Available online at www.sciencedirect.com
SciVerse ScienceDirect
Procedia Earth and Planetary Science 4 (2011) 3 – 9
Procedia
Earth and Planetary Science

Research in Shallow Marine and Fresh Water Systems

A marine groundwater spring in Stoupa, Greece: Shallow water instrumentation comparing radon and ambient sound with discharge rate

C. Tsabaris[a†], M. N. Anagnostou[b], D.L. Patiris[a], J. A. Nystuen[a,c], G. Eleftheriou[d], Th. Dakladas[a], V. Papadopoulos[a], A. Prospathopoulos[a], A. Papadopoulos[a] and E. N. Anagnostou[e]

[a]*Institute of Oceanography, Hellenic Center for Marine Research, Anavyssos 190 13, Greece*
[b]*Information Department, Sapienza University, Rome, Italy*
[c]*Applied Physics Laboratory, University of Washington, Seattle, WA-98105, USA*
[d]*Department of Physics, National Technical University of Athens, Zografou Campus, 15780 Athens, Greece*
[e]*Department of Civil and Environmental Engineering, University of Connecticut, Storrs, CT, USA*

Abstract

This work describes the combination of two autonomous in-situ systems, one using the measurements of radon progenies and the other one using underwater ambient sound, for monitoring submarine groundwater discharge (SGD). The sensors were co-located on a platform and deployed in a SGD point source at Stoupa, Messinia, Greece. Long-term monitoring of radon progenies concentration as well as acoustic measurements are presented. The radon progeny data were correlated with the flow rate during one of the deployments. The ambient sound levels apparently responded to changes in the physical structure of the spring, but not in a predictable manner. The measuring platform can be easily applied to oceanographic survey activities, such as monitoring of gases and fluxes on submarine groundwater discharges, pockmarks, volcanoes, submarine faults, as well as to the measurement of rainfall freshwater flux at the ocean surface

Selection and/or peer-review under responsibility of Istituto Nazionale di Geofisica e Vulcanologia.

Keywords: Submarine grounwater disharge, in-situ gamma-ray spectrometry, underwater acoustics, radioisotope tracing tecqniques

---

[†] Corresponding author: P.O. BOX 712, Anavyssos, GR-19013, Greece
E-mail address: tsabaris@ath.hcmr.gr

Selection and/or peer-review under responsibility of Istituto Nazionale di Geofisica e Vulcanologia.
doi:10.1016/j.proeps.2011.11.002

1. Introduction

A subsurface flow of fresh water (point or diffusive) offshore is called Submarine Groundwater Discharge (SGD) and is considered as an important pathway of dissolved matter transport to the ocean [1, 2]. SGD potentially affects the coastal environment due to various pollutants that could be transported to the ocean, especially the high dissolved matter contents like nutrients, heavy metals and organic pollutants.

The methods that have been mostly applied for the detection and the quantification of SGDs are the direct physical measurements with a seepage flux meter and various tracer techniques using geochemical species, which are naturally enriched in SGD with respect to seawater. The major tracer is ^{222}Rn (half life 3.8 days), which is an inert gas dissolved in the groundwater, is not involved in geochemical and particle cycles. ^{222}Rn has been used in previous studies in order to investigate the temporal and spatial distribution of SGD [3, 4]. Measurements of radon in water are usually conducted using laboratory methods like liquid scintillation, stripping of radon from water or in-situ methods (e.g. using RAD7) [5], whereas radon progenies can be monitored using underwater in-situ gamma spectrometry. The latter has been used for studying the temporal and spatial variations of SGD in two different coastal areas. In the work by Povinec et al. [6] a NaI underwater spectrometer connected to a portable computer acquired data for three days in the coastal zone of Donnalucata (south-eastern Sicily) and at Ubatuba Bay, Brazil. A correlation between in-situ gamma ^{222}Rn progenies measurements, salinity and tidal range was observed during those experiments [6]. When compared to radon measurements conducted with a radon monitor (RAD7), the in-situ gamma measurements were found to be about 50 times higher [7]. This divergence can be attributed to the fact that the position of the gamma spectrometry sensor was closer to the discharge location and consequently to the radon source. Recently, the KATERINA system was utilized in four SGD sites in the Mediterranean Sea (Cabbe-Monaco, Chalkida-Greece, Korfos-Greece and Stoupa-Greece) for studying radon radioactivity levels in the framework of radiological impacts to humans [8].

The ambient sound field, in the marine ocean environment, contains a lot of information about the physical, biological and anthropogenic processes taking place. The acoustic signal from a SGD is mostly unknown. If the signal is unique (identifiable in the presence of other sounds), then it may be possible to quantitatively monitor the SGD using robust and simple hydrophone technology. In this work, the acoustic signal of a SGD located close to the shore is determined and the ability to quantify the signal is explored. To this purpose, a Passive Aquatic Listener (PAL) for providing long-term measurements of underwater ambient sound, generated by the SGD, was used. A preliminary study, comparing acoustic data with time series of radon progenies, seems to be promising. Furthermore, the impact of this technology on future hydrographic surveys is discussed.

2. Study Area

Kalogria Bay, just north of Stoupa, is located in southwestern Peloponnese, in Messinia prefecture (Fig. 1a). Many locations of submarine groundwater discharge are easily visible on the sea surface around the bay. The largest groundwater source is located about 100 m offshore with two strong SGDs emanating from fissures in the bedrock at roughly 25 m depth (Fig. 1b). These submarine springs were reported in 1975, although local inhabitants were well aware of their existence, claiming the springs had never stopped emanating water during, at least, for the past 60 years. Limestone, dolomite and, to a lesser extent, metamorphic rocks characterize the geological make-up of the area. These carbonate rocks are heavily karstified and almost completely permeable. The deployment site is easily reached by a small boat and

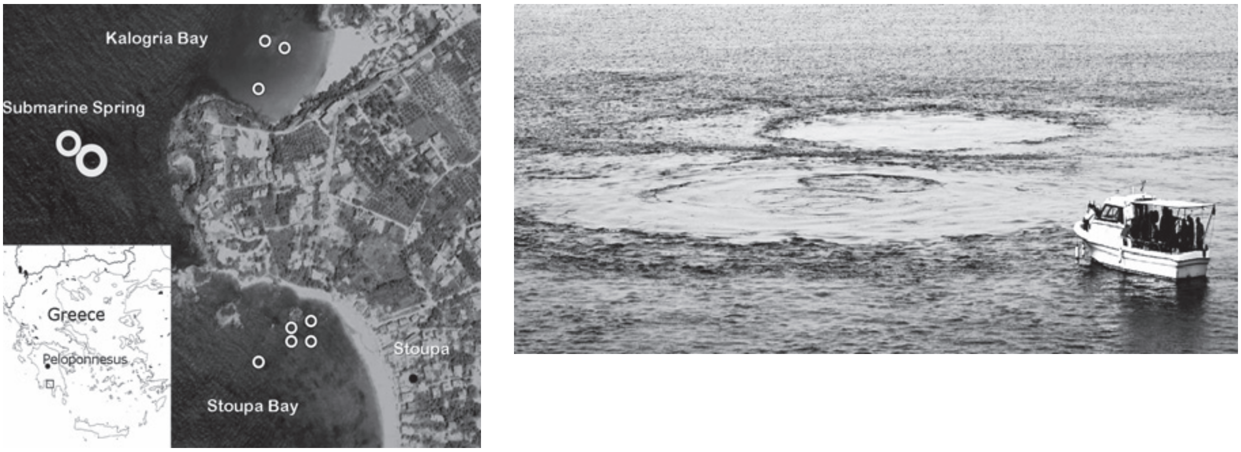

Fig. 1 (a) The location of the underwater spring at Stoupa (b) the main source as it is observed from the surface.

divers were recruited to grab water samples and deploy the measuring platform inside the cave exactly into the stream of the emanating groundwater.

3. Materials and Methods

Measurements of radon progenies were performed using the KATERINA in-situ underwater sensor, while the acoustic detections were performed using a PAL system. Additionally, a rotor flow meter and two conductivity/temperature (CT) data loggers were used to monitor the water velocity, temperature and salinity. The PAL, CT and flow meter systems were internally battery powered, whereas the KATERINA system was powered by a custom-made underwater battery which keeps the detector operable for about 25 days. Two deployments were performed: during the first one (November-December 2009), a platform co-locating KATERINA, CT and flow meter sensors were used; during the second one (May-June 2010), the PAL was also attached onto the platform (Fig. 2).

3.1. The radon progeny measuring system

Measurements of radon progenies were performed using the detection system named KATERINA [9]. The detector unit is a 3”x3” NaI detection crystal built in photomultiplier tube, preamplifier, an analog-digital converter, a high voltage controller and electronic modules for data acquisition, storage and transmission. Thin housing with low attenuation coefficient material (acetal) and low power consumption are important factors for deep deployments and long term measurements. In order to keep sensor housing size as small as possible (84 x 550 mm), high-density electronic modules are fitted inside the sensor. The power unit filters and distributes input voltage (9 - 18 V DC) towards independent modules (e.g., amplifier, high voltage converter, pre-amplifier and multichannel analyzer). The design of the electronic system keeps power consumption as low as 1.2 - 1.4 W. The system has been energy calibrated and tested for stability, including measurements of detector efficiency in aquatic environment and absolute calibration in Bq/m^3, and can be deployed up to 2000m.

The system (installed on the platform) was placed in the SGD 1.5 m above the seabed and 23.5 m below the sea surface. This distance was chosen in order to use the calibration marine efficiency as it was

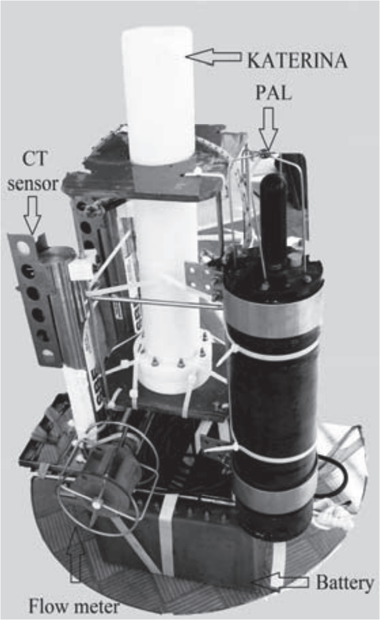

Fig. 2 The measuring platform containing the sensors KATERINA and PAL

measured with standard sources in several performance laboratory tests. Data were acquired in a special memory which was incorporated in the system; the data were extracted after the experiment of the deployment. The analysis of the measured spectrum was performed with SPECTRW [10] software and net area of the radon progenies (^{214}Pb and ^{214}Bi), in combination with the marine efficiency, provided the activity concentration (Bq/m^3) of the radon progenies. The acquisition time lag of the system was set up to 12 hours. The activity concentration of radon progenies was used for correlation purposes with the flow of the SGD as given from the flow meters.

3.2. Passive Aquatic Listener (PAL)

Passive Aquatic Listeners (PALs) are autonomous underwater acoustic recorders designed to be attached to ocean moorings. They consist of a broadband, low noise hydrophone, a signal processing board, a low-power microprocessor with a 100 kHz A/D digitizer, a 2 Gbyte memory card and a 48 Amp-hour battery pack. The sampling strategy can be designed to allow autonomous operations for up to one year. An important feature of the microprocessor is a very low-power “sleep” mode to save energy between acoustic samples. Electronically, a PAL consists of a low-noise wideband hydrophone (a Hi-Tech-92WB), signal pre-amplifiers and a recording computer (Tattletale-8). The nominal sensitivity of these instruments is -160 dB relative to 1 V/μPa and the equivalent oceanic background noise level of the pre-amplifier system is about 28 dB relative to 1 $\mu Pa^2 Hz^{-1}$. Band-pass filters are present to reduce saturation from low frequency sound (high pass at 300 Hz) and aliasing from above 50 kHz (low pass at 40 kHz). The hydrophone sensitivity also rolls off above its resonance frequency, about 40 kHz.

The PAL system is an autonomous passive system that records different sound sources generated underwater and/or in the ocean surface. Unique features of sound source spectra can be often used to identify the sources. This allows spectral levels at various frequencies, ratios of these levels, spectral slopes, and the temporal persistence of the sound source to be quantified. A data collection sequence (a single sample) consists of a 4.5-second time series collected at 100 kHz. This time series is then sub-sampled eight times – generating eight 1024 pt or 10.24 ms short time series. Each of these subsamples is fast Fourier transformed (FFT) to obtain a 512-point power spectrum (0-50 kHz). These spectra are spectrally compressed to 64 frequency bins, with frequency resolution of 200 Hz from 100-3000 Hz and 1 kHz from 3-50 kHz. These spectra are then evaluated individually to determine an acoustic source and then are recorded internally. Thus, the standard data set is a time series of spectra. The PAL has an adaptive time interval between data collection sequences that varies depending both on the acoustic source detected and the mission requirements. The default sampling interval for this experiment was set to 5 minute with the sampling interval changing to 1 minute when unusual noises were detected.

4. Results and Discussion

The 2009 deployment (Nov.'09 – Dec.'09) took place during wet, dry and rainfall periods that caused large variations in the flow rate of the SGD, which was reflected in the flux velocity measurements (Fig. 3). During this period, the measuring platform without PAL was deployed to investigate potential correlations between hydrological parameters of the shallow-water SGD spring and the activity concentration of radon progenies and potassium (^{40}K). In Fig. 3a and 3b, the acquired data concerning flux velocity and radioisotope activities are plotted. Fig. 3a shows that ^{214}Bi activity concentration exhibits a strong correlation with flux velocity (cm/s). It should be noted that the other radon progeny (^{214}Pb) was in radioactive equilibrium with ^{214}Bi, and thus ^{214}Pb exhibits the same behavior as ^{214}Bi. In contrast, the activity concentration of ^{40}K was inversely proportional to flux velocity (Fig. 3b). The above results have a physical interpretation. Seawater is rich in potassium and almost radon free, whereas groundwater is radon enhanced. Consequently, as SGD flux velocity decreases, radon concentration correspondingly decreases while ^{40}K concentration increases and vice-versa.

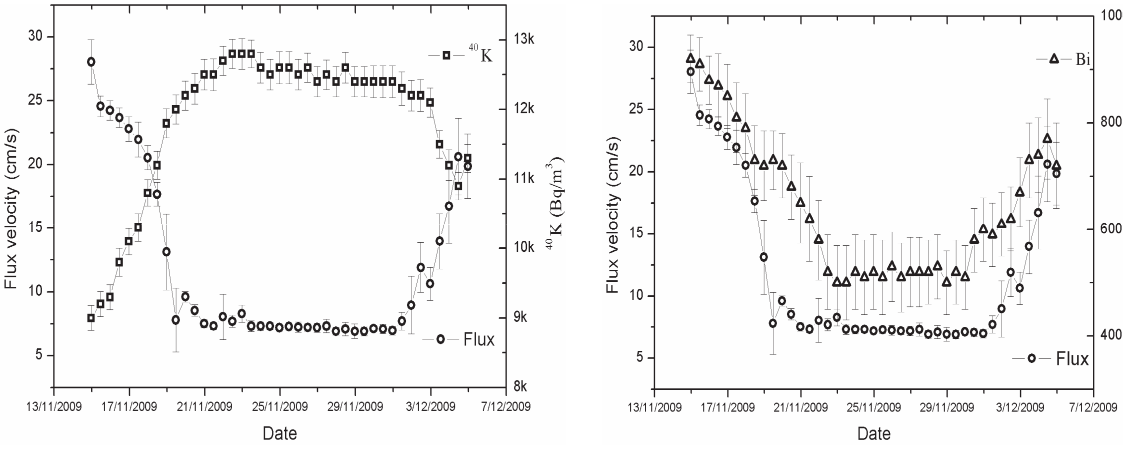

Fig. 3 (a)The activity concentration of radon progeny ^{214}Bi and (b) potassium ^{40}K together with the flux velocity of the emanating groundwater during the deployment of Nov. - Dec. 2009.

The measuring platform, including all instrumentation (KATERINA, PAL, flow meter and CT sensor), was deployed during a dry period (May 2010 – June 2010), when the flow rate exhibited lower variations. The acquired data are presented in Fig. 4 as a time series. The upper plots show coincident observations of sound intensities from the PAL at different frequencies (1, 6, and 21 kHz) and flux velocity (cm/s) from the flow meter. The middle plot shows observations from the CT sensors and the flow meter. In the last plot, ^{214}Bi and ^{40}K activity concentrations are plotted together with flux velocity. The KATERINA detector has operated for 22 days, providing a time period when all of the sensors on the platform were operating simultaneously. The data from KATERINA show that ^{214}Bi and ^{40}K (within statistical errors) activity concentrations remained almost constant with respect to the flux velocity trend. In contrast, the acoustic observations show changes that persist over long time periods (many days). There is no obvious relationship between the spring's flow rate and the ambient sound. However, the ambient sound is apparently responding to changes in the physical structure of the spring. On June, 20, 2010 the character of the spring exhibited an abrupt change as the groundwater became fresher and colder (Fig. 4b). This suggests that saltwater intrusion into the spring has been cutoff, possibly by a submarine landslide. At this time, the sound levels increased, indicating that acoustic changes, associated with the physical structure of the spring, have been detected but not in a predictable way, since the flow rate actually decreased.

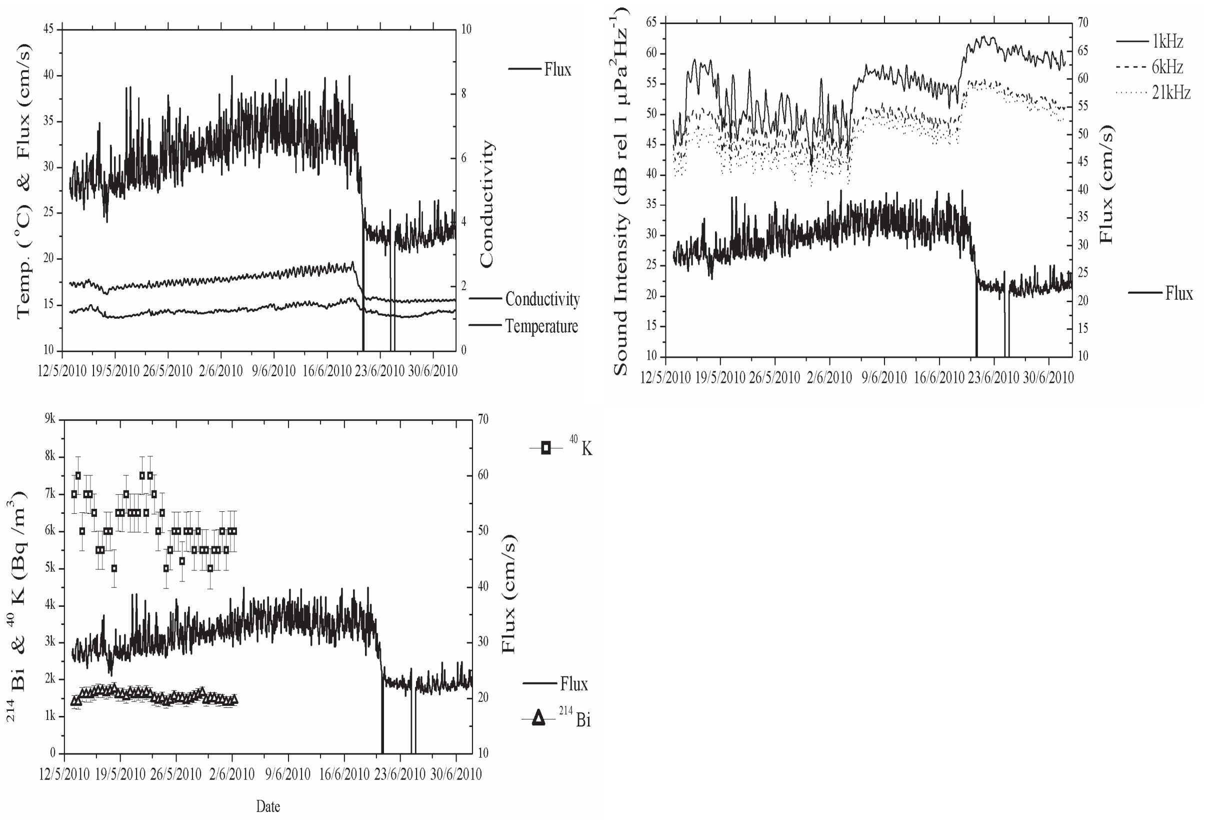

Fig. 4 (a) Sound intensity at different frequencies (b) conductivity and temperature and (c) activity concentration of ^{214}Bi and ^{40}K together with flux velocity of the emanating groundwater during the deployment of May – Jun. 2010.

5. Conclusions

The combinations of in-situ and fully autonomous sensors were used as a tool for studying a complex phenomenon in a shallow-water coastal environment. This work describes a preliminary application of a platform combining an underwater radioactivity spectrometer and a passive aquatic listener with commonly used oceanographic sensors (CT, flow meter) to investigate the flow of a SGD spring. During a period of variable flow rates the radon progeny measurements show strong correlation with the flow rate. The acoustic measurements show that the ambient sound changes, persisting over long period of time but not in a predictable manner.

During the pilot deployments of the platform the above instruments acquired simultaneously data for only a short period of time. Longer acquisition periods are required to fully describe the behavior of SGD springs. Plans of future applications of the system include deployments in different marine environments, for example different SGDs, pockmarks (gaseous discharges from marine seabeds), volcanic seeps (submarine volcanic activity) and rainfall (a freshwater flux at the ocean surface). With real-time communication these measurement systems can be used to monitor important marine features remotely in real time.

Acknowledgements

This work was supported by EU Marie Curie Excellence Grant (project PreWEC, MEXT-CT-2006-038331). Dr. Nystuen was supported by a Marie Curie International Incoming Fellowship (Project Acoustic Rainfall). The authors would like to thank the divers Mr. K. Katsaros, V. Stasinos and Th. Photopoulos which were recruited for the deployments of the system and the Captain of the vessel (D. Eksarchouleas). Moreover, the local authorities of Messina Prefecture are also acknowledged for the financial support of this study.

References

[1] Burnett WC, Bokuniewicz H, Huettel M., Moore WC and Taniguchi M. Groundwater and pore water inputs to the coastal zone. Biogeochemistry 2003; **66**: 3-33.

[2] Moore WS. The subterranean estuary: a reaction zone of ground water and sea water. Mar Chem 1999;**65**: 111-125.

[3] Burnett WC and Dulaiova H. Estimating the dynamics of groundwater input into the coastal zone via continuous radon-222 measurements. J Environ Radioact 2003; **69:** 21–35.

[4] Burnett WC, Peterson R, Moore WS, and de Oliveira J. Radon and radium isotopes as tracers of submarine groundwater discharge - Results from the Ubatuba, Brazil SGD assessment intercomparison. Estuar Coast Shelf S 2008; **76:** 501-511.

[5] Dulaiova H, Peterson R, Burnett WC, and Lane-Smith D. A multi-detector continuous monitor for assessment of ^{222}Rn in the coastal ocean. J Radioanal Nucl Ch 2005; **263:** 361-365.

[6] Povinec PP, Comanducci JF, Levy-Palomo I, Oregioni B. Monitoring of submarine groundwater discharge along the Donnalucata coast in the south-eastern Sicily using underwater gamma-ray spectrometry. Cont Shelf Res 2006; **26**: 874-884.

[7] Povinec PP, de Oliveira J, Braga ES, Comanducci JF, Gastaud J, Groening M., Levy-Palomo I, Morgenstern U, and Top Z. Isotopic, trace element and nutrient characterization of coastal waters from Ubatuba inner shelf area, south-eastern Brazil. Estuar Coast Shelf S 2008; **76**: 522-542.

[8] Tsabaris C, Scholten J, Karageorgis AP, Commanducci JF, Georgopoulos D, Kwong L-LW, Papathanassiou E. Application of an in situ underwater gamma spectrometer as a marine radon progeny monitor: continuous monitoring of groundwater discharges into the coastal zone. Radiat Prot Dosim 2010; **14:** 273-281.

[9] Tsabaris C, Bagatelas C, Dakladas Th, Papadopoulos CT, Vlastou R, Chronis GT. An autonomous in situ detection system for radioactivity measurements in the marine environment. Appl Radiat Isotopes 2008; **66:** 1419-1426.

[10] Kalfas CA. Software for gamma ray spectrum analysis. 2010 Personal communication.