



Water management problems in a karst flood-prone endorheic basin

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Abstract

In this note, a case history of improper water management in an endorheic karst basin is described with specific reference to the effect of treated wastewater on the functioning of drainage receptors. The basin is the Asso Torrent basin (Apulia region, Italy), crossed by a dendritic channel system, tributary of a set of swallow holes. The discharge into the channels of effluents deriving from sewage treatment plants (STPs) was designed about 30 years ago to increase recharge for the main regional groundwater system, a deep karstic limestone aquifer subjected to seawater intrusion. However, during this time, number and magnitude of the flood events have increased, with repeated damages to urban and rural areas. Floods depend on several causes, whose identification has required hydrological–geomorphological study, the evaluation of runoff, and the assessment of the contaminant load of the STP effluents. The results of the runoff model suggest the inability to drain storm events even in absence of clogging phenomena. Four out of five STPs are undersized and, especially in summer, discharge larger amounts of suspended solids and nutrients, thus increasing the clogging of the swallow holes. In addition, increasing of intense rain events has exacerbated the problem. As a whole, such issues confirm the necessity to skip the old water paradigms based on the assumption of stationarity of the hydrologic variables (i.e., rainfall and rain intensity) and the building of centralized water infrastructures. Examining the site-specific issues, insights are gained that may help avoid unpleasant environmental consequences in similar hydro-geomorphological settings.

Keywords Water resources management (WRM) · Managed aquifer recharge (MAR) · Fracture clogging · Swallow holes · Flood hazard

Abbreviations

BOD Biochemical oxygen demand

CN Curve number

COD Chemical oxygen demand

d Per-capita supplied water

g_0 Initial potential infiltration capacity

g_c Asymptotic infiltration

$f(t)$ Infiltration capacity at time t

i Rainfall intensity

IDF Intensity–duration–frequency

k Horton infiltration

PC Plant capacity

Q Flow rate

R_A Runoff

R_B Net rainfall intensity

R_C Rainfall intensity

R_D Infiltration

SP Served population

t Rainfall duration; time

TCEV Two-component extreme value

TP Total phosphorus

TN Total nitrogen

TDS Total dissolved solids

TSS Total suspended solids

W Runoff volume

W_{up} Upstream overflow volume

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Introduction

Water Resources Management (WRM) in karst regions has long been discussed in the literature, due to environmental hazards such as the flood proneness and the sensitivity to pollution (Kemmerly 1981; Mijatovic 1988; Bonacci 2004; Zhou 2007). Moreover, the climate change vulnerability as well as the aquifer recharge issues are nowadays considered main topics for karst environments (Butscher and Huggenberger 2009; Katz et al. 2009; Daher et al. 2011; Ekmekci and Tezcan 2011).

Managed Aquifer Recharge (MAR) deploying treated wastewater, even mixed with rainwater, is a widespread and accepted practice, aiming at increasing groundwater resources (Levine and Asano 2004; Bixio et al. 2008; Drewes 2009; Katz et al. 2009; Scanlon et al. 2016). MAR is frequently implemented in arid and semi-arid zones where saltwater intrusion and soil desertification may occur, and is now considered essential for proper WRM (Georgopoulou et al. 2001; Gale 2005; Daher et al. 2011). Environmental and health problems have been experienced in the many countries where MAR with treated wastewater has been carried out for decades, orienting management authorities toward the release of specific guidelines (NRMMC-EPHC-AHMC 2008; USEPA 2012; EC-JRC 2014). However, hydrological problems also frequently affect the MAR systems. Clogging of infiltration wells and trenches in vadose zones (Bouwer 2002) is an issue of major concern as it can lead to undesirable consequences (Pérez-Paracio and Carrera 1999; Arnon et al. 2005; Song and Liu 2013; Yoo et al. 2013; Chen et al. 2014). The reduction of the permeability of either the filters of the underground structures or the rock pores and fractures may cause the malfunctioning of the surface drainage networks in addition to the reduction of the recharge rate.

Clogging phenomena are the result of interaction between chemical, physical, mechanical, and biological processes (Martin 2013). Quantitative models are available for the prediction of the evolution of clogging in porous media (Blazewski and Murat-Blazewska 1997; Pérez-Paracio and Carrera 1999; Mays and Hunt 2005; Skolasinska 2006). Fewer contributions concern fractured rocks (Chrysikopoulos and Abdel-Salam 1997; Ross et al. 2001; Chrysikopoulos et al. 2010) and they are not resolute because the mechanisms governing the adhesion of organic and inorganic particles to fractured walls are still unclear (Arnon et al. 2005). The quantitative prediction is currently impracticable, in consideration of the difficulty in providing adequate geometrical models of the fracture network. In fractured rocks and especially in karst systems, few discrete features may control the major part of the infiltration in the vadose zone. Consequently, water circulation may be limited even if relatively

few fractures and conduits are clogged, specifically those of the near-field networks (epikarst) around infiltration structures as well as natural swallow holes¹ that commonly constitute the final receptors of endorheic basins (Mijatovic 1988; Hart 2006; Chrysikopoulos et al. 2010).

In the seasonally-arid Salento Peninsula (Lecce Province, Apulia Region, Southern Italy), the deep karstic-limestone aquifer, which provides 75% of the local water supply, is subjected to saltwater intrusion. Thus, the water available for domestic and agricultural uses has a relatively high salt content (Tadolini and Tulipano 1981) and MAR systems may be used to counteract the salinization of the groundwater. However, the swallow holes of these systems may malfunction from clogging. Thus, WRM problems arise, like for the case of the endorheic Asso Torrent basin, south-west in the peninsula, where the main receptor, a swallow hole named Vora Colucce, provides a reduced discharge capacity. As in other karst catchments (Currens and Graham 1993; Bayless et al. 1995; Milanovic 2002), this main receptor can be utilized for aquifer recharge, as well as runoff regulation and urban defense from intense precipitation (Delle Rose and Fidelibus 2016). In such situations, clogging may lead to increases number and magnitude of the flood events.

The case of Vora Colucce and the Asso Torrent basin is documented because it is representative of the concerns occurring in contexts having hydrological analogies specifically with reference to swallow holes used as receptor of MAR systems. The effect of insufficient wastewater treatment on clogging and the flood hazard are hypothesized to evaluate WRM problems in karst basins. Other issues, such as MAR efficiency, saltwater intrusion, and flood hazards, are also considered because of their relationships with WRM. Examining these site-specific issues, insights are gained that might help avoid unpleasant environmental consequences in similar hydro-geomorphological contexts.

In what follows, the case study and the used methods are shown. In detail, the geological and the hydrological features of the catchment basin and the hydro-geomorphological features of Vora Colucce are reported. The hydrologic model for the estimation of the runoff in the basin and the theoretical evaluation of the treated wastewater quality to deduce the potential amount of clogging material are described. This preliminary study addresses the possible causes of the hydrological disorder in the basin and the plans perspective to improve the WRM.

¹ Karst terminology according to USEPA (2002).



Fig. 1 Location of the Asso Torrent basin

Case study and methods

The Asso Torrent basin

The Asso Torrent is a dendritic network of natural and artificial channels, crossing several towns and agricultural areas located in the Lecce province of the Salento Peninsula (Fig. 1), and flowing toward six swallow holes, the greatest of them is Vora Colucce.²

These receptors are connected, through the vadose zone, to the regional deep karstic-limestone aquifer (Delle Rose and Fidelibus 2016). Due to the nature of karst, chemical and biological processes on the percolating water are limited and the deep aquifer is highly vulnerable to pollution. Salento is a warm temperate area with drought-prone summers (*Csa* climate type described by Peel et al. 2007—temperate dry-hot summer), mild-wet winters and about 650 mm of average annual rainfall (Zito et al. 1991; Martano et al. 2015). The area is responsive to climate variability, that can affect water resources, ecosystems, human activities, and health (Giorgi and Lionello 2008). Moreover, despite the moderate precipitation reported by historical records, most of Salento region has been recently classified as particularly prone to drought and desertification (Ladisa et al. 2012).

² Vora from Latin *vorare*, meaning “swallow,” or from Latin *gurgus*, “whirlpool”.

The catchment of the Asso Torrent lies within a graben (i.e., a large tectonic structure lowered by normal faults). Due to the very flat landscape, the watersheds are not clearly identifiable. The endorheic³ basin approximately extends 220 km². According to the regional basin authority (AdBP, *Autorità di Bacino della Puglia*), the basin area is 256 km², including also the area drained by an artificial sea channel (Fig. 2). Maximum and average elevations are 198 and 68 m, respectively, with an average slope of 2%. The main channel stretches for about 24 km in total.

The hydrographic system of the Asso Torrent basin is divided into three areas: upper, middle, and lower. The first has a clay-marl substrate (carbonate rocks outcrop close to the watershed) and slopes between 10 and 2%; the substrate of the second consists of limestone and calcarenites and slopes of around 2%; the lower has a calcarenitic substrate (partially covered by clay-marls) and slopes less than 2%. The channels of the upper area are natural, while those of the middle area are a series of hydraulic works, probably constructed by the Romans and later enlarged in the Middle Ages. Finally, the channels of the lower area (north of Nardò village, see Fig. 2) are artificial and built during reclamation works in the 1920s. As a whole, the works transformed the hydrographic system into a sort of centralized open-channel infrastructure, having the function to discharge underground the basin runoff.

Since 1991 the Asso Torrent is used for the disposal of treated wastewater from five sewage treatment plants (STPs) releasing a maximum estimated discharge of 0.2 m³/s (Masciopinto et al. 2012), and from a special treatment plant for industrial sewage. The treated wastewaters mixed with runoff recharge the deep aquifer through the set of swallow holes. The aquifer is used for irrigation by wells placed in the neighboring area (Delle Rose et al. 2000; Delle Rose 2007). This recharge is designed to reduce the seawater intrusion into the deep aquifer (Masciopinto et al. 2012); the system essentially conforms to the aquifer storage, transfer and recovery (ASTR) method of MAR (Dillon et al. 2009).

Severe meteorological events leading to floods have been reported recently for the Asso Torrent basin (Delle Rose and Fidelibus 2016). The first flood-defense works in the basin began in the late 1970s and consisted of a drainage channel flowing to the sea (sea channel in Fig. 2), diverting the Asso Torrent by means of a double sluice gate (G1 in Fig. 2, located north of Nardò). For this channel, the Asso Torrent appears as an exorheic⁴ hydrographic system. The channel should drain the strongest runoffs, but it has not provided the

³ Endorheic is a basin that normally retains runoff within the watershed.

⁴ It is the opposite of an endorheic drainage basin. In this case, runoff flows out of the watershed.

Fig. 2 Scheme of the Asso Torrent endorheic basin: the solid line delimits the basin, the dashed line includes the extension upon control of the basin authority and the dotted lines are the boundaries between upper, middle, and lower areas of the basin (upper at North). The sewage treatment plants are: 1, Neviano; 2, Aradeo; 3, Maglie; 4, Galatone; 5, Copertino

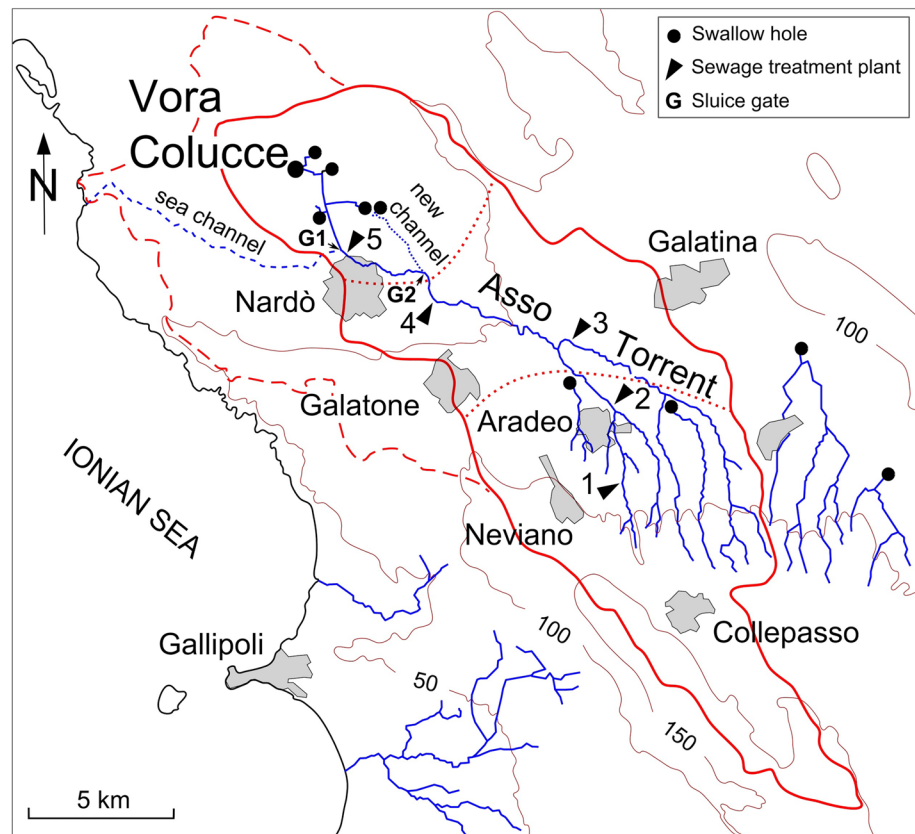


Table 1 Main floods since 1991; rain gauge stations of the regional weather service (Protezione Civile della Puglia): C, Collepasso; G, Galatina; N, Nardò (Delle Rose and Fidelibus 2016)

| Date | Damages | Rain gauges data (mm/day) |
|------------|---|----------------------------------|
| 03/11/1993 | Urban and rural flood; sewer-system spills; destruction of commercial goods | G 223.0; N 121.0; C 23.8 |
| 09/10/1996 | Rural flood | G 47.0; N 80.0; C 19.4 |
| 13/11/2004 | Urban flood; sewer-system spills | G 180.2; N 165.0; C ^a |
| 03/12/2008 | Rural flood | G 80.8; N 75.8; C 73.6 |
| 23/01/2009 | Rural flood | G 12.8; N 36.6; C 24.8 |
| 10/03/2010 | Urban and rural flood | G 53.2; N 34.2; C 90.6 |
| 02/11/2010 | Urban flood; sewer-system spills; flooding of basements and first floor building; destruction of commercial goods | G 4.2; N 178.8; C 2.2 |
| 31/10/2012 | Urban and rural flood; sewer-system spills | G 38.6; N 52.8; C 62.2 |

^aNot recorded by the station

flood protection of Nardò village. In fact, since the 1990s, floods of increased severity have occurred (Table 1), with peak discharges of around 30 m³/s with unpleasant consequences (Delle Rose 2007).

These events damaged local agricultural activities (Giordano et al. 2010) and roads, especially those close to Vora Colucce (Fig. 3).

To address the issues, the European Community Flood Directive (2007/60/CE) and Italian laws (*Decreto Legislativo* 49/2010) require the use of best practices and technologies

to identify areas exposed to floods. New flood defenses, consisting of a new channel (Fig. 2) and accessory works (settling tanks and clusters of injection wells), were designed by considering as input datum a maximum discharge of almost 200 m³/s for a return period of 200 years. The channel was partially completed in 2013; it acts as an overflow channel and is connected to a minor swallow hole with a discharge capacity of 2 m³/s, according to estimations of the local land reclaiming bureau (*Consorzio di Bonifica Arneo*). The channel flow is controlled by means of a sluice gate (G2 in



Fig. 3 The entrance of Vora Colucce; left: in dry condition at the end of a channel cleaning work (July 24, 2006); right: a flood event (December 4, 2008) resulting from an intense precipitation occurred the day before (see Table 1)

Fig. 2, located east of Nardò). Finally, as further supplementary hydraulic work, a small channel, branching out from a node close to Vora Colucce toward a dispersal tank and a small natural swallow hole, was built in 2014. In spite of these works, as a consequence of a moderate event of rain (6 March, 2015), a flood affected the rural area around the new channel, causing serious damages to the agricultural production.⁵

The Asso Torrent is currently a fully engineered hydrographic system. With the sluice gates G1 and G2 located between the main channel and the sea and between the main channel and the new channel, respectively (Fig. 2), the following options are available to the authorities: protection of the deep aquifer from seawater intrusion; protection of the groundwater quality; and prevention of urban flooding (Delle Rose and Fidelibus 2016). However, the WRM for the Asso Torrent basin remains difficult because the swallow holes (Fig. 2) are almost completely clogged or have very low discharge rates. An efficient WRM requires relating the hydraulic features of the basin to uncertainties of the precipitation for the next decades. For the Mediterranean areas, including Salento Peninsula, different scenarios have been advanced: a reduction of precipitation during summer (Hatzianastassiou et al. 2016) and even during winter (Somot et al. 2008); an increase of precipitation in summer (Palatella et al. 2010); an increase of extreme rain events coupled with a decrease of annual rainfall, as already occurred throughout the second half of the twentieth century (Alpert et al. 2002). Among these forecasts, damaging winter floods followed

by summer droughts would be the worst for the depletion of the local water resources. An efficient management system requires possible countermeasures for these various scenarios.

Geomorphological and hydrological features of Vora Colucce

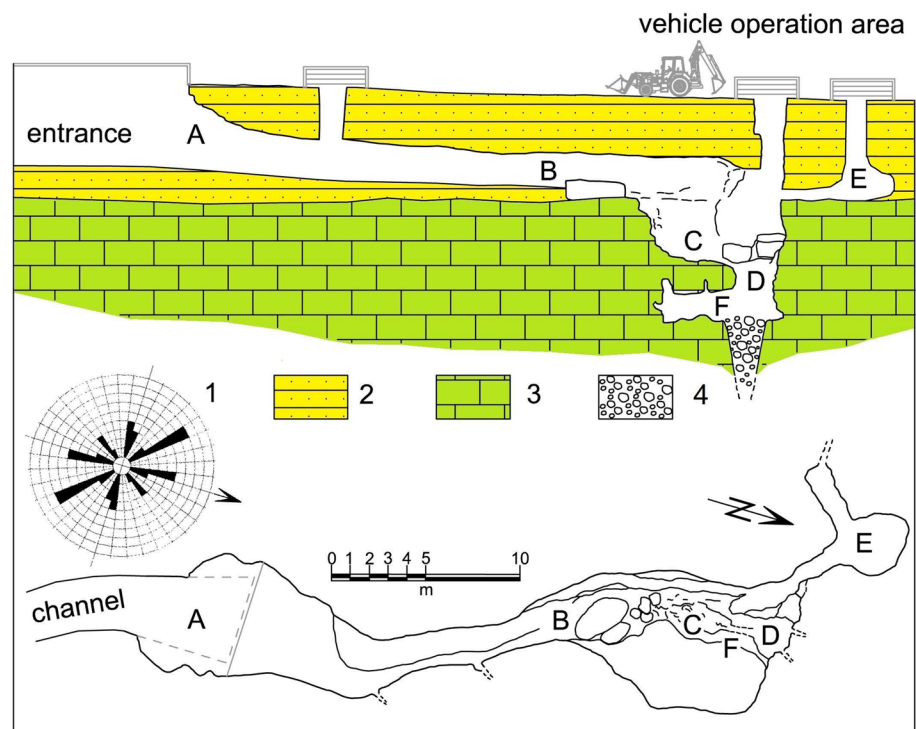
Hydraulic engineering has modified the natural shape of Vora Colucce, which is a collapse doline connected with a deeper underground set of cavities. To allow the removal of deposited sediments, during the reclamation works accomplished in the 1920s, three openings were bored in the ceiling of the cavities (Fig. 4). The volume of the swallow hole and cavities is about 850 m³. The level of the deep aquifer is about 30 m below Vora Colucce. Speleological explorations show that the cavity is connected to a rather dense network of fractures and karst conduits (the epikarst), whose hydraulic conductivity as a whole drastically decreases with depth in few meters, and to a vertically aligned karst system. The epikarst affects calcarenite bedrock up to 4–5 m below the surface, and the upper portion of the limestone basement (Fig. 4).

The discharge capacity through the mouth of Vora Colucce was estimated as 10 m³/s during the reclamation works executed in the first half of the twentieth century (Consorzio Bonifica Arneo 2012). The hydraulic functioning of this karst landform is currently conditioned by the effluents from the STPs that can lead to a physical and biological clogging. The Vora Colucce is now partially filled with sediments and only a limited amount of water may infiltrate.

Tectonic fractures in the near-field were sampled by means of measurements on the outcrop and cavities using a geological compass (Fig. 4). The shallow calcarenite

⁵ Rain data of the weather service are not available. The 6th of March, 2015, a private rain gauge station located at Galatone (see Fig. 2) measured 31.0 mm/day.

Fig. 4 Geological vertical section (above) and map (below) of Vora Colucce swallow hole. (1) frequency-weighted rose diagram of joint strikes; (2) calcarenite; (3) limestone basement; (4) detritus



shows four sub-vertical joint systems whose medial trends of dip direction measured from N to E are: 0, 45, 90, and 135 degrees, respectively. The limestone basement shows eight sub-vertical joint systems whose medial trends of dip direction are: 5, 35, 50, 80, 95, 125, 140, and 170 degrees, respectively. Another rock discontinuity is constituted by the sub-horizontal bedding planes. Over geological time, both the tectonic- and the sedimentary-discontinuity sets led to the development of a network of conduits and enlarged fractures that form the local epikarst. Despite of the acquisition of fracture data, the actual geometrical features of the epikarst around the swallow hole are unknown and a quantitative model for the clogging prediction is not available. The main element of the vertically aligned karst system of Vora Colucce is a large shaft whose mouth opens at the bottom of the hypogeum (cavity F, see Fig. 4). This shaft was already filled by high-permeable coarse-sized detritus when the first cave explorers reached it in the 1970s.

The first signals of malfunctioning of the swallow hole occurred in the late 1980s. In 1994, as a consequence of the 03 November 1993 flood event (Table 1), the land reclaiming bureau commissioned expert speleologists to clean the caverns. Plastic materials mixed with silty-sand detritus (a few cubic meters) were manually removed from the bottom of the hypogeum, together with tires, gas cylinders and other large objects (Fig. 5). A thin layer of brownish mud, containing stinky decomposing organic matter, covered the clogging deposits. The large objects and the plastic materials were probably dragged from urbanized areas in Vora

Colucce during heavy rains or manually deposited. After this first cleaning, a metal grill (see Fig. 3) was placed to avoid the littering of these objects. Since then, obstruction of the hole is due to muds only.

However, the discharge capacity of Vora Colucce progressively declined so that in 2000 the land reclaiming bureau commissioned the speleologists to perform a second cleaning. Due to the gas developed by decomposition of the organic matter,⁶ the mud of caverns D and F was only partially removed. The capacity of Vora Colucce to discharge the water of the Asso Torrent continued to decline during the 2010s. During the same period, an increase in flood events occurred (Table 1). The last cleaning, performed in 2008, required the use of clamshells, water jet pumps, and bulldozers (Fig. 5). Hundreds of cubic meters of organic brown mud were displaced from the caverns B, C, D, E, and F. Finally, speleologists manually removed the remaining sediments and attempted to wash fractures and conduits by means of hand-held water jets. However, the swallow hole is currently malfunctioning, despite the last cleaning (Fig. 5). Since the last cleaning, sediments have partially re-filled the cavities and the discharge declined again. Now it is about 1 m³/s (empirically estimated by observing the channel flow at the

⁶ Personal gas detectors revealed Hydrogen Sulphide emission.



Fig. 5 Cleaning works at Vora Colucce; left: temporary storage of the materials removed on 1994 from the interior of the cavity; right on top: the bottom of the deepest cavern (F in Fig. 4) before the start of

the 1994 works; right below: the 27th of August, 2008, a clamshell truck removed organic mud from an artificial well (vertical of cavern D, see Fig. 4)

hole entrance⁷) consistently less than the initial value of $10 \text{ m}^3/\text{s}$ of a century ago (Consorzio Bonifica Arneo 2012).

Basin runoff model

The Vora Colucce area currently undergoes frequent and damaging floods. Therefore, it is useful to evaluate the runoff of the basin. A Curve Number (CN) zonation of the basin is reported herein. CNs should encompass the contribution of land-use changes with time (Ferro 2006). The CN parameters CNI, CNII, and CNIII include the local lithology and the characteristics of both land use and agricultural practices. They range from 0 to 100 and are estimated for the analyzed basin, together with height, slope, surface, and length of main shaft (Mishra and Singh 2003). The CNII value for the Asso Basin is equal to 73. In karst endorheic areas, the use of Soil Conservation Service (SCS)-CN soil

classification (USDA 1972) for model parameterization is suggested to evaluate the surface flow rate. The SCS-CN method is not applicable (Iacobellis et al. 2015).

Precipitation is calculated in the basin using the VAPI Apulia method⁸ (Copertino and Fiorentino 1994), that is appropriate for the estimation of rainfall when specific data are sparse. VAPI is based on the definition of the distribution of the Two-Component Extreme Values (TCEVs, Rossi et al. 1984). It assumes that single rainfalls can be expressed as a mixture of two exponential components: the first one describing ordinary events (more frequent and less severe on average) and the second one referring to extraordinary extremes (more severe and less frequent). The method is used in the context of the Apulian territory and recommended by the regional basin authority (Autorità di Bacino della Puglia 2005).

⁷ This value is presumptive and is based on observations concerning both the opening of the gate and the flow through a grid that is put just upstream the mouth of Vora Colucce (see Fig. 3).

⁸ VAPI is the acronym of “VALutazione delle Piene in Italia” (assessment of flood flows in Italy), a project research funded by the Italian National Research Council.

Table 2 SCS groups and relative suggested values of g_0 , g_c , and k

| SCS group | g_0 (mm/h) | g_c (mm/h) | k (min) |
|-----------|--------------|--------------|-----------|
| A | 302.5 | 25.4 | 50 |
| B | 242 | 12.7 | 40 |
| C | 151.25 | 6.3 | 30 |
| D | 91.96 | 2.5 | 20 |

A soils with high potential infiltration (low runoff) after prolonged wetting

B s. w. moderate potential infiltration (moderate runoff)

C vs. w. low potential infiltration (moderate runoff)

D s. w. very low potential infiltration (high runoff)

The rainfall intensity–duration–frequency (IDF) curve is estimated by regional analysis of the annual maxima of rainfall intensity performed with the above-mentioned probabilistic model. In particular, the IDF curves with return period of 30, 200, and 500 years are the following:

$$i_{30} = 64.6t^{-0.799} \quad (1)$$

$$i_{200} = 97.6t^{-0.799} \quad (2)$$

$$i_{500} = 113.6t^{-0.799} \quad (3)$$

where i is the rainfall intensity [mm/h] and t is the rainfall duration [h].

The basin is discretized in sub-basins for the computation. The runoff per unit time, R_A [m^3/s], coincides with the net rainfall intensity, R_B [mm/h], multiplied by the sub-basin area. Intensity R_B is equal to $R_C - R_D$, where R_C is the rainfall intensity and R_D the infiltration evaluated by considering the effect of the swallow hole through discharge capacity. The runoff volume W [m^3] per each sub-basin derives from the integration of R_B in space and time, which is further increased by the upstream overflow volume W_{up} , when existent. For the long-term, a design hyetograph is used, by approximating R_C as uniform in space and time. The IDF for a fixed return period is used for the estimation of R_C . The infiltration capacity $g(t)$ is estimated by means of the equation of Horton (1940):

$$g(t) = g_c + (g_0 - g_c)e^{-(t/k)} \quad (4)$$

where g_0 is the potential infiltration capacity at time t_0 ; g_c is the asymptotic infiltration rate at infinite; and k is a coefficient. These parameters change with the location and are calibrated through local inspections of soil and land-use, or otherwise can be defined by referring to literature.

Herein, the data reported in a hydrological study of a conterminous basin (Iacobellis et al. 2015) are adopted. The basin is classified by the regional basin authority using groups A, B, C and D (USDA 1972) conforming to

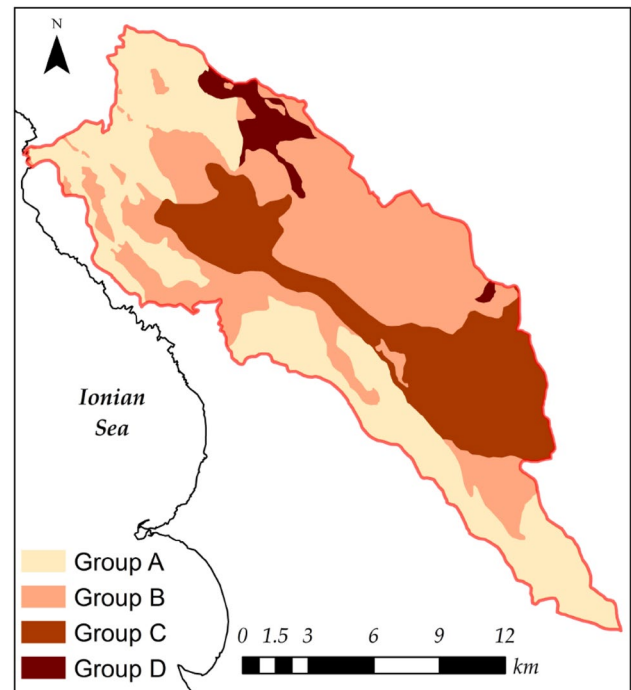


Fig. 6 Asso Torrent basin soil classification according to the regional basin authority map (cf. Fig. 2 for topographic reference points)

Table 3 Characteristics of the STPs extracted from the plan for water protection of the Apulia Region (Regione Puglia 2009)

| STP name | Served population (SP) ^a | Plant capacity (PC) ^a |
|-----------|-------------------------------------|----------------------------------|
| Galatone | 23,389 | 17,996 |
| Aradeo | 14,601 | 9755 |
| Neviano | 6596 | 7000 |
| Copertino | 69,019 | 68,173 |
| Maglie | 110,263 | 59,827 |

^aIn terms of population equivalent (PE)

the local geology and referring to the infiltration capacity of the bare soil in average soil moisture antecedent conditions. The description of the groups and the relative values of g_0 , g_c , and k are reported in Table 2.

The Asso basin is divided into four areas as shown in Fig. 6.

Evaluation of contaminant loads from the STPs

A preliminary evaluation of the clogging material in Vora Colucce by the effluents of the five STPs of the basin was carried out. The characteristics, in terms of served

Table 4 Daily BOD, COD, TSS, TN, and TP maximum amounts discharged in the Asso Torrent basin

| | SP (PE) | Q (m ³ /day) | BOD _{out} (kg/day) | COD _{out} (kg/day) | TSS _{out} (kg/day) | TN _{out} (kg/day) | TP _{out} (kg/day) |
|-----------|---------|---------------------------|-----------------------------|-----------------------------|-----------------------------|----------------------------|----------------------------|
| Galatone | | | | | | | |
| t | 17,996 | 4499 | 112 | 562 | 157 | 222 | 26 |
| u | 5393 | 1348 | 324 | 809 | 485 | 81 | 11 |
| Aradeo | | | | | | | |
| t | 9755 | 2439 | 61 | 305 | 85 | 120 | 14 |
| u | 4846 | 1212 | 291 | 727 | 436 | 73 | 10 |
| Neviano | | | | | | | |
| t | 6596 | 1649 | 41 | 206 | 58 | 81 | 10 |
| u | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Copertino | | | | | | | |
| t | 68,173 | 17,043 | 426 | 2130 | 596 | 839 | 100 |
| u | 846 | 212 | 51 | 127 | 76 | 13 | 2 |
| Maglie | | | | | | | |
| t | 59,827 | 14,957 | 374 | 1870 | 523 | 737 | 87 |
| u | 50,436 | 12,609 | 3026 | 7565 | 4539 | 757 | 101 |
| TOT | 223,868 | 55,967 | 4706 | 14,301 | 6957 | 2922 | 360 |

t. treated, u. untreated

population (SP) and plant capacity (PC) of the STPs, are given in Table 3.⁹

By the Italian law, these STP effluents should contain a maximum amount of TSS, BOD, COD, TN and TP equal to 25 mg/L, 20 mg/L, 100 mg/L, 15 mg/L, and 2 mg/L, respectively. Unfortunately, the STPs of the Asso Torrent basin are equipped with only primary and secondary treatment trains, thus there is no treatment for the abatement of TN and TP and the maximum amount of TSS, BOD, and COD in the effluents could reach values equal to 35 mg/L, 25 mg/L, and 125 mg/L, respectively. Moreover, four out of five STPs (Table 3) are undersized and during summer, when the population increases for the tourism, the wastewater production reaches maximum values. In these conditions, the effluents deriving from these STPs are rich in suspended solids and nutrients that constitute fertile environment for the formation of a biofilm around solid particles and at fractured walls in Vora Colucce.

The operative conditions of the undersized STPs can be schematized by dividing the influent flow into two parts. The first part, equal to the product of per-capita supplied water d and PC, is treated. The second part, calculated as the product of d and the difference between SP and PC, is directly delivered into the Asso Torrent without any treatment.

Results and discussion

Possible causes of the hydrological disorder

Given the type of sediments removed from the cavities of Vora Colucce during the above-mentioned cleaning works, the occurrence of a combination of physical and biological clogging phenomena is suggested. It is well recognized that bacteria may adhere to clayey particles, or other suspended solids which have a large surface area and high ion exchange capacity (Kang et al. 2013; Herrera et al. 2004; Huysman and Verstraete 1993). Once these suspended solids begin to clog the voids (pores or fractures), the occurrence of nutrients, such as nitrogen or phosphorus compounds, flowing through the medium, could generate optimal conditions for the growth of a biofilm that further closes the voids (Simpson 2008; Li et al. 2016). To this purpose, by considering the data reported in Table 3, i.e., an average d equal to 250 L/(PE day), and TSS, BOD, COD, TN, and TP discharge equal to 90 g/(PE day), 60 g/(PE day), 150 g/(PE day), 15 g/(PE day), and 2 g/(PE day) (Metcalf and Eddy 2003), respectively, the daily amount of each considered compound discharged in the Asso Torrent basin from the five STPs can be evaluated (Table 4).

The BOD, COD and TSS, amounts deriving from the treatment trains are approximately calculated by considering the maximum concentrations allowed by the Italian law (*Decreto Legislativo 152/2006*), whereas the TN and TP amounts are deduced from the consumption due to the metabolism of the activated sludges of the biological treatments. To this regard, 0.05 g of TN and 0.01 g of TP per

⁹ Data extracted from the Plan for Water Protection of the Apulia Region (*Piano di Tutela delle Acque*) drawn up by Regione Puglia (2009).

each gram of BOD removed have been considered (Metcalf and Eddy 2003). Finally, the daily amounts of BOD, COD, TSS, TN, and TP from the untreated aliquot are evaluated as the product of the difference SP-PC by the relative daily per-capita contaminant contributions.

This theoretical approach probably overestimates the contaminant content in the STP effluents and does not consider the self-purifying power of the river. Consequently, an annual monitoring campaign of BOD, COD, TSS, TN, and TP concentrations in Asso Torrent should be carried out to know the exact amount of contaminants daily reaching Vora Colucce. On the other hand, this evaluation is consistent with the clogging-induced reduction of the discharge capacity of Vora Colucce. In fact, in addition to the TSS, which probably settle along the torrent, the amounts of nitrogen and phosphorous discharged in the basin during the summer season could give rise to biological clogging. Microorganisms may adhere to sediments and fracture walls, forming a biofilm constituted by extracellular polymeric substances (EPS) in which they are embedded (Flemming and Wingender 2010). The reproduction of these colonies, and the consequent thickening of the biofilms, depends on the amount of nutrients in the wastewater. This phenomenon is well-known and even exploited for more than a century to remove nutrients and suspended solids in STPs where a porous bed (generally fine sand) keeps solids and allows the fixing of biofilms (Chaudhary et al. 2003). The accumulation of solids and the formation of a biofilm on the surfaces are the mechanisms promoting the progressive clogging of the pores and fractures that must be periodically cleaned (Bihan and Lessard 2000; Canler and Perret 1994), and can cause the biophysical clogging of the bottom shaft of Vora Colucce (Fig. 7). In addition, it is sufficient that few relatively crucial elements in the entire network of the epikarst are clogged to inhibit the fluid flow.

Consequently, the clogging of both the bottom shaft and the epikarst leads to the filling of the entire swallow hole, which happened between 1994 and 2008. It is apparent that, to decrease the proneness to clogging of Vora Colucce, the five STPs should undergo to upgrading works for enhancing the removal of nutrients. Indeed, by increasing the capacity of the STPs and adapting them to the Italian legislation, the maximum amount of contaminants, which can lead to clogging phenomena, daily discharged in Asso Torrent basin would be reduced by almost 70% (Table 5).

In addition, to avoid the intake and subsequent removal of the coarse materials (e.g., tires and gas cylinders), shown in Fig. 5, entrance of Vora Colucce should be protected with wide-mesh grates.

The above considerations may be extended to the minor swallow holes of the hydrographic system (Fig. 2).

The combination of a lower number of rainy days per year with a higher amount of precipitation per rainy day

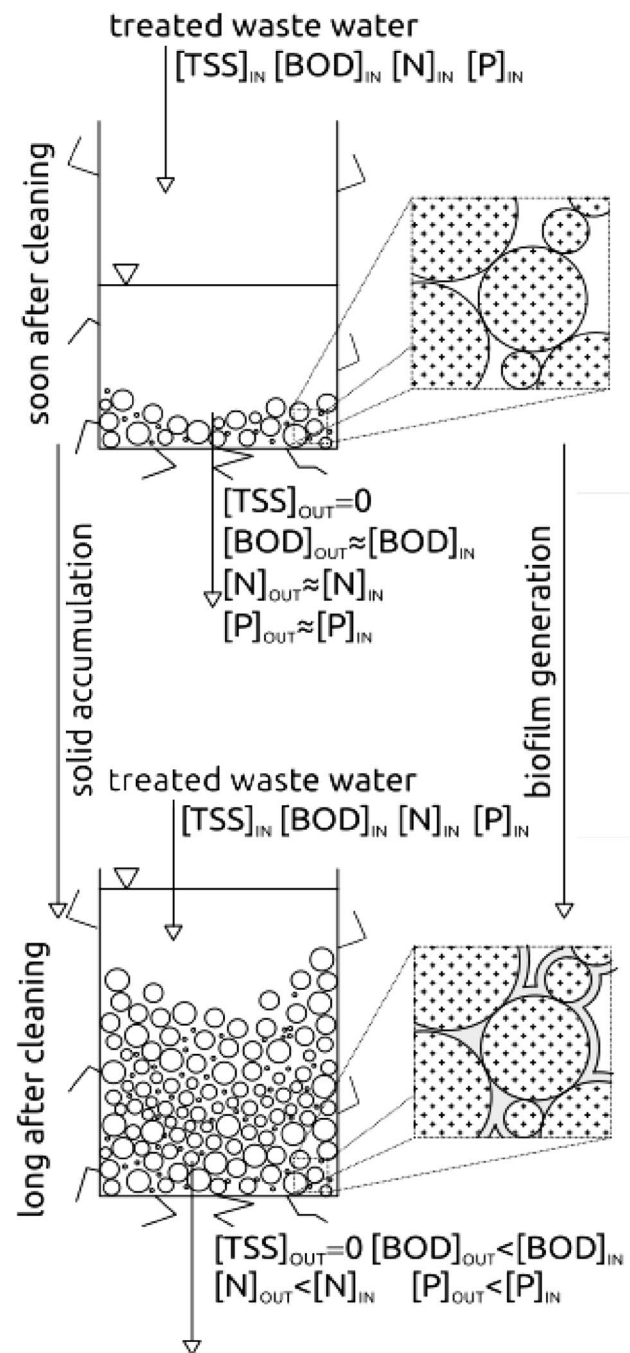


Fig. 7 Bio-physical clogging mechanism in Vora Colucce

(Alpert et al. 2002; Brunetti et al. 2006) resulted in an increase of the floods, the largest causing significant damages (Table 1). It is worth to note that, in spite of the 2013 hydraulic engineerings, the basin authority has recently

Table 5 Daily BOD, COD, TSS, TN, and TP maximum amounts discharged in the Asso Torrent basin after the STPs upgrading works

| | BOD _{out} | COD _{out} | TSS _{out} | TN _{out} | TP _{out} |
|---|--------------------|--------------------|--------------------|-------------------|-------------------|
| Maximum daily discharge (kg/day) | 1119 | 5597 | 1399 | 840 | 112 |
| Percentage reduction with respect to the actual situation (%) | 76 | 61 | 80 | 71 | 70 |

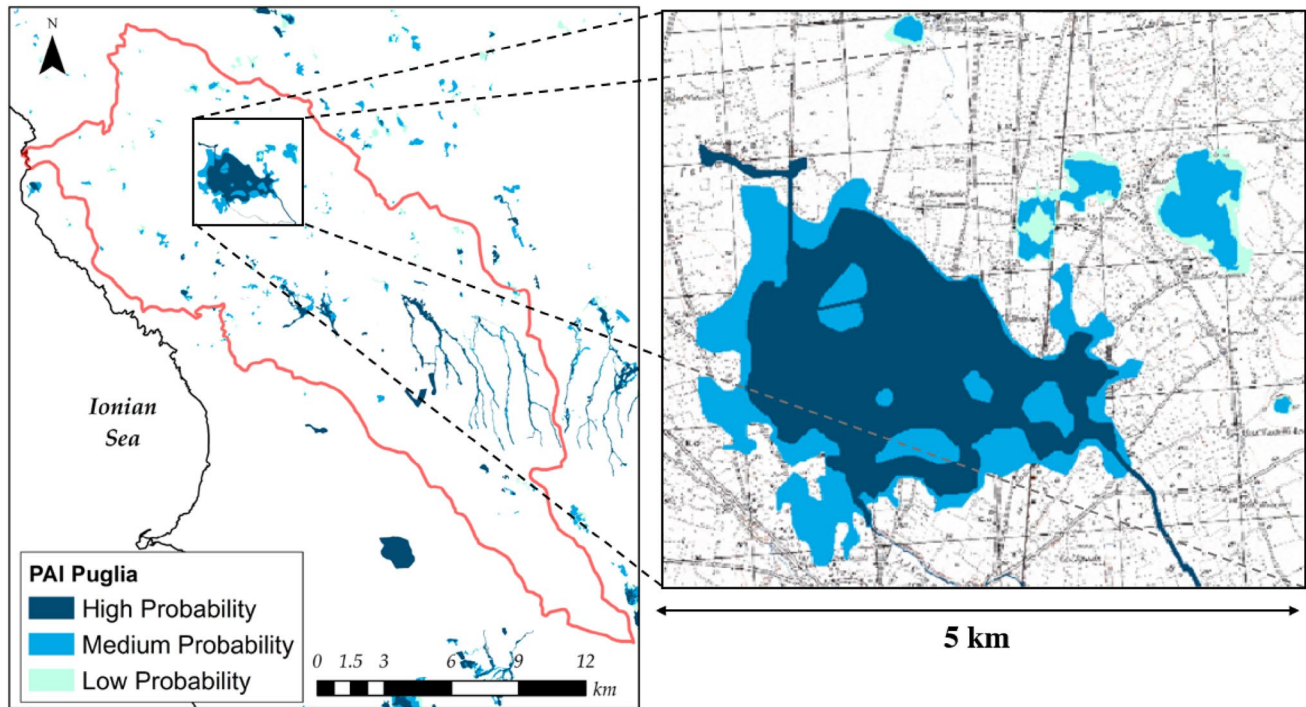


Fig. 8 Flood probability according to the regional basin authority; left: in the whole Asso basin (cf. Fig. 2 for topographic reference points); right: in the area between Vora Colucce and Nardò

Table 6 Flood volume for different return periods

| Return time (years) | Net rainfall (mm) | Flood volume (10 ⁶ m ³) |
|---------------------|-------------------|--|
| 30 | 106.3 | 0.78 |
| 200 | 139.9 | 3.40 |
| 500 | 187.0 | 4.87 |

defined the area between Nardò and Vora Colucce as affected by a high flood probability¹⁰ (Fig. 8).

As shown in Fig. 8, the new channel has moved the flooding hazard from the town to the rural area. Moreover, Vora Colucce would be insufficient to drain stormwater even in

absence of clogging phenomena. The results, obtained using the runoff model (Table 6) for three different return periods, show flood volumes higher than the discharge capacity of 10 m³/s. In particular, for a rainfall characterized by a return time of 200 years, a peak rate of 160 m³/s can be estimated, one order of magnitude larger than the maximum discharge.

On these bases, in absence of clogging phenomena, Vora Colucce maximum discharge corresponds to a rainfall characterized by return time of only 10 years. Consequently, in addition to the STPs upgrading works, some hydraulic works, such as filter ditches and dry wells, should be carried out to reduce the flood hazard even for high return times.

WRM plan perspective

To ensure the balance between water supply and demand, while minimising the impact on the local environment, efficient WRM plans should be compiled. Long-term balance forecast of water supply is affected by large uncertainties concerning population growth, urbanization, and climate

¹⁰ The basin authority periodically upgrades the regional Hydrogeological Management Plan (Piano di Assetto Idrogeologico della Puglia, in Italian). Figure 8 belongs to the 2017 upgrade.

change (Hartmann et al. 2014; Roach et al. 2018). These uncertainties hold also for the Salento Peninsula where, as previously reported, about 75% of the local water demand is currently met by exploitation of the deep aquifer that has been subjected to a salinization for several decades. During the same time, the population of the Salento Peninsula has considerably increased. The data of the Italian Institute of Statistics (ISTAT) show a growth of 22.5% in the Lecce Province between 1951 and 1991, remaining stable since then. The total plant capacity of the STPs discharging in the Asso Torrent corresponds to the 72.5% of the served population (Table 3). Upgraded design for STPs discharging into the Asso Torrent must consider the current deficit as well as the forecasts of population growth.

Throughout the second half of the twentieth century, additional infrastructures, designed by assuming the stationarity of hydrologic variables, were executed (Delle Rose and Fidelibus 2016). Now, a change in paradigm is required (Kundzewicz et al. 2008; Milly et al. 2008). By considering the basin hydro-geomorphological features, the construction of decentralized stormwater infrastructures (especially rainwater harvesting systems) may constitute an efficient environmental policy tool to reduce the runoff toward the swallow holes. Moreover, sustainable practices, such as restoration of old rooftop harvesting (abandoned tens of years ago in favor of centralized systems) are suggested. Besides the reduction of the hydrological disorder, these practices would also allow limiting the demand of water supply, thus reducing the deep aquifer exploitation and, finally, the seawater intrusion.

The efficiency of the recharge systems in any coastal aquifer must be evaluated by considering the consequent reduction of the salinization process (Daher et al. 2011; Mekni and Souissi 2016). According to the value of Total Dissolved Solids (TDS), detected in the deep aquifer at – 5 m below the sea level (Fidelibus et al. 2002), it may be stated that the MAR system has produced a containment of the seawater intrusion limited to the surroundings of Vora Colucce. However, the actual efficiency of MAR to favor the increase of groundwater availability should be evaluated at a regional scale. Unfortunately, literature data on this issue are little and source of conflicting interpretations. The case of the karst Floridan aquifer is emblematic, the recovery evaluation ranging from 25 (Bacchus et al. 2015) to 100% (USACOE 2014). Moreover, appropriate assessments of the effectiveness of MAR systems must be carried out with a multidisciplinary approach, considering also the social costs. In fact, at Voce Colucce, the water infiltrated through the swallow hole contains significant amount of enteric viruses, nitrates and ammonia (Delle Rose 2007). More recently, also the occurrence of pharmaceuticals and disinfection by-products has been noticed (Masciopinto et al. 2012). However, the social cost of diseases caused by the use in agriculture of

groundwater pumped around Vora Colucce from the deep aquifer has not been assessed yet.

Conclusions

The water management problems in the Asso Torrent basin include: (1) the almost total clogging of drainage receptors, (2) the occurrence of destructive floods, (3) the current high flood probability in rural area, (4) the limited counteraction of the salinization process in the deep aquifer and (5) the potential danger in agricultural uses of groundwater exploited from wells close to the swallow holes. Such issues confirm the necessity to refuse the old water paradigms based on the assumption of stationarity of the hydrologic variables and the building of centralized water infrastructures.

Examining the site-specific issues, some insights are gained that should be considered to avoid unpleasant environmental consequences in similar hydro-geomorphological contexts and especially in karst endorheic basins. For a correct management of the groundwater recharge and safety of the population, when treated wastewater and rainwater are discharged in swallow holes, several features must be considered. Sewage treatment plants must be correctly sized to match the served population and conform to regulatory limits, to the purpose of avoiding contamination of the groundwater reservoir and reducing the physical and biological phenomena occurring in drainage receptors. By adapting the STPs to the Italian Law, a reduction of the clogging phenomena due to biological processes could be obtained. In basins where water runoff is not externally drained, the reduction of clogging processes is even more stringent, given the increasing flood hazard in the zones close to the drainage receptors. In case of modified systems aimed at increasing the drainage toward the swallow holes, particular care must be given to both the discharge capacity and the runoff peaks to minimize the effects of floods.

The uncertainties about climate change, population growth, and urbanization are challenges for water researchers and managers. The design of engineering and hydraulic structures should be such as to exploit heavy rains to increase the groundwater availability. The principle of stationarity in hydrologic variables must be used with caution or abandoned. Additionally, the paradigm of a centralized infrastructure requires an upgrade. For a sustainable and adaptive perspective, the spreading of decentralized infrastructures at pinpointed areas of the endorheic basins might reduce the demand for water supply as well as the total runoff, thus allowing the decrease of the discharge capacity of drainage receptors for limiting the damages caused by floods. However, where favorable hydrogeologic and climate conditions occur, an increase

of intense precipitation may constitute a chance to augment groundwater resources. In coastal aquifers in arid and semi-arid environment, an important goal is containment of seawater intrusion. The need for a multidisciplinary approach seems mandatory and must combine water resources' protection with wastewater handling and flood defence.

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References

- Alpert P, Ben-Gai T, Baharad A, Benjamini Y, Yekutieli D, Colacino M, Diodato L, Ramis C, Homar V, Romero R, Michaelides S, Manes A (2002) The paradoxical increase of Mediterranean extreme daily rainfall in spite of decrease in total values. *Geophys Res Lett* 29(10):31,1–4
- Arnon S, Adar E, Ronen Z, Yakirevich A, Nativ R (2005) Impact of microbial activity on the hydraulic properties of fractured chalk. *J Contam Hydrol* 76:315–336
- Autorità di Bacino della Puglia (2005) Piano Stralcio di Assetto Idrogeologico (PAI). <http://www.adb.puglia.it>. Accessed 18 June 2018 (in Italian)
- Bacchus ST, Bernardes S, Xu W, Madden M (2015) Fractures as preferential flow paths for Aquifer Storage and Recovery (ASR) injections and withdrawals: implications for environmentally sensitive near-shore waters, wetlands of the greater Everglades Basin and the regional karst Floridan aquifer system. *J Geogr Geol* 7(2):117–155
- 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. <https://pubs.er.usgs.gov/publication/fs21195>. Accessed 16 June 2018
- Bihan YL, Lessard P (2000) Monitoring biofilter clogging: biochemical characteristics of the biomass. *Water Res* 34(17):4284–4294
- Bixio D, Thoeue C, Wintgens T, Ravazzini A, Miska V, Muston M, Chikurel H, Aharoni A, Joksimovic D, Melin T (2008) Water reclamation and reuse: implementation and management issues. *Desalination* 218:13–23
- Blazejewski R, Murat-Blazejewska S (1997) Soil clogging phenomena in constructed wetlands with subsurface flow. *Water Sci Technol* 35(5):183–188
- Bonacci O (2004) Hazards caused by natural and anthropogenic changes of catchment area in karst. *Nat Hazards Earth Syst Sci* 4:655–661
- Bouwer H (2002) Artificial recharge of groundwater: hydrogeology and engineering. *Hydrogeol J* 10(1):121–142
- Brunetti M, Maugeri M, Nanni T (2006) Trends of the daily intensity of precipitation in Italy and teleconnections. *Il Nuovo Cimento* 29:105–116
- Butscher C, Huggenberger P (2009) Modeling the temporal variability of karst groundwater vulnerability with implications for climate change. *Environ Sci Technol* 43:1665–1669
- Canler JP, Perret JM (1994) Biological aerated filters: assessment of the process based on the sewage treatment plants. *Water Sci Technol* 29:13–22
- Chaudhary DS, Vigneswaran S, Ngo HH, Shim WG, Moon H (2003) Biofilter in water and wastewater treatment. *Korean J Chem Eng* 20(6):1054–1065
- Chen X, Zhao Y, Chen L (2014) Experimental and numerical investigation of preferential flow in fractured network with clogging process. *Math Probl Eng* 2014:879189
- Chrysikopoulos CV, Abdel-Salam A (1997) Modeling colloid transport and deposition in saturated fractures. *Colloids Surf A Physicochem Eng Aspects* 121:189–202
- Chrysikopoulos CV, Masciopinto C, La Mantia R, Manariotis ID (2010) Removal of biocolloids suspended in reclaimed wastewater by injection into a fractured aquifer model. *Environ Sci Technol* 44:971–977
- Consorzio Bonifica Arneo (2012) Intervento per la mitigazione del rischio idraulico all'abitato di Nardò. Progetto esecutivo (unpublished works) (in Italian)
- Copertino VA, Fiorentino M (1994) Valutazione delle piene in Puglia. Tipolitografia La Modernissima. Lamezia Terme, Italy (in Italian)
- Currens JC, Graham DR (1993) Flooding of the sinking creek karst area in Jessamine and Woodford counties, Kentucky. Report of investigations 7. Kentucky Geological Survey, USA
- Daher W, Pistre S, Kneppers A, Bakalowicz M, Najem W (2011) Karst and artificial recharge, theoretical and practical problems: a preliminary approach to artificial recharge assessment. *J Hydrol* 408(3):189–202
- Delle Rose M (2007) Valutazione dei rischi di allagamento per incremento degli eventi meteorici estremi in bacini endoreici della Puglia centro-meridionale. *Geologi e Territorio* 3–4:49–60 (in Italian)
- Delle Rose M, Fidelibus C (2016) Water resource management in karstic catchments: the case of the Asso Torrent basin (Southern Italy). *Environ Earth Sci* 75:892
- 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, UK, pp 465–475
- Dillon P, Pavelic P, Page D, Beringen H, Ward J (2009) Managed aquifer recharge: an introduction. Waterlines Report Series 13, Government National Water Commission, Canberra, Australia
- Drewes JE (2009) Groundwater replenishment with recycled water: water quality improvements during managed aquifer recharge. *Groundwater* 47(4):502–505
- EC-JRC (2014) Water reuse in Europe, relevant guidelines, needs for and barriers to innovation. Report of Joint Research Centre, Institute for Environment and Sustainability, European Union, Luxembourg
- Ekmekci M, Tezcan L (2011) Management of karst aquifers under climate change: implications for sustainable use. In: Baba A, Tayfur G, Gündüz O, Howard K, Friedel M, Chambel A (eds) Climate change and its effects on water resources. NATO Science for Peace and Security Series C: Environmental Security, vol 3, pp 77–75
- Ferro V (2006) La sistemazione dei bacini idrografici. McGraw-Hill, Milano (in Italian)
- Fidelibus MD, Spizzico M, Tulipano L (2002) ²²²Rn activity in a karst coastal aquifer under active seawater intrusion. In: Proceeding of the 17th Salt Water Intrusion Meeting, Delft, the Netherlands, pp 262–272
- Flemming HC, Wingender J (2010) The biofilm matrix. *Nat Rev Microbiol* 8:623–633
- Gale I (2005) Strategies for managed aquifer recharge in semi-arid areas. UNESCO's International Hydrological Programme 2005, p 32
- Georgopoulou E, Lotronaou A, Koussis A, Restepo PJ, Gomez-Gotor A, Rodriguez Jimenez JJ (2001) A methodology to investigate

- brackish groundwater desalination coupled with aquifer recharge by treated wastewater as an alternative strategy for water supply in mediterranean areas. *Desalination* 36:307–315
- Giordano R, Milella P, Portoghese I, Vurro M, Apollonio C, D'Agostino D, Lamaddalena N, Scardigno A, Piccinni A (2010) An innovative monitoring system for sustainable management of groundwater resources: objectives, stakeholder acceptability and implementation strategy. In: *Proceedings of environmental energy and structural monitoring systems (EESMS), IEEE Workshop, Taranto, Italy*, pp 32–37
- Giorgi F, Lionello P (2008) Climate change projections for the Mediterranean region. *Global Planet Change* 63:90–104
- Hart EA (2006) Land use change and sinkhole flooding in Cookeville. *Tennessee Southeast Geogr* 46(1):35–50
- Hartmann A, Goldscheider N, Wagener T, Lange J, Weiler M (2014) Karst water resources in a changing world: review of hydrological modeling approaches. *Rev Geophys* 52:218–242
- Hatzianastassiou N, Papadimas CD, Lolis CJ, Bartzokas A, Levizzani V, Pnevmatikosa JD, Katsoulisa BD (2016) Spatial and temporal variability of precipitation over the Mediterranean Basin based on 32-year satellite global precipitation climatology project data, Part II: inter-annual variability and trends. *Int J Climatol* 35:4741–4754
- Herrera P, Burghardt R, Huebner HJ, Phillips TD (2004) The efficacy of sand-immobilized organoclays as filtration bed materials for bacteria. *Food Microbiol* 21:1–10
- Horton RE (1940) An approach toward a physical interpretation of infiltration capacity. *Soil Sci Soc Am J* 5:399–417
- Huysman F, Verstraete W (1993) Water-facilitated transport of bacteria in unsaturated soil columns: influence of cell surface hydrophobicity and soil properties. *Soil Biol Biochem* 25:83–90
- Iacobellis V, Castorani A, Di Santo AR, Gioia A (2015) Rationale for flood prediction in karst endorheic areas. *J Arid Environ* 112:98–108
- Kang JK, Lee CG, Park JA, Kim SB, Choi NC, Park SJ (2013) Adhesion of bacteria to pyrophyllite clay in aqueous solution. *Environ Technol* 34(6):703–710
- 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(8):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
- Kundzewicz ZW, Mata LJ, Arnell NW, Döll P, Jimenez B, Miller K, Oki T, Şen Z, Shiklomanov I (2008) The implications of projected climate change for freshwater resources and their management. *Hydrolog Sci J* 53(1):3–10
- 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
- Levine AD, Asano T (2004) Recovering sustainable water from wastewater. *Environ Sci Technol* 38:201A
- Li Q, Sand W, Zhang R (2016) Enhancement of biofilm formation on pyrite by sulfobacillus thermosulfidooxidans. *Minerals* 6(3):71–80
- Martano P, Elefante C, Grasso F (2015) Ten years water and energy surface balance from the CNR-ISAC micrometeorological station in Salento peninsula (southern Italy). *Adv Sci Res* 12:121–125
- Martin R (2013) Clogging issues associated with managed aquifer recharge methods. *IAH Commission on Managing Aquifer Recharge*, Australia
- Masciopinto C, La Mantia R, Pollice A, Laera G (2012) Managed aquifer recharge of a karstic aquifer in Nardò, Italy. In: Kazner C, Wintgens T, Dillon P (eds) *Water reclamation technologies for safe managed aquifer recharge*. IWA Publishing, London, pp 47–66
- Mays DC, Hunt JR (2005) Hydrodynamic aspects of particle clogging in porous media. *Environ Sci Technol* 39:577–584
- Mekni A, Souissi A (2016) The effectiveness of artificial recharge by treated wastewater in combating seawater intrusion—the case study of Korba-El Mida aquifer (Cape Bon, Tunisia). *Int J Innovation Appl Stud* 15(2):264–274
- Metcalfe E, Eddy M (2013) *Wastewater engineering: treatment and reuse*, 5th edn. McGraw-Hill, Boston
- 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
- Milly PCD, Betancourt J, Falkenmark M, Hirsch RM, Kundzewicz ZW, Lettenmaier DP, Stouffer RJ (2008) Stationary is dead: whither water management? *Science* 319:573–574
- Mishra SK, Singh V (2003) *Soil conservation service curve number (SCS-CN) methodology*. Springer, The Netherlands
- NRMCC-EPHC-AHMC (2008) Australian guidelines for water recycling: managing health and environmental risks, Phase 2: Augmentation of water drinking supply. *Natural Resource Management Ministerial Council, Environment Protection and Heritage Council, Australian Health Ministers' Conference*, Canberra, Australia
- Palatella L, Miglietta MM, Paradisi P, Lionello P (2010) Climate change assessment for Mediterranean agricultural areas by statistical downscaling. *Nat Hazards Earth Syst Sci* 10:1647–1661
- Peel MC, Finlayson BL, McMahon TA (2007) Updated world map of the Köppen-Geiger climate classification. *Hydrol Earth Syst Sci* 11:1633–1644
- Pérez-Paracio A, Carrera J (1999) Validity and sensitivity analysis of a new comprehensive clogging model. In: *Proceedings of the ModelCARE99 Conference*, Zurich, 1999, IAHS publ. n. 265, pp 47–53
- Regione Puglia (2009) Piano di tutela delle acque, DGR 230/2009. <http://old.regione.puglia.it/index.php?page=documenti&opz=getdoc&id=29>. Accessed 18 June 2018 (in Italian)
- Roach T, Kapelan Z, Ledbetter R (2018) A resilience-based methodology for improved water resources adaptation planning under deep uncertainty with real world application. *Water Res Manage* 32:2013–2031
- Ross N, Villemur R, Deschenes L, Samson R (2001) Clogging of a limestone fractured by stimulating groundwater microbes. *Water Res* 35(8):2029–2037
- Rossi F, Fiorentino M, Versace P (1984) Two-component extreme value distribution for flood frequency analysis. *Water Resour Res* 20(7):847–856
- Scanlon BR, Reedy RC, Faunt CC, Pool D, Uhlman K (2016) Enhancing drought resilience with conjunctive use and managed aquifer recharge in California and Arizona. *Environ Res Lett* 11:035013
- Simpson DR (2008) Biofilm processes in biologically active carbon water purification. *Water Res* 42:2839–2848
- Skolasinska K (2006) Clogging microstructures in the vadose zone, laboratory and field studies. *Hydrogeol J* 14(6):1005–1017
- Somot S, Sevault F, Déqué M, Crépon M (2008) 21st century climate change scenario for the Mediterranean using a coupled atmosphere-ocean regional climate model. *Global Planet Change* 63:112–126
- Song L, Liu W (2013) A clogging model for particles mobilized by seepage flows in a single fracture. *Elect J Geotech Eng* 8:3791–3801
- 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

- USACOE (2014) Central and Southern Florida Project, Comprehensive everglades restoration plan. Final Technical Data Report, Aquifer Storage and Recovery Regional Study. US Army Corps of Engineers, Jacksonville
- USDA (1972) National engineering handbook. In: Sect. 4: hydrology, vol 4. NRCS, Washington DC, USA
- USEPA (2002) A lexicon of cave and karst terminology with special reference to environmental karst hydrology. EPA/600/R-02/003, Washington DC, USA
- USEPA (2012) Guidelines for water reuse. EPA/600/R-12/618, Washington DC, USA
- Yoo SY, Mito Y, Ueda A, Matsuoka T (2013) Geochemical clogging in fracture and porous rock for CO₂ mineral trapping. *Energy Procedia* 37:5612–5619
- Zhou W (2007) Drainage and flooding in karst terranes. *Environ Geol* 51(6):963–973
- Zito G, Ruggiero L, Zuanni F (1991) Aspetti meteorologici e climatici della Puglia. In: *Proceeding of the 1st Workshop on Clima, Ambiente e Territorio nel Mezzogiorno*, pp 43–73 (**in Italian**)