Hanoi University of Mining and Geology (HUMG) and the International Society for Mine Surveying (ISM) organize the International Conference on Geo-spatial Technologies and Earth Resources in Hanoi, Vietnam, from 5th to 6th October 2017 (GTER 2017). The conference is to mark the 50th anniversary of the Vietnam mine surveying education (1967-2017), the special event of Vietnamese mine surveyors.

The conference theme, "Geo-spatial Technologies and Earth Resources" is an invitation to researchers, academics and professionals to present their research results and exchange their new ideas and application experiences face-to-face. GTER 2017 is also an excellent opportunity for attendees to establish research or business relations and to find partners for future collaboration.

The conference's call for papers was answered by 288 abstracts, of which 216 papers were under a double-blind review process. After the thorough reviews and selection process, 119 qualified papers from 20 countries were selected for the proceedings.

The major topics announced for GTER 2017 are listed below:
- Geo-spatial technologies;
- Advance in mining and tunneling;
- Geological engineering;
- Environmental engineering.

The content of the proceedings book provides a broad overview of recent advances in the fields of geo-spatial technologies and earth resources for readers.

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La Phu Hien

Geo-spatial Technologies
and Earth Resources (GTER 2017)

Publishing House for
Science and Technology

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Geo-spatial Technologies and Earth Resources

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Table of Contents

Foreword

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- Geo-spatial technologies;
- Advance in mining and tunneling;
- Geological engineering;
- Environmental engineering.

The conference program represents the efforts of many people. We would like to express our gratitude to the members of the Organizing Committee, Scientific Committee, and the external reviewers for their hard work in reviewing submissions. Full recognition is accorded to the kind and generous sponsors: Vietnam National Coal - Mineral Industries Holding Corporation Limited, Dong Bac Corporation, SISC Vietnam JSC, GPS Lands (Malaysia), and Henan Polytechnic University (China).

Finally, my greatest appreciation goes to Nguyen Quoc Long, Pham Thi Lan, Nguyen Viet Nghia, Khuong The Hung, Le Thi Thu Ha, and La Phu Hien for their dedication and tireless work in organizing the conference and editing this volume of the proceedings.

GETR-2017 Conference Chair

Prof. Le Hai An

3D modelling of saltwater intrusion in coastal area combine with geophysics and isotopic approaches

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Abstract

Models of groundwater subjects to variable density suffer from several difficulties:1) The change of the aquifer permeability due to density of salinity is difficult to take into account during simulation and generates instability. 2) Influences of heterogeneity in this context are more important than in other setting having constant density. 3) Data set must be detailed in order to get a reliable model results. 4) In general, the results of modeling are less robust. This research focuses on the effect of variable density in groundwater on the modeling of seawater intrusion in coastal aquifers.

To address and discuss these problems, we set up a three-dimensions variable density groundwater model using FEFLOW. The studied area is the Crau aquifer, in the Mediterranean region of Southern France. The area has been chosen because of having long term records of hydrogeological and climatic data such as salinity, piezometric levels, water geochemistry, rainfall, irrigation seepages and exploitation, etc.

The results indicate that the interface between freshwater and saltwater is very influenced by the heterogeneities in aquifer properties and the effects of irrigation and groundwater withdrawal. To better constraint the data set for the variable-density flow model, geophysical acquisitions have been carried out using Electrical Resistivity Tomography (ERT) and Electromagnetic (EM) surveys. This has provided subsurface information on vertical salinity and lithology distribution. Furthermore, groundwater discharges into ponds and canals surrounding the study area, were assessed during the course of this study by using ^{222}Radon mass balance between ponds and groundwater, as well as salinity data. The groundwater flux has been estimated by ^{222}Radon experiment in single well.

Keywords: saltwater intrusion, FEFLOW, EM-34, ERT, Radon, Crau aquifer.

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1. Introduction

Shi and Singh (2003) estimated that by 2050, 72% of the world population would live in coastal zones with a rapidly increasing demand in water supply. In this perspective, coastal groundwater is considered today as a strategic resource for future urban development, agriculture and industry. Coastal groundwater resources were therefore the focus of a large number of studies, including characterization of resources, modeling, vulnerability assessment and prediction (Werner et al, 2013). In many cases, seawater intrusion is the main process responsible for degradation of groundwater quality in coastal zones. A good example of aquifer vulnerable to salinization is the Crau aquifer, close to the Mediterranean Sea in southern France (Fig.1). This aquifer provides today high quality water for about 300,000 inhabitants, 57,036 ha of farming land (INRA, 2013), about 5,000 ha of protected natural area (Coussouls National Reserve) and several industrial complexes (industrial harbor of Marseille). Groundwater induces diffuse springs all along the Viguerat wetland/marsh (Fig.1), which is a fragile humid ecosystem (Ramsar and Natura 2000 site). The spring water draines to canals (Viguerat, Vergiere and Centre-Crau canals, Fig. 1) then enters the wetland area and contributes to the regulation of its salinity and water level.

Groundwater salinity in the Crau aquifer has been constantly monitored since 1984. Although an increase in salinity has been observed close to the Vigueirat wetland system, the saltwater front seems to be relatively stable over time. This nearly steady-state condition could however change in the near future due to the increasing exploitation rate of this water resource, sea-level rise and change in groundwater recharge, as discussed by Olioso et al. (2012), and also in response to the general global-change scenario as discussed by Holman et al. (2012). Quantification of groundwater flows in this setting is therefore an important step toward the management of groundwater resource, i.e. its survey, control and optimization.

In this study, radon activity in groundwater was used to estimate groundwater-to-surface-water fluxes downstream of the Crau aquifer. The salinity distribution was also measured by using geophysics methods including electrical resistivity tomography (ERT) and Electromagnetic (EM). These data were finally used to validate and calibrate a 3-D numerical model of flow and saltwater intrusion into this coastal aquifer.

2. Study area

The study area is the downstream, coastal part of the Crau aquifer (southeastern France, Fig. 1), located to the East of the Rhône River delta (Camargue National Park). The Crau aquifer corresponds to the 600 km^2 paleo-delta of the Durance River, extending between the cities of Arles, Salon-de-Provence and Fos-sur-mer (Boyer et al., 2005; De Montety et al., 2008, Molliex et al., 2013). This study focused in particular on the SW downstream part of this aquifer, on an area of about 140 km^2 (Fig. 1) where the aquifer is partially affected by saltwater intrusion.

The aquifer is made of Quaternary coarse-grain deposits lying on a Pliocene marl substratum (Vella et al, 2005). The depositional age of the sediments varies between 2.0 and 0.6 million years (My) in the western side (ancient Crau), between 0.6 and 0.1 My in the eastern area (recent Crau), and between 100 and 10 ky in the north-east sector (town of Miramas).

The deposits are mainly composed by gravels and pebbles from the Alps, having variable lithology, with dominant contributions of magmatic rocks (granites). Locally these sediments are partially cemented (conglomerates) or associated to a matrix of finer materials (silty sand). The thickness of the deposit is variable, from a few meters to 50 m in river paleo-channels (Roure et al., 2004). In the studied sector, the depositional surfaces have a slight slope to the southwest, which is also the general trend of groundwater flow. Due to the alluvial placer dynamic, the hydraulic conductivity (K) is very variable. Estimates of K range between 4.0×10^{-5} and 1.6×10^{-2} m/s (BRGM, 1995) and between 1×10^{-5} and 8×10^{-2} m/s (INRA, 2013). Resulting transmissivity generally varies between 5×10^{-3} and 5×10^{-1} m^2/s.

The Crau aquifer is commonly unconfined, but becomes semi-confined and confined in the marsh area of Vigueirat and Landre ponds (Fig.1), due to the presence of semi-pervious material (Rhône river sediments and lacustrine deposits). Thickness of this material varies from 0 to 7 m and its hydraulic conductivity (K) is between 3.7×10^{-5} and 8.7×10^{-3} m/s (INRA, 2013). The specific yield of the aquifer, obtained from pumping tests, is in the range of 0.01 to 0.18 attesting to the unconfined to semi-confined (leaky) behavior of the aquifer.

The hydraulic head is about 7.5 - 8.0 m above sea level (asl) in the north-eastern area and decreases to the west with a mean hydraulic gradient of 2-3‰.

The aquifer is recharged by rainfall and irrigation water. About 15,000 ha of meadow are irrigated with water from the Durance River through a dense network of channels while about 5,000 ha of orchards are irrigated with local groundwater. Irrigation is estimated to contribute 50% to 80% of the total recharge. Rainfall mainly occurs during December and January while irrigation mainly occurs during the summer. Groundwater discharges into the ponds of the Vigueirat Natural Reserve and likely into the Rhône River. The aquifer is subject to intensive water withdrawal that reaches about 56,600 m^3 a day. Part of this exploitation is used for irrigation and another returns into the aquifer.

The study area is bordered by the Arles-Fos canal that has its supply of freshwater from the Rhône River and constitutes a stable boundary condition. Groundwater locally presents significant salinity that may have different origins. One of them is the digging of the industrial harbour of Fos-Marseille, during which the Rhône and Crau deposits were removed, causing the direct contact of the fresh groundwater with seawater. Another source of salinity is the important evaporation occurring at the Vigueirat - Landre ponds/marshes, which increases the salt content of the subsurface water. Finally, a salt-water origin may be the ancient shoreline that was north of the Vigueirat ponds 2,000 years ago (Fig.1).

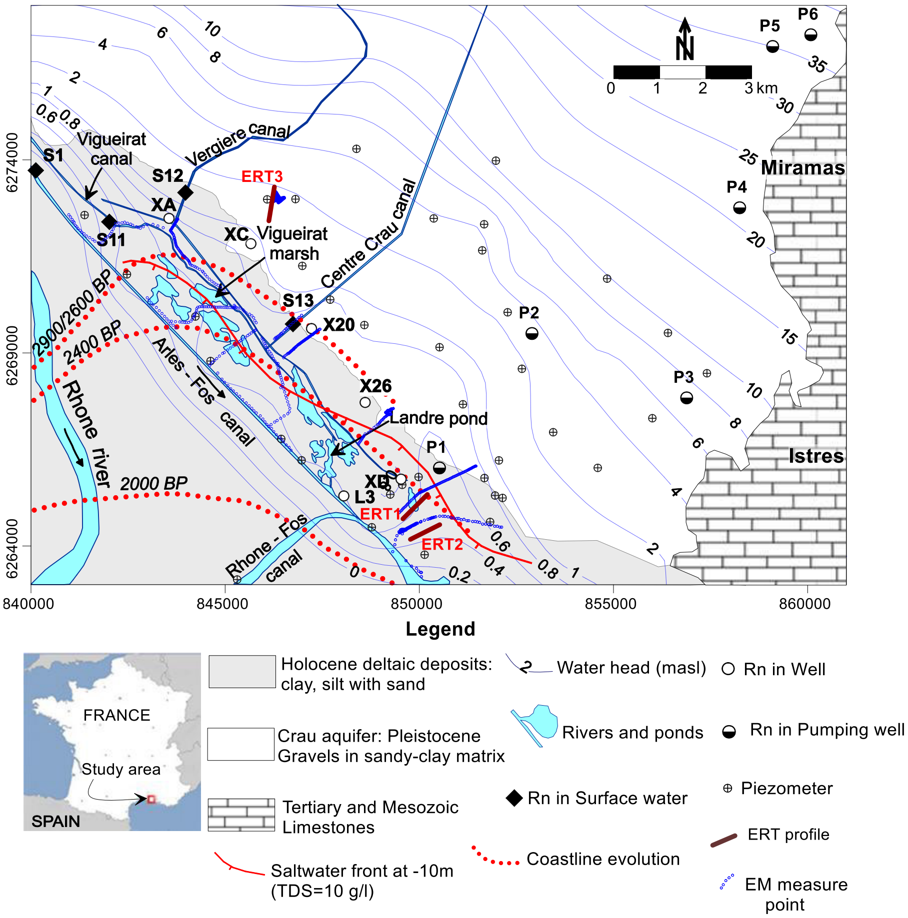

Fig. 1. Geological sketch map of the south-west termination of the Crau aquifer. Water-table contour lines (fine black lines) were obtained from piezometric surveys done during this study. The limit of the saltwater front (thick black line) was obtained from electrical conductivity logs. Evolution of past coastline (dotted lines) is redrawn after Vella et al. (2005).

3. Methods applied to the research area

The research focuses on the constraints related to the modeling of groundwater in the coastal downstream part of the Crau aquifer. In such aquifer, the concomitant presence of freshwater and saltwater modifies flow patterns typically represented by the Darcy equation. Works on this groundwater are difficult because of the influence of salinity on properties (density and permeability) and the complex mathematical representation of the flow equations. Moreover, the influence of heterogeneities makes the model parameterization and calibration to be more difficult.

To help such works, we propose to combine four methods:

(i) Hydrodynamic measurements to precise the boundary conditions, including two different measurements:

- Monthly water head measurements for a period more than one year to determine hydraulic head gradient, then groundwater flow direction and velocity.
- Continuous recording of hydraulic head, temperature and salinity for a long period to compare and validate the simulations.

(ii) Geophysical investigations to provide information about the solutes concentration distribution in groundwater (by the mean of electrical resistivity distribution) and validate the model, including two different methods:

- Electrical resistivity tomography (ERT) to provide continuous characterization of subsurface electrical conductivity,
- Electromagnetic (EM) to mapping terrain conductivity.

(iii) Isotopic measurements to quantify groundwater velocity and discharge and validate the simulated flow, including two different experiences:

- Radon (^{222}Rn) monitoring for water in canals and ponds to estimate groundwater discharge to the surface water,
- Estimate the ^{222}Rn decay in single well to estimate groundwater flow rate (Darcy velocity) in aquifer,

(iv) 3D numerical modeling to simulate flow and saltwater intrusion into this coastal aquifer.

3.1. Geophysics investigations

3.1.1. Electromagnetic (EM) mapping

One of the most popular geophysical methods currently used to provide information about the spatial variation of soil properties is EM induction. EM methods were originally developed for mine exploration and have been widely used over the last decades for groundwater investigations with cost effective and reliable. These techniques have been described in geophysical handbooks and scientific papers (Borne, 1990; McNeill, 1980; Santos, 2004; Stewart and Gay, 1986; Stewart, 1982; Triantafilis et al., 2003). This technique is widely used for engineering purposes and is cost effective and reliable. Then, despite the qualitative nature of the provided information, this method is widely applied for hydrogeological and environmental investigations. Many applications of electromagnetic surveys were applied for resources management in coastal aquifer (Frohlich et al., 1994; Goldman et al., 1991; Stewart, 1982)

In this study EM31 and EM34-3 (Geonics Ltd) were used to map the terrain conductivity. These equipments could create a map of ER while the operator were walking.

3.1.2. The Electrical Resistivity Topography (ERT)

Electrical resistivity (ER) is one of the main properties adapted to hydro-geophysical studies. The resistivity of rocks is affected by different factors (Matsui et al, 2000), e.g. porosity, pore fluid resistivity, water saturation, water content by volume and clay content, etc. The advantage of this method is the quality of the electrical resistivity data obtained with relatively high spatial resolution and the possibility to obtain continuous coverage of the underground in 2D and 3D spaces.

In this research, three ERT profiles (SW-NE oriented) were measured. Profiles ERT1 and ERT2 were located SW of area, perpendicularly to the saltwater-freshwater limit. ERT3 profile was done in the center of area to determine the geological features (Fig.1). Investigations were done with a multi-electrode ABEM Lund Imaging System, with inter-electrode spacing of 5m.

3.2. Radon (^{222}Rn) measurements to estimate groundwater discharge into surface water

Radon (^{222}Rn) is a radioactive gas produced by the decay of radium (^{226}Ra). In groundwater, radon activity originates essentially from ^{226}Ra adsorbed on mineral surfaces in the aquifer with a little contribution from dissolved ^{226}Ra. Natural radon is a good groundwater tracer because of its inert chemical behavior, its elevated concentrations in groundwater and its "lack of memory" after a few days (half-life = 3.8 days). Several recent studies also used radon activity in surface water surveys to localize and quantify groundwater discharges into rivers, lakes, lagoons and the sea (eg. Dimova et al, 2013, Rodellas et al, 2012, Stieglitz et al, 2013).

The observed enrichment of radon in groundwater relative to the surface water bodies, e.g. water in the sea, helps to understand the groundwater-seawater interactions occurring in a wide range of time scales. Because the ^{222}Rn concentrations in surface waters are usually low and due to its short half-life, large volume water are required for the measurement of ^{222}Rn and hence in situ monitoring is required using RAD7 radon monitors (Durridge Co. Inc.) and RAD H2O and a RADAQUA water exchanger

3.3. Numerical modeling of heterogeneity and variable-density flow using FEFLOW

In this study FEFLOW (Finite Element Subsurface Flow Simulation System) program was used to model the heterogeneity and variable-density flow. The FEFLOW is a finite-element package for simulating 3D and 2D fluid density coupled flow, contaminant mass (salinity) and heat transport in porous and fractured media.

The package is fully graphics-based and interactive. Pre-, main- and post processing are integrated. There is a data interface to GIS (Geographic Information System) and a programming interface. The implemented numerical features allow the solution of large problems. Adaptive techniques are incorporated.

4. Results and discussion

4.1. Geophysics survey

The main objectives of geophysical methods are saline intrusion mapping and aquifer characterization (depth of aquifer/water head, spatial dimensions and properties of geological formations).

In order to interpret the indirect geophysical measurements, a comparison have been done between geophysical data and lithological information from boreholes and water level, electrical conductivity measurements from piezometers in this area.

4.1.1. Electromagnetic mapping with EM34

After two campaigns of EM survey, 12 profiles of EM34 have been done (Fig.1) in the marsh area, with 10 profiles perpendicular with salt-freshwater limit and two others along the canals. The spatial distribution of apparent soil electrical conductivity (σ_a - mS/m) of EM34-20 was compared with a spatial distribution of electrical conductivity (EC) measured from in pore water at 10 m depth. The small σ_a (<30 mS/m) characterizes a freshwater zone in the center and northeast of Crau. In the zone along the Colmatage canal in center of marsh area, σ_a varies from 30-80 mS/m characterizing a saline intrusion zone, equivalent to EC from 6000-18000 µS/cm. In the southwest area, σ_a is very high (>100 mS/m) characterizing the saltwater zone.

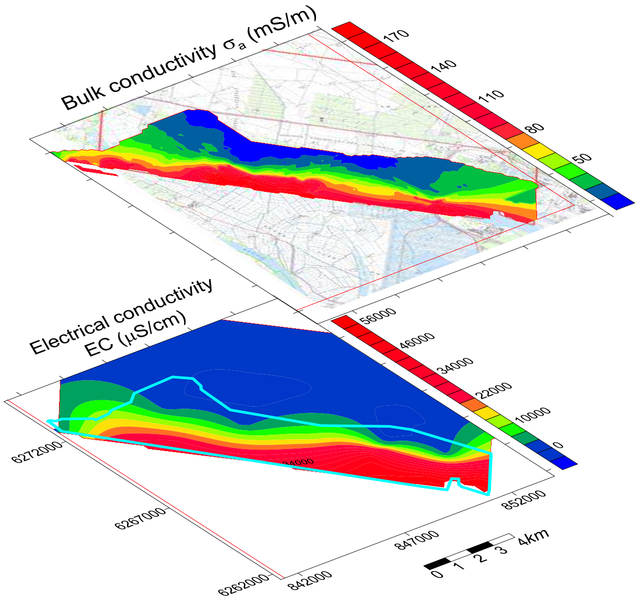

Fig. 2. Spatial distribution of apparent electrical conductivity σ_a (mS/m) with EM34-20m HDM (upper) and electrical conductivity EC_e (µS/cm) in groundwater at -10m depth from groundwater level in piezometers (lower), red and blue colours represent the conductive and resistive layers

4.1.2. Electrical Resistivity Tomography (ERT)

It was revealed a high contrast of electrical resistivity along the Profile 1 (Fig.3). Below 30 m depth, very low resistivity (a few ohm.m) are observed and probably interpreted as the substratum of clays and marl of Pliocene. Between 20-30 m depth, resistivity varies between 10 and 40 ohm.m that reflects salt and brackish water coming from SW to NE. At about 5 to 20 m depth a high resistivity (> 40 ohm.m) was observed, reflecting the aquifer of gravel with freshwater/brackish water. The shallow part of the profile (up to 5 m) showed low resistivity corresponding to superficial Holocene sediments made of sandy clay. Low resistivity may also result from the increase of salt content due to the evaporation (transpiration). High resistivity zone in the shallow part is due to the channel fresh water.

4.1.3. Aquifer porosity

The porosity was estimated using Archie's law. The relationship between bulk resistivity of a saturated porous medium ρr (Ohm.m) and its porosity ϕ and resistivity of pore water ρw (Ohm.m) is expressed by Archie's equation (Archie, 1942)

$$\rho_r = \rho_w \frac{a}{\phi^m} = F\rho_w \tag{1}$$

And similar for the bulk electrical conductivity (σ) and pore water conductivity (σ_w)

$$\sigma_r = \sigma_w \frac{\phi^m}{a} = \frac{\sigma_w}{F} \tag{2}$$

where $F = a/\phi^m$ (Humble formula, in (Winsauer et al., 1952) is an intrinsic parameter representing the micro-geometry of the material; m and a are dimensionless material-dependent empirical factors; m is known as the cementation index and a is the coefficient of pore tortuosity. For unconsolidated sandstone formation, parameters a and m can be set to 0.81 and 2 respectively (Winsauer et al., 1952), then $F=0.81\phi^2$.

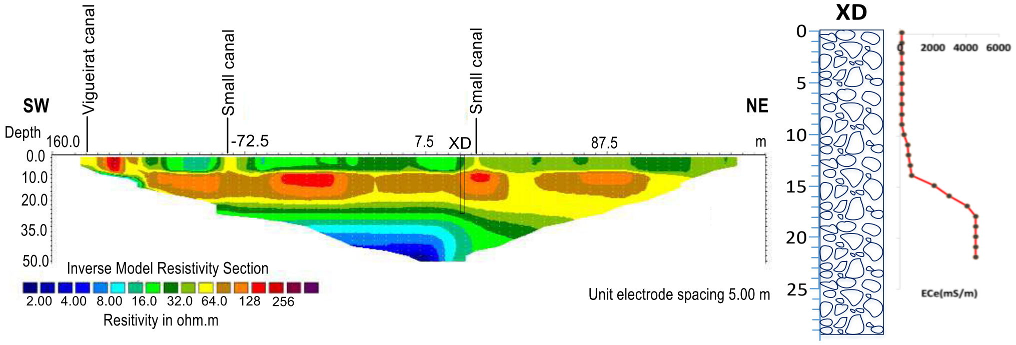

Fig.3. (left) 2-D electrical resistivity tomography on section ERT1 profile (with location of XD borehole) and (right) vertical distribution of electrical conductivity in pore water of XD

The porosity calculated using Archie's law varies from 4% to more than 30% on top, with an average of 11.5%. This value is comparable to the one found in another research for the Crau aquifer (Olioso et al., 2013) . The very high porosity between 0 and 8 m depth corresponds to the high content of clay constituting the Holocene sediment. The porosity values at some depth are quite small (about 4-5%) that can be explained by the conglomeration (cementation) of sand and gravels.

4.2. Groundwater discharge into ponds

The radon mass balance imposes that the total input of radon equals the total output of radon. For the Crau-Vigueirat system, and assuming a steady-state condition, the radon mass balance may be written as:

$$F_{river} + F_{diff} + F_{Ra} + F_{gw} = F_{decay} + F_{air} + F_{out} \tag{3}$$

F_{river} is the radon flux from the river (Bq/d), $F_{river} = Rn_{river} \cdot Q_{river}$, where Q_{river} is the river water flow in the three canals (Vigueirat, Centre Crau and Vergiere) and estimated as high as 3 m^3 per s; Rn_{river} is the weighted average radon activity measured in the canals. The flux F_{river} accounts for 72.8 MBq/d.

F_{diff} is the radon flux produced by sediments diffusion. This term is a constant radon input through the sediment interface even in the absence of groundwater discharge. The value of F_{diff} (2.2 Bq/m^2/d, i.e. 2.1 MBq/d for the total pond surface of 0.95 km^2) comes from a previous study (Radakovitch et al. 2007; GIZCAM, 2009) made on sediments having similar origin and permeability in a nearby zone (Vaccares).

F_{Ra} is the flux produced by the disintegration of the dissolved ^{226}Ra. This flux accounts for 0.9 Bq/m^2/d, i.e. 0.9 MBq/d for the total pond and was calculated as $I_{226\text{-}Ra} \cdot \lambda^{222}$, where $I_{226\text{-}Ra}$ is the inventory of ^{226}Ra in the water column, using a water column height (h) of 0.5 m and a ^{226}Ra activity of 10 Bq/m^3 as measured in the Vaccares pond (Radakovitch et al. 2007; GIZCAM, 2009); λ^{222} is the decay constant of ^{222}Rn (1/d).

F_{decay} was calculated as $I_{222\text{-}Rn} \cdot \lambda^{222}$, where $I_{222\text{-}Rn}$ is the radon inventory, estimated as $Rn_{ave} \times h$, where Rn_{ave} is the average radon concentration measured in 26 individual points within the pond. Rn_{ave}=76 Bq/m^3 with an error of 15-30%). The calculation gave F_{decay} = 6.6 MBq/d.

F_{air} is the flux of radon emanated to the atmosphere. The F_{air} was evaluated using the gas transfer velocity (k) approach.

F_{out} is the radon output flux due to the water leaving the pond through the Landre outlet and it was obtained by multiplying the average radon activity measured 13 times at the outlet of the pond with ±7 Bq/m^3 by the total water outflow (m^3/d). The latter was calculated as the sum of all water inputs into the ponds corrected for the evaporation. This assumes a steady state condition in terms of water volume over the pond surface. The total water input to the pond is the sum of river and canal inputs and it was as high as 3.01 m^3/s, groundwater (initially assumed to be negligible) and rainfall cumulated during the water residence period preceding the radon measurements (12 mm rainfall from 21st to 23rd March 2014, equivalent to a total rainfall input of +0.07 m^3/s). The evaporation during the same period is 0.027 m^3/s. Hourly data used to calculate the cumulated rainfall and evaporation were obtained from the INRA station of Salon de Provence. The total radon loss at the outlet of the pond was 3.49 MBq/d.

From equation (3), the radon flux due to groundwater discharge into the ponds F_{gw} could be calculated based on the data obtained either by direct measurement in the field or estimation as presented above. The values of all variables used in this calculation are summarized in table 5.

Using eq. 3, the total daily inputs of radon into the ponds, beside groundwater, was estimated as high as 76 MBq/d. On the other hand, the total outputs were in a range of 101–128 MBq/d as estimated by the atmospheric flux model developed by Cockenpot et al (2015) with its analytical uncertainty. The imbalance due to the F_{gw} is thus ranged from 26 to 52 MBq/day. The radon activity in the wells was found to be 10 kBq per m^3, thus the vertical water seepage necessary to support the radon flux F_{gw} would be as high as 2.7 to 5.5 mm/day, e.g. 2.7 to 5.5 l/m^2/day. This seepage over the pond area corresponds to a total groundwater discharge of $2.5{\cdot}10^3$ to $5.2{\cdot}10^3$ m^3/day or 30 to 60 l/s. Such groundwater flow accounts for about 1 to 2 % of the total freshwater input from canals of 3.0 m^3/s. This flux is thus negligible in terms of water supplied to the pond and corroborates the initial assumption of no groundwater flux for the calculation of F_{out}. The total uncertainty in the final mass balance is difficult to estimate since the calculation is strongly dependent of the model of k and of the steady-state condition. The groundwater discharge remains, however, negligible over the range of F_{air} deduced from the model uncertainty (table 5) and represents, in any case, the largest flux affecting the radon mass-balance of the Landre Pond of up to 91 % of the total output flux.

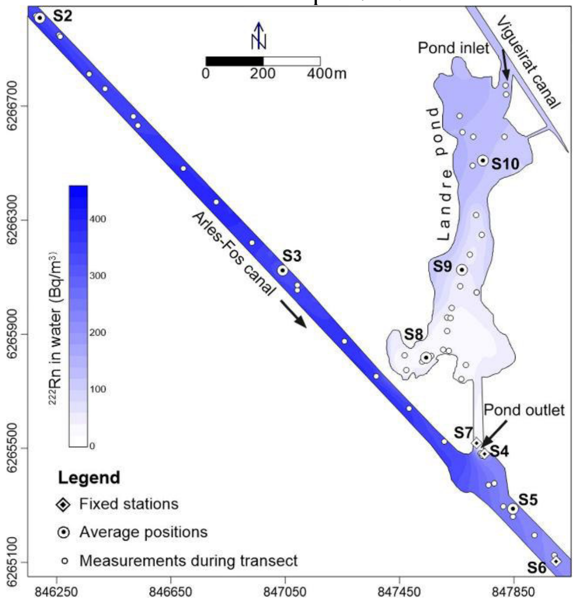

Figure 4. Enlarged inset of Fig.1. Activity of radon measured in surface water in the Arles-Fos canal and in the Landre pond during the navigation. Stationary stations S2 to S10 are radon measurement points with a boat maintained in a fixed location (counting time was 45 min). Average positions are the centroids of several consecutive points of continuous radon measurement done during a boat transect. White dots represent positions reached during transects and 15-minute integrated measurements.

4.7 Groundwater discharge into Arles – Fos canal

The Arles – Fos canal is excavated to the limit between the Holocene Rhône sediments and the Crau formation. The depth of the canal (more than 2 m, with a water height of about 1.7m) is sufficient to intercept the upper part of the coarse material of the Crau aquifer (thickness of sandy silt being 2 to 3 m as indicated by borehole logs). Therefore, a significant input of groundwater is expected to discharge into the canal. The high radon activity measured in the canal (312 Bq/m^3) confirmed a significant groundwater discharge. The groundwater flux necessary to support the observed radon activity in the canal was calculated, assuming that the measured activity was at a steady-state, i.e. the radon lost by degassing and decay are compensated by groundwater discharge, diffusion and radium decay:

$$F_{diff} + F_{Ra} + F_{gw} = F_{decay} + F_{air} \tag{4}$$

For the calculation, F_{diff} and the activity of ^{226}Ra in water in the previous section were resumed, and water column of 1.8 m for radium and radon inventories in the canal were also assumed. F_{atm} was taken from the previous section. The F_{gw} necessary to support radon activity in the canal was then estimated as high as 548 Bq/m^2/day. This flux does not generate a high radon activity in the canal (312 Bq/m^3) but corresponds to the flux required only to maintain a stationary radon activity. The calculated groundwater discharge into the canal is 55 l/m^2/day (Mayer et al., 2016).

4.3. Numerical model

The topography is based on kriged information from 203 boreholes/wells and national geodesic points (http://geodesie.ign.fr/). The main geometric-structural and hydrogeological characteristics of the study area were based on geological and lithological descriptions of boreholes and results of geophysics surveys (3 ERT profiles and 12 EM profiles). The digital elevation model (DEM) of each layer surface was interpolated by ordinary kriging.

From both 3D models from geophysics and groundwater model, the distribution of EC and TDS are qualitatively comparable.

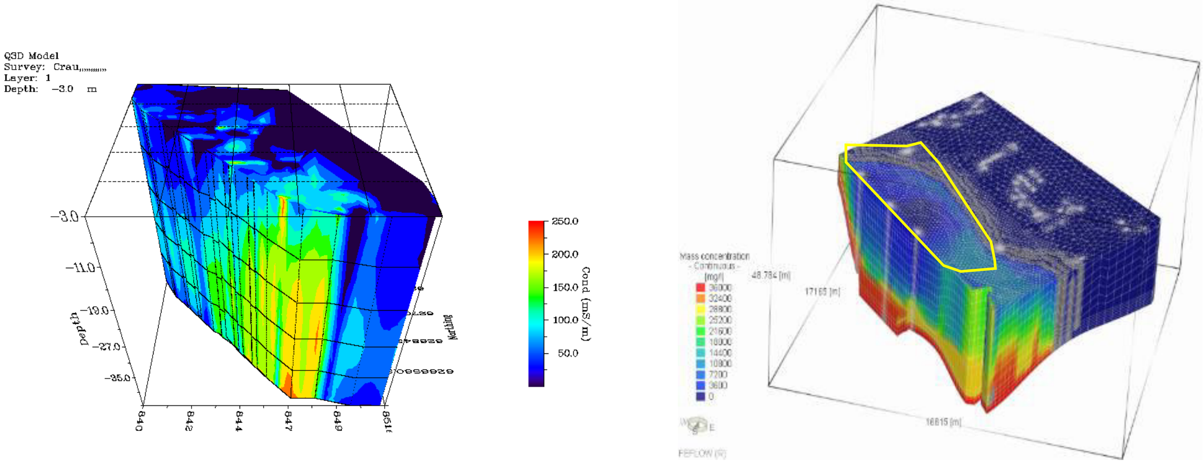

Fig.5. 3D distribution of estimated EC (σ - ms/m) from a joint inversion of EM34-10, EM34-20 and EM34-40 data using a 1-D laterally contrained algorithm for quasi-3D EC imaging (left) and 3D distribution of TDS concentration (mg/l) from 3D groundwater model (right)

Conclusions

Simulation of variable-density flow system in heterogeneous hydrogeological conditions is complicated and sensitive due to the non-linear coupling between the flow and transport equations. Thus, observed data of salinity from wells and boreholes are normally not enough to validate a saltwater intrusion model. Combination of different methods like geophysics and isotopes would help to better parameterize and validate the saltwater intrusion modeling.

In this study radon-222 activity in water from boreholes and wells was used to assess groundwater velocities in the Crau aquifer (France), to highlight pattern of groundwater discharges and to constraint water-mass balance. The radon activity in groundwater and surface water was used to estimate the exchange between groundwater and surface water. Using the data of continuous ^{222}Rn measurements and the balance box model the groundwater and surface water mass-balance was calculated. The surveys of Rn activity in surface water suggested insignificant discharge of groundwater to surface water (55 l/m^2/day). The method applied could be useful for large areas of surface water and/or too deep to install a seepage meter.

Results of the ERT and EM investigations showed a low resistivity area characterizing for low salt intrusion is located in the southwest of the study area. In the marsh area, low resistivity was found near the surface confirming the presence of a clay layer on top and the salinity in surface water might be caused by the evaporation. A 3D finite element model was built with FEFLOW software to simulate groundwater flow and the transition between saltwater and freshwater and it was validated well with the experimental measurement.

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