Journal of Coastal Research	SI	58	26–34	West Palm Beach, Florida	Winter 2011

Carbonate Coastal Aquifer of Vlora Bay and Groundwater Submarine Discharge (Southwestern Albania)

www.cerf-jcr.org

Maurizio Polemio[†], Arben Pambuku[‡], Pier Paolo Limoni[†], and Olga Petrucci[§]

[†]CNR-IRPI
Bari Department
Via Amendola 122/i
70124 Bari, Italy
m.polemio@ba.irpi.cnr.it
p.limoni@ba.irpi.cnr.it

[‡]Albanian Geological Service
Hydrogeological Department
Tirana, Albania
urtesi2001@yahoo.com

[§]CNR-IRPI
Cosenza Department
Via Cavour 4/6
87030, Rende, Italy
o.petrucci@irpi.cnr.it

ABSTRACT

POLEMIO, M.; PAMBUKU, A.; LIMONI, P.P., and PETRUCCI, O., 2011. Carbonate coastal aquifer of Vlora Bay and groundwater submarine discharge (southwestern Albania). *In:* Tursi, A. and Corselli, C. (eds.), *Coastal Research in Albania: Vlora Gulf,* Journal of Coastal Research, Special Issue No. 58, pp. 26–34. West Palm Beach (Florida), ISSN 0749-0208.

The study discusses the large karstic coastal aquifer of Vlora Bay. This case is peculiar, as the submarine groundwater discharge has a relevant rate of terrestrial inflow in an almost closed bay that is located in an environmentally valuable area.

The study is based on four methodological activities: geological and hydrogeological conceptualisation, climatic study and hydrological balance, numerical modelling, and monitoring. A geodatabase was created considering hundreds of data points (wells, springs, rivers, lagoons, and seas) and monthly time series of rainfall, temperature, and river discharge. Monitoring activity was realised over a hydrological year, installing a rainfall network tool and using a network of tens of sampling points, including springs, wells, lagoons, and sea. Chemical–physical and stable isotope determinations were realised.

Two main groups of aerial springs are fed by the aquifer, one of which is of a coastal type. The total spring discharge is roughly 4 m^3/s. The submarine groundwater discharge (SGD) was assessed as being equal to 1.4 m^3/s on the basis of the current rate of anthropic discharge and climatic conditions. The study showed the peculiarities of this carbonate coastal aquifer and the importance of its groundwater, which is the chief water source for the third-largest Albanian town.The groundwater quality was generally high, mainly due to the negligible presence of contamination sources on the relief in which the aquifer outcrops. The rate of seawater intrusion effects was also low, thanks to favourable aquifer three-dimensional geometry and high recharge levels.

The increasing anthropic activities constitute a relevant risk in the absence of the introduction of rigorous land and water management criteria.

ADDITIONAL INDEX WORDS: *Submarine groundwater discharge, seawater intrusion, karstic aquifer, Albania.*

INTRODUCTION

Water and chemical fluxes across the seafloor provide an important link between terrestrial and marine environments (Langevin *et al.*, 2007). Oceanographers recognise that these fluxes may act as a source of nutrients or as other harmful contaminants to marine systems (*e.g.,* Valiela *et al.*, 1990). These fluxes may also act as a beneficial source of freshwater for coastal marine, wetland, and lagoon environments. Hydrogeologists recognise that fluxes across the seafloor are an important part of the water balance for coastal aquifers (Zektser and Loaicuga, 1993).

Submarine groundwater discharge (SGD) has become a popular term in the literature; Burnett *et al.* (2003) define SGD as the discharge of groundwater across the seafloor into the sea. Using a combined hydrological and hydrogeological method, the mean annual contribution to the Mediterranean Sea was estimated to be about equal to 1700 m^3/s (Zektser and Loaicuga, 1993). In terms of linear mean contribution, 8 km of European coast feed the Mediterranean Sea at levels of 1 m^3/s.

Around the world, the runoff yield that is discharged in the sea is up to 10 times greater than groundwater discharge (UNESCO, 2004a) except in karstic areas, where the latter prevails. This is the case in numerous Mediterranean karstic coastal aquifers, such as the Apulian karstic aquifers, which are wide coastal aquifers located in southern Italy, where the SGD is more than the double the discharge of surface runoff, notwithstanding the current overexploitation by wells (Polemio, Dragone, and Limoni, 2009a). In total, 62 study cases were recognised along the European coast of the Mediterranean Sea, not considering the Albanian coast (COST, 2005). Many wide coastal karstic aquifers are located in Albania as well; between these, the case of the large karstic coastal aquifer of Vlora Bay (southwestern Albania), which is discussed in this article, is peculiar worldwide, as the SGD

DOI:10.2112/SI_58_4 received and accepted in revision 12 April 2010.

Figure 1. Albania and study area map, including main national rivers and lakes.

is a relevant rate of terrestrial inflow in a mostly closed bay (Figure 1). In these cases, the modifications of the quality and quantity of current coastal karstic groundwater discharge can provoke severe effects on the hydrological and ecological equilibrium of the sea and in coastal areas (UNESCO, 2004a).

It is well known that karstic aquifers are highly vulnerable to contamination because of their particular characteristics such as thin soils, point recharge in dolines and swallow holes, and high hydraulic conductivity (COST, 2003). Karstic groundwater contamination is widespread because of direct pollution from agricultural activities and houses, but also very often because of a wide range of anthropogenic modifications, as is the case for the Apulian aquifers (Polemio, Dragone, and Limoni, 2009b). In this case, forest and stone clearing, which have been undertaken widely because of the advent of machinery to provide land suitable for farming; quarrying, which destroyed the epikarst; and poor management of water resources are relevant. The unplanned enlargement of urban and rural areas is another widespread phenomenon, as seen in the recent history of Albania.

Coastal karstic aquifers are also vulnerable to salinisation caused by seawater intrusion, including upconing effects, which is also a common problem in the Mediterranean coasts (COST 2005).The sustainable management of coastal aquifers is a key goal that requires careful estimates of recharge and other hydrological components, such as groundwater discharge. Oceanographers, marine scientists, and those studying and managing saltwater intrusion in coastal aquifers pursue the common goal of quantifying and understanding the interactions of groundwater and seawater (Langevin *et al.*, 2007). The case of the Vlora Bay aquifer was selected to contribute to these efforts.

METHODS

In the case of coastal aquifers, a wide range of methodological approaches can be used to quantify the groundwater resources and to define the groundwater quality and degradation risks (Bear and Verrujt, 1987; Davis and De Wiest, 1991; UNESCO, 2004b). For each case study, the methodological choice should reflect the main goals, hydrogeological peculiarities of the case, the type of available data, the technologies, time, and economical resources. We proposed a reliable approach for a karstic coastal aquifer for which the availability of historical monitoring data is low and for which it was possible to realise a monitoring program for not less than one hydrological year. The method applied can be schematically described as a succession of four activities, some of which can be realised simultaneously: these are conceptualisation, hydrological balance, modelling, and monitoring.

The first activity is the geological and hydrogeological conceptualisation of the aquifer. Any available geological and hydrogeological data, which were collected in disparate formats and scales, were integrated into a geodatabase that included geographic, geologic, and hydrogeological data (San Juan and Kolm, 1996). Each data set was analysed in a geographic information system (GIS) environment to characterise surface and subsurface conditions and the hydrologic system. Specific layers considered data on geological formations, tectonical information, geomorphological and karstic features, rivers, lakes, lagoons, wells, including piezometric heads, and springs, including spring outflow yields. The data set was also analysed and validated by specific on-site surveys. The groundwater flow system, conceptualised as a three-dimensional (3-D) interconnected system, was so defined by distinguishing hydrogeological complexes, which include lithotypes, with similar hydrogeological characteristics. For this purpose, the assessment of complexes considered piezometric values, landforms, surface water features, geology (depositional patterns, faulting, etc…), and hydraulic conductivity data, if available. The main output of this activity was the hydrogeological map and the sections (Figure 2) that form the basis for the hydrological balance and modelling activities. The conceptualisation was considered as validated if the results of the hydrological balance and modelling activities, at the end of the second and third activities, were consistent with the monitored data and hypotheses on the basis of the assumption of the conceptualisation.

The climate characterisation and hydrological balance activity (Johansson 1987) was realised using monthly rainfall, temperature, and river flow yield time series in concert with the assessment of the infiltration rate of net

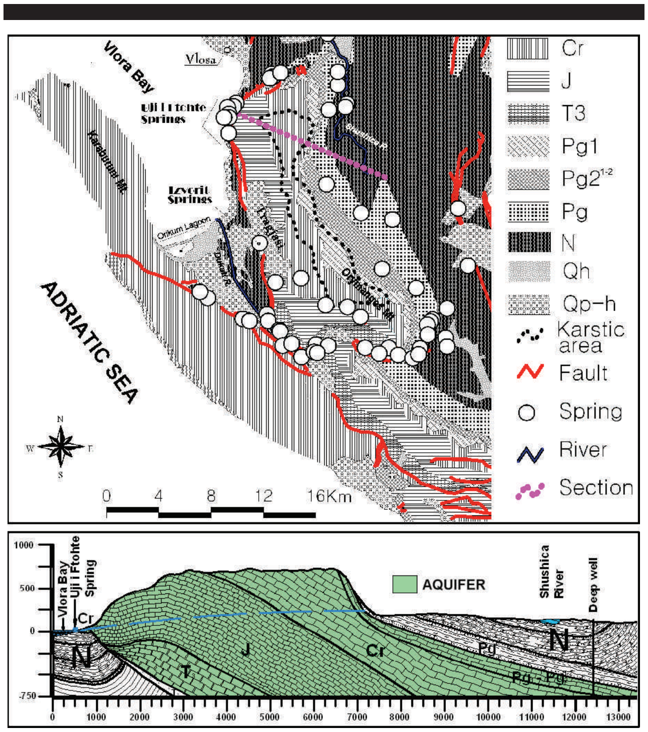

Figure 2. Geological and hydrogeological schematic map and section. Main aquifer: Cr, J, T3, Pg1, and Pg2$^{1-2}$ are Cretaceous fissured and karstified limestones, dolomitic limestones and dolostones, Triassic fissured dolostones, and Paleogene–Eocene limestones and limestones with cherts, respectively. Impervious formations: Pg and N are Paleogenic and Neogenic soils, respectively, and rocks, mainly claystones, silts, and marlstones. Secondary aquifer: Qp-h and Qh respectively are Quaternary gravel, sand, and poorly consolidated boulders, covered by shallow clay in the former case.

rainfall of outcropping hydrogeological complexes, as explained in detail when discussing the case study. The main output is the assessment of the mean total groundwater outflow. The reliability of the hydrological balance is preliminarily calibrated considering the balance of a monitored drainage basin that includes a part of the studied hydrogeological basin. The final validation considers the amount of calculated SGD, using both hydrological balance and modelling.

The numerical modelling utilised a variable-density groundwater flow and solute transport model, which are usually used to simulate saltwater intrusion (Langevin *et al.*, 2007). In this case, these same models can also be used to provide quantitative estimates of SGD. Numerical modelling is a reliable tool of distributing aquifer recharge, in space and time, to the outflow boundaries. Use of numerical models is appealing because a simulation can provide spatially and temporally detailed estimates of SGD rates. Numerical models can also be used to predict future SGD rates or rates for other hydrological conditions, such as increasing anthropic discharge, climate change, and processes of quality degradation.

The groundwater flow was numerically simulated on the basis of a model the core of which is the MODFLOW model, a freeware code from the U.S. Geological Survey (McDonald and Harbaugh, 1988). The model is the 3-D numerical model that is the most used in the world. The seawater intrusion was simulated using the SEAWAT code, which is combined with the very famous flow code MODFLOW and the transport code MT3DMS (Zheng and Wang, 1999). The main outputs were the assessment of GSD and, second, the aquifer piezometric map and the groundwater salinity map. The final validation is based on the results' coherence with the hydrogeological measurements.

The fourth activity is a monitoring program that concerned rainfall, rivers, lagoons, wells, springs, and seawaters during a hydrological year with seasonal frequency. In situ chemical–-physical measurements, water sampling, and analyses of physical, chemical, and isotopic data were used on all types of waters. Quantitative measurements of rainfall and of spring discharge were also undertaken. The main output is the physical, chemical, and isotopic characteristics of waters. These data validate the conceptualisation and the modelling from a hydrological and geochemical point of view.

STUDY CASE

Albania has a surface of 28,748 km^2 and a perimeter of 720 km (Figure 1). The coasts along the Adriatic and Ionian seas extend for 362 km. Along the coast, the alluvial plains, which are 16 km in width, as per the mean value, represent the unique flat areas. Despite the massive land reclamation for agricultural purposes, about 109 km^2 of coastal wetlands or lagoons still exist, especially along the Adriatic coast (Cullhaj *et al.* 2005).

The Albanian climate is subtropical Mediterranean. The mean annual temperature ranges from 7 to 15°C, whereas the mean annual rainfall ranges from less than 600 mm to more than 3000 mm (the mean national value is about 1500 mm). Groundwater is the only source for drinking water in the entire country (Ministry of Environment, 2002). A lack of detailed knowledge on the availability of groundwater and its recharge, and the nonsystematic monitoring causes management problems where discharge is high and localised, like in some coastal areas in which seawater intrusion can also be observed.

The paper describes the study of the large karstic coastal aquifer of Vlora Bay, which is dominated by Oyramanges Mt. (1864 m above sea level [asl]) (Figures 1 and 2). Two main groups of springs are fed by the aquifer, one of which is of a coastal type. Spring groundwater feeds the drinking supply of the town of Vlora, which is one of the most important in the country (Polemio, Pambuku, and Petrucci, 2008).

Geological and Hydrogeological Conceptualisation

Approximately 70% of the territory is mountainous, with peaks higher than 2700 m asl; reliefs, called Albanides, are constituted mainly by the S branch of the Mediterranean Alpine Belt. Two major paleogeographic domains can be distinguished: the Internal Albanides to the east, and the External Albanides in the west sector, where the study area is located (Figure 1). The External Albanides, characterised by regular structural belts, which are associated with thrust and tectonic cover, developed alongside the west passive margin and continental shelf of the Adriatic plate. The External Albanides are affected only by the latest paleotectonic stages, and are characterised by regular structural belts, which are associated with thrust and tectonic cover (Pano and Flasheri 2007). Some of these belts are bordered by tectonic lines along which Mesozoic carbonate rocks are bounded by tertiary sediments.

In the Vlora area, this is the case for the so-called Logorà, Selenica, and Tepelena lines that determined the valleys of the Dukati, Shushica, and Dhrino rivers, respectively (Figures 1 and 2). The Logorà line (Dukati River, Figure 2) is particularly important as it corresponds to the limit between the two southernmost tectonic zones of the country (called Sazani and Jonic zones). The Vlora coastal area is dominated by mountains of so-called Epirotes Chains in which anticline folds create parallel belts that are oriented NW-SE. Along these anticlines, Mesozoic limestone outcrops, as well as, in the synclines, youngest flysch complexes, can be found (Figure 1). The peak width of Vlora Bay, which is partially closed by the relief of the Karaburuni Peninsula, is 9.5 km.

The studied aquifer is formed by carbonatic rocks of the large Tragjasi anticline, the periclinal of which is located in the S and SW portions of the study zone. The anticline is about 22 km in length and 6–10 km in width, with an asymmetric structure that is inverted toward the west. Moving from the core, the anticline is composed of Upper Triassic (T3) dolostone and limestone, Jurassic (J), Cretaceous (Cr), and Paleocene–Eocene (Pg1–$Pg2^{1-2}$) limestones, dolostones, and limestones with cherts. The carbonatic aquifer is bounded on the E, N and NW sides by Paleogene–Neogene flysch formations (claystones, siltstones, and sandstones) (Meço and Aliaj, 2000), and the area in which the aquifer outcrops is 147 km^2. There is no leakage from the aquifer, which is also due to a continuous outcrop of quaternary clayey soils, locally including sands and gravels, which extend along almost the entire W side of the aquifer. The inland portion of the aquifer shows karstic features (Figure 2).

On the W side, the carbonatic rocks and flysch come into transgressive contact with angle discordance placed in the Dukati Valley. The relief of the left valley side constitutes the Acrocerauni belt, which includes the carbonatic cretaceous reliefs of the Karaburuni and Mali I Kanalit Mountains. In the Dukati Plain, a shallow aquifer of Quaternary gravel, sand, and poorly consolidated boulders can be distinguished. This aquifer, about 10 m thick, lies on hundreds of metres of impervious soils and rocks. The recharge is mainly due to the leakage of the Dukati River. On the left side of the coastal plain, the Orikumi Lagoon completes the environmentally valuable bay. On the other side of the aquifer, we come across the hilly Shushica River valley, where Neogenic soil outcroppings are composed mainly of claystones, siltstones, and marlstones that are hundreds of meters thick. The discharge from the aquifer occurs as a result of the springs located near or immediately below the margin of outcropping limestone. There are no wells in the area where limestone outcrops, as these are only found in the valley of the Dukati River or where Quaternary soils outcrop.

Table 1. *Characteristics of rain and temperature gauges and time series used for the hydrological balance.*

Gauge	Altitude (m asl)	Mean Annual Rainfall (mm)	Mean Annual Temperature (°C)	Monitoring Period (years)
Brataj	270	2085.3	14.4	20
Dukat-Ferme	85	1419.3	15.8	20
Dukat-Fshat	375	2270.8	14.2	21
Kuc	610	2335.7	15.5	20
Llakatund	27	1049.4	16.7	25
Vlore	1	984.4		27

Two main flow paths go from the high karstic plateau of Mt. Oyramanges to two spring areas. These areas are found at a distance of 10 km on the W side of the aquifer, where it outcrops at the lowest altitude.

The former is the group of coastal springs of Uji i Ftohtë, which is located at sea level. This group includes three springs tapped by short tunnels and is used for the Vlora aqueduct. The tunnel of I Jonufrës Cape, which is 1700 m in length, connects the outflow of 32 coastal springs, which taps in different sectors along the coastal line. Moving from N to S, the first sector includes tapping from the tunnel road, which is 185 m in length. The mean annual discharge is roughly 0.40 m^3/s. Unexploited springs, some of which are submarine, are located from the end the of tunnel road to a maximum distance of about 300 m. From this point to the lighthouse, another tunnel is able to tap a mean discharge equal to 0.64 m^3/s. From the lighthouse to the Castle, about 400 m, four unexploited small springs can be observed. The last sector includes the old road tunnel where 11 tapped springs are placed, for a mean total discharge of 0.94 m^3/s. The mean spring yield discharged in this group is roughly equal to 2.0 m^3/s.

The second group of springs are known as Izvorit and are located at about 40 m asl in the Tragjasi Village. The springs are placed along the mostly straight outcropping limit between carbonatic rocks (J-T3) and Neogene clays. The springs of both groups are roughly found along a straight N-NW S-SE tectonic line. A low percentage of the Izvorit spring outflow rises up to some villages; the rest was measured using tracer tests. The whole mean outflow of the spring group is roughly equal to 1.8 m^3/s. The total discharge of subaerial spring discharge is roughly equal to 3.8 m^3/s.

Climate Characterisation and Hydrological Balance

Monthly data describing rainfall and temperature from six gauges were considered (Table 1 and Figure 3). In addition, the time series of the monthly river flow yield of Drashvice Bridge on Shusica River was used to define the hydrological balance. All these data were collected by the national monitoring system. It is assumed that, in terms of mean hydrological year, the hydrological balance of a hydrological basin is described by the relationship:

$$P = I + R + Er$$

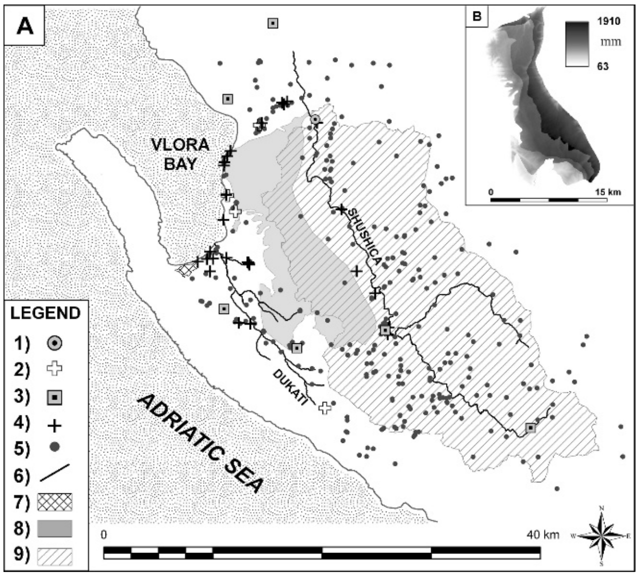

Figure 3. Hydrological balance map (rectangle A) and aquifer infiltration or recharge map (rectangle B, mm). A: (1) Drashovice River discharge gauge of national network (hydrometer), (2) rain gauge of study monitoring program, (3) rain and temperature gauge of the national network, (4) main springs and other sampling points, (5) spring or well, (6) river, (7) lagoon, (8) outcropping karstic aquifer, (9) Shushica River drainage basin at Drashovice gauge.

where P, I, R, and $E\mathrm{r}$ are precipitation, infiltration, runoff, and real or actual evapotranspiration, respectively.

Both P and T showed a statistically relevant straight-line correlation with altitude. On the basis of the digital elevation model (DEM), determined in the GIS environment studying cell sizes with a width of 40 m, the spatial variability of P and temperature was assessed. $E\mathrm{r}$ was calculated in each cell using Turc's formula (1954) and the modified temperature, as defined by Santoro (1970) for Mediterranean areas. The amount of mean annual net rainfall $P\mathrm{n}$ was thus calculated as $P\mathrm{n} = P - E\mathrm{r}$.

In the Shushica River drainage basin and in the outcropping karstic aquifer (Figures 2 and 3) 21 hydrogeological complexes were distinguished, from claystones (very low hydraulic conductivity) to stratified, fissured, and karstic limestones (very high hydraulic conductivity).

The net infiltration coefficient $C\mathrm{i}$, defined as $I/P\mathrm{n}$, for each outcropping hydrogeological complex was assessed. The preliminary $C\mathrm{i}$ assessment was based on the previous experiences of certain authors and considered the peculiar hydrogeological characteristics of the complexes (Cotecchia, D'Ecclesiis, and Polemio, 1990; Polemio, Casarano, and Limoni, 2009). The infiltration I was assessed in each cell as $I = P\mathrm{n}C\mathrm{i}$.

The basin of the Shushica River was used to calibrate the hydrologic model, including $C\mathrm{i}$ values. At the Drashovice gauge, where the Shushica drainage basin is 587 km^2, the mean river yield R' was assessed as being equal to 19.8 m^3/s on the basis of the monitoring.

The mean spatial annual rainfall was 1840 mm in the Shushica drainage basin. On the basis of the hydrologic balance relationship, the mean river yield, R'', can be also assessed as P, I, and $E\mathrm{r}$ were known. Calibrating $C\mathrm{i}$ values to reduce to zero $R' - R''$, $C\mathrm{i}$ ranged from 0.10 to 0.80. On this basis, the mean annual recharge on cells of the outcropping karstic aquifer was in the range of 63–1910 mm (Figure 3B). The mean spatial annual infiltration or recharge of the karstic aquifer outcrop was equal to 1127 mm, which corresponds to 5.2 m^3/s. The difference between recharge and total aerial spring outflow, roughly equal to 1.4 m^3/s, can be preliminarily considered to be equal to the groundwater submarine discharge, since the well discharge is almost zero. The SGD should be reasonably concentrated near the Uji i Ftohtë spring area, where the carbonate aquifer is directly bordered by the sea (Figure 2). The reliability of these hypotheses was tested using the modelling activity.

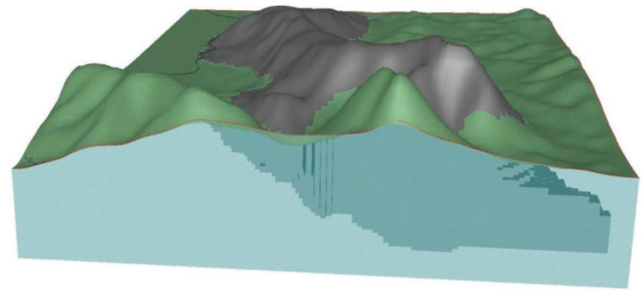

Figure 4. 3-D view of aquifer (grey) and of the surrounding area as discretised for hydrogeological modelling. The view is from S to N; Vlora Bay is in the upper left corner.

Numerical Modelling

Because of the steep nature of the outcropping aquifer, the population lives mainly at the bottom of the karstic relief, where impervious complex outcrops and high spring discharges are freely available. An effect of this is that discharging wells in karstic aquifers do not exist and the creation of monitoring wells would require hundred-meter boring to be created far from secondary roads. For this reasons, hydrogeological data on the karstic rocks cannot be measured in situ.

Realistic values were defined for the hydraulic conductivity (10^{-4} m/s) and the specific yield (0.15) to be spatially calibrated using numerical tools. The basic numerical model was based on a grid with a width of 250 m, and considering up to 11 levels, or strata (Figure 4 and Figure 5). The boundary conditions were assigned using the following type of boundary conditions: general head boundary conditions where limestone outcrops in proximity of the coast and recharge conditions in the rest of limestone outcropping area, using as an input the spatial output of the hydrological balance application (Figure 3B).

An automatic calibration procedure, called PEST, was used (Doherty, 2001). This procedure minimises an objective function related to the square difference between a number

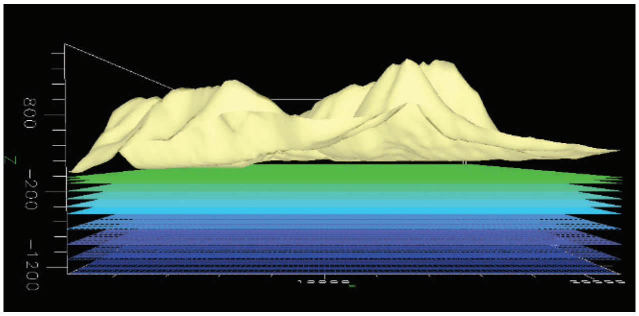

Figure 5. Strata and vertical aquifer discretisation for modelling.

of observed and simulated variables, such as piezometric heads. The calibration was based on two assumptions to test their reliability. The first was that some springs with low discharge and at high altitude, located to SE of Tragjiasi, were due to the main groundwater flow domain; the latter considered that these are due to perched groundwater flow. The results of the former calibration were completely unrealistic, so the first hypothesis was rejected, whereas in the latter case the results were completely coherent with all of the available information.

The SGD was confirmed to be equal to 1.4 m^3/s. The SGD is located at the bottom of the area surrounding the Uji i Ftohtë area.

The SEAWAT code was used to simulate numerically the effects of seawater intrusion in terms of salinity variations and groundwater quality degradation. This code uses a density-driven flow effect coupled to a MODFLOW flow code and to a MT3DMS transport code (Zheng and Wang, 1999). The mesh was ticked, using cells up to 100 m in width in the coastal area, thus improving the reliability of the results. Recently, the effects of seawater intrusion are bounded by a coastal strip of hundreds of metres in width. The spatial salinity variability was coherent with the monitoring results, which are discussed below.

Monitoring and Groundwater Characteristics

The first phase of this study was the collection of chemical–physical groundwater data in about 200 wells and springs in the study area (Figure 3). These data were validated and uploaded in the geodatabase system.

Many springs were placed in the data set; the majority of these showed discharges of less than a litre per second, but the entire range was from 0.1 to about 2000 L/s. The wells are located in the valleys of the Dukatit and Shushica rivers, where aquifer Quaternary soils have discharge yields of generally less than 10 L/s.

The preliminary analysis of ion concentration confirmed from a geochemical point of view the results of the conceptualisation.

The monitoring program was defined after some surveys, and was used to define a monitoring network. Up to 30 water sampling points were selected (Figure 3). They were mainly springs, but wells, rivers, lagoons, and the sea were also considered. In addition, rainfall monitoring was undertaken. Five rain gauges were installed to measure monthly rainfall and two for the monthly sampling for analyses of stable isotopes, namely, oxygen-18 and deuterium. Four rain gauges were located in the study area (Figure 3), defining the altitude range as 18–1055 m asl. The remaining rain gauge was installed close to the Italian Adriatic coast, inside the Bari CNR-IRPI building (located in Apulia, about 200 km W-NW from the study area) to obtain a reference point for the discussion of isotopic data.

Water sampling of springs, wells, rivers, lagoons, and the sea were undertaken seasonally from October 2007 to July 2008, covering one hydrological year (altitude ranging from sea level to 310 m asl). Some parameters were measured on site (specific electrical conductivity [EC], pH, oxidation-reduction potential [Eh], and total dissolved solids [TDS], with the remaining results measured in a laboratory (Table 2).

The chemical and physical characteristics of groundwater tapped springs are almost identical, except for some minor spring feeds in Quaternary secondary aquifers. The groundwater of Vlora Bay is generally weakly alkaline (mean pH 7.6), almost fresh (mean TDS 0.3 mg/L), and cold (mean temperature about 15°C).

By analysing the data set from the groundwater in greater detail, it was found that the temperature variations were due to well-known seasonal effects of atmospheric temperature but were due also to spatial variations. The latter effect was the progressive temperature increase due to heat exchange between flowing water and rocks. It was a low increase observed from main recharge areas, located from the highest altitude to the main spring areas. The correlation between temperature and spring altitude was found to be very low or negligible. All these results suggest that the groundwater flow is fast and concentrated in the main paths, such as fissured and karstic discontinuities.

EC and TDS were mostly steady and homogenous. The maximum salinity (0.9 g/L), considering also observation points near the coast, is, in any case, low if the potential effect of seawater intrusion is considered. So, the salt degradation for seawater intrusion is low in recent years.

The pH variations are very low in time and space. It slightly increases when in closer proximity to the coast, rivers, and lagoons. Eh is mostly high and generally positive. Main exceptions at this schematic view of pH and Eh are due to secondary springs.

If the Na-Cl concentrations are plotted (Figure 6), it is evident that the dilution of pure fresh groundwater with water is due to seawater intrusion. If the threshold criterion defined by Polemio, Dragone, and Limoni (2009b) for the Apulian coastal karstic aquifer is adopted, pure fresh groundwater should show up to 44 mg/L of chloride, equal to 1.26 meq/L (Figure 6). In this case, we indentify a group of points in which the groundwater is degraded by seawater intrusion.

The hydrochemical type is HCO_3-Ca-Mg, which was consistent with the carbonate nature of aquifer rocks (Figure 7). The Piper diagram showed also the evident effect

Table 2. *Statistical values (minimum, maximum, mean) of groundwater sampled in the monitoring period. Some extreme temperature measurements were influenced by atmospheric temperature; this effect concerns secondary springs and was not avoidable for the local sampling conditions.*

	October 2007			January 2008			April 2008			July 2008		
Parameter	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
T (°C)	12.4	21.7	15.2	9.6	15.6	13.3	12.3	28.8	14.8	12.0	25.0	16.3
EC (mS/cm at 25°C)	0.3	1.6	0.6	0.3	1.6	0.6	0.3	1.4	0.6	0.3	1.4	0.6
pH	6.8	8.3	7.6	6.9	8.2	7.6	7.2	8.3	7.7	6.7	8.3	7.5
Eh (mV)	−183	247	122	−16	198	133	44	248	197	11	233	176
TDS (g/L)	0.2	0.8	0.3	0.2	0.8	0.3	0.2	0.7	0.3	0.1	0.9	0.3
Na (meq/L)	0.2	7.2	0.9	0.1	5.3	0.8	0.1	5.3	0.8	0.1	5.8	0.7
K (meq/L)	0.0	0.2	0.0	0.0	1.8	0.1	0.0	1.7	0.1	0.0	0.3	0.0
Mg (meq/L)	0.3	4.0	1.5	0.3	3.8	1.5	0.3	4.1	1.5	0.3	3.5	1.5
Ca (meq/L)	2.3	7.1	3.8	2.5	9.4	4.3	2.4	9.4	4.3	2.3	9.2	3.8
F (meq/L)	0.002	0.036	0.010	0.002	0.447	0.025	0.002	0.049	0.011	0.002	0.428	0.028
Cl (meq/L)	0.1	9.3	0.9	0.1	6.6	0.9	0.1	6.6	0.9	0.1	7.8	0.8
Br (meq/L)	0.0005	0.0127	0.0033	0.0002	0.0103	0.0021	0.0001	0.0101	0.0019	0.0002	0.0121	0.0015
NO_3 (meq/L)	0.0	1.7	0.3	0.0	1.5	0.2	0.0	1.3	0.2	0.0	1.3	0.2
SO_4 (meq/L)	0.1	2.6	0.7	0.1	1.9	0.7	0.1	2.1	0.8	0.0	2.5	0.7
HCO_3 (meq/L)	2.2	7.6	4.4	3.0	7.9	4.8	3.1	8.1	4.9	3.1	7.9	4.4

of mixing of the type of natural waters, namely, the groundwater and the sea.

The characteristics of river water were basically similar to that of groundwater. Leakage from drainage network to the karstic aquifer is unlikely both on the basis of conceptualisation and of the water characteristics. In any case, the quality of river water seems mostly high, thanks to a very low anthropic rate of use of drainage basin area, particularly in the case of the Shushica River.

The temporal variability of the water chemical characteristics was low (Table 2). Main variations are due to variable dilution of the groundwater with very freshwater due to the infiltration of rainwater.

There is neither evidence of contamination nor relevant effects of seawater intrusion. The low seawater intrusion effect can be tied to the favourable stratigraphical conditions and the high rate of groundwater flow, which is concentrated in a narrow coastal strip in which the impervious boundaries of Quaternary formations do not outcrop. The main quality variations are highlighted in small springs, which are located mostly near the first sector of the Uji i Ftohtë spring group, where salinity is found up to 0.9 mg/L; chloride is about double the amount of the value observed in the main springs. This seems to be the overlapped effect of natural secondary groundwater path flows with increasing discharge due to recent diffuse house building.

Moving to the determination of the stable isotopes oxygen-18 and deuterium, a negative straight-line correlation was verified between isotopic ratios and the rain gauge altitude. By way of example, a gradient of $-0.16\ \delta\ ^{18}O‰/100$ m was observed for autumn 2007. The deuterium ratio was always similar, but was also lower than the oxygen isotope. If we

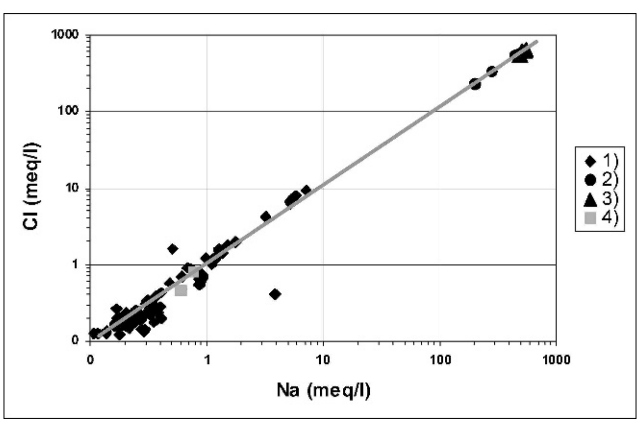

Figure 6. Na-Cl diagram and straight-line correlation of water sampled in springs, wells, rivers, lagoons, and the sea during the monitoring period. (1) Spring or well, (2) lagoon, (3) sea, (4) river.

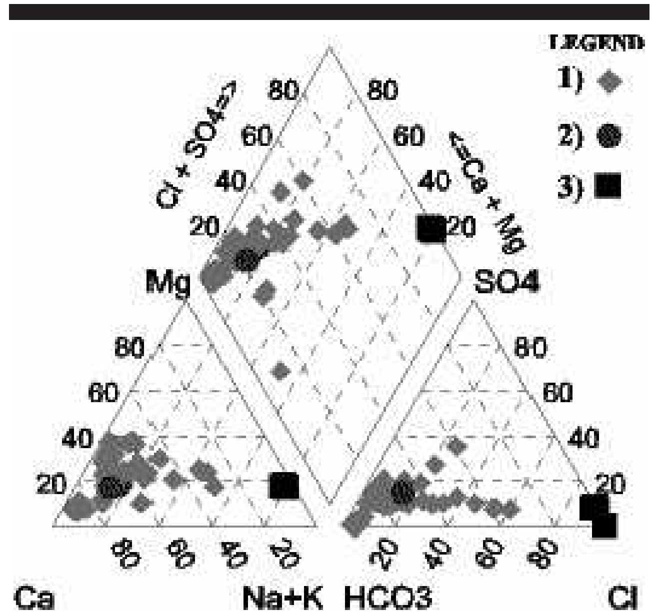

Figure 7. Piper diagram of water sampled in springs, wells, rivers, lagoons, and the sea during the monitoring period. (1) Spring or well, (2) river, (3) sea and lagoon.

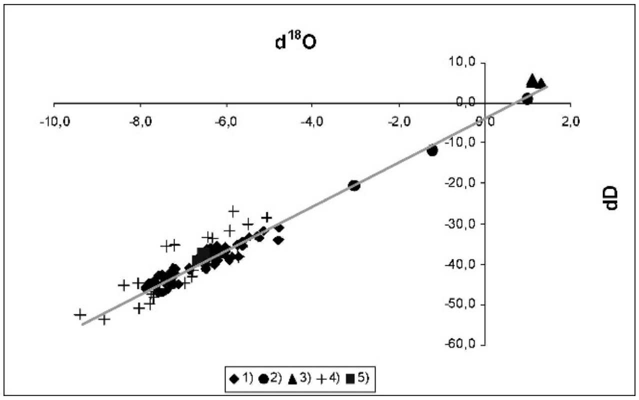

Figure 8. Diagram of isotopic ratios of water sampled in springs, wells, rivers, lagoons, and the sea during the monitoring period. (1) Spring or well, (2) lagoon, (3) sea, (4) rain, (5) river. The straight-line correlation is based on groundwater samples.

focus on the spring located closest to the sea, the δ ^{18}O‰ value, which was about −8, shows that the recharge area is located at altitudes greater than 800 m asl.

There was a generally high positive correlation between oxygen-18 and deuterium ratios (Figure 8). If we consider only groundwater samples, the straight-line correlation was particularly high ($R_2 = 0.99$), as it is typical of Mediterranean aquifers located in the proximity of the sea. The correlation between isotope ratios and spring altitude was very low or negligible. As in the case of temperature, this suggests that the flow is concentrated in main flow paths.

All of the results of water characteristics discussed here confirmed the results of previous studies.

Conclusions

The study showed the peculiarities of this carbonate coastal aquifer and the importance of its groundwater, which is the chief water resource for the third largest Albanian town. The amount of aquifer recharge and GSD assessment were assessed with a double activity based on hydrological balance and numerical modelling, notwithstanding the very complex geological framework and the practical difficulties to complete on-site hydrogeological tests. The GSD was assessed as being equal to 1.4 m^3/s on the basis of the current rate of anthropic groundwater discharge and the climatic conditions.

The quality of the groundwater was generally high. The rate of seawater intrusion effects is still low thanks to favourable aquifer 3-D geometry and high recharge levels. At the same time, the main flow paths were very rapid, which indirectly confirms the extreme vulnerability of these types of aquifers. The qualitative positive results can be explained by considering the negligible presence of contamination sources on the relief in which the aquifer outcrops.

Groundwater is the main natural source of direct continental inflow for Vlora Bay. The enlargement of urban areas of Vlora and of the surrounding villages, promoted by tourism and by the very high economic growth rate of the local population, was basically unplanned. The social–economical development also causes an increase in water demand. Both these qualitative trends and the intrinsic vulnerable nature of Vlora groundwater resources suggest the application of rigorous land and water management criteria. The deficiencies of these practical criteria will cause a rapid decrease in groundwater quality and availability, with delayed, but not negligible, effects on the quality of the Vlora Bay water.

In the meantime, the regular monitoring that began with this study should be continued to characterise the risks to groundwater quality and availability degradation and for the entire environmentally valuable Vlora area.

LITERATURE CITED

Bear, J. and Verrujt, A., 1987. *Modelling Groundwater Flow and Pollution*. Dordrecht, The Netherlands: D. Reidel Publishing Company, 414p.

Burnett, W.C.; Bokuniewicz, H.; Huettel, M.; Moore, W.S., and Taniguchi, M., 2003. Groundwater and pore water inputs to the coastal zone. *Biogeochemistry,* 66, 3–33.

COST, 2003. COST Action 620, Vulnerability and risk mapping for the protection of carbonate (karst) aquifers. European Commission, Directorate-General for Research, Report EUR 20912, Luxemburg.

COST, 2005. COST Action 621, Groundwater management of coastal karstic aquifers. European Commission, Directorate-General for Research, Report EUR 21366, Luxemburg.

Cotecchia, V.; D'Ecclesiis, G., and Polemio, M., 1990. Geological and hydrogeological study of Maratea Mountains. *Geologia Applicata e Idrogeologia,* 25, 139–179 [in Italian].

Cullaj, A.; Hasko, A.; Miho, A.; Schanz, F.; Brandl, H., and Bachofen, R., 2005. The quality of Albanian natural waters and the human impact. *Environmental International,* 31, 133–146.

Davis, S.N. and De Wiest, R.J.M., 1991. *Hydrogeology*. Krieger Publishing Company, 463p.

Doherty, J., 2001. *PEST-ASP Users' Manual*. Brisbane, Australia: Watermark Numerical Computing.

Johansson, P.O., 1987. Methods for estimation of natural groundwater recharge directly from precipitation—comparative studies in sandy till. *In:* Simmers, I. (ed.), *Estimation of Natural Recharge of Groundwater*. NATO Science Series C, 222, 239–270.

Langevin, C.; Sanford, W.; Polemio, M., and Povinec, P., 2007. Background and summary: a new focus on groundwater–seawater interactions. *In: A New Focus on Groundwater–Seawater Interactions* IAHS, 312, 3–10.

McDonald, M.G. and Harbaugh, A.W., 1988. A modular three-dimensional finite-difference ground-water flow model. Reston, Virginia: U.S. Geological Survey Techniques of Water-Resources Investigations, 6, Chapter A1, 586p.

Meço, S. and Aliaj, Sh., 2000. *Geology of Albania*. Stuttgart: Gebruder Borntrager Berlin.

Ministry of Environment, 2002. The First National Communication of Albania to the United Nations Framework Convention on Climate Change (UNFCCC). Repubblica di Albania, Tirana, Albania, 2002.

Pano, N. and Frasheri, A., 2007. Principal aspects of the ecosystem Vlora bay—Narta lagoon—Vjosa river mouth. CISM Project, www.cismalbania.it (accessed December 2007).

Polemio, M.; Casarano, D., and Limoni, P. P., 2009. Karstic aquifer vulnerability assessment methods and results at a test site (Apulia, Southern Italy). *Natural Hazards and Earth System Sciences,* 9(4), 1461–1470.

Polemio, M.; Dragone, V., and Limoni, P.P., 2009a. The piezometric stress in the coastal aquifers of a karstic region (Apulia, Italy). *In:* Makoto T.; Dausman A.; Howard K.; Lakshmanan E.; Polemio M., and Schmid. W. (eds.), *Sustainability of Groundwater in Highly Stressed Aquifers*. IAHS Publ., Red book n. 329, 138–144.

Polemio, M.; Dragone, V., and Limoni, P.P., 2009b. Monitoring and methods to analyse the groundwater quality degradation risk in coastal karstic aquifers (Apulia, Southern Italy). *Environmental Geology,* 58(2), 299–312.

Polemio, M.; Pambuku, A., and Petrucci, O, 2008. The coastal karstic aquifer of Vlora (Albania). *In: Proceedings of 20th Salt Water Intrusion Meeting* (Naples, Florida), pp. 199–202.

San Juan, C. and Kolm, K.E. 1996. Conceptualization, characterization, and numerical modeling of the Jackson Hole alluvial aquifer using ARC/INFO and MODFLOW. *Engineering Geology,* 42(2–3), 119–137.

Santoro, M., 1970. Sulla applicabilità della formula di Turc per il calcolo dell'evapotraspirazione effettiva in Sicilia. Proceedings of the International Congress on Groundwater, I.A.H. (Palermo, Italy).

Turc, L., 1954. Le bilan d'eau des sols. Relation entre les précipitations, l'évaporation et l'écoulement. *Annales Agronomique,* 5, 491–596; 6, 5–131.

UNESCO, 2004a. Submarine groundwater discharge. *IHP Groundwater Series n. 5*.

UNESCO, 2004b. Groundwater studies, an international guide for hydrogeological investigations. *In:* Kovalevsky V.S.; Kruseman G.P., and Rushton, K.J. (eds.), IHP-VI, *Series on Groundwater n. 3*.

Valiela, I.; Costa, J.; Foreman, K.; Teal, J.M.; Howes, B.L., and Aubrey, D.G., 1990. Transport of groundwater-borne nutrients from watersheds and their effects on coastal waters. *Biogeochemistry,* 10, 177–197.

Zektser, I.S. and Loaicuga, H., 1993. Groundwater fluxesin the global hydrologic cycle: past, present and future. *Journal of Hydrology,* 144, 405–427.

Zheng, C. and Wang, P.P., 1999. MT3DMS, a modular three-dimensional multispecies transport model for simulation of advection, dispersion and chemical reactions of contaminants in groundwater systems; documentation and user's guide. Vicksburg, MS: U.S. Army Engineer Research and Development Center Contract Report SERDP-99-1, 202p.