Detection and quantification of low submarine groundwater discharge flows by radionuclides to support conceptual hydrogeological model of porous aquifers

S. Santoni^{1,2,*}, E. Garel^{1,2}, A. Mayer³, O. Radakovitch^{4,5}, Y. Travi³, F. Huneau^{1,2}

¹Université de Corse Pascal Paoli, Faculté des Sciences et Techniques, Département d'Hydrogéologie, Campus Grimaldi, BP 52, F-20250 Corte, France.

²CNRS, UMR 6134, SPE, F-20250 Corte, France.

³Avignon Université, UMR 1114 EMMAH, UAPV, 301 rue Baruch de Spinoza, BP 21239, F-84916 Avignon, France.

⁴Aix-Marseille Univ, CNRS, IRD, INRA, Coll France, CEREGE, 13545 Aix-en-Provence, France.

⁵Institut de Radioprotection et de Sûreté Nucléaire (IRSN), PSE-ENV/SRTE/LRTA, BP 3, 13115 Saint-Paul-Les-Durance, France.

(*) Corresponding author: Sébastien Santoni, Département d'Hydrogéologie, UMR CNRS SPE 6134 Université de Corse Pascal Paoli, Campus Grimaldi, F-20250 Corte, France. Contact: santoni_s@univ-corse.fr or santonisebastien17@gmail.com

Highlights

- Low and diffuse submarine groundwater discharge flows are investigated.
- Groundwater flow velocity from ²²²Rn and from Darcy law are in agreement.
- Discharge rates are in agreement with recharge rates solving aquifer water balance.

Abstract

Submarine groundwater discharge (SGD) is considered as a good indicator of the natural behavior of coastal aquifers especially in the case of intense groundwater withdrawal or when the aquifer recharge conditions are limited. Indeed, a decrease in SGD flows would result in saline intrusion compromising the groundwater reservoir use. The need for SGD studies in Mediterranean and semi-arid environments have long been recognized and little is known on low and diffuse flows. For this reason, the detection and quantification of low and diffuse SGD flows have been attempted in a Mediterranean porous aquifer with low potential of recharge and high touristic pressure from using a multi-tracing approach combining aerial thermal infrared images (TIR), temperature (T), electric conductivity (E.C.), major ions, selected trace elements, ²H, ¹⁸O, ²²²Rn, ²²³Ra and ²²⁴Ra. The TIR images allowed the detection of slight temperature variations at the seawater surface. Contrasted lithology and strong water-rock interactions due to groundwater residence time of many decades favor the ²²²Rn, ²²³Ra and ²²⁴Ra contents in groundwater that reach the seashores. Low temperature and E.C, as well as high radon and radium activities, evidenced SGD flows in agreement with the known flow conditions within the aquifer. The quantification of SGD flows revealed in

very good agreement with the known recharge rates of the aquifer that validates its conceptual hydrogeological model. For the first time in the Mediterranean or in semi-arid context, a natural tracing experiment based on geochemistry and isotope hydrology tools allowed the quantification of SGD flows to validate the hydrogeological conceptual model and to solve the water balance at the whole aquifer scale. Such a methodology could be applied worldwide to other similar coastal aquifers with low and diffuse SGD flow conditions.

Keywords

Diffused SGD flows, Low Recharge, TIR imagery, Radon, Radium, Aquifer Water Balance.

1. Introduction

To ensure sustainable management of groundwater resources, it is necessary to rely on detailed conceptual hydrogeological models. This includes the quantification of all water balance terms at the aquifer scale. For coastal aquifers, an important water balance term is the submarine groundwater discharge (SGD) (Burnett *et al.*, 2006; Baudron *et al.*, 2015). The aquifer recharge areas contributing to SGD flows being frequently densely populated, SGD flows are then recognized to be a source of nutrients, contaminants and pollutants that may affect the coastal hydrosystems functioning (Kaleris, 2006; Tomasky-Holmes *et al.*, 2013; Rodellas *et al.*, 2015). Furthermore, the amount of fresh SGD flows can reduce or even disappear due to over-pumping, causing seawater intrusion into coastal aquifers compromising the groundwater reservoir use (Moujabber *et al.*, 2006; Mahlnecht *et al.*, 2017; Nlend *et al.*, 2018).

The issue of seawater intrusion is obviously stronger for coastal aquifers displaying large interface with the sea that can be worsened by pumping rates (McCoy and Corbett, 2009; Mahlnecht *et al.*, 2017) and/or by increasing climate change effects such as seawater rise (Sherif and Singh, 1999; Barlow and Reichard, 2009; Werner *et al.*, 2013) or modifications in aquifer recharge conditions governing groundwater

levels (Holding *et al.*, 2016; Meixner *et al.*, 2016; Santoni *et al.*, 2018). Bokuniewicz *et al.* (2003) propose a typology for coastal groundwater and provides order of magnitude for SGD flows rates in porous media from various location and climate conditions highlighting very low values around 1 – 2 litter/day/linear meter in arid regions. Such coastal aquifers displaying low SGD flows are then more vulnerable to saline intrusion due to the precarious balance between freshwater and seawater of the salt wedge. Dependant of climate change, coastal drainage geometry and groundwater withdrawal for coastal population, irrigation, and industrial activities, the presence of SGD flows is consequently considered as a good indicator of the natural behavior of aquifers (Sawyer *et al.*, 2017).

Coastal aquifers of the Mediterranean area are known to be particularly vulnerable facing climate and anthropogenic pressures, so much so saline intrusions are already common (Richits *et al.*, 2011; Pachauri *et al.*, 2014). Destouni and Prieto (2003) made a numerical modelling of whole-aquifer water balance terms including SGD flows in a selection of porous aquifers in Israel, Greece and Cyprus for several management conditions. Later, Mazi *et al.* (2014, 2016) used an analytical approach to optimize groundwater exploitation conditions in a selection of porous aquifers located in the Nile Delta, Israel, and Cyprus based on water balance components quantification at the whole aquifer scale too. They also define the concept of sustainable management space to prevent any major seawater intrusion.

In addition to numerical modelling and analytical solutions, experimental methodologies have been developed to study SGD flows. TIR Imagery be used to localize them, based on the detection of warm or cold groundwater inputs into the sea with a contrasted temperature (Rapaglia *et al.*, 2015; Tamborski *et al.*, 2015). This technique has been employed worldwide and may be combined with *in situ*

measurements of T, E.C. and/or geochemical tracers including natural radioactive isotopes, particularly radon and radium isotopes (Mulligan and Charette, 2009; Mejías *et al.*, 2012; Povinec *et al.*, 2012; Lee, 2014; Rapaglia *et al.*, 2015; Tamborski *et al.*, 2015). These radionuclides are produced in the aquifer or poral waters of the sediment by the decay chain of uranium and thorium within the aquifer rocks and sediments, and are released in coastal waters by advection or diffusion, making them useful tracers of SGD flows (Moore, 2000; Burnett *et al.*, 2006; Beck *et al.*, 2010). Radium isotopes are indeed relevant tools thanks to their wide range of half-lives (from 3.63 days for ^{224}Ra to 1600 years for ^{226}Ra). They can also be used to describe SGD processes in discriminating freshwater inputs from rivers or aquifers with those of recirculated seawater (Moore, 1996; Povinec *et al.*, 2006; Stieglitz *et al.*, 2010; Bejannin *et al.*, 2017). In the current literature, SGD flows are widely investigated through experimental methodologies in mainly large diffuse or channelized flows provided by karst, fractured or porous aquifers (Burnett *et al.*, 2003; Burnett *et al.*, 2006; Lamontagne *et al.*, 2008; Povinec *et al.*, 2008; Mejías *et al.*, 2012; Santos *et al.*, 2012; Post *et al.*, 2013; Montiel *et al.*, 2018). However, to our knowledge, experimental methodologies have never been used to quantify diffuse SGD flows necessary to solve the water balance at the whole aquifer scale in Mediterranean and semi-arid areas.

An experimental multi-tracing approach combining TIR imagery, T, E.C., major ions, selected trace elements, ^2H , ^{18}O , ^{222}Rn , ^{223}Ra and ^{224}Ra was attempted on the well documented Mediterranean coastal aquifer of Bonifacio (Corsica Island, France). Even if no major seawater intrusion is yet detected, the Bonifacio aquifer is highly vulnerable facing seawater intrusion because more than a half of its boundaries conditions are the Mediterranean Sea (Santoni, 2016). In addition, the equilibrium

between groundwater and seawater is fragile since SGD flows are expected to be low due to limited recharge conditions typical of the Mediterranean area (Stigter *et al.*, 2012; Ghiglieri *et al.*, 2014). Previous studies already demonstrated its low potential of recharge (Chesnaux *et al.*, 2018; Santoni *et al.*, 2018) and highlighted its porous matrix composition (Orsini *et al.*, 2010; Reynaud *et al.*, 2012). As a consequence, the Bonifacio coastal aquifer is an ideal study site to evaluate the potential of TIR, geochemical and isotope tools to detect and quantify low and diffuse SGD flow conditions. For this aquifer, recharge and groundwater withdrawal rates being already known, the SGD flows quantification is intended to validate its conceptual hydrogeological model as well as to solve the water balance at the whole aquifer scale.

2. Study site

The Bonifacio aquifer (Corsica Island, France) is part of a coastal plateau located in the western Mediterranean (Figure 1). The study site is under a typical Mediterranean climate with mean annual precipitation and temperature about 605 mm and 16.8 °C respectively (calculated from 01/2000 to 01/2012 at the Bonifacio Meteo France station). The sector of Bonifacio is known for its wind blowing up to 300 days per year, often with gusts above 60–80 km/h especially in the extreme south of the plateau.

The Bonifacio plateau is constrained in equal proportions by the Mediterranean Sea at the South and Northeast and by granites on East and West. Its shape is triangular and it extends over only 25 km² with a mean elevation of 80 m asl. It is made of Miocene sediments filling a fractured Hercynian granitic depression up to 270 m deep continuing in the surface at an altitude of 243 m at the Monte Corbu (west) and of

144 113 m at the Punta di San Mulari (Rossi and Cocherie, 1991; Orsini *et al.*, 2010). The
145 3,000 inhabitants of the Bonifacio city reside mainly along the St. Julien and the St.
146 Jean valleys and also around the harbour. All the Bonifacio municipality coastlines
147 constitute a Natural marine reserve of National importance. Many campgrounds and
148 villas spread all over the plateau are crowded during the summer due to tourism
149 activities equivalent to 1.8 million people each year.

150 The hydrogeology of the Bonifacio plateau consists of two aquifer levels separated
151 by an aquitard (Santoni, 2016). The two aquifers levels are mainly found in the
152 Bonifacio and Balistra geologic formations (Reynaud *et al.*, 2012), forming an upper
153 and a lower aquifer level, respectively. They are separated by an aquitard
154 corresponding to a silty layer of the Cala di Labra geologic formation. Both aquifer
155 levels are composed of sandy calcarenites and calcareous sandstones representing
156 a very compacted material with a cemented granular structure whose effective
157 porosity is on average 7% (Dörfliger *et al.*, 2002; Chesnaux *et al.*, 2018).
158 Potentiometric levels and geochemical tracers highlighted a recharge area on the
159 plateau (autochthonous recharge) and another within the surrounding fractured
160 granitic massifs (allochthonous recharge) from which two main flow lines are
161 identified in direction of the Bonifacio Harbour and of the Sant'Amanza Bay (Figure
162 1). The Canali River is the only permanent river and it has very low flow. It takes its
163 source at the West within granitic massifs before flowing on the plateau and draining
164 the upper aquifer until the Sant'Amanza bay (Santoni, 2016).

165 The carbonate plateau of Bonifacio is in continuity with the large Miocene
166 sedimentary basin developing between Corsica and Sardinia islands. The
167 sedimentary deposits of the Bonifacio plateau are conditioned by the granitic
168 substratum and the thickness of the sediments is a function of the palaeo-

morphology of this one. Since no karst morphology is observed and considering the porous matrix of the aquifer, the SGD flows are expected to reach the sea very close to the shorelines and according to the salt wedge position (Figure 1).

The groundwater residence time was estimated from dissolved anthropogenic gases CFCs and SF₆ concentrations in groundwater (Santoni *et al.*, 2016b). Weighted ages range from 0 to 50 years in the upper aquifer and from 35 to 60 years in the lower aquifer implying a low dynamic of renewal and a long residence time amplifying water-rock interactions. An approach using ⁸⁷Sr/⁸⁶Sr validated groundwater flow pattern and residence time by computing water-rocks interaction kinetics and mixing rates between the granites, the upper and the lower aquifer (Santoni *et al.*, 2016a). Recently, Chesnaux *et al.* (2018) and Santoni *et al.* (2018) highlighted favourable aquifer recharge rates about respectively 23 and 26 % of annual rainfall that suggests the presence of low but detectable SGD flows near the coastal shores.

3. Method

The investigation strategy consisted in three main steps: (i) the acquisition of airborne TIR images of the coastlines on the 9th September 2011 to detect and quantify SGD flows; (ii) the measurement of physicochemical parameters, short half-lives radionuclides (²²²Rn, ²²³Ra, ²²⁴Ra), major ions, trace elements and stable isotopes of the water molecule in one stream and nine groundwater samples (Figure 1) on the 27th, 28th and 30th October 2012. A fixed measurement for ²²²Rn in position A in the Harbour was also made; (iii) the measurement of temperature, E.C., ²²²Rn ²²³Ra and ²²⁴Ra in seashores to validate and refine the SGD flows localisation and also to try their quantification on the 8th, 9th, and 10th January 2014. The objective of the groundwater and river sampling was to identify the main hydrochemical

features to ensure the presence of sufficient radon and radium activities in groundwater to detect SGD flows later in the sea.

3.1.1. Thermal Infrared imagery

TIR images were acquired along the carbonated rocks shores on the 09th September 2011 using a FLIR thermal system B20HSV. This period was chosen to provide the best thermal contrast between groundwater and seawater. The flight acquisition of airborne TIR images was performed by the service-provider company “l’Avion Jaune”. The flight was conducted at 2200 m altitude from 10:30 am to 11:00 am without any cloud and during low wind (7.8 m/s, ESE direction at the Meteo France weather Station of Bonifacio, Pertusato). The atmospheric temperature during the flight was 24.2°C and no significant rain event was observed during the last 6 days. The TIR camera wave-length range from 7.5 to 14 µm with 16384 grey levels set on a temperature palette between -40 to +150°C with an accuracy of ± 1°C. At 2200 m altitude, the pixel field of view is about 2.0 × 2.0 m.

3.1.2. Geochemistry and stable isotopes of the water molecule

E.C. and T were directly measured in the field using a WTW Cond 3310 (WTW GmbH, Weilheim, Germany). Bicarbonates were also determined in the field with a HACH digital titrator (HACH Company, Loveland, USA). Major ions samples were filtrated through 0.45 mm nitrocellulose membranes in two 50 mL polyethylene bottles before storage at 4°C. One bottle was acidified using ultrapure nitric acid for cation analysis. A Dionex ICS 1100 chromatograph (Thermo Fischer Scientific, Waltham, USA) was used to determine ionic concentrations at the EMMAH

laboratory of the University of Avignon, France. The analysis quality was validated for ionic balance error of less than 5%.

Samples for trace elements were filtered through 0.20 μm nitrocellulose membranes and acidified with ultrapure nitric acid in 50 mL polyethylene bottles before storage at 4°C. A Thermo Fisher Q-ICP MS X-series II was used to determine trace elements concentrations at the AETE technical platform of the University of Montpellier, France. Samples for the analysis of stable isotopes of the water molecule were collected in 20 mL amber glass bottles with no head-space. A liquid–water stable isotope analyzer DLT-100 (Los Gatos Research, San Jose, USA) was used in accordance with the analytical scheme recommended by the International Atomic Energy Agency (Penna et al., 2010) at the EMMAH laboratory of the University of Avignon, France. The analysis quality was checked with standard deviation conditions up to 0.1‰ for $\delta^{18}\text{O}$ and 1‰ for $\delta^2\text{H}$.

3.1.3. ^{222}Rn , ^{223}Ra and ^{224}Ra activities measurements

The ^{222}Rn activity was measured in groundwater and in seawater along the coastlines and within the Bonifacio Harbour in six fixed positions by using a RAD7 radon monitor combined with a RADAQUA water exchanger (DurrIDGE Co. Inc.). Prior to the radon measurements, the wind was moderate (from 4.0 to 19.6 m/s, ESE direction) from the 27th to the 30th October 2012 and low (from 3.8 to 5.0 m/s, SW direction) from the 8th to the 10th January 2014. Each sampling campaign were preceded by slight to moderate rain events (45 mm on the 23rd October 2012; 20 mm on the 05th January 2014). Since seawater typically displays low activity, the sensitivity of the system was increased using two RAD7 monitors connected with the RAD-AQUA in closed loop (Mayer et al., 2016). The water was pumped with a 4.5

l/min flow rate for injection into the RADAQUA water exchanger. The ^{222}Rn activity measure is determined from the decay of daughter isotope ^{218}Po when the equilibrium in the air-loop between the gas-exchanger and the two RAD7 monitors is reached (Dimova *et al.*, 2009). The ^{222}Rn activity of water is then calculated from that of air knowing the partition Ostwald coefficient, which depends on salinity and temperature (Schubert *et al.*, 2011). For the coastlines survey, all devices were installed on a semi-rigid vessel equipped with GPS, E.C. and T data loggers. The system allowed continuous measurements during navigation or fixed position. For more detailed information, sampling and analytical process are consistent with those outlined in (Mayer *et al.*, 2016).

The ^{223}Ra and ^{224}Ra activities were measured using Mn-fibers by filtration of surface water, groundwater, and seawater samples. Sample positions for the Bonifacio Harbour are the same as for ^{222}Rn . The fibers were analysed using RaDeCC counters systems at the EMMAH and CEREGE laboratories (Moore and Arnold, 1996). Calibration was made by using in-house mono-isotope standards of ^{227}Ac and ^{232}Th (parents of ^{223}Ra and ^{224}Ra respectively) and multi-isotope standards, containing ^{227}Ac , ^{232}Th , and ^{226}Ra . All standards were prepared according to the technique of Scholten *et al.* (2010). Efficiencies changes with time are within the error range and thus not significant. Errors were calculated according to Garcia-Solsona *et al.* (2008).

To assess whether the diffusive release of radionuclides from sediments could be a significant radon source, five sediment samples were collected from the sea beaches of Paraguanu, Pertusatu, San Mulari, Sant'Amanza and Canettu (Figure 1). To estimate ^{222}Rn diffusion from sediment, activities in pore water were analysed following the equilibration method after Corbett *et al.* etc (Corbett *et al.*, 1998; Burnett

et al., 2007; Kluge *et al.*, 2012). Experiments were performed with 500 g of dry sediment equilibrated in closed glass bottles with 900 mL of Ra-free seawater, previously filtrated through Mn-fiber. Seawater and sediment equilibrated in closed bottles over one month, according to the protocol of Corbett *et al* 1998.

4. Results and discussion

4.1. SGD flows detection from airborne TIR images

The seawater surface temperature obtained in September 2011 through the TIR image varies from 19.7 to 23.5°C along the coast (Figure 2). In the Harbour, red hotspots correspond to pontoons and moored boats. The most common value range between 21.2°C and 23.5°C due to summer conditions, but the temperature may be less than 21.2°C locally. This is especially the case in the Sant'Amanza Bay and in the Bonifacio Harbour where a discreet but detectable decrease in temperature is observed. This low thermal contrast is obviously the result of a high thermal diffusion of groundwater in the sea. No plumes are visible unlike on other SGD flows studies (Tamborski *et al.*, 2015; Bejannin *et al.*, 2017), but this weak and progressive decrease in temperature is a first clue arguing in favour of low and diffuse SGD flows as expected for this Mediterranean porous aquifer. The slight decrease in temperature is detectable over a length of around 350 m in the Sant'Amanaza bay and 140 m in the Bonifacio Harbour. Furthermore, cooler temperatures less than 21.2°C are also observed at the extreme south of the plateau. This is probably due to the wind occurring in this specific area during the flight (7.8 m/s, ESE direction measured at the Pertusato Meteo France weather station).

4.2. Groundwater-rock interactions as a source of radionuclides in SGD flows

Groundwater from the upper aquifer (Bonifacio geologic formation) and stream water were investigated to characterize their hydrochemical and isotopic signatures and to identify mineralization processes that may further help the SGD flows detection (Table 1). Groundwater temperatures are close to the average annual atmospheric temperature at Bonifacio (+16.8°C) involving a low dynamic of renewal that favour water-rocks interactions within the aquifer (Santoni *et al.*, 2016b). The EC is rather high for all samples with values from 990 to 2040 $\mu\text{S}/\text{cm}$, and is mainly influenced by HCO_3 , Cl, Ca and Na contents. The pH values as well as the high contents in HCO_3 and Ca indicate interactions with the aquifer carbonate matrix. The high Na, Cl and Mg contents denote an influence from the sea, but the negative $\delta^2\text{H}$ and $\delta^{18}\text{O}$ signatures exclude any large seawater intrusion into the aquifer and rather suggest the influence of sea sprays in the mineralization (Santoni *et al.*, 2016a). Groundwater NO_3 contents comply with those found in natural waters, except for three samples above 20 mg/L which highlight locally the vulnerability of the aquifer influenced by human activities. SiO_2 and U contents are noticeable with values up to 17 mg/L and 1.5 $\mu\text{g}/\text{L}$, respectively, with a correlation coefficient r^2 about 0.81. These are elements sourced by granitic rocks surrounding the aquifer or sourced by the calcarenites of the aquifer that include sediments from the granite weathering.

The ^{222}Rn , ^{224}Ra and ^{223}Ra activities were measured in stream and groundwater (Table 2). The ^{223}Ra activity is low (less than 1.5 Bq/m^3) compared to the ^{222}Rn and ^{224}Ra activity, varying from 1199 to 27853 Bq/m^3 and from 8.8 to 34.3 Bq/m^3 , respectively. Radon is fairly well correlated to dissolved uranium in groundwater, ($r^2 = 0.79$, Table 1), suggesting that the main sources of radon are the Herynian granites.

The higher activities are found in groundwater sampled at the interface with the fractured granites (REP-B18 and CPO-B10). Stream water CANR-R1 and groundwater from the plateau display lower radon activities, between 1199 and 6081 Bq/m³. Bonifacio groundwater and stream water have therefore radon activities sufficiently elevated to provide a radon signature in seawater expected to be detectable using our Rad7 system near the discharges points.

Figure 3 displays binary scatter plots combining hydrochemical and isotope data of groundwater along the flow path from the recharge areas until the coastal outlets where the SGD flows measurement is carried out. The (Na+Cl)/(Ca+HCO₃) vs Na graph (Figure 3-A) shows the influence of both marine context and carbonated lithology on the groundwater mineralization through the Na+Cl and Ca+HCO₃, respectively. From the recharge areas to the aquifers outlets, the Na content coming from sea sprays decrease by dilution due to a mixing of flow lines originated from different recharge process such as focused recharge (fast transfert of rainwater to the water table) or irrigation recharge (Santoni *et al.*, 2018). In the same time, the (Na+Cl)/(Ca+HCO₃) ratio decreases, highlighting an increase in the (Ca+HCO₃) content due to the calcite dissolution. This is well supported by the increase in the saturation indexes (SI) of calcite plotted in Figure 3-B. Moreover, in the same figure, the increase in the SI of strontianite with calcite suggests the control of the magmatic and sedimentary lithologies on groundwater mineralization along the flow path from the granites to the carbonate aquifer as also observed in Santoni *et al.* (2016a). Indeed, the high correlation coefficient between saturation indexes of calcite and strontianite highlights dissolution of granites and of calcarenites that includes calcite and granitic alteration products. The groundwater mineralization is consequently

influenced by the groundwater origins, by the contrasted lithologies found along the flow path and finally by complex mixing processes.

This is also true for the groundwater radon activity: the groundwater flow line originating from the granite surroundings (allochthonous recharge area) displays the higher U concentration and radon activity (Figure 3-C). This feature slightly decreases toward the Stentinu (Canali valley, Sant'Amanza Bay) outlet, probably due to mixing with surface water with groundwater from the calcarenites. This is well supported by the $\delta^{18}\text{O}$ enrichment suggesting the progressive addition of evaporated surface water (Santoni *et al.*, 2018). In addition, the groundwater flow line originating from the plateau (autochthonous recharge area) displays lower U concentration and radon activity that remains relatively high and quite stable until the outlet of the Saint Julien valley (Bonifacio Harbour). The SGD flows detection from ^{222}Rn survey along the coastlines is then expected to be fruitful in this context.

4.3. SGD flows detection from *in situ* T, E.C. and ^{222}Rn survey along the coastlines

The *in situ* seawater temperatures measured along the coastline during the survey are mainly comprised between 14.5 and 15.0°C (Figure 4-A), typical for winter in the western Mediterranean. The local decrease in temperature can be probably related to temperature equilibrium with the cold atmosphere, especially in shallow areas. In addition, thermal contrast between the groundwater and the sea or the atmosphere is expected to be very limited, especially in case of diffuse outflow during winter when the difference of temperature between the sea and the groundwater is the smallest. It is then more relevant to refer to the Figure 2 for discussing temperature contrasts, more visible and relevant during summer. Nevertheless, TIR images and *in situ*

temperature give insights on coastal water bodies structure, with differentiated water bodies in the Stentinu and in the Maora areas of the Sant'Amanza bay as well as within the Bonifacio Harbour. These water bodies does not instantly mix with external seawater, suggesting low advection processes.

To detect the presence of continental freshwater inputs to the seashores, *in situ* E.C. was also measured during the survey (Figure 4-B). The highest values are between 58 and 61 mS/cm and are found along the eastern granitic part of the study site as well as between the Bonifacio Harbour and Pertusato. In opposition, lower values between 55 and 58 mS/cm are found especially in the northern, southern and western part of the Bonifacio plateau coasts including the Bonifacio Harbour and the Sant'Amanza Bay (Stentinu). Since the E.C. variation is independent of environmental temperature, it is then reasonable to relate a decrease in E.C. to a continental water inflow even if it does not allow to distinguish between surface and groundwater inputs.

The Figure 4-C displays the radon activity distribution along the coastline. The eastern granitic part and the northern plateau coasts display intermediate radon activity, comprised between 0 and 40 Bq/m³. The punctual increase observed along the eastern coast may be explained by very local inputs of fresh groundwater through the intense fracturation of the Hercynian granites (Orsini *et al.*, 2010; Santoni *et al.*, 2016a), but in any case they cannot be considered as Bonifacio aquifer outlets. The coasts surrounding the Bonifacio plateau display no or low radon activity at the south and the west, except in the harbour and in the Sant'Amanza bay where the values may be greater than 50 Bq/m³, especially in the Maora and Stentinu areas. The low E.C. value and low radon activity found at the south and west part of the plateau can be explained by a weak input of surface water. In opposition, the low E.C. and high

radon activity found in the Bonifacio Harbour and in the Sant'Amanza Bay (including the narrow Stentinu area of 70 m wide) reveals the presence of SGD flows. This is in very good agreement with the potentiometric and ageing groundwater flow line directions from Santoni (2016) and with the slight decrease in seawater temperature observed from the TIR images displayed in Figure 2.

The Figure 5 displays E.C. box plots as a function of ^{222}Rn activity classes for all the coastline survey data. The correlation coefficient r^2 between E.C. and ^{222}Rn activity is about 0.53, highlighting a relation between these two variables: the lower is the E.C., higher is the radon activity. This means that the E.C. may be relevant for the detection of SGD flows along the coastlines. Nevertheless, SGD flows may have contrasted effects on coastal seawater E.C and ^{222}Rn activity according to the groundwater origins (*i.e.* recharge areas). The Figure 3-C clearly shows a wide range of ^{222}Rn activity in groundwater, with the highest values for groundwater coming from the granites area and reaching the Stentinu (Figure 1, Figure 4-C). As a consequence, low SGD flow rates may provide a high ^{222}Rn activity with no major influence on E.C. This observation may explain the moderate r^2 value (Figure 5). Even if each parameter individually presents its limits, their combination allows here to clearly detect the presence of SGD flows.

4.4. Estimates of SGD seepage velocities from radon and radium activities

An estimate of SGD seepage velocities using radon and radium activities from the fixed measurements carried out over the 1800 m length of the Bonifacio Harbour (Figure 1) is here attempted. As suggested by *in situ* temperature repartition along seashores (Figure 4A) highlighting different water masses, this calculation assumes that the mixing with external seawater is negligible. This assumption was tested evaluating the eddy diffusion (D_{eddy}) coefficient in the harbour's water as in Moore

(2000). Under the assumption of isotropic medium and steady state condition, the eddy diffusion coefficient is given by equation 1:

$$D_{Eddy} = \sqrt{\frac{\lambda}{\frac{\partial \ln(C)}{\partial x}}} \quad (\text{equation 1})$$

where C is the activity of tracer (radon or radium isotope), x the distance from the input point and lambda the decay constant of the tracer. The computed distance vs. logarithm activities regression line and eddy diffusion coefficients are reported in Figure 6 and Table 4, respectively. The very good correlation between logarithm of radionuclide activities and distance (Figure. 6), as well as the low eddy diffusion coefficients deduced from them suggests that advection is minimal, diffusion and radioactive decay from groundwater inputs in the inner side of the harbour are the dominant processes governing the activity of these tracers in this setting and-at the time scales of the half lives of these tracers (3.8 days for ^{222}Rn , 11.3 days for ^{223}Ra , and 3.6 days for ^{224}Ra). This is probably due to the reduced volume and narrow configuration of the Harbour.

The wind was low to moderate during the surveys (cf 3.1.3), and the narrow configuration of the Bonifacio Harbour clearly limits the radon degassing from seawater in this area. The radon degassing was therefore not taken into account in the SGD seepage velocity calculation. The incertitude introduced by neglecting the degassing term is discussed later. To evaluate the potential influence of ^{222}Rn diffusion from the sediment (not associated to the SGD flows from the aquifer), a selection of near-shore sediments were sampled over the study area and analysed for the ^{222}Rn activity produced by their equilibration with seawater (Figure1, Table 3). The ^{222}Rn diffusive flux obtained from these sediments is very low, in the range from

441 1.4 to 6.2 Bq/m²/day. These marine sediments thus cannot constitute a source of
442 ²²²Rn capable to prevent the detection of SGD flux.

443 In order to calculate SGD seepage velocities, the ²²²Rn, ²²³Ra, and ²²⁴Ra inventories
444 in the harbour have been determined. Radon and radium activities in function of
445 distance have been fitted by exponential curves that are then integrated over the
446 1800 m length of the harbour (Figure 6). The general pattern of ²²²Rn, ²²³Ra and
447 ²²⁴Ra data clearly shows an exponential decrease in their activities with distance,
448 implying that the dilution of the isotopic signature with external seawater is negligible.

449 The good exponential data-fit also suggests that the activities of these tracers are
450 probably in a steady state equilibrium condition between sources (groundwater
451 advection) and sinks (diffusions and decay). In the case of the present study, the
452 narrow morphology of the harbour and the piezometric gradient organisation implies
453 major flowlines converging into the internal part of the Bonificio harbour (Santoni,
454 2016). For these reasons, SGD seepage directly through the bottom sediments of the
455 harbour are expected to be low. Assuming horizontal SGD flows as constrained by
456 the geomorphology and the salt wedge position (i.e. horizontal convergence of
457 groundwater flow lines in Figure 1), the radionuclides activities in groundwater inputs
458 are considered as vertically constant on the innermost face of the harbour made of
459 concretes and limestone. Then, the integrals of the activity in harbour water over the
460 distance correspond to the horizontal tracer's inventories for 1 m² surface units
461 flowing perpendicularly to the innermost face of the harbour and in direction toward
462 the sea (sampling point A to the sampling point F in Figure 1). Parameters of this
463 calculation (distances, activities, exponential regression equations, inventories and
464 resulting seepages for ²²²Rn, ²²³Ra and ²²⁴Ra) are reported in Table 4. Under these

assumptions, the calculated horizontal inventories are independent of the water depths in the harbour.

From the horizontal tracer inventories, the activity flux ($\text{Bq/m}^2/\text{day}$) of ^{222}Rn , ^{223}Ra and ^{224}Ra necessary to maintain the diffusive – radioactive decay profile may be calculated for a unit surface perpendicular to the length of the harbour (Table 4), assuming a steady state condition. The groundwater seepage supporting this flux is then calculated dividing the activity flux by the groundwater activity C_{GW} as measured in the sampled point ORE-W2 (Figure 1, Table 4). The computed SGD seepage velocities necessary to compensate for diffusion and decay thus result about 2.24 and 3.19 m/day for ^{222}Rn (for 2012 and 2014, respectively), 22.32 m/day for ^{223}Ra and 23.67 m/day for ^{224}Ra .

The same approach was applied in the Sant'Amanza Bay, second outlet of the aquifer. From using the *in situ* ^{222}Rn in the Stentinu and considering C_{GW} as the sampled point CPO-B10, the computed SGD flows seepage velocity necessary to compensate for the diffusion and decay is about 1.84 m/day (Table 4). However, this estimation is probably impacted by degassing process during flow within the Canali Valley until the Stentinu. To avoid this, a computation may also be performed considering C_{GW} as the canali river sample point CAN-R1. The computed SGD flows seepage velocity is then about 18.6 m/day (Table 4).

The SGD seepage velocities calculated from ^{222}Rn , ^{223}Ra and ^{224}Ra are in good agreement with other similar contexts in the Mediterranean as obtained in the Port-Miou Calanques, southern France (0.1 to 0.4 m/s), in open Mediterranean sea in the Gulf of Lion, southern France (23 m/s,) by Bejannin *et al.* (2017). Nevertheless, in

view of the fairly large range of SGD flows seepage velocities obtained, it appears necessary to validate and better constrain these results.

4.5. Validation of SGD flows velocities by groundwater Darcy velocity

The eddy mixing coefficients deduced from the good exponential fit of radionuclides activities over the 1800 m of the Bonifacio Harbour allow the application of the first Fick's law to calculate the SGD freshwater seepage velocity necessary to dilute the seawater salinity in the Harbour as observed in the E.C. profile. The flux calculated using the first Fick's law assumes a freshwater fraction gradient in the harbour of $-1.89\text{E}^{-05} \text{ (m}^{-1}\text{)}$. This gradient is calculated from 3.5% freshwater dilution, obtained from the E.C. difference between inner harbour and offshore waters, over a total length of 1800 m (Figure 1). Assuming a steady state condition and E.C. conservative, the seepage velocity of SGD flows of the “pure” freshwater component, necessary to sustain the diffusive profile observed for E.C., is between 0.44 and 2.06 m/day (Table 4), using respectively the D_{eddy} obtained from ^{223}Ra and ^{224}Ra profiles.

Unlike for E.C., the SGD seepage velocities based on ^{222}Rn , ^{223}Ra , and ^{224}Ra corresponds to the sum of two flows, fresh groundwater and recycled seawater. The quantification of the seawater recycling is however particularly difficult using radium and radon isotopes because these tracers may be partially scavenged from seawater when intruding a coastal aquifer, yielding in this case to an underestimation of total SGD (Zhang *et al.*, 2017). In other setting, the recycled seawater flux may constitute a net tracer input in seawater inventory, yielding to an overestimation of the real “continental” water SGD flux (Rodellas *et al.*, 2015).

Nevertheless, by comparing the total SGD seepage velocity obtained from the radon mass balance (2.25 m/d) and the freshwater SGD seepage velocity obtained from the salinity profile with the first Fick's Law (2.04 m/d), we may roughly estimate that the recycled seawater component represents about 10 % of the total SGD. The fraction of recycled seawater estimated by comparing ^{224}Ra or ^{223}Ra seepage velocities and freshwater SGD seepage velocity from salinity profile is instead much larger (seawater recycling would be about 10 times the freshwater SGD). We tend to prefer the estimate based on ^{222}Rn because sediment equilibration experiments showed that radon diffusion from sediment is very low. Seawater recycling through these sediments would therefore not affect significantly the total input flux of radon and so the estimate of total SGD. Conversely, for the radium isotopes, since radium diffusion from near shore sediments is unknown, the effect of seawater recycling on the total SGD calculation cannot be estimated. The total SGD estimate based on ^{222}Rn (and the radon-based seawater recycling fraction) was also preferred because the seepage velocities values obtained in 2012 and 2014 yielded similar results (Table 4).

In order to validate the SGD velocities estimates, they are now compared with the Darcy velocity deduced from hydrodynamic modelling and aquifer recharge rate estimations previously published.

Table 5 shows Permeability (K) for the Bonifacio aquifer from existing literature and associated Darcy velocity (q) computed between EB-B1 and ORE-W2 in the Saint Julien Valley considering $\Delta L = 1173$ m and $\Delta H = 48$ m. The q values deduced from Proton Magnetic Resonance and pumping tests are between 0.46 and 1.06 m/d. These values are slightly lower but closest and in the same order of value to SGD

seepage velocities from radon and from the Fick law (Table 4). Uncertainties nevertheless remain on q values because they are computed from permeability coefficients K issued from different method as well as from various location over the plateau. Furthermore, the Darcy groundwater velocities assume a steady state and isotropic porous media, which is the case at the Saint Julien Valley's scale (Chesneaux et al., 2018) but not the case at the whole aquifer scale (Santoni et al., 2018).

The SGD seepage velocities from radon and from the Fick law are also in very good agreement with values of groundwater Darcy velocity within the Bonifacio aquifer from combining analytical solution with geochemical and dating tracers (Table 5). Considering a steady-state Dupuit-type flow in the Saint Julien Valley, the analytical solution of Chesnaux *et al.* (2018) applied between the sampling points EB-B1 and ORE-W2 and assuming groundwater transit time of 30 years, an effective porosity of 7%, and a hydraulic conductivity from 1.3 to 3.0×10^{-4} m/s, the recharge was calculated to be of 115 mm/year i.e. 23 % of the annual rainfall. This value is in very good agreement with the aquifer functioning and with the 132 mm/year (26%) obtained previously for this aquifer using 8 other methods by Santoni *et al.* (2018). This highlights the strong relationship of groundwater flow velocity with groundwater residence time, effective porosity, permeability and recharge for this aquifer. From this steady-state Dupuit-type flow in the Saint Julien Valley, the Darcy groundwater velocity computed considering the permeability range give values between 0.46 and 1.06 m/day, that is in the same order of value for the SGD flows seepage velocity calculated from ^{222}Rn and from the Fick law, allowing the SGD seepage velocities from radon to be considered as robust.

4.6. SGD seepage flow and water balance quantification of the Bonifacio Mediterranean porous aquifer

As shown through TIR images and in situ measurements, the aquifer outlet generates diffuse outflow in the Bonifacio Harbour and within the Sant'Amanza Bay including the Stentinu area. The computed SGD seepage flow velocities for surface units of 1 m² being now considered as robust, SGD seepage flow rates can be computed by multiplying SGD seepage flow velocities with the discharge area at the outlets. The computation of SGD seepage flow rates assumes an outlet width of 140 m and 1.4 m depth in the Bonifacio Harbour, a outlet of 350 m width and 1.5 m depth in the Sant'Amanza bay and a outlet of 70 m width and 1.5 m depth in the Stentinu. The ²²²Rn seepage velocity considered is 2.24 m/d for the Bonifacio Harbour, 1.84 m/d in the Sant'Amanza Bay and 18.60 m/d in the Stentinu. The total seepage flow rate obtained is then 38.9 L/s, with 5.1 L/s in the Bonifacio Harbour, 11.2 L/s in Sant'Amanza and 22.6 L/s in the Stentinu (including the Canali River flow).

The SGD seepage flow rates can now be related to the hydrogeological functioning of the Bonifacio aquifer. Considering a recharge about 132 mm/y in a 33 Km² watershed, *i.e.* 138 L/s (Santoni *et al.*, 2018) and a public water supply about 174,638 m³/y, *i.e.* 5.5 L/s (Santoni, 2016), the expected SGD seepage flow rate is expected to be 132.5 L/s. In these conditions, the total 38.9 L/s SGD seepage flow rate obtained represents 29 % of the expected flow, *i.e.* 28 % of the aquifer recharge rate. According to this observation, 68 % of the recharge water are missing at the identified aquifer outlets.

Assuming that the aquifer recharge value is robust (Chesnaux *et al.*, 2018; Santoni *et al.*, 2018), many hypothesis may be formulated on this result : (1) the field campaign corresponds to a low water level period, underestimating the SGD seepage flow rate

due to a loss of water pressure within the aquifer ; (2) due to diffuse SGD flow conditions, the major part of the SGD flows is not detected ; (3) the major part of the recharge water in the upper aquifer level supplies the lower aquifer level by downward drainance. The first hypothesis can be rejected because ^{222}Rn measurements have been performed in the Bonifacio Harbour during October 2012 at low water level and during January 2014 at high water level without this causing any major change in the SGD seepage flow velocities (2.24 m/d in Oct. 2012 and 3.19 m/d in Jan. 2014; Table 4) that is in relation with the known inertial behavior of the aquifer (Santoni, 2016). The second hypothesis cannot be refuted as it stands but the third hypothesis seems to be the most probable. Indeed, according to Santoni *et al.* (2016a), the recharge of the lower aquifer by downward drainance is estimated by a combined $\text{H}_2^{18}\text{O} - ^{86}\text{Sr}/^{87}\text{Sr}$ approach to be 65 – 70 %. This observation implies that the outlet of the lower aquifer is different from those of the upper one. The first should be governed by the paleomorphology of the underlying fractured granites whereas the second one may be directly dependant of the present surface morphology organized in valleys WSW-ENE oriented explaining the Bonifacio Harbour and Sant'Amanza outlets. The outlet(s) of the lower aquifer is(are) probably located further offshore and at greater depth, which explains its(their) non-detection during the survey at 1 m depth performed for this study.

The SGD seepage flow being now solved, it is possible to propose a water balance budget for the whole Bonifacio Mediterranean porous aquifer (Figure 7). From an aquifer recharge rate about 132 mm/y, 32 % of the recharge water flows within the upper aquifer until the Bonifacio Harbour (4 %), the Sant'Amanza Bay (8%) and until the Stentinu as SGD flows and river flow (16 %). The public drinking water supply also represents an outlet to the upper aquifer (4%). Finally, 68 % of the aquifer

recharge rate supply the lower aquifer level by downward drainance from the upper aquifer. This water balance then validate and improve the conceptual hydrogeological functioning of the Bonifacio aquifer.

From a management point of view, the detection and localization of SGD flows suggest a natural behavior of the aquifer excluding major over-pumping and seawater intrusion despite the limited potential of recharge, the large interface with the sea, the touristic pressure and the changes in the climate. This seems to be related to a low withdrawal pressure yet exerted on the aquifer as well as to a predominant focused recharge process implying a fast transfer of rainwater to the water table that may be favored by the increase in high rainfall events due to climate change in the Mediterranean (Hartmann *et al.*, 2017; Santoni *et al.*, 2018).

5. Conclusions

This study allowed to validate and improve the conceptual hydrogeological model of a Mediterranean porous aquifer with low potential of recharge and high vulnerability due to a large interface with the sea, the tourism pressure and the changes in the climate. The experimental approach coupling TIR, T, E.C., majors ions, selected trace elements, ^2H , ^{18}O , ^{222}Rn , ^{223}Ra and ^{224}Ra proved to be relevant in the detection and quantification of low and diffuse SGD flows, highlighting quite natural flow conditions and excluding any major over-pumping. The acquisition of TIR images is able to detect slight temperature variations at the seawater surface. Such imagery nevertheless loses effectiveness in windy areas. The *in situ* geochemical and isotopic investigations allows ensuring the presence of sufficient radon and radium activities in groundwater to detect SGD flows along the seashores. Favourable lithology and strong water-rock interactions involved by long groundwater residence time favours

the radon content in coastal aquifer outlets. Most of the time, the lower is the temperature and the E.C., the higher are the radon and radium activities. The SGD flow velocity required for flow rates calculation from ^{222}Rn is validated with groundwater Darcy velocity in the aquifer. The quantification of SGD flows rates revealed in very good agreement with the known recharge rates and flow conditions within the aquifer. Such a methodology could be applied to other similar coastal aquifers with low and diffuse SGD flow conditions worldwide. For the first time in the Mediterranean or in semi-arid context, a natural tracing experiment based on geochemistry and isotope hydrology tools allowed the quantification of SGD flows to validate the hydrogeological conceptual model and to solve the water balance at the whole aquifer scale. This study finally helped to better define the scope in terms of detection limits for TIR images associated with *in situ* geochemical and isotopic tools in the detection of low and diffuse SGD flows.

Acknowledgements

The PhD grant of Sébastien Santoni was financially supported by the Regional Council of Corsica (Collectivité de Corse). The authors would like to thank the municipality of Bonifacio for their support and contribution to the implementation of the project as well as the Bonifacio inhabitants for access to their wells and boreholes during the field sampling. The authors are also grateful to S. Cockenpot and C. Claude for help provided at the very beginning of the project.

References

- Barlow, P.M., Reichard, E.G., 2009. Saltwater intrusion in coastal regions of North America. *Hydrogeology Journal*, 18(1): 247-260. DOI:10.1007/s10040-009-0514-3
- Baudron, P., Cockenpot, S., Lopez-Castejon, F., Radakovitch, O., Gilabert, J., Mayer, A., Garcia-Arostegui, J.L., Martinez-Vicente, D., Leduc, C., Claude, C., 2015. Combining radon, short-lived radium isotopes and hydrodynamic modeling to assess submarine groundwater discharge from an anthropized semiarid watershed to a Mediterranean lagoon (Mar Menor, SE Spain). *Journal of Hydrology*, 525: 55-71. DOI:<http://dx.doi.org/10.1016/j.jhydrol.2015.03.015>
- Beck, A.J., Dulaiova, H., Cochran, J.K., 2010. Journal of Environmental Radioactivity special issue: Radium and Radon Isotopes as Environmental Tracers. *Journal of Environmental Radioactivity*, 101: 519-520. DOI:10.1016/j.jenvrad.2010.04.013
- Bejannin, S., van Beek, P., Stieglitz, T., Souhaut, M., Tamborski, J., 2017. Combining airborne thermal infrared images and radium isotopes to study submarine groundwater discharge along the French Mediterranean coastline. *Journal of Hydrology: Regional Studies*, 13: 72-90. DOI:10.1016/j.ejrh.2017.08.001
- Bokuniewicz, H., Buddemeier, R., Maxwell, B., Smith, C., 2003. The typological approach to submarine groundwater discharge (SGD). *Biogeochemistry*, 66: 145-158.
- Burnett, W.C., Aggarwal, P.K., Aureli, A., Bokuniewicz, H., Cable, J.E., Charette, M.A., Kontar, E., Krupa, S., Kulkarni, K.M., Loveless, A., Moore, W.S., Oberdorfer, J.A., Oliveira, J., Ozyurt, N., Povinec, P., Privitera, A.M.G., Rajar, R., Ramessur, R.T., Scholten, J., Stieglitz, T., Taniguchi, M., Turner, J.V., 2006. Quantifying submarine groundwater discharge in the coastal zone via multiple methods. *Science of The Total Environment*, 367: 498-543. DOI:10.1016/j.scitotenv.2006.05.009
- Burnett, W.C., Bokuniewicz, H., Huettel, M., Moore, W.S., Taniguchi, M., 2003. Groundwater and pore water inputs to the coastal zone. *Biogeochemistry*, 66: 3-33. DOI:10.1023/B:BI0G.0000006066.21240.53
- Burnett, W.C., Santos, I.R., Weinstein, Y., Swarzenski, P.W., Herut, B., 2007. Remaining uncertainties in the use of Rn-222 as a quantitative tracer of submarine groundwater discharge. *IAHS Publ.*, 312. DOI:9781901502046
- Chesnaux, R., Santoni, S., Garel, E., Huneau, F., 2018. An Analytical Method for Assessing Recharge Using Groundwater Travel Time in Dupuit-Forchheimer Aquifers. *Ground Water*. DOI:10.1111/gwat.12794
- Corbett, D.R., Burnett, W.C., Cable, P., Clarck, S., 1998. A multiple approach to the determination of radon fluxes from sediments. *Journal of radioanalytical and nuclear chemistry*, 236(1-2). DOI: <https://doi.org/10.1007/BF02386351>
- Destouni, G., Prieto, C., 2003. On the possibility for generic modeling of submarine groundwater discharge. *Biogeochemistry*, 66: 171-186. DOI:10.1023/B:BI0G.0000006101.12076.10
- Dimova, N., Burnett, W.C., Lane-Smith, D., 2009. Improved Automated Analysis of Radon (²²²Rn) and Thoron (²²⁰Rn) in Natural Waters. *Environ. Sci. Technol.*, 43(22): 8599-8603. DOI:10.1021/es902045c
- Dörfliger, N., Ferrandini, J., Ferrandini, M., Mathieu, F., 2002. Caractérisation géométrique et hydrodynamique du causse de Bonifacio (Corse) à partir d'une synthèse des connaissances géologiques et hydrogéologiques et par méthodes géophysiques., BRGM/RP-51860-FR. DOI:BRGM/RP-51860-FR
- Garcia-Solsona, E., Masqué, P., Garcia-Orellana, J., Rapaglia, J., Beck, A.J., Cochran, J.K., Bokuniewicz, H.J., Zaggia, L., Collavini, F., 2008. Estimating submarine groundwater discharge around Isola La Cura, northern Venice Lagoon (Italy), by using the radium quartet. *Marine Chemistry*, 109: 292-306. DOI:10.1016/j.marchem.2008.02.007
- Ghiglieri, G., Carletti, A., Pittalis, D., 2014. Runoff coefficient and average yearly natural aquifer recharge assessment by physiography-based indirect methods for the island of Sardinia

- (Italy) and its NW area (Nurra). *Journal of Hydrology*, 519: 1779-1791.
DOI:10.1016/j.jhydrol.2014.09.054
- Hartmann, A., Gleeson, T., Wada, Y., Wagener, T., 2017. Enhanced groundwater recharge rates and altered recharge sensitivity to climate variability through subsurface heterogeneity. *Proceedings of the National Academy of Sciences*, 114: 2842-2847.
DOI:10.1073/pnas.1614941114
- Holding, S., Allen, D.M., Foster, S., Hsieh, A., Larocque, I., Klassen, J., Van Pelt, S.C., 2016. Groundwater vulnerability on small islands. *Nature Climate Change*, 6(12): 1100-1103.
DOI:10.1038/nclimate3128
- Kaleris, V., 2006. Submarine groundwater discharge: Effects of hydrogeology and of near shore surface water bodies. *Journal of Hydrology*, 325: 96-117. DOI:10.1016/j.jhydrol.2005.10.008
- Kluge, T., von Rohden, C., Sonntag, P., Lorenz, S., Wieser, M., Aeschbach-Hertig, W., Ilmberger, J., 2012. Localising and quantifying groundwater inflow into lakes using high-precision 222Rn profiles. *Journal of Hydrology*, 450-451: 70-81. DOI:10.1016/j.jhydrol.2012.05.026
- Lamontagne, S., Le Gal La Salle, C., Hancock, G.J., Webster, I.T., Simmons, C.T., Love, A.J., James-Smith, J., Smith, A.J., Kämpf, J., Fallowfield, H.J., 2008. Radium and radon radioisotopes in regional groundwater, intertidal groundwater, and seawater in the Adelaide Coastal Waters Study area: Implications for the evaluation of submarine groundwater discharge. *Marine Chemistry*, 109: 318-336. DOI:10.1016/j.marchem.2007.08.010
- Lee, J.-Y., 2014. Use of environmental and applied tracers for groundwater studies in Korea. *Geosciences Journal*, 18: 115-123. DOI:10.1007/s12303-013-0050-y
- Mahlknecht, J., Merchan, D., Rosner, M., Meixner, A., Ledesma-Ruiz, R., 2017. Assessing seawater intrusion in an arid coastal aquifer under high anthropogenic influence using major constituents, Sr and B isotopes in groundwater. *Sci Total Environ*, 587-588: 282-295.
DOI:10.1016/j.scitotenv.2017.02.137
- Mayer, A., Nguyen, B.T., Banton, O., 2016. Using radon-222 to study coastal groundwater/surface-water interaction in the Crau coastal aquifer (southeastern France). *Hydrogeology Journal*, 24: 1775-1789. DOI:10.1007/s10040-016-1424-9
- Mazi, K., Koussis, A.D., Destouni, G., 2014. Intensively exploited Mediterranean aquifers: resilience to seawater intrusion and proximity to critical thresholds. *Hydrology and Earth System Sciences*, 18: 1663-1677. DOI:https://doi.org/10.5194/hess-18-1663-2014
- Mazi, K., Koussis, A.D., Destouni, G., 2016. Quantifying a Sustainable Management Space for Human Use of Coastal Groundwater under Multiple Change Pressures. *Water Resources Management*, 30: 4063-4080. DOI:10.1007/s11269-016-1363-1
- McCoy, C.A., Corbett, D.R., 2009. Review of submarine groundwater discharge (SGD) in coastal zones of the Southeast and Gulf Coast regions of the United States with management implications. *Journal of Environmental Management*, 90: 644-651. DOI:10.1016/j.jenvman.2008.03.002
- Meixner, T., Manning, A.H., Stonestrom, D.A., Allen, D.M., Ajami, H., Blasch, K.W., Brookfield, A.E., Castro, C.L., Clark, J.F., Gochis, D.J., Flint, A.L., Neff, K.L., Niraula, R., Rodell, M., Scanlon, B.R., Singha, K., Walvoord, M.A., 2016. Implications of projected climate change for groundwater recharge in the western United States. *Journal of Hydrology*, 534: 124-138.
DOI:10.1016/j.jhydrol.2015.12.027
- Mejías, M., Ballesteros, B.J., Antón-Pacheco, C., Domínguez, J.A., Garcia-Orellana, J., Garcia-Solsona, E., Masqué, P., 2012. Methodological study of submarine groundwater discharge from a karstic aquifer in the Western Mediterranean Sea. *Journal of Hydrology*, 464-465: 27-40.
DOI:10.1016/j.jhydrol.2012.06.020
- Montiel, D., Dimova, N., Andreo, B., Prieto, J., García-Orellana, J., Rodellas, V., 2018. Assessing submarine groundwater discharge (SGD) and nitrate fluxes in highly heterogeneous coastal karst aquifers: Challenges and solutions. *Journal of Hydrology*, 557: 222-242.
DOI:10.1016/j.jhydrol.2017.12.036
- Moore, W.S., 1996. Large groundwater inputs to coastal waters revealed by 226Ra enrichments. *Nature*, 380: 612-614. DOI:10.1038/380612a0

- Moore, W.S., 2000. Determining coastal mixing rates using radium isotopes. *Continental Shelf Research*, 20: 1993-2007. DOI:10.1016/S0278-4343(00)00054-6
- Moujabber, M.E., Samra, B.B., Darwish, T., Atallah, T., 2006. Comparison of Different Indicators for Groundwater Contamination by Seawater Intrusion on the Lebanese Coast. *Water Resources Management*, 20(2): 161-180. DOI:10.1007/s11269-006-7376-4
- Mulligan, A.E., Charette, M., 2009. Groundwater Flow to the coastal ocean. *Reference Module in Earth Systems and Environmental Sciences, Encyclopedia of Ocean Sciences, Marine Chemistry and Geochemistry*, 2: 88-97. DOI:https://doi.org/10.1016/B978-012374473-9.00645-7
- Nlend, B., Celle-Jeanton, H., Huneau, F., Ketchemen-Tandia, B., Fantong, W.Y., Boum-Nkot, S.N., Etame, J., 2018. The impact of urban development on aquifers in large coastal cities of West Africa: Present status and future challenges. *Land Use Policy*, 75: 352-363. DOI:10.1016/j.landusepol.2018.03.007
- Orsini, J.-B., Ferrandini, J., Ferrandini, M., Loÿe, M.-D., Pluquet, F., Guennoc, P., Thinon, I., Santiago, M., Reynaud, J.-Y., Oggiano, G., Cherchi, G., Gattaccaca, J., Orrù, P., Puliga, G., Pintus, M., Ulzega, A., 2010. Notice explicative, carte géol. France (1/50 000), feuille Sotta-Bonifacio-Santa-Teresa-di-Gallura (1127). BRGM Orléans, 258 pp. ISBN: 78-2-7159-2127-6
- Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., Dasgupta, P., Dubash, N.K., Edenhofer, O., Elgizouli, I., Field, C.B., Forster, P., Friedlingstein, P., Fuglestad, J., Gomez-Echeverri, L., Hallegatte, S., Hegerl, G., Howden, M., Jiang, K., Jimenez Cisneros, B., K., V., , Lee, H., Mach, K.J., Marotzke, J., Mastrandrea, M.D., Meyer, L., Minx, J., Mulugetta, Y., O'Brien, K., Oppenheimer, M., Pereira, J.J., Pichs-Madruga, R., Plattner, G.K., Pörtner, H.O., Power, S.B., Preston, B., Ravindranath, N.H., Reisinger, A., Riahi, K., Rusticucci, M., Scholes, R., Seyboth, K., Sokona, Y., Stavins, R., Stocker, T.F., Tschakert, P., van Vuuren, D., van Ypersele, J.P., 2014. IPCC Synthesis Report. *Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Contribution of Working Groups I, II and III. DOI: https://ar5-syr.ipcc.ch/ipcc/ipcc/resources/pdf/IPCC_SynthesisReport.pdf.
- Post, V.E., Groen, J., Kooi, H., Person, M., Ge, S., Edmunds, W.M., 2013. Offshore fresh groundwater reserves as a global phenomenon. *Nature*, 504(7478): 71-8. DOI:10.1038/nature12858
- Povinec, P.P., Aggarwal, P.K., Aureli, A., Burnett, W.C., Kontar, E.A., Kulkarni, K.M., Moore, W.S., Rajar, R., Taniguchi, M., Comanducci, J.-F., Cusimano, G., Dulaiova, H., Gatto, L., Groening, M., Hauser, S., Levy-Palomo, I., Oregioni, B., Ozorovich, Y.R., Privitera, A.M.G., Schiavo, M.A., 2006. Characterisation of submarine groundwater discharge offshore south-eastern Sicily. *Journal of Environmental Radioactivity*, 89: 81-101. DOI:10.1016/j.jenvrad.2006.03.008
- Povinec, P.P., Bokuniewicz, H., Burnett, W.C., Cable, J., Charette, M., Comanducci, J.-F., Kontar, E.A., Moore, W.S., Oberdorfer, J.A., de Oliveira, J., Peterson, R., Stieglitz, T., Taniguchi, M., 2008. Isotope tracing of submarine groundwater discharge offshore Ubatuba, Brazil: results of the IAEA-UNESCO SGD project. *Journal of Environmental Radioactivity*, 99: 1596-1610. DOI:10.1016/j.jenvrad.2008.06.010
- Povinec, P.P., Burnett, W.C., Beck, A., Bokuniewicz, H., Charette, M., Gonneea, M.E., Groening, M., Ishitobi, T., Kontar, E., Liong Wee Kwong, L., Marie, D.E.P., Moore, W.S., Oberdorfer, J.A., Peterson, R., Ramessur, R., Rapaglia, J., Stieglitz, T., Top, Z., 2012. Isotopic, geophysical and biogeochemical investigation of submarine groundwater discharge: IAEA-UNESCO intercomparison exercise at Mauritius Island. *Journal of Environmental Radioactivity*, 104: 24-45. DOI:10.1016/j.jenvrad.2011.09.009
- Rapaglia, J., Grant, C., Bokuniewicz, H., Pick, T., Scholten, J., 2015. A GIS typology to locate sites of submarine groundwater discharge. *J Environ Radioact*, 145: 10-18. DOI:10.1016/j.jenvrad.2015.03.016
- Reynaud, J.-Y., Ferrandini, M., Ferrandini, J., Santiago, M., Thinon, I., André, J.-P., Barthet, Y., Guennoc, P., Tessier, B., 2012. From non-tidal shelf to tide-dominated strait: The Miocene Bonifacio Basin, Southern Corsica. *Sedimentology*, 60: 599-623. DOI:10.1111/j.1365-3091.2012.01352.x

- Richts, A., Struckmaier, W.-F., Zaekpe, M., 2011. WHYMAP and the Groundwater Resources Map of the World 1:25,000,000. *Sustaining Groundwater Resources, International Year of Planet Earth Book*: 159-173. DOI: https://doi.org/10.1007/978-90-481-3426-7_10
- Rodellas, V., Garcia-Orellana, J., Masqué, P., Feldman, M., Weinstein, Y., 2015. Submarine groundwater discharge as a major source of nutrients to the Mediterranean Sea. *PNAS*, 112(13): 3926-3930. DOI: <https://doi.org/10.1073/pnas.1419049112>
- Rossi, P., Cocherie, A., 1991. Genesis of a Variscan batholith: Field, petrological and mineralogical evidence from the Corsica-Sardinia batholith. *Tectonophysics*, 195(2-4): 319-346. DOI:10.1016/0040-1951(91)90219-i
- Santoni, S., 2016. Contributions du multi-traçage géochimique et isotopique à la compréhension des aquifères côtiers : mise en place d'un modèle de fonctionnement de l'aquifère de Bonifacio (Corse-du-Sud), Ph. D. Thesis, Université de Corse Pascal Paoli, France, 281 pp.
- Santoni, S., Huneau, F., Garel, E., Aquilina, L., Vergnaud-Ayraud, V., Labasque, T., Celle-Jeanton, H., 2016a. Strontium isotopes as tracers of water-rocks interactions, mixing processes and residence time indicator of groundwater within the granite-carbonate coastal aquifer of Bonifacio (Corsica, France). *Science of The Total Environment*, 573: 233-246. DOI:10.1016/j.scitotenv.2016.08.087
- Santoni, S., Huneau, F., Garel, E., Celle-Jeanton, H., 2018. Multiple recharge processes to heterogeneous Mediterranean coastal aquifers and implications on recharge rates evolution in time. *Journal of Hydrology*, 559: 669-683. DOI:10.1016/j.jhydrol.2018.02.068
- Santoni, S., Huneau, F., Garel, E., Vergnaud-Ayraud, V., Labasque, T., Aquilina, L., Jaunat, J., Celle-Jeanton, H., 2016b. Residence time, mineralization processes and groundwater origin within a carbonate coastal aquifer with a thick unsaturated zone. *Journal of Hydrology*, 540: 50-63. DOI:10.1016/j.jhydrol.2016.06.001
- Santos, I.R., Eyre, B.D., Huettel, M., 2012. The driving forces of porewater and groundwater flow in permeable coastal sediments: A review. *Estuarine, Coastal and Shelf Science*, 98: 1-15. DOI:10.1016/j.ecss.2011.10.024
- Sawyer, A.-H., David, C.-H., Famiglietti, J.-S., 2017. Continental patterns of submarine groundwater discharge reveal coastal vulnerabilities. *Science*, 353(6300): 705-707. DOI:10.1126/science.aag1058
- Scholten, J.C., Pham, M.K., Blinova, O., Charette, M.A., Dulaiova, H., Eriksson, M., 2010. Preparation of Mn-fiber standards for the efficiency calibration of the delayed coincidence counting system (RaDeCC). *Marine Chemistry*, 121(1-4): 206-214. DOI:10.1016/j.marchem.2010.04.009
- Schubert, M., Brueggemann, L., Knoeller, K., Schirmer, M., 2011. Using radon as an environmental tracer for estimating groundwater flow velocities in single-well tests. *Water Resources Research*, 47(3). DOI:10.1029/2010wr009572
- Sherif, M., Singh, P., 1999. Effect of climate change on sea water intrusion in coastal aquifers. *Hydrological Processes*, 13(8): 1277-1287. DOI: [https://doi.org/10.1002/\(SICI\)1099-1085\(19990615\)13:8<1277::AID-HYP765>3.0.CO;2-W](https://doi.org/10.1002/(SICI)1099-1085(19990615)13:8<1277::AID-HYP765>3.0.CO;2-W)
- Stieglitz, T.C., Cook, P.G., Burnett, W.C., 2010. Inferring coastal processes from regional-scale mapping of 222Radon and salinity: examples from the Great Barrier Reef, Australia. *Journal of Environmental Radioactivity*, 101: 544-552. DOI:10.1016/j.jenvrad.2009.11.012
- Stigter, T.Y., Nunes, J.P., Pisani, B., Fakir, Y., Hugman, R., Li, Y., Tomé, S., Ribeiro, L., Samper, J., Oliveira, R., Monteiro, J.P., Silva, A., Tavares, P.C.F., Shapouri, M., Cancela da Fonseca, L., El Himer, H., 2012. Comparative assessment of climate change and its impacts on three coastal aquifers in the Mediterranean. *Regional Environmental Change*, 14(S1): 41-56. DOI:10.1007/s10113-012-0377-3
- Tamborski, J.J., Rogers, A.D., Bokuniewicz, H.J., Cochran, J.K., Young, C.R., 2015. Identification and quantification of diffuse fresh submarine groundwater discharge via airborne thermal infrared remote sensing. *Remote Sensing of Environment*, 171: 202-217. DOI:10.1016/j.rse.2015.10.010

- Tomasky-Holmes, G., Valiela, I., Charette, M.A., 2013. Determination of water mass ages using radium isotopes as tracers: Implications for phytoplankton dynamics in estuaries. *Marine Chemistry*, 156: 18-26. DOI:10.1016/j.marchem.2013.02.002
- Werner, A.D., Bakker, M., Post, V.E.A., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., Simmons, C.T., Barry, D.A., 2013. Seawater intrusion processes, investigation and management: Recent advances and future challenges. *Advances in Water Resources*, 51: 3-26. DOI:10.1016/j.advwatres.2012.03.004
- Zhang, Y., Li, H., Xiao, K., Wang, X., Lu, X., Zhang, M., An, A., Qu, W., Wan, L., Zheng, C., 2017. Improving estimation of submarine groundwater discharge using radium and radon tracers: application in Jiaozhou Bay, China. *Journal of Geophysical Research: Oceans*, 122(10): 8263-8277.

874 **List of tables**

875

876 **Table 1:** Physicochemical parameters, major ions, selected trace elements and
877 stable isotopes of the water molecule of the stream (CANR-R1) and groundwater
878 samples (October 2012).

879 **Table 2:** Radon and Radium radionuclide activity of stream (CANR-R1) and
880 groundwater (October 2012).

881 **Table 3:** Radon activities for 5 sand sediment samples spread all over the study area
882 (January 2014).

883 **Table 4:** Estimates of SGD flows seepage velocities in the Bonifacio Harbour and the
884 Sant'Amanza Bay (Stentinu) from radon and radium activities. SGD flows seepage
885 velocities from the Fick law is also added for the Bonifacio Harbour. (*) Flux
886 calculated using the first Fick's law assuming a freshwater fraction gradient in the
887 harbour of $-1.89 \times 10^{-5} \text{ (m}^{-1}\text{)}$. This gradient is calculated from 3.5% freshwater dilution,
888 obtained from the salinity difference between inner harbour- and offshore waters, and
889 a total length of the harbour of 1800 m.

890 **Table 5:** Permeability (K) for the Bonifacio aquifer from existing literature and
891 associated Darcy velocity (q) computed between EB-B1 and ORE-W2 in the Saint
892 Julien Valley considering $\Delta L = 1173 \text{ m}$ and $\Delta H = 48 \text{ m}$.

893

List of figures

Figure 1: Location of the study site, general lithology simplified from Reynaud et al., 2012, sampling points (A) and cross section of the Bonifacio Harbour with details on fixed measurements A to F for ^{222}Rn , ^{223}Ra and ^{224}Ra (B).

Figure 2: Airborne TIR images of the study site's coastlines (on the 9th September 2011).

Figure 3: Hydrochemistry, saturation index, and isotopes content in groundwater highlighting an increase in groundwater-rocks interaction (A; B) with a focus on the potential ^{222}Rn sources in groundwater before discharge in the sea (C). Bubble plot size in (C) is proportional to U ($\mu\text{g/L}$) concentration.

Figure 4: Measured T, E.C., and ^{222}Rn activity along the coastlines (January 2014).

Figure 5: Box plots of E.C. values vs activity classes of ^{222}Rn from all the coastline survey. Mean E.C. values are also represented with blue squares as well as their corresponding regression line in blue dotted line for each activity class of ^{222}Rn .

Figure 6: ^{222}Rn , ^{224}Ra and ^{223}Ra Ln activity regressions from the 6 fixed measurements carried out within the Bonifacio Harbour as function of distance

Figure 7: Water balance of the Bonifacio aquifer.

Figures

Figure 1 : Location of the study site, general lithology simplified from Reynaud et al., 2012, sampling points (A) and cross section of the Bonifacio Harbour with details on fixed measurements A to F for ^{222}Rn , ^{223}Ra and ^{224}Ra (B).

Figure 2 : Airborne TIR images of the study site's coastlines (on the 9th September 2011).

Figure 3: hydrochemistry, saturation index, and isotopes content in groundwater highlighting an increase in groundwater-rocks interaction (A; B) with a focus on the potential ^{222}Rn sources in groundwater before discharge in the sea (C). Bubble plot size in (C) is proportional to U ($\mu\text{g/L}$) concentration.

Figure 4 : measured T, E.C., and ^{222}Rn activity along the coastlines (January 2014).

Figure 5 : box plots of E.C. (B) values vs activity classes of ^{222}Rn from all the coastline survey. Mean E.C. values are also represented with blue squares as well as their corresponding regression line in blue dotted line for each activity class of ^{222}Rn .

Figure 6:

Figure 7: ²²²Rn, ²²⁴Ra and ²²³Ra activities from the 6 fixed measurement carried out within the Bonifacio Harbor as function of distance

Figure 8: water balance of the Bonifacio aquifer

Tables

Table 1: physicochemical parameters, major ions, selected trace elements and stable isotopes of the water molecule of the stream (CANR-R1) and groundwater samples (October 2012).

	T	pH	EC	HCO ₃	Cl	NO ₃	SO ₄	Na	K	Mg	Ca	SiO ₂	U	Sr	δ ² H	δ ¹⁸ O
	°C		μS/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	μg/L	μg/L	‰	‰
CPO-B10	16.8	6.73	2040	478	374.5	37.6	55.9	170.0	3.9	21.8	213.1	12.7	1.9	297.4	-36.9	-5.96
ARA-W4	18.4	7.03	1200	409	163.0	9.8	28.6	88.3	2.6	12.3	140.8	10.0	0.6	181.3	-38.2	-6.32
CANR-R1	14.0	7.64	1160	351	181.4	1.1	46.1	98.0	2.8	15.6	128.8	13.7	2.8	216.0	-36.0	-5.97
CUC-B6	18.0	7.29	1280	357	205.5	5.5	28.1	113.3	2.6	15.8	116.6	10.5	0.5	189.9	-35.6	-5.84
EB-B1	16.6	6.91	1650	432	278.7	28.9	58.8	147.3	3.3	27.0	157.0	10.2	1.5	410.4	-36.3	-5.77
ORE-W2	17.5	7.07	990	338	132.3	21.3	25.3	65.5	1.8	9.3	122.1	11.2	0.7	138.6	-38.2	-6.17
GEN-W3	20.7	6.80	1082	396	137.9	7.2	32.9	70.1	3.7	11.0	140.7	16.9	0.7	196.9	-37.7	-6.24
REP-B18	16.5	6.88	1215	387	174.1	8.4	43.2	108.2	3.2	14.1	121.3	16.1	2.8	237.1	-38.0	-6.15
VB-B5	16.9	7.47	1066	395	140.3	0.3	0.5	77.0	3.1	13.2	104.2	9.0	0.0	286.0	-37.9	-6.16

954

955

956 Table 2 : Radon and Radium radionuclides activity of stream (CANR-R1) and groundwater (October 2012).

	²²² Rn (Bq/m3)		²²⁴ Ra (Bq/m3)		²²³ Ra (Bq/m3)	
		Std.		Std.		Std.
CPO-B10	10823	173	33.9	2.0	1.4	0.3
ARA-W4	6081	133	13.3	0.8	0.6	0.1
CANR-R1			10.7	0.9	0.1	0.0
CUC-B6	3528	95	15.7	1.3	1.0	0.1
EB-B1	4092	97	28.3	1.7	1.5	0.3
ORE-W2	3393	89	16.3	0.9	0.4	0.1
GEN-W3	3714	93	15.2	1.3	1.1	0.1
REP-B18	27853	340	34.3	1.6	0.5	0.1
VB-B5	1199	68	8.8	0.5	0.1	0.0

957

958 Table 3: Radon activities for 6 sand sediment samples spread all over the study area (January 2014).

Beach sediment sample	²²² Rn (Bq/m ³)	
		Std.
Canettu	2.3	0.6
Sant'Amanza	3.1	0.5
Paraguano	3.5	0.7
San Mulari	6.2	1.0
Pertusato	1.4	0.8

959

960 Table 4 :

	Bonifacio Harbour			Sant'Amanza Bay
	²²² Rn	²²³ Ra	²²⁴ Ra	²²² Rn
Distance vs. logarithm activities regression line equation	y = -0.0013x + 4.1722	y = -0.0013x + 1.8632	y = -0.0016x + 0.5507	y = -0.002x + 5.5393
Isotope half-lives (day)	3.86	11.8	3.6	3.86
Isotope lambda (day ⁻¹)	0.180	0.059	0.193	0.180
Computed seawater mixing coefficients, D _{eddy} (m ² /s)	1.23	0.40	1.32	1.84
Distance vs. activities exponential regression equation	y = 57.6776e ^{-0.0012x}	y = 0.4553e ^{-0.0010x}	y = 5.3360e ^{-0.0012x}	y = 254.497e ^{-0.00199x}
Isotope horizontal inventories for 1 m ² of water parcel flowing from A to F (Bq/m ²)	42268	380	3934	110954
Isotope fluxes from groundwater input in the harbor (Bq/m ² /day)	7590	22	757	19924
isotope activities in groundwater, C _{GW} (Bq/m ³)	3393	0.4	16.3	10823
Computed SGD seepage velocities (m/day)	2.24	55.81	46.47	1.84
Computed SGD seepage flow (L/s)	2.5	63.3	52.7	24.6

961

962

963