

Water resource management in karstic catchments: the case of the Asso Torrent basin (Southern Italy)

Marco Delle Rose¹ · Corrado Fidelibus²

Received: 12 November 2015 / Accepted: 25 April 2016 / Published online: 13 May 2016
© Springer-Verlag Berlin Heidelberg 2016

Abstract In karstic endorheic basins the hydraulic works for runoff regulation, marshland reclaiming and defense from inundations usually consist of channels tributary to sinkholes vertically connected to aquifers through karstic conduits and fractures. The drainage capacity of such basins reduces as conduits and fractures are progressively clogged by sediments; thus, floodings may occur during heavy rains. The sinks may also be utilized to inject treated wastewater underground. This note concerns the management issues of the Asso Torrent basin (Italy), where the recharge through water sinks preserves the deep aquifer from saltwater intrusion. The basin represents a controversial case for which the sequence of infrastructures produced a critical system, and nowadays, it is difficult to find a compromise among mitigation of flood hazard, safeguard of groundwater resources and preservation of human health. The hydrogeological framework and the hydraulic works executed in the basin are described, followed by considerations on the environmental effects of the decision-making process. Finally, statements concerning alternative measures for the management of the water resources are given. Management actions conforming to the Integrated Water Resources Management recommendations fail in the studied case because there is an intrinsic difficulty to transform the related concepts to practical and robust solutions.

Keywords Karst endorheic basin · Water sinks · Flash flood · Water resource management · Decision-making process

Introduction

Hydraulic works for runoff regulation, marshland reclaiming and defense from inundations may produce severe modifications to the land morphology and alter the hydrological cycle. Nowadays, with the development of large and articulated urban and industrial quarters, such modifications are even more pronounced; thus, problems concerning the management of the water resources arise (Worthington 2014; Drechsel et al. 2015).

In karstic basins, when there is no connection with a river or the sea (endorheic basin), the hydraulic works for the runoff disposal usually consist of a network of channels tributary to natural “water sinks,” like sinkholes and dolines (Kemmerly 1981; Gams et al. 1993). Such surface landforms are vertically connected to the deep aquifer through a network of karstic conduits and fractures and laterally to an epikarst, i.e., a surficial highly percolative network of open joints mostly. The drainage capacity of a basin depends on the swallow capacity of the water sinks and the conductivity of both related epikarsts and connectors in the vadose zone (Gunn 1986; Zhou 2007). These hydrological parameters may reduce with time, as the elements are progressively clogged by fine-grained sediments; thus, the global basin drainage capacity is hampered and floodings may occur, sometimes disastrous, during intense precipitation events like the flash storms (Currens and Graham 1993; Bayless et al. 1995). Cetinje (Montenegro) in 1986 (Mijatovic 1988; Milanovic 2002) and Cookeville (Tennessee) in 1998 (Hart 2006) are documented cases of floodings in such a context.

✉ Corrado Fidelibus
corrado.fidelibus@poliba.it

¹ Istituto di Scienze dell’Atmosfera e del Clima, Consiglio Nazionale delle Ricerche, str. prov. Lecce-Monteroni km 1.2, Lecce, Italy

² Dipartimento di Ingegneria Civile, Ambientale, Edile e di Chimica, Politecnico di Bari, Via E. Orabona 4, Bari, Italy

Nevertheless, since late 60s the *water stress* (i.e., the scarcity and quality deterioration of water sources) has been considered a worldwide problem (Bixio et al. 2006) also with reference to karst aquifers (Katz et al. 2009; Magal et al. 2013; Morasch 2013). It is apparent that the water sinks are a criticality of the global drainage system in karst endorheic karst basins; therefore, the good functioning of these elements should be preserved through monitoring and periodical removal of clogging materials. Sometimes for old practice the water sinks are utilized for the recharge of the deep aquifer by using treated water from municipal plants in addition to the runoff water. The content of sediments in the wastewater is considerable; therefore, the clogging of the water sinks and connected elements may accelerate. Moreover, the treatment plants may malfunction and, as a consequence, a contamination of the deep aquifer may be provoked (Marin et al. 2000; Renken et al. 2005). Where karst aquifers are the main or the sole source of water, this induced risk of contamination raises a management question concerning the efficiency of such a collection system and the vulnerability to pathogens results a topic of social interest (Toze et al. 2010; Page et al. 2010).

This note deals with a controversial case of endorheic karst basin, the Asso Torrent basin (Salento, Apulia region, Italy), in which a network of natural and artificial channels discharges into karst holes and dispersal wells. Such a complex hydrographic system absolves to the following functions: (a) deep aquifer recharge and preservation of the resource from the saltwater intrusion; (b) runoff regulation and urban defense from intense precipitation events; (c) underground injection of treated wastewater. Social, economic and environmental disputes frequently occur due to the difficulty to find a reasonable compromise among: (1) the need of mitigation of flood hazard, (2) the safeguard of groundwater resources and (3) the preservation of human health. These issues are managed by different authorities, and a general plan is currently lacking. In order to establish the basis of the decision-making processes the authors conducted archive and field inquiries and performed hydrogeological evaluations, reported herein according to a new historical perspective that is exclusive of this note.

In what follows the environmental context and info concerning the history of the local water resources policy are given. Then the hydrological features of all the channels and water sinks are described; considerations on the environmental effects of the decision-making process are subsequently reported, and finally, conclusive statements are given concerning possible alternative measures for a more efficient management of the runoff and water resources. The study case may constitute a reference in providing some insights about the application of the

Integrated Water Resources Management (IWRM) (Rahaman and Varis 2005) in karstic basins of semiarid or warm temperate regions.

Regional framework

Environmental geology

The Salento peninsula belongs to a crustal domain, named Apulian Carbonate Platform, having a horst-and-graben tectonic arrangement due to the microplate geodynamics and the converging migration of both the Apenninic and the Dinaric chains (Funicello et al. 1991). The platform is formed by Mesozoic limestones, and dolomitic limestones overlain by Tertiary and Quaternary clastic carbonates and clayey marls (Fig. 1). The horst are constituted by Cretaceous rocks, while younger stratigraphic units cover the graben. The bedrock has karstic features for the prevalence of calcareous rocks. Due to the Mediterranean location of the Salento peninsula, the climate is characterized by warm and dry summers and mild and wet winters (Ulbrich et al. 2012). The average annual rainfall is about 650 mm.

The groundwater of the Salento peninsula is stored in several reservoirs. The main reservoir is a deep aquifer, while the other small groundwater bodies are shallow aquifers. The deep aquifer mainly consists of Cretaceous limestones and contain a large lens of freshwater floating on saltwater of continental intrusion (Tadolini and Tulipano 1981) with a thick transition zone of variable saline content (see section A–A' in Fig. 1). It constitutes the only available drinking water resource in the Salento peninsula and currently provides about 75 % of the local demand, the remainder provided by external source. Shallow aquifers, formed by clastic carbonates overlying clayey marls, temporarily intercept up to two-third of the effective infiltration. They are exploited for irrigation; nevertheless, they are not considered a strategic resource by the regional authorities (Delle Rose 2007b). Meteoric water rapidly infiltrates from the Cretaceous outcrops into the deep aquifer due to the high permeability of the vadose zone, while it may take tens of years for the meteoric water to reach the shallow aquifers through the Tertiary and Quaternary deposits (Delle Rose 2001). Moreover, faults dissecting the tectonic blocks constitute hydraulic connections among the aquifers, thus complicating the hydrogeological setting (Tulipano 1988). Groundwater flows in the shallow aquifers through both pores and karstified discontinuities. Inside the deep aquifer, groundwater flows in large or relatively large pipe-like conduits and in discontinuities. The latter features are affected by karst dissolution resulting in widening the apertures that range from few millimeters up to several meters. Due to the randomness of the

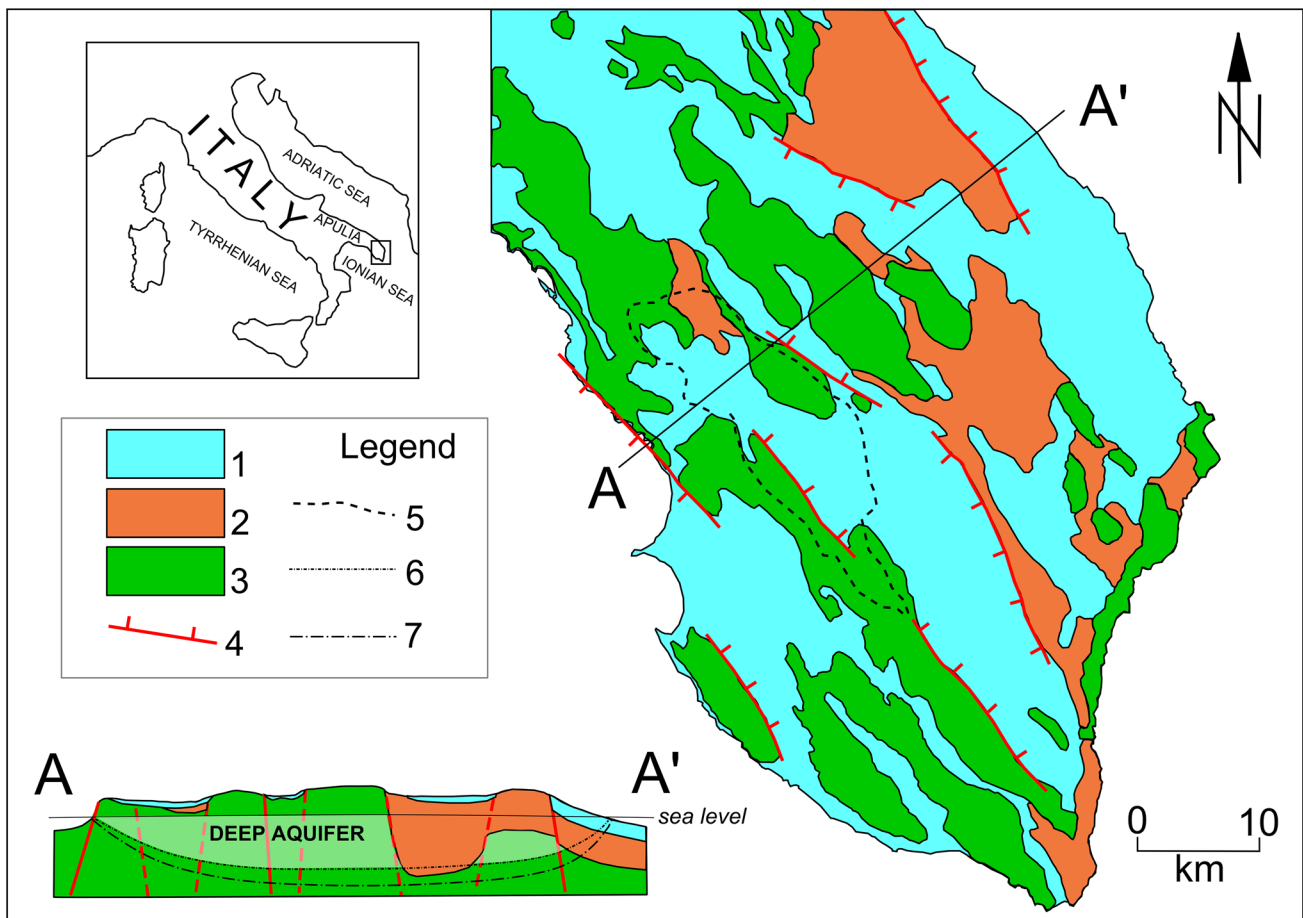


Fig. 1 Geographical location and simplified geological map of Salento peninsula. Legend: 1 Late Pliocene and Quaternary formations, 2 Oligocene and Miocene formations, 3 Cretaceous (Eocene along the SE coast) formations, 4 main faults (*dashes* indicate

downthrown blocks), 5 Asso Basin contour, 6 fresh water/brackish water interface, 7 brackish water/saltwater interface. Vertical scale exaggeration ten times in A–A' section

geometry of the network of discontinuities and conduits, stochastic models can be applied for the prediction of contaminant fate and transport (Delle Rose et al. 2000).

Flat landscapes characterize the Salento peninsula that shows on the whole as a plateau gently dipping from southeast (mean altitude 100 m a.s.l.) to northwest (mean altitude 35 m a.s.l.). The highest relief is almost at 200 m a.s.l. About three quarter of the territory has topographic gradients less than 1 %, and only one-tenth has gradients around 3 %. Actually, it does not show well-defined watersheds. Drainage pattern is formed by a number of small systems of gullies that allow to identify both endorheic and exorheic basins (Fig. 2a). Inside the former basins, karst landforms as dolines, holes and crevices act as “water sinks.” In the past, the enlargement of these sinks or the construction of additional wells around was considered good solutions to increase the draining capacity of the subsoil to face large runoff. This practice reveals a profound historical relationship among the local communities and the environment, dating back to the first rural

settlements. In fact, most of the villages are located close to the boundaries between Cretaceous units and Miocene, Pliocene or Quaternary units; according to Morch (1978), this circumstance can be explained with the availability of groundwater. With the development of the agriculture techniques, the communities continuously modified the hydrography of Salento peninsula. The changes mainly consisted in three types of hydraulic works: removal of the detritus from the channel beds; containment of the enlargement of the moist zones; and modification of the rate of runoff infiltrating underground in the endorheic basins. Early pre-Roman communities used to drain the runoff toward dolines to defense the villages from flood and also probably to store water (Delle Rose 2004). Hydraulic works became organized activities especially during the Medieval age, when Salento was frequently flooded (Arthur 1999). Until the beginning of the twentieth century, large portions of the ground were inundated for long times also during the dry seasons; thus, additional hydraulic works were built, especially in order to reclaim

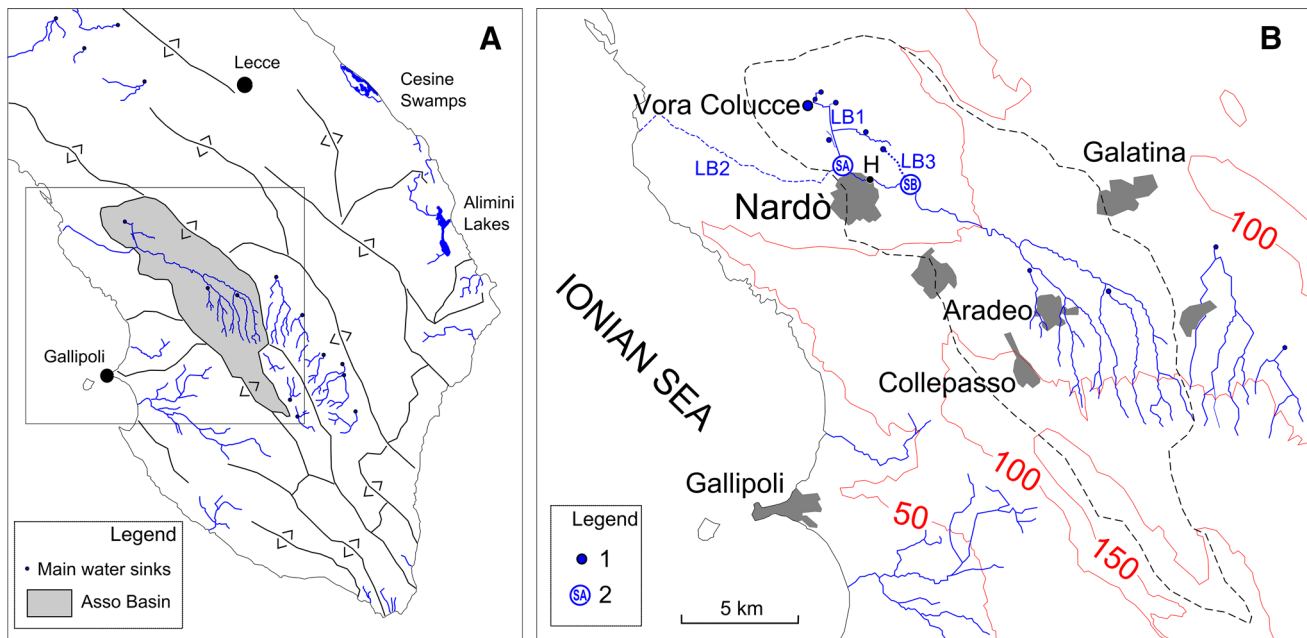


Fig. 2 Hydrography schemes. **a** Main catchment basins of the Salento peninsula. Asso Torrent basin is highlighted. Low-order watersheds are not reported; **b** schematic map of the Asso Torrent basin. Legend: 1 water sinks, 2 sluice gates (SA, SB). H indicates the hydrometer location

the marshland (De Giorgi 1884). Gullies and channels were modified to drain the surplus of runoff into karst cavities or artificial wells. Almost one hundred natural or artificial sinks were modified to increase the total amount of the infiltrating water. Dolines and sinkholes were enlarged and emptied out of debris; explosives were used to fracture the bedrock, thus improving the conductivity. Since then, systematic works of maintenance of water sinks and streams were accomplished by the territory governance. However, in the last decades the runoff has been altered by intensive agricultural practice, urbanization and new infrastructures; several sinks and gullies were abandoned and even buried, also because of the reduction of both the annual precipitation and the rainy days that occurred in the 70s and in the 80s on the whole Southern Italy (Brunetti et al. 2004). Nowadays, urban and country areas are often subjected to floods and the related social and economic costs increase (Delle Rose 2007a; Iacobellis et al. 2015).

Water resources policy

The Salento peninsula is characterized by both karstic features and lack of infiltration during spring/summer.

For centuries, the local communities practiced strategies for the exploitation and maintenance of the water resources.¹ The land remained arid for long. The evolution of the

¹ During the first century A.C. the Roman poet Horace defined the land of Apulia as *sitticulosa* (“thirsty”) and described the efforts to rationalize the water use.

traditional water collection, storage and distribution technologies resulted from a compromise between the sense of resignation toward the hard environmental conditions (resulting from the scarcity of surficial water and the semiarid climate) and the endeavor to develop ingenious ways to collect water (Grassini 2012). In the first half of the twentieth century, with the construction of large water infrastructures requested by the enhanced increase of both urban and agricultural demands, the situation dramatically changed because of the construction of the Apulian Aqueduct, one of the worldwide largest networks of pipelines transporting water. In addition, reclamation works in marshlands were accomplished to eradicate the malaria scourge. Meantime, the first noticeable flood disasters occurred in Apulia region, the more calamitous at Bari on the November 6, 1926, that caused 19 dead and 50 injured (Baldassarre and Francescangeli 1987). However, about 70 years passed for the first regulatory actions concerning the defense from urban flood.

After the II WW, the strong economical growth drove to a vast urbanization not accompanied by the construction of adequate sewage pipelines because of the lack of environmental regulation. Sinkholes, dolines and other karst landforms, such as holes and chasms, and drilled boreholes were therefore used to dump the wastewaters without any control of the quality of the groundwater. The consequent pollution of the aquifers became a social issue in the 80s. In the meanwhile a deficit of the groundwater recharge due to a rainfall decrease occurred; therefore, the authorities settled a regional office for the governance of the water

resources; then, the Salento peninsula became almost self-sufficient with respect to the water supply.

At the end of 90s, following a directive of the European Community, a new Italian law (D. Lgs. 152/1999) forbade the underground disposal of wastewater. Such a regulation pushed new works to update the existing sewage pipeline systems, and tens of underground discharges were modified to drain surface wastewater in gullies and channels defined by law “not significant” (due to low flow rates), among which those of the Asso Torrent system. Since then, the conditions of the deep aquifer became critical. Large and uncontrolled withdrawals favored saltwater intrusion; thus, nowadays groundwater with low saline content (i.e., less than 0.5 g/l) can be barely found (Tulipano 1988, 2001; Fidelibus et al. 2002). Meanwhile, the committee of the European Community launched the statement to contrast both desertification and *water stress*, leading to a change in water management policies. Concepts as “sustainability” and “integrated management” recurred in public debates. The regional bureau stated that all the Apulian territory belongs to critical and fragile areas, prone to become increasingly arid according to the MEditerranean Desertification And Land USe (MEDALUS) Project (Ladisa et al. 2012), while a national law (D.M. 185/2003) allowed the reuse of treated wastewater for agricultural purposes. Three years later a new national law (D. Lgs. 152/2006) introduced the principle of an integrated water resource management consisting of a careful planning of the water use in order to avoid loss of quality and enable sustainable water consumption. Finally, in 2009 the regional government launched the Plan of Water Safeguard (PWS), whose main target was to reduce the withdrawal from the deep karst aquifer for both irrigation and industrial purposes and reuse treated wastewaters. In PWS, the condition of the Asso Torrent basin was defined as particularly critical and the necessity to reduce the pollution deriving from the wastewater treatment effluents of the network was advanced. Despite PWS, the policy of the regional water resources in the framework of the integrated management still remains difficult. In fact, even if nearly 200 municipal treatment plants operate in Apulia, only 10 % of the urban agglomerates efficiently treats the wastewater. In Salento peninsula the functionality of the plants is generally compromised (cf. De Donno et al. 2001), with associated risks of the human health, as confirmed by statistics concerning the incidence of some specific pathologies. For example, in the last ten years the incidence of typhoid fever increased to 12.11 out of 100,000 inhabitants, whereas in Italy the average is 2.91 (Lugoli et al. 2011). Thus, the basic principle of the Framework Water Directive (FWD) (European Union 2000) to promote “sustainable water use based on a long-term protection of available water resources” is an ineludible goal for the Salento peninsula. Nevertheless,

“the measure to prevent or limit input of pollutants into groundwater” prescribed by the Groundwater Directive (GD) of the EU (European Union 2006) must be applied without further delay.

The Asso Torrent basin

Physical setting and hydrography

The Asso Torrent basin is a network of gullies and artificial channels flowing toward artificial dispersal wells and karst holes, and among them the largest is the collapse sinkhole “Vora Colucce” (also named Vora del Parlatano).² It is a collapse sinkhole laterally connected with both a cave and an epikarst zone consisting of the more open and karstified surficial fractures and bedding having a conductivity reducing with depth and vertically connected with the deep aquifer through fractures and karst conduits (Fig. 3).

The basin is 220 km² wide and is located within a large graben-polje (sensu Gams 1978), crossing at the center the Salento peninsula (Fig. 1) and including other endorheic basins (Fig. 2).

The hydrographic system of Asso Torrent is divided into three branches: upper, middle and lower. The first branch has a clayey-marly substratum and slopes between 10 and 2 %. The second and the third branches have clastic carbonates for substrata and slopes less than 2 %. Clastic carbonates bedrock forms an epikarst zone affecting the infiltration. Tectonic and hydraulic features of epikarst are described by Delle Rose et al. (2000). The channels of the upper branch are natural, whereas those of the middle are the result of a series of hydraulic works, probably executed by the Romans (first century BC), as deduced by the interpretation of orthophotos and field survey of the near ruins marking the land divisions (*centuration*). The channels of the lower branch (north of the city of Nardò, see Fig. 2b) are completely artificial and are the result of the reclamation works made in the first half of the last century for both the defense of the town of Nardò from floods and the fight against the malaria plague (LB1 in Fig. 2b). The layout of the channels was established by considering the location of the Vora Colucce sinkhole as reported in documents of the Italian State Archive.

To obtain a reasonably accurate history of the remote flood events, the authors consulted old newspapers; the results of this quest are shown in Table 1. Since the late 40s in Nardò, inundations caused by storms were an issue

² In local dialect sinkhole and doline—as well as each “water sink”—are called “vora,” from the Latin *vorare*, meaning “swallow,” or from the Latin *gurgus*, meaning “whirlpool.”

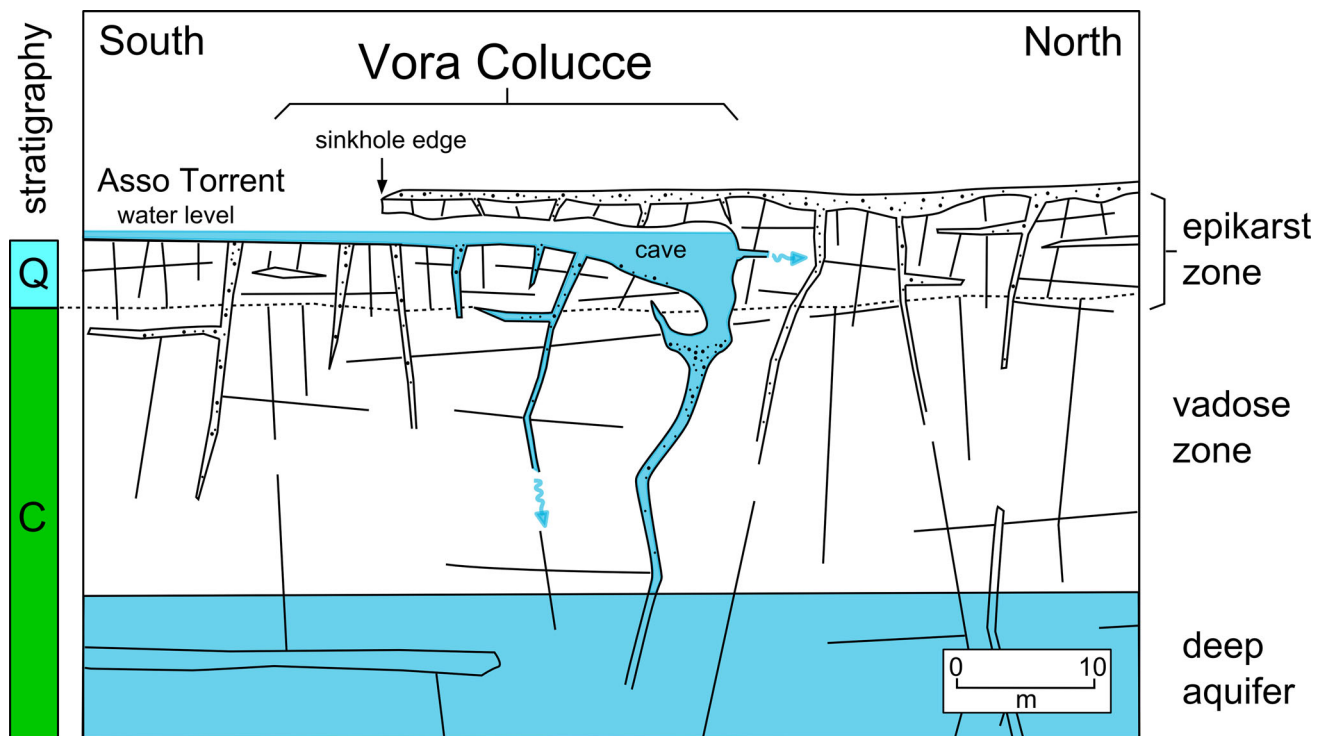


Fig. 3 Schematic hydrogeological section across the Vora Colucce area. *Q* Quaternary clastic carbonates; *C* Cretaceous limestones. Dots represent soil and detritus

of strong social relevance for the damage caused to houses, infrastructures and crops. Other villages (especially Ara-deo, see Fig. 2b) experienced damaging floods. In the late 70s, to strengthen the defense from inundations the hydrological system of Asso Torrent underwent several modification works, the most important consisting of a new draining channel (LB2 in Fig. 2b) flowing to the sea, connected to Asso Torrent by means of a double sluice gate (SA in Fig. 2b). Other important works were the expansion and cementation of the channels of LB1, as reported in several technical documents of *Consorzio di Bonifica Arneo*.

Since 1991 Asso Torrent is also used to discharge municipal wastewater effluent from five plants for the treatment of municipal water (design maximum discharge of $2 \text{ m}^3/\text{s}$) and from one plant treating industrial water. The treated waters mix with the natural runoff and then are injected through the sinks in the vadose zone of the deep aquifer; the quality of the mixed water is low for the high contents of bacteria and nitrates and traces of ammonia (Delle Rose 2007a). As a consequence, high risks of contamination derive for the deep water resource that is still used for irrigation, even if the saline content ranges from 0.5 to 1.0 g/l (Fig. 4). However, the discharge is considered a measure to counteract the seawater intrusion in the deep aquifer (Masciopinto and Carrieri 2002; Masciopinto 2006).

As previously stated, another issue that complicates the management of the hydrological system is the burial of channels and sinks. The treated wastewater from the plants includes organic mud in a sufficient quote for a significant increase of the transported sediment. In fact, every 5/10 years the channels of the lower branch and the sinks of the network are cleaned by removing the debris and solid waste. Evidently, without the wastewater the Asso Torrent basin would be dry most of the year except for few days after the rainfalls. The flow rate reaches some tens of cubic meters per second during the strongest winter rainfalls (Table 1), when inundation of the nearby urban and rural areas occurs. Up to $30 \text{ m}^3/\text{s}$ in 12–15 h was recorded recently. The extreme rainfall ever recorded is 100 mm in 9–12 h.

A critical situation occurs at the “Vora Colucce” sink, where, despite a recent cleaning (eight years ago), the absorbing capacity is now very limited because of the high amount of organic mud from the municipal wastewater (Fig. 5). According to the report of the marshland reclaiming works of one century ago, the “Vora Colucce” sink should absorb $10 \text{ m}^3/\text{s}$ and each other secondary sink $2 \text{ m}^3/\text{s}$. Now these figures are consistently reduced.

Extensive new hydraulic works to change the hydrography of the lower branch of the work were planned in 2009. The project was inspired to the conventional hydraulic paradigm of the concentration time

Table 1 Main floods occurred at the lower branch of the Asso Torrent basin as reported in newspapers and technical documents stored at the State Archive of Italy

Date	Damages	Rain gauges data (mm/day)
26/10/1947	Rural flood; destruction of agricultural products	No 47.3; R 48.4
28/01/1954	Collapses of stone pavement; buildings damaged	G 26.7; Na 50.1
28/09/1955	Flooding of basements; buildings damaged	G 66.2; Na 21.3
24/11/1959	Buildings and historical churches damaged	G 34.6; Na 20.4
10/02/1960	Rural flood	G 28.8; Na 38.0
05/10/1964	Destruction of some houses	G 73.0; Na 28.2
05/03/1969	Rural flood	G 34.2; Na 38.2
30/09/1971	Damages of public buildings	G 20.4; Na 13.2; C 35.0
19/11/1976	Urban and rural flood	G 107.0; Na 87.0; C 118.4
03/11/1993	Urban and rural flood; sewer system spills	G 223.0; Na 121.0; C 23.8
09/10/1996	Rural flood	G 47.0; Na 80.0; C 19.4
13/11/2004	Urban flood; sewer system spills	G 180.2; Na 165.0; C –
03/12/2008	Rural flood	G 80.8; Na 75.8; C 73.6
02/11/2010	Urban flood; sewer system spills; hygienic and sanitary problems; flooding of basements and first floor building; destruction of commercial goods	G 4.2; Na 178.8; C 2.2
31/10/2012	Urban and rural flood; sewer system spills	G 38.6; Na 52.8; C 62.2

Gauges data from “Annali idrologici” of the *Ufficio Idrografico e Mareografico*

Rain gauge stations: C Collepasso, G Galatina, Na Nardò, No Novoli, R Ruffano

(Grimaldi et al. 2012). A new channel (LB3 in Fig. 2b) and accessory works (the most important among them are several *settling tanks* and three clusters of injection wells) were designed in consideration of a maximum discharge of 228.75 m³/s that is related to a return period of 200 years. Until now, only parts of the new channel have been built, whereas the control of the flow in LB1 is performed by means of a sluice gate (SB in Fig. 2b). The present LB3 acts as an overflow channel and is connected with a minor water sink that absorb only 2 m³/s. The works are now suspended due to budgetary constraints. During the years 2014–2015, as supplementary hydraulic work, a new channel branching out from close the Vora Colucce to a dispersal tank and another small natural water sink was built.

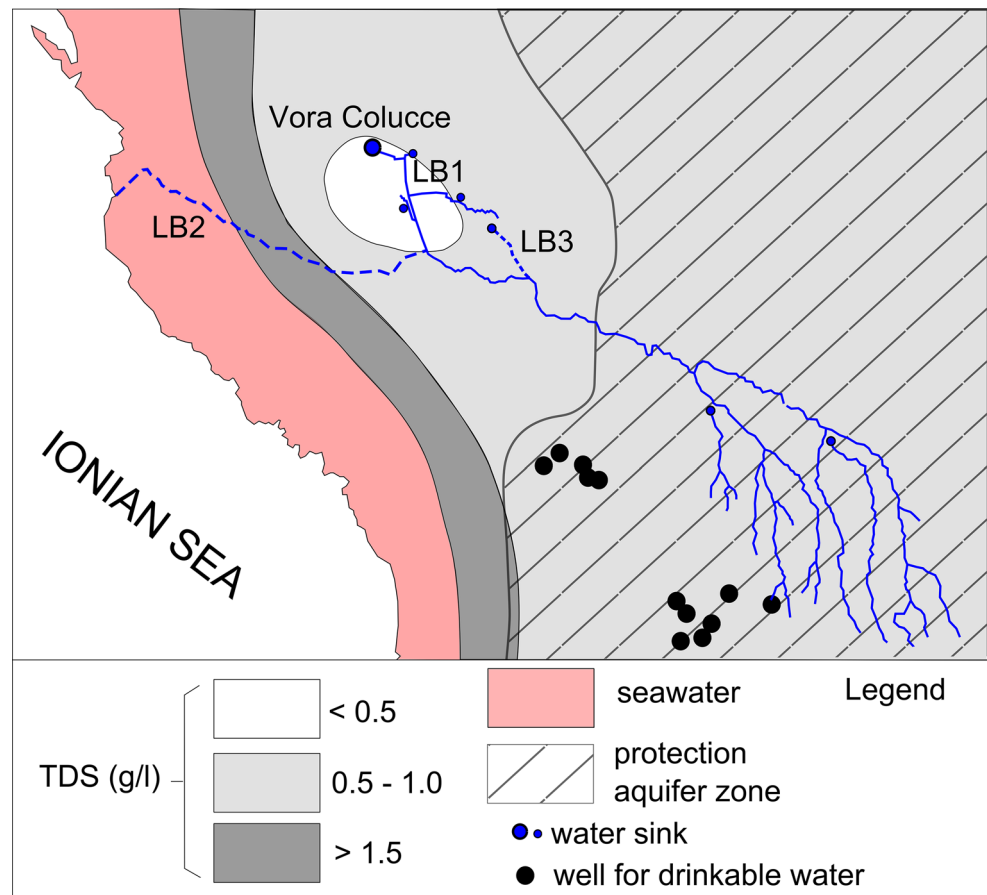
Risk of flooding and precipitations

The towns of Nardò and Aradeo inside the Asso Torrent basin (Fig. 2b) are frequently subjected to floodings. The conditions predisposing the floodings threatening Nardò are described in what follows because the related risk is of higher level. In the history of these events two crucial periods can be identified with respect to intensity of precipitations and type of damage. In the first period (before the 80s), private and public constructions resulted frequently damaged for a rain intensity usually not exceeding 60–70 mm/day. During the second period (beginning in the 90s) the urban territory was mainly affected by sewage

system outflow, while the daily precipitations strongly increased (Table 1). Moreover, as previously mentioned, the works of the end of 70s drastically modified the lower branch. In order to both counteract the seawater intrusion in the deep aquifer and reduce the risk of flooding the level of the urban stretch of the channel was continuously observed and the discharge toward the water sinks ruled by the opening of the gate SA (see Fig. 2b). Upon request the gate diverts the water toward the sea (by means of LB2), thus limiting the discharge into the LB1 for the ground-water recharge.

In particular, the flash events occurred in November 13, 2004, and November 2, 2010, required care in decision making. The first event was framed into a mesoscale convective system moving from the Atlas Mountains that became vigorous over the Mediterranean during the propagation toward Europe (Laviola et al. 2011). Later on, the persistence of a low-pressure zone supported the intense convective activity leading to heavy rains on the Salento peninsula (Fig. 6a). The 10/2/2010 event shows different features. For three days before the event, Italy was hit by storms that caused some fatalities and infrastructures damages. A massive warm and moist air front persisted on Apulia and Ionian Sea, thus producing V-shaped storms (McCann 1983). The precipitation values of the second event show a wide range (Fig. 6b); available official data are in mm/day but rains lasted no longer than 6 h. As far as the Asso Torrent basin is concerned, only the area of the lower branch was affected by a storm, as field-surveyed by the authors.

Fig. 4 Total dissolved solids (TDS) inside the deep aquifer at a depth of -5 m below the sea level (modified from Fidelibus et al. 2002)



The management of the urban floods was regulated by opening of the sluice SA (see Fig. 2b for location). As regards the first event, SA was perhaps opened too late, whereas in the second event the opening was well timed. It is to remark that during the 10/2/2010 event the wave propagation into the Asso Torrent (insert of Fig. 6b) was measured by the hydrometer H (Fig. 2b).

Had the management focused on the control of the sewage outflows rather than on the damage to the constructions, the hydraulic paradigm would have been changed from the modeling of floodings to the attenuation of the effects of extreme events. The Civil Protection Plan for the town of Nardò (Provincia di Lecce 2006) effectively considered the following adverse effects of a flooding: (a) limitations in road usability and danger for traffic especially in extra-urban roads; (b) flooding of basements and first floors; (c) diffusion of pollutants in soil and groundwater; (d) danger of drowning for people living in basements.

After the hydraulic works carried out in the last years the distribution of the flood hazard has changed. The urban zones would be affected by a lower hazard level (Fig. 7), provided that the sluice SB functions in limiting the water discharge in the lower-branch channels. The level of the

old channel LB1 is monitored by hydrometer H (see Fig. 2b). Such a level is another decision-making factor.

Groundwater pollution and health risks

The intrinsic vulnerability of groundwater to surface contamination of the lower branch of the Asso Torrent basin was evaluated by resorting to the EPIK index (Doerfliger et al. 1999) and the DRISTPI index (Jiménez-Madrid et al. 2012). The EPIK is between 17 and 20 and is considered very high. The values of the DRISTPI index fall into the high vulnerability class. The intensity of pressure is moderate; however, the occurrence of petrol stations and treatment plants of industrial wastewater imply a higher value of the parameter; thus, the level of risk becomes high.

Chemical and microbiological data on both superficial water and groundwater of the Asso Torrent basin would require care in policy and management (Delle Rose 2007a; Polieri et al. 2009). In this respect, it is worth to note that the average content of pathogens as *Escherichia*, *Campylobacter*, *Cryptosporidium* and *Rotavirus* frequently exceeded allowable doses and chemical parameters as total nitrogen contribution (TNC), dissolved organic carbon (COD), biochemical oxygen



Fig. 5 Water levels in LB1 at Vora Colucce water sink. *Above* low water level during dry season (picture taken September 9, 2007); *below* high water level and surrounding flooding during wet season (picture taken April 4, 2010)

demand (BOD), adsorbable organic halogen (AOH) are beyond the limits (Masciopinto et al. 2004, 2006); thus, concerns about the health risks arise. However, the groundwater recharge with reclaimed wastewater

produced appreciable effects against the salinization of the deep aquifer in the surrounding of the water sinks (see Fig. 4). In fact, field investigations and Landsat images of the coastal spring outflow confirm an overall

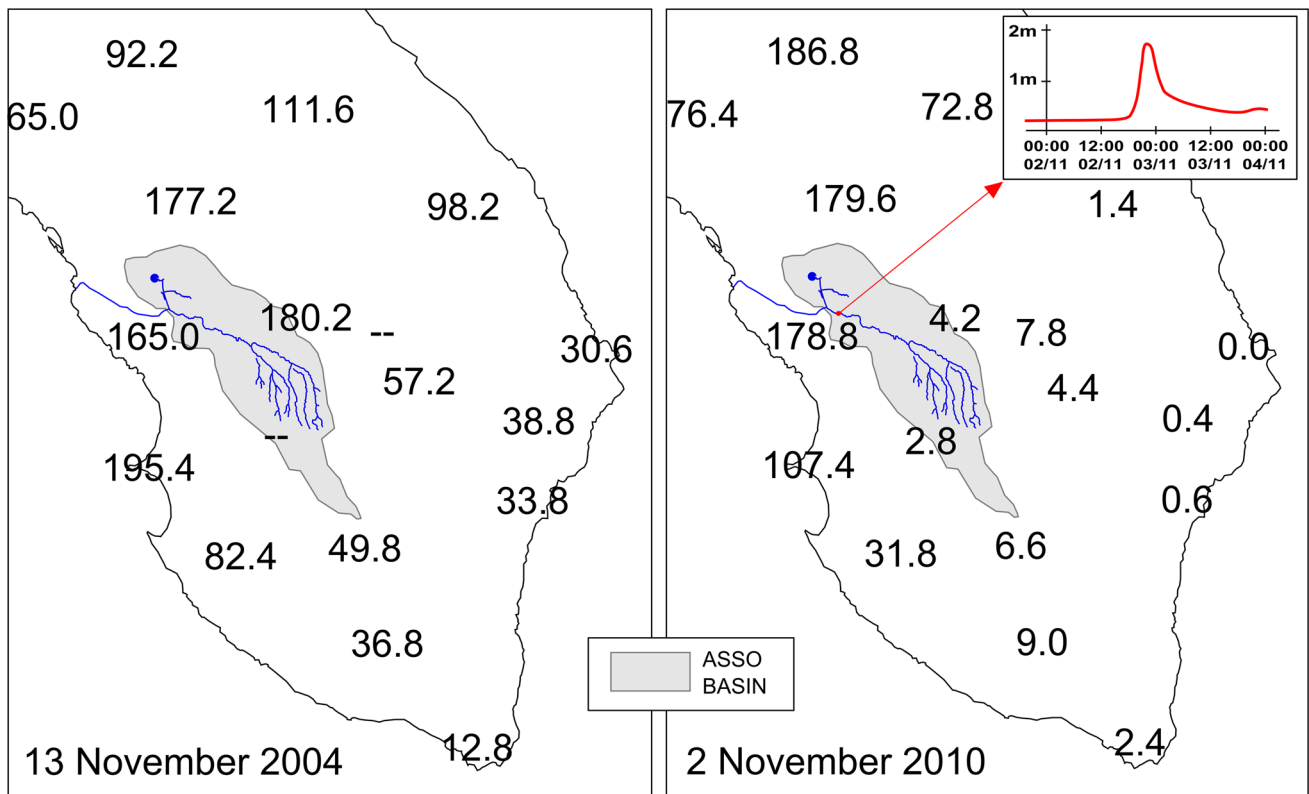
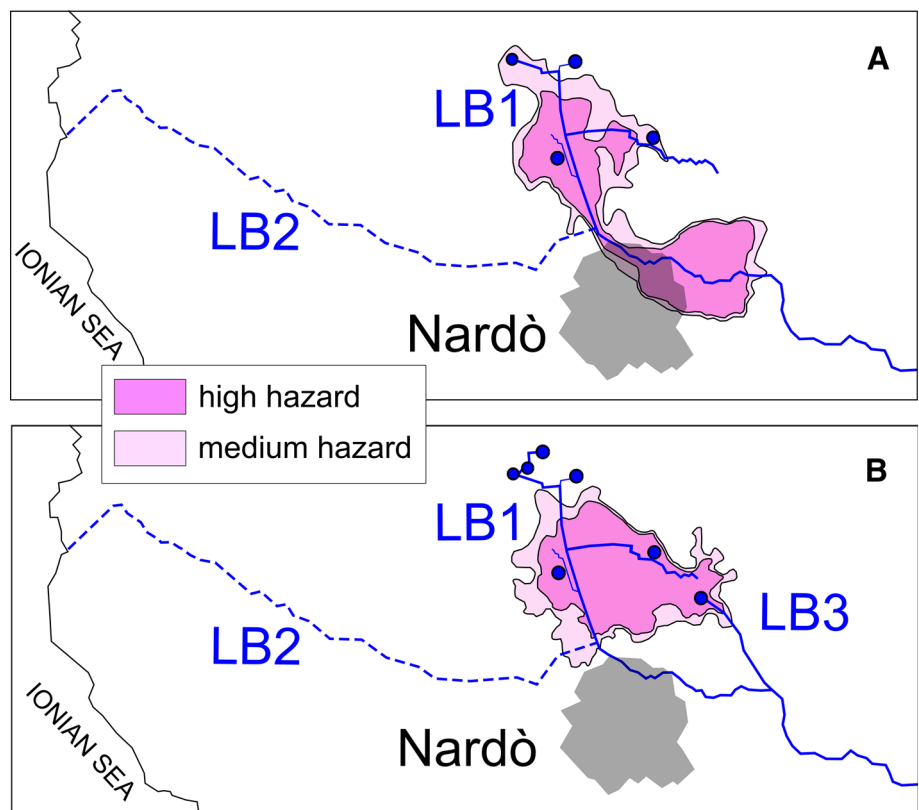


Fig. 6 Cumulative 24-h precipitation of the November 13, 2004, and the November 2, 2010, events. The inset at the high right side displays hydrometer levels (from Hydrologic Annals of the *Ufficio Idrografico e Mareografico*)

Fig. 7 Zonation of the flood hazard carried out by HEC-RAS 2D modeling. **a** Before the 2010–2012 hydraulic works; **b** current situation (data excerpted by technical documents of *Consorzio di Bonifica Arneo*)



reduction of the salt content in freshwater (Masciopinto 2006).

The rural area north of Nardò is largely used for agriculture. Groundwater is exploited by tens of wells, whose large part is managed by a regional agency (*Consorzio di Bonifica Arneo*). Health risks regard more the production and consumption of crops than the domestic water use. According to Ayuso-Gabella et al. (2011), two types of exposure scenarios have to be considered: (1) ingestion of the aerosol produced during irrigation; (2) consumption of crops irrigated with water containing pathogens. Farmers are therefore exposed to enteric infections of bacterial or viral origin.

The efficiency of the municipal treatment plants discharging into the Asso Torrent is not improving (Table 2), and as a consequence, in the waters outflowing the plants, COD and BOD assume large values, sometimes beyond the limits and tracks of *Escherichia coli* presence are also recorded. Nevertheless, with reference to the groundwater exploited north of Nardò, previous estimations of the pathogen decay rates suggest to increase the time of storage of the injected water in order to reduce the health risks (Ayuso-Gabella et al. 2011).

The last hydraulic works that redefined the hydrography of the lower branch of the Asso Torrent also changed the area affected by the recharge. In fact, while until 2012 the water flowing in the Asso Torrent have been injected into a zone of the deep aquifer with saline content from 0.5 to 1.0 through the water sinks (see Fig. 4) because the channel LB1 was completely cemented, and now, with the new channel LB3 operative, water infiltration occurs being the channel permeable. Due to a spillway, LB3 becomes active during from low-to-medium intensity rains and drains all the discharge of the torrent when the rain is of medium to high intensity. Moreover, such new area of recharge is nearest to the protection zone where the deep aquifer provides drinking water (see Fig. 4). Consequently, the reduction of the chemical and microbiological parameters of the reclaimed wastewater becomes a crucial issue.

Decision-making issues

As reported above in the Asso Torrent basin, for a series of modifications of the land use, the water resources policy and the conventional hydraulic paradigm, artificial and natural water sinks and channels were connected to form the current system that is managed by different authorities, whose decisions are relevant for: (1) protection of the groundwater from salinization; (2) flood prevention; (3) preservation of human health. In addition, groundwater discharge occurs through “discrete” elements, whose full functioning must be ensured. The demand of a good

management is even stronger for the threat of short and intense storms that can be considered new climatic features.

Over the years the management pursued standard engineering solutions based on the concentration time paradigm; these solutions allowed the authorities to intervene upon necessity. For this reason the double-gate SA (Fig. 8) was built to divert in case the water in the channel to the sea, thus limiting the amount of water discharged to the Vora Colucce and the other natural sinks and to the artificial dispersal wells. The decision-making process is then condensed in operating the sluice gates when the water in the channel would reach a pre-defined threshold. The logical assertion underpinning this solution is that the proper functioning of the entire network is ensured by limiting the discharge to the sinks, having these elements a finite swallow capacity. Albeit such a solution appears adequate, for several concurrent factors the assertion may be confuted: (1) the swallow capacity of the natural (as well as of the artificial) sinks is not constant, being hampered by the progressive clogging of the fractures due to the sediments; (2) the flash storms are more and more intense; thus, the sections of the channels will become insufficient even in the short term, leading to new works.

It is fairly evident that the complex system of the Asso Torrent basin should be managed through a more articulated decision-making process where additional elements are controlled and compared to pre-defined thresholds, thus conditioning the opening of the gates. Such elements may be, for example, the content of the contaminants of the wastewater released by the treatment plants and the content of sediments of the water of the channels. In this respect, it is worth to remark that high-quality treated water might be directly used for the irrigation rather than injected into the aquifer (Sicolo 2006). Moreover, when an intense storm occurs, the water should be mainly dispersed on the ground (by LB3) and then infiltrate in the vadose zone of the aquifer, given that during the floodings (that seem inevitable) the water is contaminated by the sewage for the malfunctioning of the pipes.

For the intrinsic complexity of the hydrographic system and the need to coordinate the actions of the competent authorities, the necessity of a general plan for decision making arises. In particular, in view of a sustainable use of the resources, such a plan should conform to the FWD principles (European Union 2000, 2006). A scheme of the plan is reported in Fig. 9, in which a specific management target is pursued by diverting the waters in a corresponding channel through the maneuvering of SA and/or SB, in consideration of the values assumed by the input variables. Secondary effects are associated with each management target. For example, in case a high urban flood prevention is required, waters are diverted to LB3; as associated effect

Table 2 Municipal treatment plant parameters; maximum values registered during 2013 (data from *Agenzia Regionale per la Prevenzione la Protezione dell'Ambiente*)

Plant name	BOD (mg/l)	COD (mg/l)	TNC (mg/l)	<i>Escherichia coli</i> UFC/100 ml	Anionic surfactant (mg/l)
Aradeo	45.2 (January)	149.0 (January)	10.5 (April) ^a	25,000 (July)	0.24 (August)
Copertino	15.4 (June)	44.7 (June) 42.5 (April)	21.0 (January)	12,000 (January)	0.40 (September) 0.39 (July)
Galatina	13.7 (March)	62.0 (March)	20.0 (February)	45,000 (June) 24,000 (May)	0.15 (August)
Galatone	17.2 (March)	67.3 (March) 64.4 (September)	22.0 (March)	29,000 (March)	0.15 (March) 0.15 (September)
Maglie	48.7 (May)	94.0 (May) 87.7 (June)	20.8 (September)	^b	^b

^a Few reliable measures

^b No reliable measures

the level of groundwater protection from pollution is lowered.

In the near future, in spite of forecasting uncertainties, two weather scenarios can be envisioned: (a) an increase of extreme events in a context of climatic drought and (b) an increase of the average annual rain and rainy days per year (Younger et al. 2002; Todd et al. 2011; Hertig et al. 2013; Scoccimarro et al. 2013). In the first case the decision making is crucial for the mitigation of the flooding-induced damage experienced by the town of Nardò and the safeguard of the karst aquifer by operating the recharge by using waters of high quality. In the second case, by improving the monitoring of all the discharges of the channels, the efficiency of the wastewater plants would be less stringent. However, due to the uncertainties about the next climatic change, a careful policy of the water resources should primarily consider innovation strategies as the construction of treatment wetland plants, some of which are effectively in use in Salento peninsula (Semeraro et al. 2015).

The experience of the Asso Torrent basin shows that “rigid” systems do not properly work when artificial and natural factors dramatically change with time; thus, the management should envision new scenarios and consequently adapt the structures as well as the decision making. As it was customary in the past the maintenance works must be continuous, even if within the budgetary limits, and “chirurgical,” rather than occasionally and massive, while the decision-making process should consider more the feedback of investigations and monitoring (Fig. 8). Such considerations may be extended to other urbanized karst catchments, especially those belonging to semiarid or warm temperate regions (see, e.g., Kemmerly 1981; Currens and Graham 1993; Gams et al. 1993; Marin et al. 2000; Bonacci 2004; Renken et al. 2005; Hart 2006; Katz

et al. 2009; Page et al. 2010; Magal et al. 2013). Vulnerability to pollution and sensitivity to drying up of the karst water resources should lead the authorities to adopt new solutions to minimize both the use of freshwater in agriculture and the volume of wastewater produced. Improvement of the quality of the effluents outflowing from the traditional treatment plants and the satisfactory outcome of the treatment wetland plants are the ineludible issues. The achievement of the objectives of the European Union (2000, 2006) and the updating of the policy procedures conforming to the IWRM recommendations (Rahaman and Varis 2005) both require participatory processes among the authorities with competence in water resources management (Martínez-Navarrete et al. 2011) and, possibly, with specific reference to the sustainability, in association with the local communities.

Conclusion

With reference to the hydrographic system of the Asso Torrent basin in this note issues concerning the management of subsurface and surficial waters are reported. The basin represents a controversial case for which a long sequence of infrastructural interventions and modifications gave rise to a critical and complex system. As such it is difficult to find a good compromise among: (1) the need of mitigation of flood hazard, (2) the safeguard of groundwater resources and (3) the preservation of human health.

As far as the hydraulic works are concerned, they were conceived following conventional models inspired to the old paradigm of the concentration time. The new paradigm should follow the logic of the prevention from the flash floods, whose intensity is considered the reference factor in the context of the climatic change. There are already



Fig. 8 Above the sluice gate SA along LB1 is closed to drain Asso Torrent toward the sea through LB2. Below on the left the gate SB is regulated for a low flow in LB1. Below on the right the hydrometer H monitoring helps the decision making

authoritative opinions against the old paradigm: among the others, Grimaldi et al. (2012) state that the available approaches for the numerical estimation of the time of concentration may lead to predictions with a scatter of 500 %. It is apparent that the current system of channels (even after the recent modifications) is not adequate to collect the waters during the flash floods because it was conceived conforming to the old paradigm.

The Salento peninsula, like several semiarid or warm temperate regions, is at the onset of a critical phase in which the water stress problem may dramatically arise (Bixio et al. 2006). Countermeasures should be based on new models and innovative concepts. In this respect the wastewater may be considered a resource rather than a tool, for example by directly using the wastewater for the irrigation, provided that the treatment is enhanced. The old

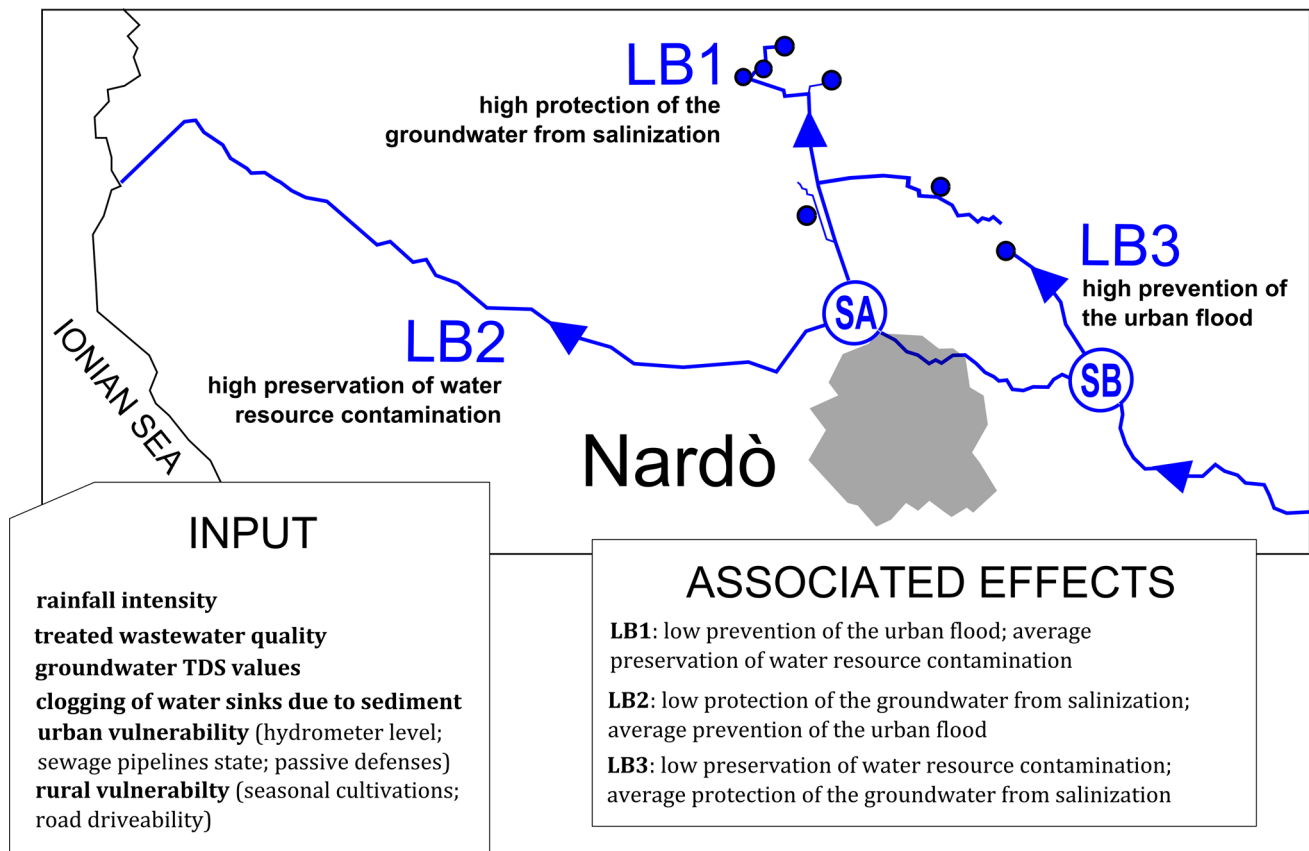


Fig. 9 Scheme of decision making for the water management

engineering practice implies to pave parking slots everywhere, even when not necessary, thus increasing the water discharging to the channels during the storms; new open naturalistic solutions with sufficient bearing capacity are available instead of concrete pavements. Finally, the monitoring of multiple meteorological and hydraulic factors is a key for an efficient management.

Policy and management actions conforming to the IWRM recommendations may fail in contexts like the Asso Torrent basin. It is a further demonstration of the inefficiency of such actions more in general, as pointed out by Biswas (2004), who highlights the difficulty to transform high-level concepts to practical and robust solutions.

Acknowledgments The authors would like to thank *Consorzio di Bonifica Agrario* and Italian State Archive of Lecce for the access to the technical documents concerning the Asso Torrent basin.

References

- Arthur P (1999) Grubenhauser nella Puglia bizantina: a proposito di recenti scavi a Supersano (Le). *Archeol Mediev* 26:171–178 (in Italian)
- Ayuso-Gabella N, Page D, Masciopinto C, Aharoni A, Salgot M, Wintgens T (2011) Quantifying the effect of managed aquifer recharge on the microbiological human health risks of irrigating crops with recycled water. *Agric Water Manag* 99:93–102
- Baldassarre G, Francescangeli R (1987) Osservazioni e considerazioni sulla inondazione del 6 novembre 1296 in Bari e su un relativo deposito. *Mem Soc Geol Ital* 37:7–16 (in Italian)
- Bayless ER, Taylor CJ, Hopkins MS, Arvin DV (1995) Directions of ground-water flow in the Lost River watershed near Orleans, Indiana. US Geol Serv Fact Sheet, FS-211-95
- Biswas AK (2004) Integrated water resources management: a reassessment. *Water Int* 29(2):248–256
- Bixio D, Thoeye C, De Koning J, Joksimovic D, Savic D, Wintgens T, Melin T (2006) Wastewater reuse in Europe. *Desalination* 187:89–101
- Bonacci O (2004) Hazards caused by natural and anthropogenic changes of catchment area in karst. *Nat Hazards Earth Syst Sci* 4:655–661
- Brunetti M, Maugeri M, Monti F (2004) Changes in daily precipitation frequency and distribution in Italy over the last 120 years. *J Geophys Res* 109:D05102. doi:10.1029/2003JD004296
- Currens JC, Graham DR (1993) Flooding of the sinking Creek karst area in Jessamine and Woodford counties, Kentucky. Kentucky Geological Survey, Report of investigations 7
- De Donno A, Prontera L, Galante MM, Gabutti G (2001) Groundwater quality in the province of Lecce: critical revision of the historical data. *J Prev Med Hyg* 42:45–51
- De Giorgi C (1884) *Cenni di geografia fisica della Provincia di Lecce*. Editrice Salentina, Lecce (in Italian)
- Delle Rose M (2001) Geological constraints on the location of industrial waste landfills in Salento karst areas (southern Italy). In: Brebbia CA (ed) *Water pollution VI, modelling, measuring*

- and prediction. Wessex Institute of Technology Press, Southampton, pp 57–68
- Delle Rose M (2004) Uso idrologico di forme carsiche nei centri messapici di Egnazia e Cavallino. *Umanesimo della Pietra* 27:113–130 (in Italian)
- Delle Rose M (2007a) Valutazione dei rischi di allagamento per incremento degli eventi meteorici estremi in bacini endoreici della Puglia centro-meridionale. *Geol Territ* 3–4:49–60 (in Italian)
- Delle Rose M (2007b) Sedimentological features of the Plio–Quaternary aquifers of Salento (Puglia). *Mem Descr Carta Geol d'Italia* 76:137–146
- Delle Rose M, Federico A, Fidelibus C (2000) A computer simulation of groundwater salinization risk in Salento peninsula (Italy). In: Brebbia CA (ed) Risk analysis II. Witpress, Southampton, pp 465–475
- Doerfliger N, Jeannin PY, Zwahlen F (1999) Water vulnerability assessment in karst environments: a new method of defining protection areas using a multi-attribute approach and GIS tools (EPIK method). *Environ Geol* 39(2):165–176
- Drechsel P, Qadir M, Wichelns D (eds) (2015) Wastewater: economic asset in an urbanizing world. Springer, Berlin
- European Union (2000) Water framework directive 2000/60/EC
- European Union (2006) Groundwater directive 2006/118/EC
- Fidelibus MD, Spizzico M, Tulipano L (2002) ^{222}Rn activity in a karst coastal aquifer under active seawater intrusion. In: Proceeding 17th salt water intrusion meeting, Delft, pp 262–272
- Funicello R, Montone P, Parotto M, Salvini F, Tozzi M (1991) Geodynamical evolution of an intraorogenic foreland: the Apulia case history (Italy). *Boll Soc Geol Ital* 110:419–425
- Gams I (1978) The polje: the problems of definition. *Z Geomorphol* 22:170–181
- Gams I, Nicod J, Julian M, Anthony E, Sauro U (1993) Environmental change and human impacts on the Mediterranean karsts of France, Italy and dinaric region. *Catena Suppl* 25:59–98
- Grassini L (2012) Water resources management and territorial development: technological changes in Apulia during the post-urbanization period. *Plurimondi* 11:89–123
- Grimaldi S, Petroselli A, Tauro F, Porfiri M (2012) Time of concentration: a paradox in modern hydrology. *Hydrol Sci J* 57(2):217–228
- Gunn J (1986) Solute processes and karst landforms. In: Trudgill ST (ed) Solute processes. Wiley, Chichester, pp 363–437
- Hart EA (2006) Land use change and sinkhole flooding in Cookeville, Tennessee. *Southeast Geogr* 46(1):35–50
- Hertig E, Seubert S, Paxian A, Vogt G, Paeth H, Jacobeit J (2013) Changes of total versus extreme precipitation and dry periods until the end of the twenty-first century: statistical assessments for the Mediterranean area. *Theor Appl Climatol* 111:1–20
- Iacobellis V, Castorani A, Di Santo AR, Gioia A (2015) Rationale for flood prediction in karst endorheic areas. *J Arid Environ* 112:98–108
- Jiménez-Madrid A, Carrasco-Cantos F, Martínez-Navarrete C (2012) Protection of groundwater intended for human consumption: a proposed methodology for defining safeguard zones. *Environ Earth Sci* 65:2391–2406
- Katz BG, Griffin DW, Davis JH (2009) Groundwater quality impacts from the land application of treated municipal wastewater in a large karstic spring basin: chemical and microbiological indicators. *Sci Total Environ* 407:2872–2886
- Kemmerly P (1981) The need for recognition and implementation of a sinkhole-floodplain hazard designation in urban karst terrains. *Environ Geol* 3:281–292
- Ladisa G, Todorovic M, Trisorio Liuzzi G (2012) A GIS-based approach for desertification risk assessment in Apulia region, SE Italy. *Phys Chem Earth* 49:103–113
- Laviola S, Moscatello A, Miglietta MM, Cattani E, Levizzani V (2011) Satellite and numerical model investigation of two heavy rain events over the central Mediterranean. *J Hydrometeorol* 12:634–649
- Lugoli F, Leopizzi MI, Bagordo F, Grassi T, Guidi M, De Donno A (2011) Widespread microbiological groundwater contamination in the south-eastern Salento (Puglia-Italy). *J Environ Monit* 13:192–200
- Magal E, Arbel Y, Caspi S, Glazman H, Greenbaum N, Yechieli Y (2013) Determination of pollution and recovery time of karst springs, an example from a carbonate aquifer in Israel. *J Contam Hydrol* 145:26–36
- Marin LE, Steinich B, Pacheco J, Escolaro OA (2000) Hydrogeology of contaminated sole-source karst aquifer, Merida, Yucatan, Mexico. *Geofis Int* 39(4):359–365
- Martínez-Navarrete C, Jiménez-Madrid A, Sánchez-Navarro I, Carrasco-Cantos F, Moreno-Merino L (2011) Conceptual framework for protecting groundwater quality. *Int J Water Resour Dev* 27:227–243
- Masciopinto C (2006) Simulation of coastal groundwater remediation: the case of Nardò fractured aquifer in Southern Italy. *Environ Model Softw* 21:85–97
- Masciopinto C, Carrieri C (2002) Assessment of water quality after 10 years of reclaimed water injection: the Nardò fractured aquifer (Southern Italy). *Ground Water Monit Remediat Winter* 88:88–97
- Masciopinto C, La Mantia R, Jatta E, Calvario A (2004) Rischio di contaminazione patogena per approvvigionamenti domestici da pozzi nel Salento. *L'acqua* 5:41–50 (in Italian)
- Masciopinto C, Semeraro F, La Mantia R, Inguscio S, Rossi E (2006) Stygofauna abundance and distribution in the fissures and caves of the Nardò (Southern Italy) fractured aquifer subject to reclaimed water injections. *Geomicrobiol J* 23:1–12
- McCann DW (1983) The enhanced-V: a satellite observable severe storm signature. *Mon Weather Rev* 111:887–894
- Mijatovic BF (1988) Catastrophic flood in the Polje of Cetinje in February 1986, a typical example of the environmental impact of karst. *Environ Geol Water Sci* 12(2):117–121
- Milanovic P (2002) The environmental impacts of human activities and engineering constructions in karst regions. *Episodes* 25(1):13–21
- Morasch B (2013) Occurrence and dynamics of micropollutants in a karst aquifer. *Environ Pollut* 173:133–137
- Morch H (1978) Location of rural settlements and geology, a case study of the Salento peninsula (Southern Italy). *Geogr Tidsskr* 87:42–49
- Page D, Dillon P, Vanderzalm J, Toze S, Sidhu J, Barry K, Levett K, Kremer S, Regel R (2010) Risk assessment of aquifer storage transfer and recovery with urban stormwater for producing water of a potable quality. *J Environ Qual* 39:2029–2039
- Polieri R, Barbieri V, Balice R, Lorusso D (2009) Sistema di monitoraggio quali-quantitativo dei corpi idrici sotterranei della Puglia. In: Atti 13a Conferenza Nazionale ASITA (in Italian)
- Provincia di Lecce (2006) Il piano comunale di protezione civile. Provincia di Lecce ed., Lecce (in Italian)
- Rahaman M, Varis O (2005) Integrated water resources management: evolution, prospects and future challenges. *Sustain Sci Pract Policy* 1(1):15–21
- Renken RA, Cunningham KJ, Zygnerski MR, Wacker MA, Shapiro AM, Harvey RW, Metge DW, Osborn CL, Ryan JN (2005) Assessing the vulnerability of a municipal well field to contamination in a karst aquifer. *Environ Eng Geosci* 11(4):319–331
- Scoccimarro E, Gualdi S, Bellucci A, Zampieri M, Navarra A (2013) Heavy precipitation events in a warmer climate: results from CMIP5 models. *J Clim* 26:7902–7911

- Semeraro T, Giannuzzi C, Beccarisi L, Aretano R, De Marco A, Pasimeni MR, Zurlini G, Petrosillo I (2015) A constructed treatment wetland as an opportunity to enhance biodiversity and ecosystem services. *Ecol Eng* 82:517–526
- Sicolo N (2006) Uso, riuso e sovrasfruttamento della risorsa acqua nel territorio salentino. *Geol Territ* 1–3:22–30 (**in Italian**)
- Tadolini T, Tulipano L (1981) The evolution of fresh-water/salt-water equilibrium in connection with withdrawals from coastal carbonate and karstic aquifer of the Salentine peninsula. *Geol Jb* 29:69–85
- Todd MC, Taylor RG, Osborn TJ, Kingston DG, Arnell NW, Gosling SN (2011) Uncertainty in climate change impacts on basin-scale freshwater resources—preface to the special issue: the QUEST-GSI methodology and synthesis of results. *Hydrol Earth Syst Sci* 15:1035–1046
- Toze S, Bekele E, Page D, Sidhu J, Shackleton M (2010) Use of static quantitative microbial risk assessment to determine pathogen risks in an unconfined carbonate aquifer used for managed aquifer recharge. *Water Res* 44:1038–1049
- Tulipano L (1988) Temperature logs interpretation for the identification of preferential flow pathway in the coastal carbonatic and karstic aquifer of the Salento peninsula (southern Italy). In: *Proceedings of IAH 21st Congress, Giulini*, vol 2, pp 956–961
- Tulipano L (2001) La progressiva salinizzazione delle acque sotterranee nell’acquifero carsico della Penisola Salentina. *Grotte e dintorni* 2:29–38 (**in Italian**)
- Ulbrich U, Lionello P, Belusic D et al (2012) Climate of the Mediterranean: synoptic patterns, temperature, precipitation, winds, and their extremes. In: Lionello P (ed) *The climate of the mediterranean region*. Elsevier, Amsterdam, pp 301–346
- Worthington AC (2014) A review of frontier approaches to efficiency and productivity measurement in urban water utilities. *Urban Water J* 11(1):55–73
- Younger PL, Teutsch G, Custodio E, Elliot T, Manzano M, Sauter M (2002) Assessments of the sensitivity to climate change of flow and natural water quality in four major carbonate aquifers of Europe. *Geol Soc Lond Spec Publ* 193:303–323
- Zhou W (2007) Drainage and flooding in karst terraines. *Environ Geol* 51:963–973