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INFILTRATION/IRRIGATION TRENCH FOR SUSTAINABLE COASTAL DRAINAGE MANAGEMENT: EMILIA-ROMAGNA (ITALY)

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Abstract

The current trends in Mediterranean climate indicate longer periods of drought and hot temperature in summer and shorter and more intense precipitation in spring and autumn, which require reconsidering the current water management. The Emilia-Romagna coastal area (Northeastern Adriatic Sea, Italy) is entirely drained by a network of channels connected to more than 70 water pumping stations. Although drainage is fundamental in wet periods to keep the land dry, during long periods of stable weather, the fresh portion of drainage water could be reused for irrigation or managed aquifer recharge purposes. The proposed Managed Aquifer Recharge (MAR) project involves the reuse of drainage water towards infiltration trenches for both irrigation and natural infiltration purposes. Four possible locations in the Ravenna area were assessed and recommended for the implementation of drainage/irrigation/infiltration projects. It was estimated that, maintaining a raised level of +0.5 m respect to the current water level, a freshwater recharge of about 0.4 million m^3 could be achieved in 120 days of operation by the combined-use of the trenches (total length of 8200 m). If water level in the trench was maintained at +1 m respect to the current level, the freshwater amount available for the aquifer recharge could reach about 0.7 million m^3. This additional freshwater availability would allow irrigation for over 1500 hectares of land and could increase the agricultural gross marketable production of 50%.

Key words: aquifer, drainage, infiltration, MAR, water management

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1. Introduction

1.1. Research framework

Groundwater in coastal areas is one of the main freshwater supplies for both human activities and agro-ecosystems. Agricultural activities can cause groundwater quality degradation (due to nitrogen and phosphorus excess and pesticides) and, vice versa, groundwater quality can affect agricultural yield, especially in case of soil salinization (Mastrocicco et al., 2013). In the last decades, anthropogenic pressures have caused negative impacts on groundwater resources availability. Urbanization and over-drainage decrease aquifer natural recharge producing the conditions for saltwater intrusion in coastal aquifers, soil salinization with severe consequences in agriculture, and the deterioration of groundwater quality as well as the connected ecosystems, such as wetlands (Antonellini and Mollema, 2010; Greggio et al., 2012; Man et al., 2016). In particular, coastal areas of the Mediterranean basin are experiencing the greatest variations in water resources usage and strong conflicts for allocation and management, especially between agricultural and touristic purposes (Ferragina, 2010). Problems in water resource management are tackled by proposing solutions and alternative approaches that always generate heated debates related to their effectiveness and environmental sustainability (Cosgrove and Loucks, 2015). The construction of dams, for example, requires time and economic resources (even for the

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social acceptability of design ideas) and, in addition, it occupies large portions of territory and causes population relocation. Furthermore, it does not guarantee an adequate solution to the problem of supply, since it is strictly dependent on precipitation (Rossetto and Bonari, 2014). Other options to face water scarcity and increasing requirements could be desalination plants even if there are still open issues related to production and disposal of brines and high construction costs, management and maintenance.

A real opportunity is the possibility to accumulate water into aquifers using non-drinking-quality water or water from periods of rainfall abundance. These technologies are known as Managed Aquifer Recharge (MAR). In recent years, an increased number of MAR projects were carried out around the world to store water from various sources, such as storm water, reclaimed water, desalinated seawater, rainwater or even groundwater from other aquifers (Dillon et al., 2009; Sprenger et al., 2017). MAR technologies, beside the advantage of storing water for later use, also contribute to increase the water quality characteristics of the infiltrated water. MAR techniques need to be adapted to the local situation and depend on the type of aquifer, topography, land use, water available for recharge, technical feasibility, and local population and administration acceptance. Currently, in Emilia-Romagna, only one case of MAR was set in place with the main objective to increase the piezometric level in the aquifer of the Marecchia alluvial fan that is strategically relevant for public water supply (Severi et al., 2014).

Since ancient times, water management in the Po River plain has always been of primary importance. In the II century BC, the Romans applied hydraulic techniques to distribute the water from the high lands in the Apennine foothills towards the low-lying lands of the Po River plain. They also made land cultivable thanks to artificial interventions (digging of canals and river dikes construction) on the natural river framework (Stefani and Zuppiroli, 2010). In the Middle Ages, marsh areas and wetlands in the low-lying zones were dried up by digging large canals which, leading the drainage water to the sea, allowed the establishment of a flourishing agriculture. During the '800s, land reclamation was performed by diverting natural streams and rivers into the areas to be reclaimed, so that sediment deposition allowed for the progressive increase in land elevation (Saltini, 2006). At the beginning of the '900, the availability of large steam and electrical pumps permitted the mechanical land reclamation that quickly drained the low-lying coastal lands (Antonellini et al., 2015). Nowadays, being most of the Ravenna area below or around 0 m a.s.l. in elevation, a drainage system, consisting in a network of drainage ditches and 12 water pumping stations, is required to keep the effective soil depth for agriculture practices and maintain land and infrastructure dry. The drainage ditches are also used as irrigation channels during summer (June-September) receiving surface water from nearby rivers via a system of pipes and sluice gates. The water management is accomplished by several Land Reclamation Authorities, which ensure the efficiency of irrigation distribution in support of the rural and industrial economy, urban, and civil activities. These Land Reclamation Authorities manage water scarcity emergencies in summer drought periods through water saving techniques and actions to reduce withdrawals and to rationalize the water distribution. The local economy is strongly related to agriculture and the production of high value crops, which require a considerable amount of irrigation water throughout late spring and the summer months.

In this context, the possibility to apply Managed Aquifer Recharge (MAR) techniques, specifically infiltration trenches, are investigated with the multiple objectives of reusing drainage water for irrigation and aquifer recharge by infiltration. In this paper, preliminary evaluations (not including yet a detailed economic assessment and environmental impact analysis) and recommendations for possible MAR multi-objective project locations in the low-lying coastal territory of Ravenna are presented. This study investigates the possibility to attribute an economic value to the drainage water that would otherwise no longer be used once it is lifted by the water pumping stations and collected into the final channel toward the sea. The presented MAR solution is adapted to the local territory and needs, in an area where these solutions are non-existent and their possibilities have not been investigated in detail, yet.

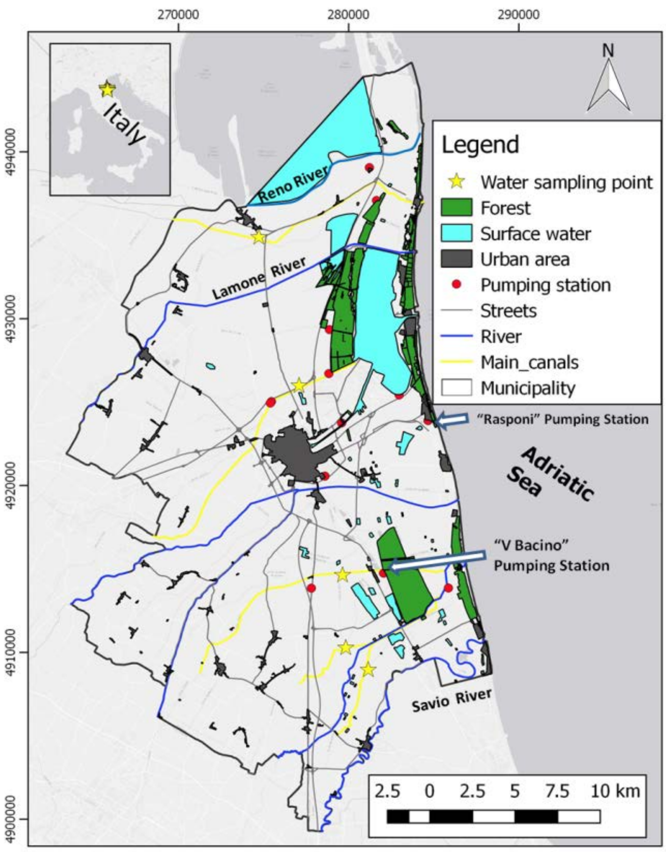
1.2. Regulatory framework of MAR: from Europe to Italy

The Water Framework Directive (WFD) (EC Directive, 2000/60) of the European Commission "requires that surface and groundwater achieve good status and a specific aspect of good status is the quantitative state of those water bodies". Over-abstraction and salinization are considered as major threats for European groundwater and, where this problem occurs, the WFD requires identifying and adopting measures to tackle the pressures. Among the measures aiming at reducing extraction and decreasing salinization, aquifer recharge with reuse of good quality water is one of the most promoted, especially because it can be seen as an alternative to conventional surface water storage and use. As reported by last EU guideline for water planning and management (EC Guideline, 2016), there are several advantages in artificial recharge: contrasting saltwater intrusion, decreasing evaporation, avoiding secondary contamination by animals and algal blooms, and limiting pipelines construction. Despite these benefits, the WFD sets out that artificial recharge needs a prior authorisation and imposes the use of sources that do not compromise the achievement of the environmental objectives established for recharged groundwater body (EC Directive 118, 2006). If at EU level the artificial recharge was regulated since 2000, not the same has been for Italy. Only with the national governmental decision n. 97/2013 (GD, 2013), in fact, the artificial recharge of groundwater bodies was allowed, changing art. 104 of the Legislative Decree 152/2006 (GD, 2006). Recently, thanks to the law n. 100/2016, the Italian Ministry of the Environment defined an authorization process (GD, 2016) for artificial recharge of water bodies. The Law identify in the Regional Water Authorities the administrative entities in charge of defining water bodies available for artificial recharge. Quality and quantity status of involved water bodies have to be constantly monitored pre- and post- intervention ensuring the maintenance of "good status" or the improvement for both water bodies. At the time of writing (2018), no database of water bodies potentially interested by MAR are available for the Emilia-Romagna Region.

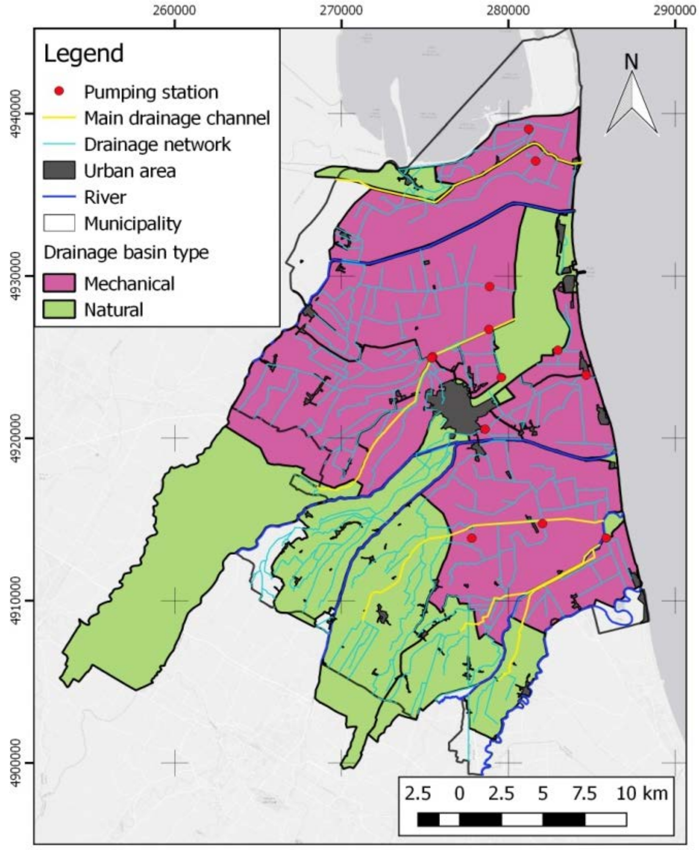
2. Local setting

The study area is in the Ravenna Municipality and extends from the mouth of the Reno River in the north, up to the Savio River's mouth in the south (Fig. 1a). The area is flat and comprises important natural areas within the *Po Delta Regional Park*, such as coastal forests and lagoons included in the Natura 2000 Special Areas of Conservation (SAC – Habitats Directive) (EC Directive, 1992/43). Large portions of the territory have topography ranging from 0.5 to -0.5 m a.s.l. In order to guarantee agriculture and all human activities, a dense network of drainage ditches and canals was set in place during the past century (Fig. 1b) (Antonellini et al., 2015). The whole area was separated in 15 drainage basins: eight basins require mechanical water drainage by pumping stations in order to discharge water toward the Adriatic Sea, while the other seven basins have natural hydraulic gradient (Fig. 1b). In the Ravenna Municipality there are nine pumping stations, which are active over the whole year; three additional pumping stations are activated in case of emergency. Two land Reclamation Authorities operate in this area: the Reclamation Consortium of Western Romagna for the northern area of the Lamone River, and the Reclamation Consortium of Romagna managing the southern zone. Basin extension ranges from 100 ha (closest basin to the Ravenna city), up to 10000 ha of the largest "V Basin" in the south (Mollema et al., 2012).

The hydrogeological setting of the shallow coastal aquifer consists of Holocene sediments (30 m in thickness) deposited during the last transgression-regression cycle started 18 ky ago (Greggio et al., 2017). The Pleistocene continental clays represent the impermeable unit and aquifer basement. From bottom to top, 2 - 3 m of transgressive fine-sand layer is overlapped by a thick prodelta unit ranging from 15 to 20 m in thickness; the uppermost unit consists of 7-10 m of sandy unit related to the ongoing beach progradation process (Amorosi et al., 1999). The aquifer is phreatic in the coastal portion, close to the Adriatic Sea, corresponding with the paleo- and current dune systems (Fig. 1c), while it becomes semi-confined by alluvial silty-clay layer westward, toward the Ravenna city (Antonellini et al., 2008; Greggio et al., 2012; Mollema et al., 2013a).



(a)



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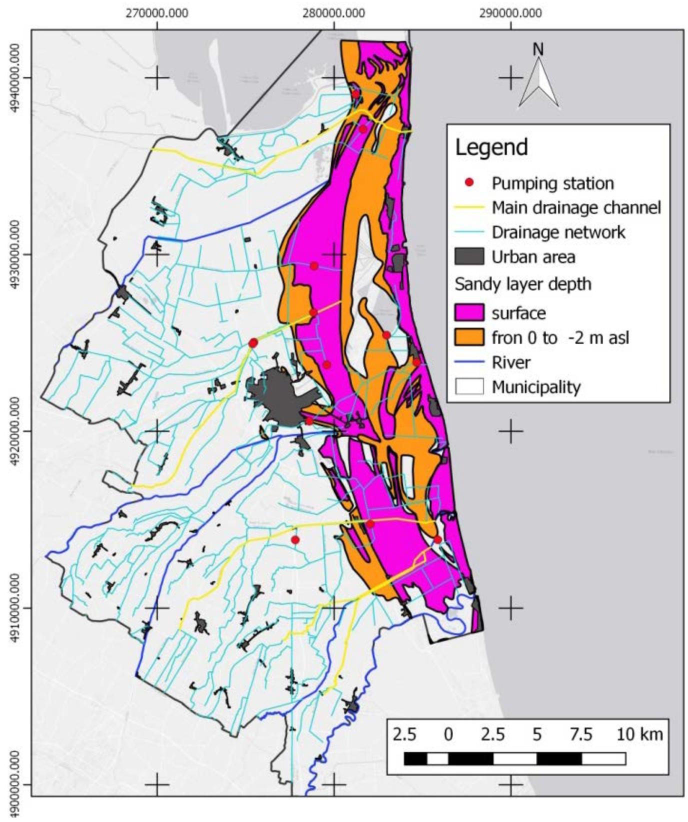

(c)

Fig. 1. (a) Study area location. The natural areas (pine forests, wetlands), surface water bodies, rivers and water sampling points are shown, (b) Drainage basins (mechanical and natural drainage), pumping stations, and drainage network, (c) Surface geology and coastal aquifer sandy unit depth

Many authors investigated the quality of the Emilia-Romagna coastal aquifer and pointed out that it is completely salinized (Antonellini et al., 2008; Giambastiani et al., 2007, 2013; Greggio et al., 2012; Mollema et al., 2013b). Generally, the water table is below or close to sea level, so that freshwater lenses in the dunes are seasonal and generally too thin to counteract regional groundwater and soil salinization processes. At a local scale, however, freshwater lenses can be important for irrigation purposes and sustainability of natural habitats (Cozzolino et al., 2017; Giambastiani et al., 2018; Vandenbohede et al., 2014).

2.1. Drainage system

The total water amount, which is drained by 12 water pumping stations across the Ravenna territory, is about 70 10^6 m^3/year with oscillations of ± 30 10^6 m^3 based on precipitation regime. The V Basin water pumping station (see Fig. 1a for location) serves the inland southern part of Ravenna (almost 9252 ha) and drains about 1/3 of the total yearly volume. By way of example, Fig. 2 shows the comparison between daily precipitation and drainage water volume of the V Basin and Rasponi water pumping stations for the 2015. The Rasponi pumping station serves a small reclamation area along the coast (2638 ha) (Fig. 1a for location). The water lifted by the pumping stations is higher during and just after strong rainfall events, but some pumping still takes place also in periods of no rainfall and during the dry summer months in order to keep the lowest coastal area dry.

Table 1 lists the average monthly precipitation and potential evapotranspiration over the period 1971-2015 and drainage averaged over the period 2000-2015. Drainage data are from the Land Reclamation Authority (http://www.bonificaromagna.it/); precipitation data (P) are from the Ravenna weather station (Regional Agency for environmental Protection database http://www.smr.arpa.emr.it/dext3r/), while potential evapotranspiration data (PET) are calculated by the Thornthwaite method according to the real length of the month and theoretical sunshine hours for local latitude. Data in Table 1 indicate a hydrological deficit (P-PET) in summer and water surplus in winter, when the drainage is at its peak. Over the entire period (1971-2015), average precipitation and evapotranspiration are 640 mm and 770 mm, respectively, in line with the previous water budget studies carried out in the same zone (Mollema et al., 2012, 2013a). The two pumping stations have drained together about 30 10^6 m^3 among which 5 10^6 m^3 during the summer period.

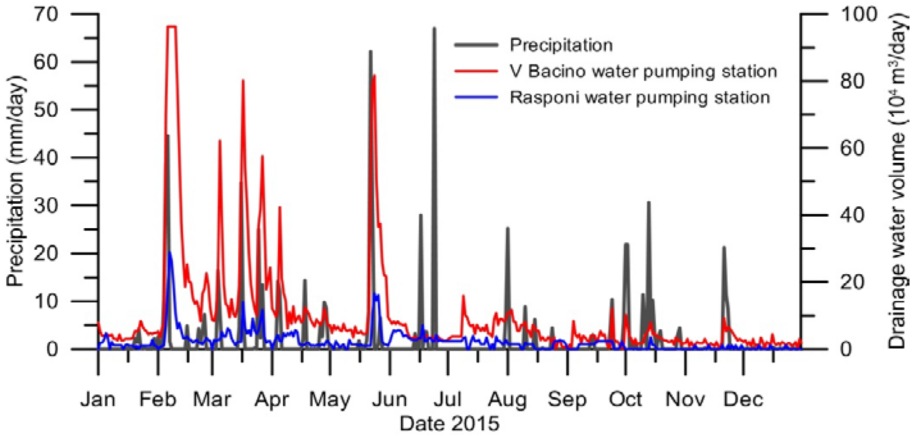

Fig. 2. Daily precipitation (mm) and daily drainage water volume (10^4 m^3) of "V Bacino" and "Rasponi" water pumping stations for the year 2015

Table 1. Average monthly drainage water (2000-2015), monthly precipitation and evaporation (1971-2015). The red colour indicates months characterized by hydrologic water deficit

	Month												*Total*
	1	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	
V Bacino water pumping station (mm/month)	22.2	30.8	36.1	28.7	22.6	14.6	15.4	13.2	13.0	15.4	15.7	22.4	**250.2**
Rasponi water pumping station (mm/month)	18.1	23.0	26.8	19.1	16.8	14.0	9.7	7.5	5.6	6.8	9.8	17.4	**174.6**
P (mm/month)	41.9	42.0	53.5	55.8	48.3	45.1	37.4	55.0	68.5	71.2	72.6	50.6	**642.0**
PET (mm/month)	4.6	9.5	27.1	49.8	93.3	126.5	153.1	138.1	89.9	53.2	20.1	6.2	**771.4**
P - PET (mm/month)	37.2	32.5	26.4	6.0	-45.0	-81.4	-115.7	-83.1	-21.3	18.1	52.5	44.4	**-129.4**

2.2. Water quality

The comparison of salinity values and chemical composition (Fig. 3) among different water samples collected from the main rivers and drainage channels across the study area (monitoring points in Fig. 1a) shows similar water composition in all samples. Although salinity of drainage water is slightly higher than salinity of natural bodies, it remains less than 1 g/l, far away from the values of 20-25 g/l of the Adriatic Sea, recorded in front of the coast and confirmed by previous studies (Cozzolino et al., 2017; Mollema et al., 2013b). The chemical composition of drainage water shows enrichments for all investigated species but chloride remains on average below 500 ppm. This ensures the possibility to reuse drainage water for irrigation and/or aquifer recharge by infiltration (GD, 2006).

3. Proposal – Technical solutions and requirements

The project assessment takes into account the local geology, water infrastructure availability, and drainage water quality. The water supply is drainage water that is annually released to the sea even during dry periods. The project would involve the excavation of a strategically located infiltration trench, which intercepts the top sandy units of the aquifer. The infiltration trench needs to be close to pumping station for the water supply and agricultural areas requiring irrigation.

Once the proper location is defined and the trench excavated, water will be collected from the main drainage channel, which currently brings drainage water from the water pumping stations to the sea, and delivered to the infiltration trench by a pipeline, following the natural hydraulic gradient. The infiltration trench will be kept full for four months from May to August and it would make water available for irrigation. Moreover, the water level in the trench will be higher than the surrounding water table, creating aquifer recharge. A preliminary case study in the Ravenna area considered an irrigation trench 1 km long, 5 m large and 2 m deep and calculated a recharge rate of 1 m^3 per day per unit length of channel, allowing an estimated aquifer recharge of 10^5 m^3 for summer operation (Vandenbohede et al., 2014). However, that situation is slightly different than the cases presented in this paper. In the site considered by Vandenbohede et al. (2014), in fact, aquifer recharge was totally accidental because location, trench size and operation time were completely based on agronomic needs (water-dependent and season crops). As a result, the trench was not continuously kept operative for four months as proposed in this paper. Besides, the geological setting in Vandenbohede et al. (2014) was different and not ideal for infiltration because of the presence of shallow silty-clay layers, which limited flow from trench to aquifer in the western trench bank. Given that many differences in management exist among the site of Vandenbohede et al. (2014) and the ones proposed here, in order to estimate the aquifer recharge, the following analytical solution for a drainage/recharge trench (Chiesa, 2004) is used (Eq. 1):

$$\frac{\partial^2 s}{\partial x^2} = \frac{S}{T}\frac{\partial s}{\partial t} \tag{1}$$

where: s [m] is the increase of water table (piezometric level) in the aquifer as a function of time t [days] and distance x [m] from the trench following a sudden water level increase s_0 [m] in the trench; S is the storativity [-] and T the aquifer transmissivity [m^2/day].

The analytical solution is for the transitory state and derived for confined aquifers. Since the aquifer thickness is considered close to the saturated thickness, Eq. (1) can be also used for phreatic aquifers (Chiesa, 2004). Using the initial condition $s(x, 0) = 0$ and boundary conditions $s(\infty, t) = 0$, $s(0, t) = s_0$ in Eq. (1), it is obtained (Eq. 2):

$$s = s_0\left(1 - erf\left(\frac{x}{\sqrt{\frac{4Tt}{S}}}\right)\right) \tag{2}$$

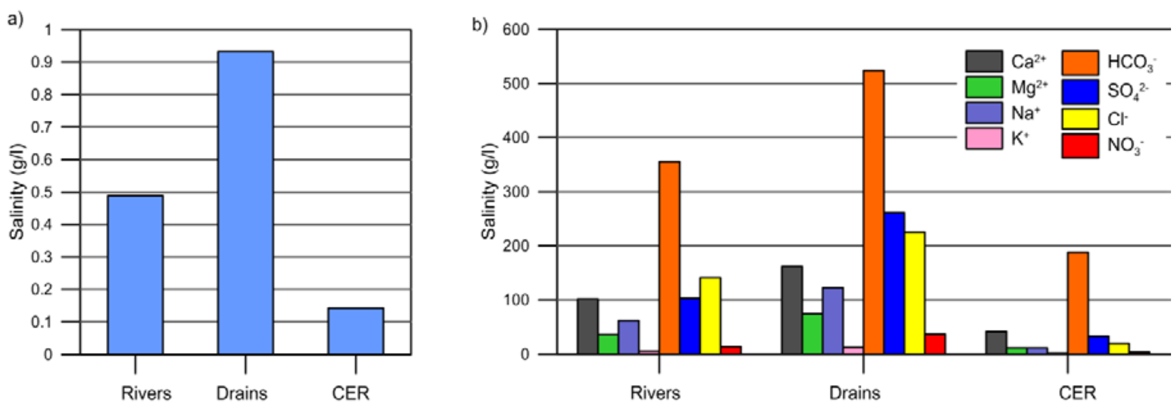

Fig. 3. Average salinity values (a) and chemical concentrations of the main ions (b) of river, drainage channels and CER water. Note: CER stands for "Canale Emiliano-Romagnolo" and represents a large regional irrigation infrastructure developed to guarantee delivery of high-quality water for agriculture. CER water is included in the analysis as irrigation water standard

For a phreatic aquifer, *s* can be set as (Eq. 3):

$$s = \frac{(H^2 - h^2)}{2b} \quad (3)$$

where: *b* is the saturated thickness of the aquifer [m], *H* and *h* are the current and increased hydraulic head in the trench, respectively [m]. The flow rate per unit length in the trench is (Chiesa, 2004) (Eq. 4):

$$Q_0 = s_0\sqrt{\frac{S_y T}{\pi t}} = \frac{K(H^2 - h^2)}{2\sqrt{\frac{Tt\pi}{S_y}}} \quad (4)$$

where *K* is the hydraulic conductivity [m/day], and, for the unconfined aquifer case, the storativity *S* is almost equal to the specific yield (S_y).

The amounts of water required to maintain a constant water increase of 0.5 m and 1 m in each proposed trench with respect to the current water table were calculated. These two proposed water levels in the trench are in line with the water table measurements conducted by Mollema et al. (2013a) in the coastal basin of Ravenna. The variable values used in the calculation and the total water requirements for 120 days of trench operation are listed in Table 3. It is important to note that the amounts of estimated water do not include water loss by direct evaporation processes, neither withdrawal for irrigation, and reflect only the quantity of drainage water infiltrating the aquifer.

In order to indicate possible benefits not only for groundwater and environment, but also for agriculture, simple calculation related to Gross Marketable Production (GMP) are performed. Based on what reported by Fanfani and Pieri (2015), the Gross Marketable Production (GMP) per ha for local extensive crops was about 1000 € in 2015, but four time higher in case of irrigated crops. For the estimates presented in this paper, an average of 2000 € GMP per ha for irrigated fields (Fanfani and Pieri, 2015) is adopted. It is also assumed that only half of current extensive crops could be converted in high value crops because of increasing need of manpower and technology by current agricultural companies.

4. Best sites identification

Based on the requirements listed in Table 2, four sites were selected as best locations for the infiltration trenches. Fig. 4 shows their locations and Table 3 lists the main characteristics of each project with the related estimates of recharge amounts.

Site 1 (Fig. 4) belongs to the “Casalborsetti” basin that drains more than 4700 ha of lowland. The Land Reclamation Water Authority of Western Romagna manages this basin. The withdrawal point is hypothesized immediately downstream of the pumping station, where the water is around 0 m a.s.l.

Table 2. Specific requirements considered to find the best locations for infiltration trenches in the Ravenna territory

Requirement	***Conditions***	***Advantage***	***Disadvantage***
Geological setting	The excavation must intercept the aquifer in its shallow sandy units (Fig. 1c) and the minimum size must be 5 m wide and 2 m deep (Vandenbohede et al., 2014)	Higher infiltration water rates and aquifer recharge. Development of shallow freshwater lenses above the saltwater (Cozzolino et al., 2017)	Not all territory is suitable for infiltration trenches because of potential waterlogging, presence of silty clay layers, and shallow water table
Water supply channel	The water supply is the channel that brings drainage water from the water pumping station towards the sea. Possibly the hydraulic head of this channel must be higher than the surrounding aquifer water level in order to have a natural hydraulic gradient.	No costs to lift up drainage water and fill the infiltration trench (the natural hydraulic gradient is used)	Not all channels are suitable as water supply channels.
Vicinity to water pumping station	Withdrawal point close to water pumping station.	Reuse of drainage water that, otherwise, would be delivered directly to sea without any other reuse. The economic value and cost of water in this point is at its lowest.	
Farmland	Proximity to farmland in need of irrigation	Availability of an infiltration trench for irrigation. Conversion from extensive agriculture to horticultural or fruit crops (higher marketable value).	Lack of stakeholder involvement. Lack of awareness between farmers.

Table 3. Summary of the characteristics of the selected sites and estimates of recharge amounts

Site	*Drainage basin name*	*Infiltration trench length (m)*	*Cumulative aquifer recharge (after120 days of trench operation) for 0.5 m water level increase (*) (m^3/120 day)s*	*Cumulative aquifer recharge (after120 days of trench operation) for 1 m water level increase (*) (m^3/120 day)*	*Agriculture area (ha)*	*GMP gain (k€/y)*
1	"Casalborsetti"	2400	$1.1\ 10^5$	$2.1\ 10^5$	350	175
2	"Canala-Valtorto"	2000	$9.0\ 10^4$	$1.8\ 10^5$	150	75
3	"V Basin"	2300	$1.0\ 10^5$	$2.1\ 10^5$	600	300
4	"Bevanella"	1500	$6.7\ 10^4$	$1.3\ 10^5$	400	200
TOTAL		**8200**	$\mathbf{3.7\ 10^5}$	$\mathbf{7.3\ 10^5}$	**1500**	**750**

(*) To be noted: Flow rate values are calculated based on Eq. 3 assuming: K = 10 m/day; S_y = 0.25 (Giambastiani et al., 2007; Mollema et al., 2013a), t = 120 days, H = 6 m; h= 6.5 m and 7 m in order to simulate the two scenarios s_o = 0.5 m and 1 m, respectively. This water would not include evaporative losses from the trench, trench filling water and any possible use of water for irrigation.

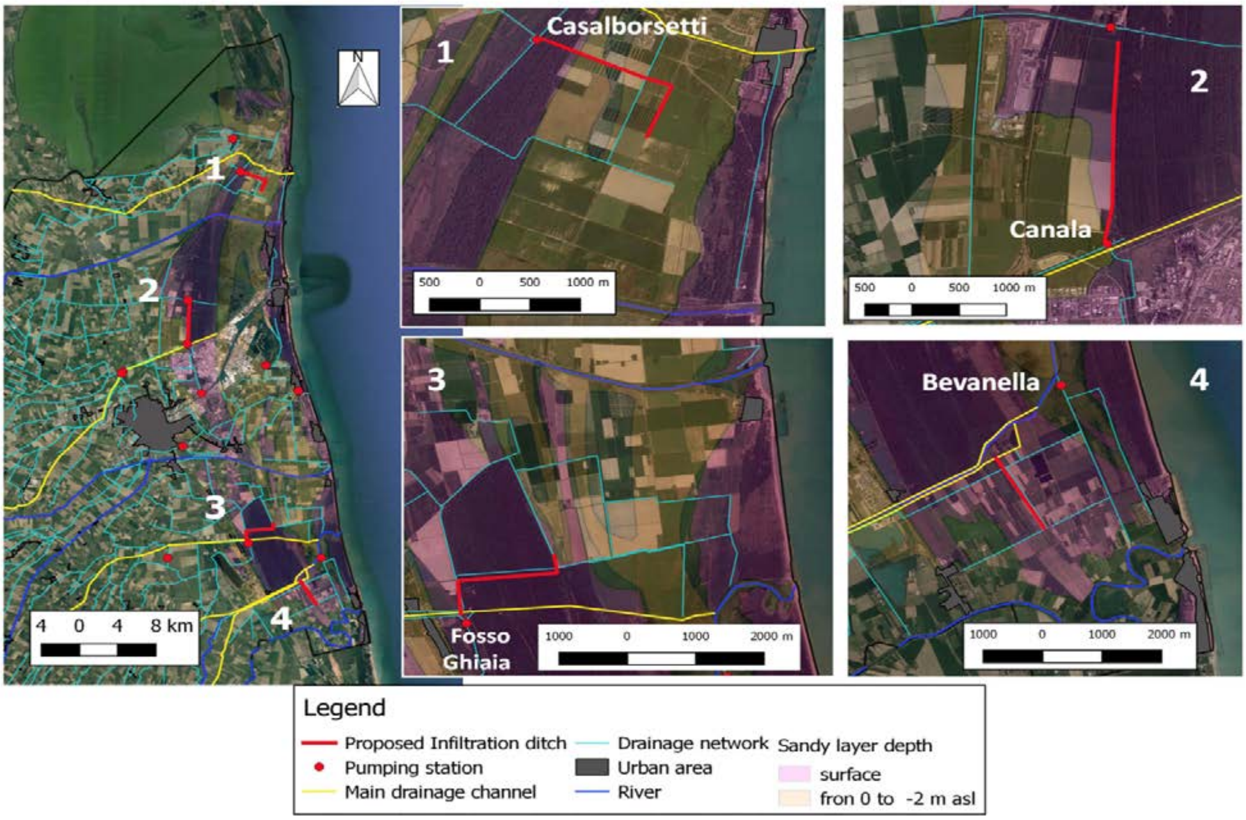

Fig. 4. Location of the four selected best sites (numbered as 1, 2, 3 and 4) for the proposed irrigation trenches. Pumping stations (named in figure) are indicated by red dots, rivers are in blue color, main drainage channels in yellow lines, while drainage network in cyan color

The agricultural area eastward to the channel is about 350 ha, entirely on extensive crops such as maize, grains and hay. The pumping station is located on the western border of a pine forest and the proposed trench starts from there and proceeds eastward, through the forest until the agricultural fields. The total length is over 2400 m, 500 m of which inside the pine forest. The aquifer is unconfined in the pine forest, and semi-confined by 1 m of shallow silty clay sediments in the cultivated area. Assuming to adopt trench dimensions as proposed by Vandenbohede et al. (2014) (5 m wide, 2 m deep) and considering 1.8 m of water column in the trench and a trapezoidal section (4.5 and 3 m for the two bases), the total trench volume would be around 16000 m^3. Based on Eq. (3), the amount of water required to maintain water level increases of 0.5 m and 1 m in the trench, with respect to the water table, are 1.1 10^5 and 2.1 10^5 m^3 of drainage water for 120 operation days, respectively. Based on the assumption described in chapter 3, the shifting from extensive crops to irrigated crops could generate a GMP increasing of 175 k€/y.

Site 2 is located near the water pumping station called "Canala" (Fig. 4); it is part of the inner “Canala-Valtorto” basin, which has an area of 7000 ha. In this site, the drainage channel has a natural gradient toward the sea and it can deliver water to the proposed infiltration trench without the installation of additional equipment. As shown in Fig. 4, the new trench should be excavated along the western border of a pine forest, where the aquifer is unconfined. The total planned trench length is about 2 km and trench shape and dimensions are the same as in the previous site (1). In this case, the trench volume is around 13000 m^3. About 150 ha of agricultural fields adjacent to the infiltration trench could be supplied by drainage water. The estimates point out that about 9 10^4 and 1.8 10^5 m^3 of reused water could be stored during 120 days of activity if the water level in the trench were constantly maintained 0.5 and 1 m higher than the current water table, respectively. At the same time, if farmers decided to replace half of the current crops with irrigated crops, an increase of 75 k€/y of GMP would be expected.

Site 3 is located in the southern part of the study area (Fig. 4). It is included in the V Basin, which is the largest of the area with an extension of more than 10000 ha. The water supply would be the ditch called “Fosso Ghiaia”. Also, in this case the water from the supply channel can naturally flow into the infiltration trench by natural hydraulic gradient without the use of additional equipment having this portion of the territory the lowest elevation and hydraulic level in Ravenna (-2 m a.s.l.). As in site 2, the vicinity of the withdrawal point to a coastal pine forest can add relevant environmental benefits in terms of improving groundwater quality and developing relevant freshwater habitats. The majority part of the proposed trench would be located inside the pine forest until the agricultural fields that border the eastern portion of the forest (Fig. 4). The trench would be 2.3 km long and, considering the same above-mentioned size, the volume of possible water storage would be about 15000 m^3, while the estimated aquifer recharge would be around 10^5 and 2.1 10^5 m^3 for 120 days of operation, considering 0.5 and 1 m of water level increase in the trench, respectively. Considering that more than 600 ha could be supplied by drained water and only 300 converted from extensive to irrigated crops, the estimated increase in GMP would be 300 k€/y.

Site 4 is within the “Bevanella” basin. The surface geology shows wide portion of unconfined aquifer with sandy units at the top (Fig. 4). The “Bevanella” drainage channel, which drains water from the inner part of the *Bevanella* basin, would supply water for the infiltration trench. The planned infiltration trench extends southward of the *Bevanella* channel for 1.5 km, potentially providing irrigation water for more than 400 ha of agricultural land. Based on the above-mentioned trench dimensions, infiltration rates and GMP values, water storage of about 10000 m^3 with an aquifer recharge of about 6.7 10^4 (s_0 = 0.5 m) and 1.3 10^5 (s_0 = 1 m) m^3 water for 120 days of operation are estimated, along with an increase of 200 k€/y in GMP.

5. Discussions

The current trends in Mediterranean climate indicate longer periods of drought and hot temperature in summer and shorter and more intense precipitation in spring and autumn, which lead to a deficit of freshwater resources to both agro- and natural ecosystems, requiring a reconsideration of the current water management (Mollema et al., 2012, 2013a). Decreasing natural aquifer recharge induces saltwater intrusion in coastal aquifers, soil salinization (crop yield reduction), and deterioration of groundwater-dependent natural ecosystems (Antonellini and Mollema, 2010; Greggio et al., 2012). As reported by Ferragina (2010) strong conflicts are rising for freshwater allocation between the need of drainage from one side and the irrigation water supply from the other side. Thanks to the advantage of storing water for later use, several MAR projects have been put in place around the world (Dillon et al., 2009; Sprenger et al., 2017; Stefan and Ansems, 2018).

The hydrogeological and anthropic settings in the study area, along with the previous findings by Vandenbohede et al. (2014), suggest the adoption of infiltration trench among the available MAR techniques. The advantages of this solution, compared to other MAR techniques, are well summarized by Bouwer (2002) and essentially include: low costs, reduced evaporative losses and clogging, as well as easy to be blended with surrounding agro-ecosystems. Other advantages here are the good quality of water supply for infiltration and the fact that the proposed trenches are identified as portion of already operating drainage network, which could be temporarily shifted from original drainage function and used as infiltration trench from May to August. This last point would reduce costs and need to expropriate land from farmers for trench excavation.

Four requirements have been identified in order to select the places for MAR implementations (Table 2). All identified locations are located within or in proximity of the historical paleodune systems (nowadays covered by historical pinewood of San Vitale and Classe) where the coastal aquifer is phreatic (Amorosi et al., 1999; Antonellini et al., 2008). The other fundamental requirements are the vicinity of drainage channel and pumping station. The closer they are, the lowest the cost for water supply. The last requirement of proximity to farmland has been easily solved being the area strongly agriculture-oriented.

Regarding the estimated benefits, the infiltration trenches could guarantee infiltration and storage into coastal aquifer of about 4 - 7 10^5 m^3/120 days of good quality drainage water, alternately wasted to the sea. The estimation does not include the irrigation water withdrawn from trenches. Based on the water irrigation demand projection for irrigated crops calculated by Gallo et al. (2012) of about 1000 m^3/ha*120 days, a rough estimate of saved water would reach 0.8 - 1.4 10^6 m^3/120 day. These data correspond to about 20% of the annual withdrawal from a local river (Lamone River) (CER, 2016). Considering that the Po Delta coastal plain has similar drainage infrastructure and groundwater is historically affected by salinization (Colombani et al., 2017a, 2017b), the application of the proposed MAR solution to the entire Delta area will allow reusing millions m^3 of drainage water for irrigation and aquifer recharge, avoiding withdrawals from rivers and deep groundwater abstraction.

The agricultural land potentially served by the proposed irrigation opportunities amounts to 1500 ha, about 2% of the Ravenna province. Based on the economic data by Fanfani and Pieri (2015), and considering that only half of current extensive crops could be converted into irrigated crops, the GMP gain is about 750 k€/y.

The infiltration trenches would also generate benefits for the adjacent pine forests (San Vitale and Classe pine forest), historically affected by groundwater salinization (Giambastiani et al., 2007). The forests could benefit from the groundwater freshening generated by the trenches with positive benefits in terms of freshwater habitat and biodiversity increase (Antonellini and Mollema, 2010; Janssen et al., 2016).

Apart from direct costs of the intervention, two main limitations would affect the wide implementation of this solution across the study area: water cost and maintenance/clogging of the trenches. Regarding drainage water cost, although the withdrawal point is supposed as close as possible to a pumping station, Land Reclamation Water Authority claims an economic compensation (lower than the common lease) for the volume of water derived from its channels. The designation of an equilibrate drainage water cost among farmers associations and Land Reclamation Water Authority is fundamental. The cost should take into account, firstly, the relevant environmental benefits for aquifer, and, secondly, agricultural uses.

The trench maintenance essentially depends on clogging of subsoil with consequent and gradual decrease of infiltration rates till complete trench obstruction (Masciopinto, 2013). Although trenches and ditches are less sensitive to clogging than other shallow methods (i.e. ponds) because of steep banks that increase water velocity, a once-a-year operation of trench reshaped should be accounted for clogged material removal and restoration of initial infiltration rate (Masciopinto et al., 2017).

6. Conclusions

In the low-lying coastal areas of Ravenna (Po River plain, Northern Adriatic Sea, Italy), the increasing demands for water supplies both as consumptive (irrigation, industry, domestic use) and non-consumptive (ecosystem services) commodity, force administrators to reconsider the current water management and find sustainable solutions. A recently introduced national regulatory network with specific indications and procedures for managed aquifer recharge (MAR) opens the possibility for the projects that are proposed in this paper. The discussed MAR projects plan the reuse of drainage water, which is annually released to the sea without any further reuse even during periods of high-water scarcity. This water could be intercepted immediately upstream of pumping stations and released in close infiltration trenches for both irrigation and aquifer recharge purposes. Chemical analysis performed on samples of drainage water reveal acceptable quality, suitable for irrigation and aquifer recharge according to the current regulations.

Since MAR system performance and efficiency depends upon site-specific conditions, four most important requirements are identified: geological setting, drainage channel (water supply) availability, proximity to water pumping station, and presence of agricultural fields in need of irrigation. The four proposed MAR sites comply with these requirements.

The infiltration trenches can operate for four months, from May to August, making water available during the irrigation season and guaranteeing aquifer recharge by infiltration. Overall, a total of 8200 m of infiltration trenches would provide storage of more than 0.7 million m^3 of water and irrigation for over 1500 ha of farmland. The water estimates do not include water loss by direct evaporation processes. Although no detailed economic analysis regarding setting-up and installation costs were reported in this work, the proposed MAR projects represent a relative low-cost intervention considering the resulting benefits in terms of water saving and storage.

The benefits for groundwater and agricultural sectors are evident and also nearby natural areas would benefit from the projects, with the possibility to create new freshwater habitats in coastal areas currently dominated by low-biodiversity brackish or saltwater habitats.

Costs are estimated to be about € 50000 for a 1000-m-long trench (RER, 2018), including: planning, design, excavation and monitoring instruments installation. Considering that water flows into infiltration trenches thanks to natural gradient and no more energy or additional equipment are required, this kind of intervention is cost-effective and win-to-win solution where compared with other MAR techniques. The main limitations of the proposed MAR project are water cost and clogging risk. The definition of an accessible water cost dedicated to irrigation need to be defined by farm associations and Land Reclamation Water Authority.

Future research directions include the development of a test-demonstration site where real costs are evaluated and stored water and crop yield increase measured in order to foster the adoption of this practice. At the same time the instauration of a periodic round table of all stakeholders is needed in order to overtake current different visions among users (farmers and environmental agencies) and water suppliers (Land Reclamation Water Authority and Municipalities). Despite a site-specific economic assessment and environmental impact analysis are required to complete the current proposal, this study could support the round table participants to improve water use efficiency and plan future water infrastructures.

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