Na^+ and Cl^- ions only. A petrophysical calibration based on core and log analysis is needed, therefore characterising the site, in geological terms (depending on the lateral variability of the site), in hydrogeological (salinity of the pore fluid) and in petrophysical (porosity, density, connectivity) terms.

The data recorded by the observatory depends on the nature and amount of clays, porosity, grain density, pore connectivity, temperature and pore fluid salinity.

From *Sundberg (1932)*, the electrical resistivity R_o of a porous media can be written as a simple product $R_o = F.R_w$ of the electrical formation factor F by the resistivity R_w of the pore fluid (in Ω.m). After *Archie (1942)*, the electrical formation factor F is also related to porosity with:

$$F = \emptyset^{-m} \qquad (1)$$

with Ø for porosity and *m* as a connectivity term for porosity. *m* depends on pore shape, varying from 1,3 for non consolidated sands to 2,5 for cemented carbonates, for example.

From *Sundberg (1932)* and since conductivity is the inverse of electrical resisitivity, we have:

$$\frac{1}{R_0} = C_0 = \frac{C_w}{F} (2)$$

with C_o for porous media electrical conductivity and C_w for pore fluid conductivity. This first order model is however limited to the electrolytic conduction in pore volumes. However, surface electrical conduction cannot be neglected with respect to this electrolytic conduction term in most near surface cases due to the presence of clays. A more complete model proposed by *Waxman*

& Smits (1968) and integrating a surface conductivity term *(C_s)* should be used in this case, with:

$$C_0 = \frac{C_w}{F} + C_s \qquad (3)$$

The surface conductivity term (C_s) is related to the circulation of cations within the Gouy-Stern double layer in relation to the cation exchange capacity (*CEC*) of the minerals. The CEC relates to the number of mobile cations in the pore space per unit mass, expressed in $C.kg^{-1}$. Per unit volume, the *CEC* is called Q_v (expressed in $eq.l^{-1}$, where 1 eq = 96 320 C), with:

$$Q_v = \frac{(1-\emptyset)}{\emptyset} \cdot \rho_m \cdot CEC \qquad (4)$$

where Ø is porosity and ρ_m is grain density (in $kg.m^{-3}$). After *Revil et Glover (1998),* the surface electrical conductivity is expressed in shaly sands by:

$$C_s = \frac{2}{3} \cdot \rho_m \cdot \beta_s \cdot CEC \qquad (5)$$

where β_s accounts for cations mobility in the external part of the double layer. After *Revil et Glover (1998),* β_s = $0{,}51.10^{-8}\ m^2.s^{-1}.V^{-1}$ for an NaCl solution. The surface conductivity can therefore be calculated for a series of selected core samples. These values are then associated to a series of lithofacies, deduced from the Spectral Gamma ray and core descriptions.

Each of these lithofacies therefore has an assigned set of petrophysical data (C_s, Ø and m). From this, C_w is directly obtained by relating the measured C_o to the petrophysical data sets by rearranging equation (3):

$$C_w = (C_0 - C_s) \cdot F \quad (6)$$

The pore fluid salinity is directly obtained by using the UNESCO International Equation of State (IES 80) as described in Fofonoff (1985).

.3 RESULTS

3.1. Salinization of a coastal aquifer (SW France)

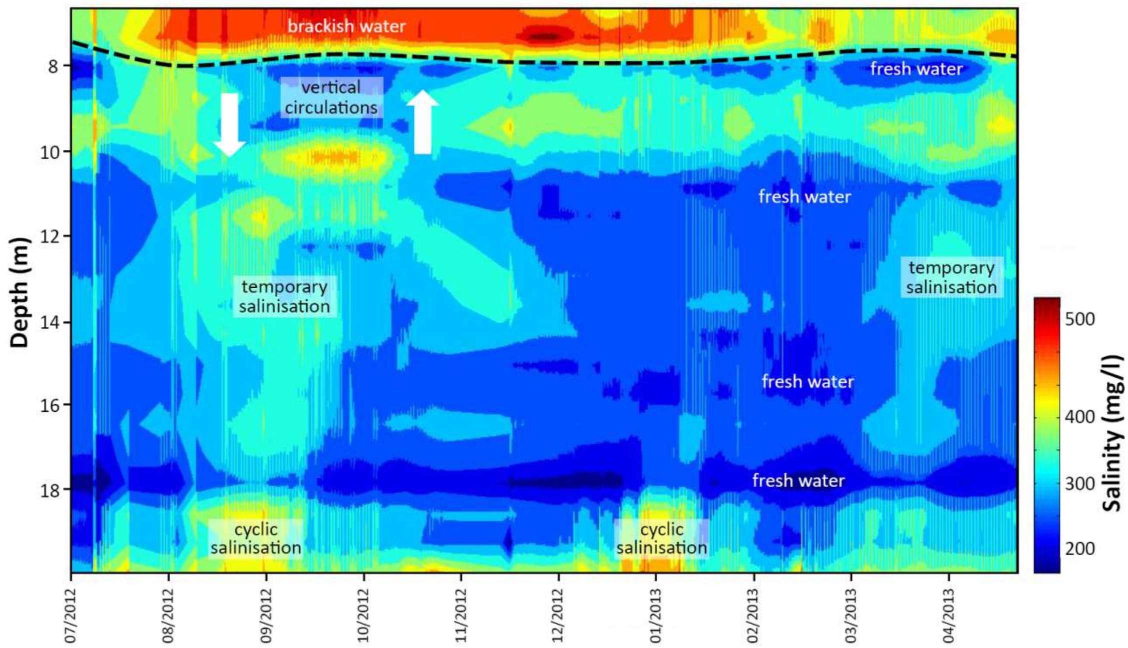

Fig. 1 - Aquifer pore fluid salinity over a 9 month period as derived from resistivity data measured in a dedicated hole equipped with the SMD

In Hossegor (SW France), the coastal aquifer has seen an increase in salinity develop over the past 10 years, especially in case of summer droughts. The goal was to study the mechanism of gradual salinization and to provide the necessary data to emplace a more adequate aquifer management strategy. The observatory installed in Hossegor is equipped from the surface down to 21 m in depth with 70 cm spaced permanent electrodes. It was calibrated against induction resistivity logs recorded in a nearby borehole.

The downhole pore fluid salinity is not homogeneous throughout the studied sequence, revealing details of the aquifer's sensitivity to salinization. More than 9 months of daily probing show not only seasonal changes but also a heterogeneous profile of pore fluid salinity, far from the first order model expected from the Ghyben-Herzberg gravity model.

From 6.0 to 8.0 m depth (Figure 1; zone 1), seasonal changes in salt content are noticed independently of pumping in the nearby hole, showing the impact of a pumping zone (called AEP) located more to the west. From 8.0 to 12.0 m depth (Figure 1; zone 2), the salinization is less severe than above, restricted to a 2 m-thick zone appearing to deepen with time in relation to pumping. For these two zones, the hypothesis of a surface source for the salinization is thus preferred. From 18.0 to 20.0 m depth (Figure 1; zone 3), a more cyclic signal is obtain, with an apparent relationship to pumping (indicated by vertical line within the Figure 1). The salinity decrease obtained in the fall, after the relative over drafting in summer, provides a proof that the aquifer is presently not over exploited by the nearby hole.

3.2. Infiltration of treated wastewater

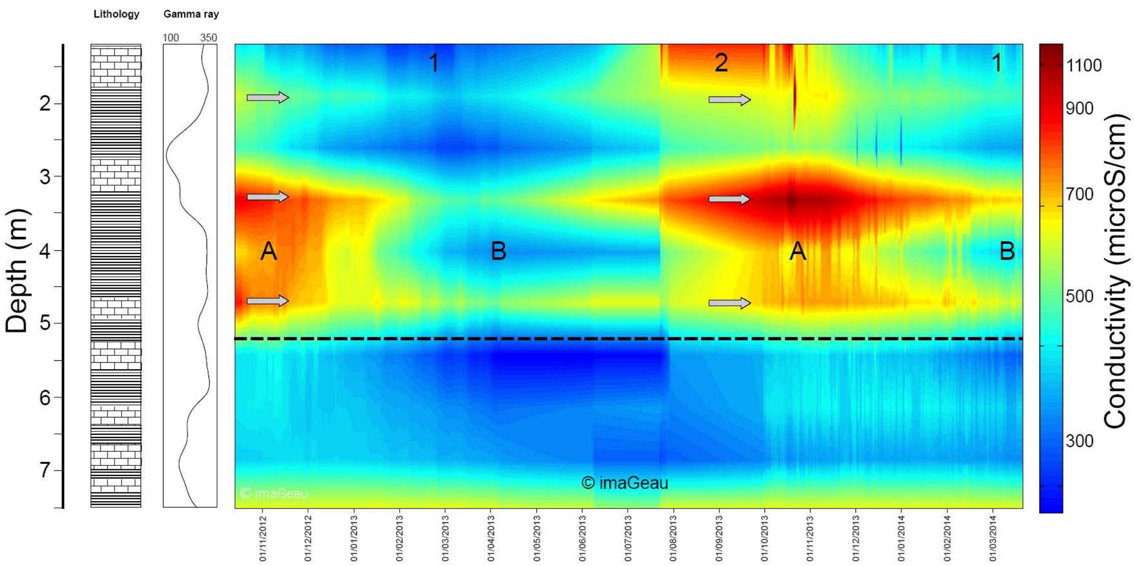

Fig. 2 - Aquifer pore fluid conductivity over a 18 month period as derived from resistivity data measured in a dedicated hole equipped with the SMD. Gamma ray indicates the presence and amount of clay. 1: rainwater, 2: treated wastewater near the surface, A: treated wastewater within the aquifer, B: fresh water

A process of treated wastewater infiltration is experimented by the Saur Company at Coutières, West France. In this project, the groundwater quality is a critical parameter and is therefore monitoring with 2 SMD that are equipped from the surface down to 9 m in depth with 70 cm and 35 cm spaced permanent electrodes. The two SMD were calibrated against induction resistivity logs recorded in a nearby borehole. Over 18 month, the downhole pore fluid conductivity reveals the entry of treated wastewater into the groundwater and the efficiency of natural wastewater treatment played by rock-fluid exchanges between treated wastewater and clays as parts of the groundwater on the one hand and dilution on the other hand. It is noteworthy that the pore fluid conductivity is highest soon after groundwater low tides, while the lowest conductivity is obtained during groundwater recharge and raining season.

RÉFÉRENCES BIBLIOGRAPHIQUES

ARCHIE G.E., 1942 – The electrical resistivity log as an aid in determining some reservoir characteristics. . *Petroleum Transactions of AIME., 146, 54-62.*

GUEGUEN, PALCIAUSKA, 1992 – Introduction à la physique des roches. *192 pages.*

RAYNAL, O., BOUCHETTE, F., CERTAIN, R., SERANNE, M., DEZILEAU, L., SABATIER, P., LOFI, J., BUI XUAN HY, A., BRIQUEU, L., PEZARD, P.A., TESSIER, B., 2009 – Control of along shore-oriented sand spits on the dynamic of a wave-dominated coastal system (Holocene deposits, northern Gulf of Lions, France). *Marine Geology, 264, 242-257.*

REVIL A., CATHLES, L.M., 1999 – Permeability of shaly sands. Water *Resources Research, 35, 3, 651-662.*

REVIL A., GLOVER, R., 1998 – Nature of surface electrical conductivity in natural sands, sandstones, and clays. *Geophysical Research Letters, 25, 5, 691-694.*

WAXMAN M.H., SMITS L.J.M., 1968 – Electrical conductivities in oil-bearing shaly sands. *SPE Journal, 8, 2, 107–122.*

WYLLIE M.R.J., GREGORY A.R., GARDNER L.W., 1956 – Elastic wave velocities in heterogeneous and porous media. *Geophysics, 21, 41-70.*