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ORIGINAL ARTICLE

Groundwater monitoring at a building site of the tidal flood protection system "MOSE" in the Lagoon of Venice, Italy

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Abstract To protect Venice against tidal flooding, the MOSE system (Experimental Electro-mechanic Module) has been under construction since 2003. This safeguarding system is composed of four batteries of mobile barriers at the Lagoon's inlets (Lido, Malamocco, Chioggia), which will be lifted before the occurrence of exceptional high tides (>1.10 m above the mean sea level), isolating the Venetian Lagoon from the sea. The end of the construction work is foreseen by 2016. In this paper, the results of the groundwater monitoring at the building site of Punta Sabbioni at the Lido inlet are described. A large dewatered basin (*tura*), formerly occupied by the sea and close to the shoreline, was used for the precasting of the mobile barriers, and the impact of groundwater control was therefore monitored in the phreatic and shallow confined aquifers. Although a slurry wall barrier was excavated to isolate the *tura*, a drawdown cone in the confined aquifer was observed, extending to 1 km from the construction site. In contrast, the phreatic aquifer was only influenced by tides, rainfall and evapotranspiration, and the slurry wall of the *tura* had a positive effect of decreasing the groundwater salinity by limiting the seawater intrusion, as confirmed by the electrical conductivity profiles measured inside the piezometers. The monitoring activity was successful in assessing the impacts of the construction work on the aquifer system and in distinguishing them from the effects of natural driving forces.

Keywords Groundwater monitoring · MOSE · Dewatering · Groundwater control · Coastal aquifer · Venice

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Introduction

The city of Venice is known worldwide for its canals, its monuments and its unique cultural heritage, but this fragile treasure is threatened by floods caused by high tides in the Adriatic Sea. The best known part of the historical centre, Piazza San Marco, is also the most exposed, being flooded about 50 times a year (Harleman 2002). Besides the degradation of its artistic patrimony, flooding in the historical centre of Venice impairs the quality of life of its inhabitants, contributing to a massive migration towards the mainland.

In the last century, the severity and the frequency of flooding has been worsened by both eustatism and man-induced subsidence, causing a relative sea level rise of 23 cm between 1908 and 1980 (Bras et al. 2001; Gatto and Carbognin 1981). The sea level rising trend observed since the end of nineteenth century (1.8 ± 0.5 mm/year) is due to the Earth global warming (Bindoff et al. 2007). Subsidence in the Venetian Lagoon, which has been monitored in the last 50 years by topographic surveys (Carbognin et al. 1977) and recently by DGPS and SAR interferometry (Teatini et al. 2005; Tosi et al. 2007, 2009, 2012), is also caused by the natural compaction of the sediments and deep movements in the pre-Quaternary basement (Fontes and Bortolami 1973), but the aquifer depressurization induced by water pumping in the Marghera industrial district was the most important driving force until the 1970s (Carbognin et al. 1995). In the last 40 years, the groundwater extraction for industrial purposes has been drastically reduced with a consequent stabilization of land subsidence in Venice and in the central lagoon. The northern and southern parts, instead, are still being affected by this phenomenon due to pumping for agricultural purposes, peat oxidation caused by reclamation work and geochemical compaction due to saltwater intrusion (Tosi et al. 2009).

The most severe tidal flooding in Venice (+1.94 m at the tide gauge station of Punta della Salute) occurred on November 4th 1966, inundating almost the whole historical centre. After this calamity, the Italian Government declared the safeguarding of Venice and its lagoon as a national priority. The evaluation of technical alternatives took several years, and the preliminary project phase started in the 1980s with the so-called Experimental Electro-mechanic Module—MOSE (Fice and Scotti 1990). The definitive project was approved in 2002, the construction works started on September 2003 and their end is foreseen in 2016. The Venice hydraulic safeguarding system is composed of four batteries of mobile barriers at the Lagoon's inlets (Lido, Malamocco, Chioggia, see Fig. 1), which have to be lifted before the occurrence of exceptional high tides (more than +1.10 m above mean sea level), isolating the Venetian Lagoon from the sea (Cecconi 1997). Rinaldo et al. (2008) proved the adequacy of the barriers for the protection of Venice from floods, even during prolonged barrier closures, when a large runoff volume is expected to be discharged into the Lagoon from its catchments. The raising of many embankments and some modifications of the seawalls and coastal defences are also foreseen to mitigate the effects of moderate storm surges (MOSE Venezia 2013). Three harbours connected by a lock gate are under construction at the Lagoon inlets, to ensure a navigation path while the barriers are lifted (Fig. 2). Two of them, in Punta Sabbioni (Lido) and Ca' Roman (Chioggia), were also used as provisional building sites for the concrete lodging caissons of mobile barriers, limiting the soil occupation and the impact of the construction work on the mainland. The navigation lock of Punta Sabbioni was used for this purpose for 5 years (January 2007–March 2012), while the one in Ca' Roman was dewatered from April 2008 to March 2014. Each of these basins was bounded by slurry walls and cofferdams and drained by a system of dewatering wells. A possible adverse side effect of groundwater control is represented by the depletion and depressurization of aquifers outside the bounded area, that can also causes differential settlements (Powers et al. 2007) and saltwater intrusion (Bear 1999). For these reasons, groundwater monitoring activities were therefore started in 2005 by Politecnico di Torino, under the supervision of CORILA,[1] in order to assess the impact of the dewatering operations on the nearby area and aquifer system. The aim of this study is to describe the groundwater monitoring program at the site of Punta Sabbioni, which was completed on May 2013, with a focus on the criteria followed in the design of the monitoring well network, on the choice of the measurements to be carried out and on the reaction of the aquifer system to the natural and anthropogenic driving forces, as observed in almost 8 years of work.

The monitored site

The Punta Sabbioni construction site is located in the northern part of the Lagoon, at the Lido inlet, on the edge of the Peninsula of Cavallino (Figs. 1, 2). This land strip acquired its actual shape after the construction of the seawalls of the Lido inlet (1907), which fostered the deposition of sand transported by sea currents, and the land reclamation works with sand fillings (1930) which transformed this marshland into a cropland. The harbour of Punta Sabbioni at the southern edge of the Peninsula of Cavallino is composed of two basins connected by a navigation lock to allow the boats to pass through the inlets when the mobile barriers are lifted. The southern basin (*tura*)[2] was bounded by cofferdams (Fig. 2) and dried up starting from January 2007 by means of 18 dewatering wells, 10 of them installed in the upper part of the boundary of the basin and 8 at the bottom. In this way, a provisional construction site was created for the mobile gates, in which the groundwater levels were kept below the elevation of the bottom (8.70 m below mean sea level), to reduce the soil occupancy on the mainland and the impact on the local main economical activities (greenhouse horticulture and tourism). One of the main concerns about this technical solution was the impact on the aquifers on the mainland, since a continuous dewatering pumping is required in order to keep the groundwater level inside the basin below a safety threshold. A slurry wall was therefore dredged with the Cutter Soil Mixing technique to a depth of 28 m, crossing both the shallow aquifers (Bringiotti et al. 2008; Gerressen et al. 2008), with the aim of limiting the extension of the drawdown cone, and a continuous groundwater level monitoring program was set up. The dewatering operations lasted 5 years and they were stopped on March 2012 to allow the recovery of pristine conditions.

[1] Consortium for coordination of research activities concerning the Venice lagoon system.

[2] *Tura* is the ancient Venetian word to designate the bounded basins used for the wooden pole foundations of the palaces of Venice.

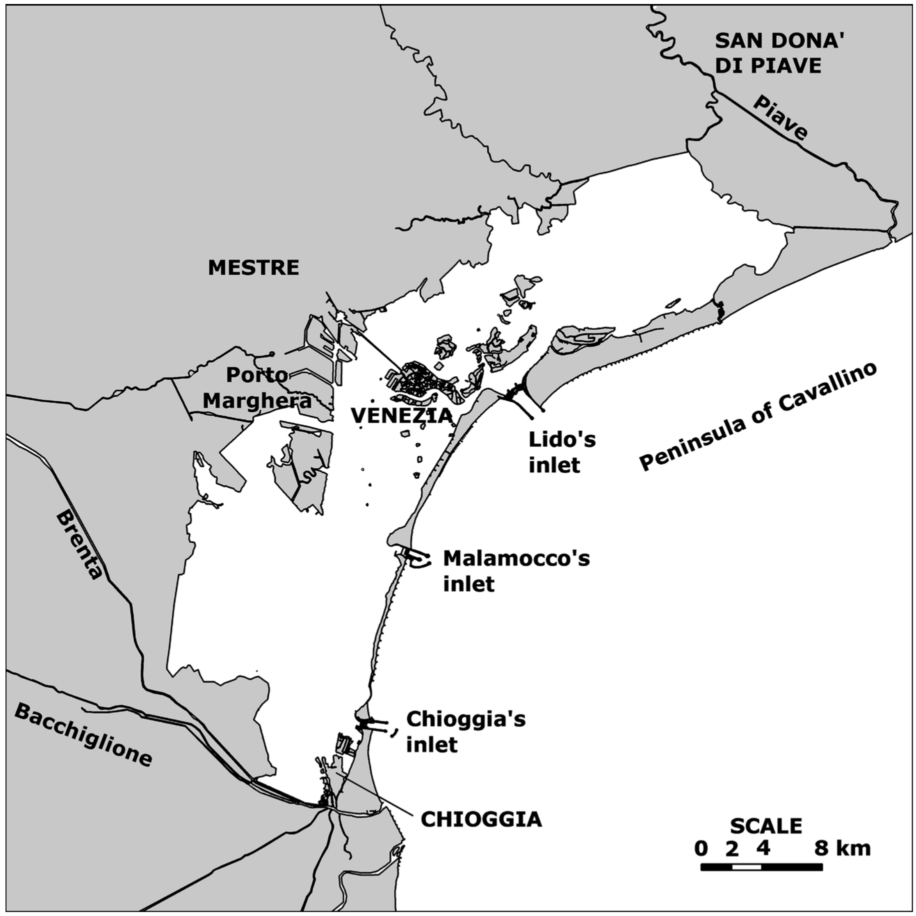

Fig. 1 Map of the Venetian Lagoon showing the main rivers, the urban centres and the MOSE construction sites at the Lido, Malamocco and Chioggia inlets

After the drying up phase (January 2007), the dewatering discharge was set to around 600 m^3/day in order to keep the hydraulic head at 11 m below m.s.l. inside the basin. In the following years, the safety threshold was elevated to 10 m below m.s.l., thus reducing the total well flow rate to 550 m^3/day in October 2009 and to 450 m^3/day in September 2011, up to the end of this activity in March 2012.

The shallow stratigraphy of the building site is composed of a sequence of sub-horizontal poorly consolidated sedimentary layers, with different origin and grain size. The most superficial stratum, layer A, is a silty sand with a thickness of 15 m, that began to form during the Holocene sea transgression (7,000 years ago) and, more recently, its thickness was increased by the land reclamation works. It contains a phreatic aquifer which is extended all over the Peninsula of Cavallino (Rapaglia et al. 2010), with an average hydraulic conductivity $K = 1.8 \times 10^{-5}$ m/s (varying in the range $K = 4.7 \times 10^{-6}$–2.8×10^{-5} m/s) that was estimated with mechanical slug tests (Di Molfetta and Sethi 2012). The underlying strata were formed during the late Pleistocene alluvial deposition, which took place until 18,000 years BP (Strozzi et al. 2009; Tosi et al. 2007): a clayey silt aquiclude (layer B) at a depth ranging 15–20 m separates the phreatic aquifer from the confined one (layer C) at 20–25 m from ground surface level, with an average $K = 4.8 \times 10^{-6}$ m/s (range $K = 2.2$–6.9×10^{-6} m/s). The 3D stratigraphy in Fig. 3 reproduces the spatial variation of the thickness of the three shallow layers, and confirms that the aquiclude (layer B) does not show spatial discontinuities which could connect the unconfined (layer A) and the confined aquifer (layer C). Both these aquifers are local systems bounded by the Peninsula of Cavallino, while the shallowest regional aquifer, according to the classification of Da Lio et al. (2013), ranges between 55 and 74 m below mean sea level and it is separated from layer C by a thick stratum of silt. Since it is characterized by a low permeability and a high salinity, it is poorly exploited, unlike the underlying six aquifers (ranging from 81 to 340 m below m.s.l.) which are the main source of drinking water, for agriculture and industry in the lagoon and in a large part of the Veneto Region.

The monitoring activities

A network of 11 monitoring stations, each one composed of two piezometers drilled into the aquifer layers A (PS01–

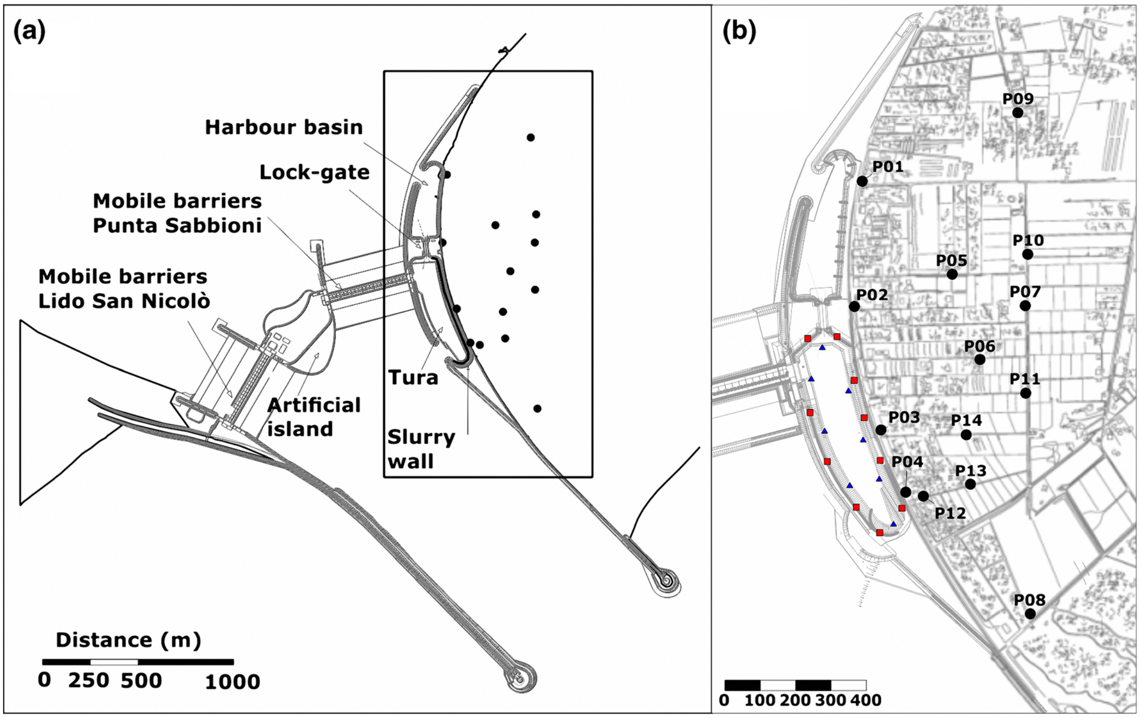

Fig. 2 The building site (**a**) of Punta Sabbioni, located in the north-eastern part of the Lido's inlet, and the detail of the dewatered basin and the groundwater monitoring network (**b**) of the site, which is composed of 14 monitoring stations (*black circles*): all of them are equipped with a piezometer screened in the deep aquifer (PP01/PP14) and 11 of them with a shallow piezometer (PS01/PS11). The groundwater control system is composed of 18 wells, 10 of them installed in the upper part of the boundary of the basin (*red squares*) and 8 wells at the bottom (*blue triangles*)

PS11) and C (PP01–PP11), was installed close to the building site on July 2005 (Di Molfetta et al. 2005). The underlying aquifers were not monitored, since they are separated by a thick impervious layer and hence they are deemed to be not influenced by the construction work. The observation wells (Fig. 2) were installed at a distance of 125–1,100 m from the centre of the *tura* and of 15–500 m from the coastline, covering an area of about 70 ha with a very high spatial resolution. Three additional deep piezometers (PP12–PP14) were installed in November 2008 to enhance the effectiveness of measurement of the spatial distribution of the hydraulic heads close to the dewatered basin.

Coastal aquifers are usually very sensitive to climate driving forces, due to their low depth to water table and to the influence of tides: consequently, a synchronous measurement of hydraulic heads is vital for a correct representation of the flow field. Each well is therefore equipped with an automatic pressure transducer acquiring data at a frequency of one measure every 10 min. Since groundwater density is variable in the monitored aquifers, the water pressure (p) measured by submerged data loggers is converted into freshwater hydraulic head, according to the following formula (Post et al. 2007):

$$h = z_i + \frac{p}{\rho_f g} \tag{1}$$

where $\rho_f = 1{,}000\ \mathrm{kg/m^3}$ is the freshwater density and $z_i = -6.036$ m a.s.l. is the reference elevation, at which the transducers are installed.

The monitored aquifers are not exploited for human consumption or agriculture but, especially in the phreatic aquifer, an increase in groundwater salinity induced by dewatering would be detrimental for vegetation and crops. Chloride content and salinity are strongly correlated with the electrical conductivity (EC) of groundwater (Cimino et al. 2008; El Moujabber et al. 2006; Katznelson 2004), and EC values are often used as a threshold for the acceptability of water for irrigation purpose: for example, according to Lee and Song (2007), the limit is 2 mS/cm for most species, and 15 mS/cm for the most salt-resistant ones. Monthly EC vertical profiles were therefore measured using a multi-parametric probe, in order to study the evolution of the interface between freshwater and salt water (saltwater wedge) and to ascertain if the dewatering activity in the *tura* was triggering the saltwater intrusion on the mainland. Although water samplings give better detail on groundwater geochemistry and how it varies through

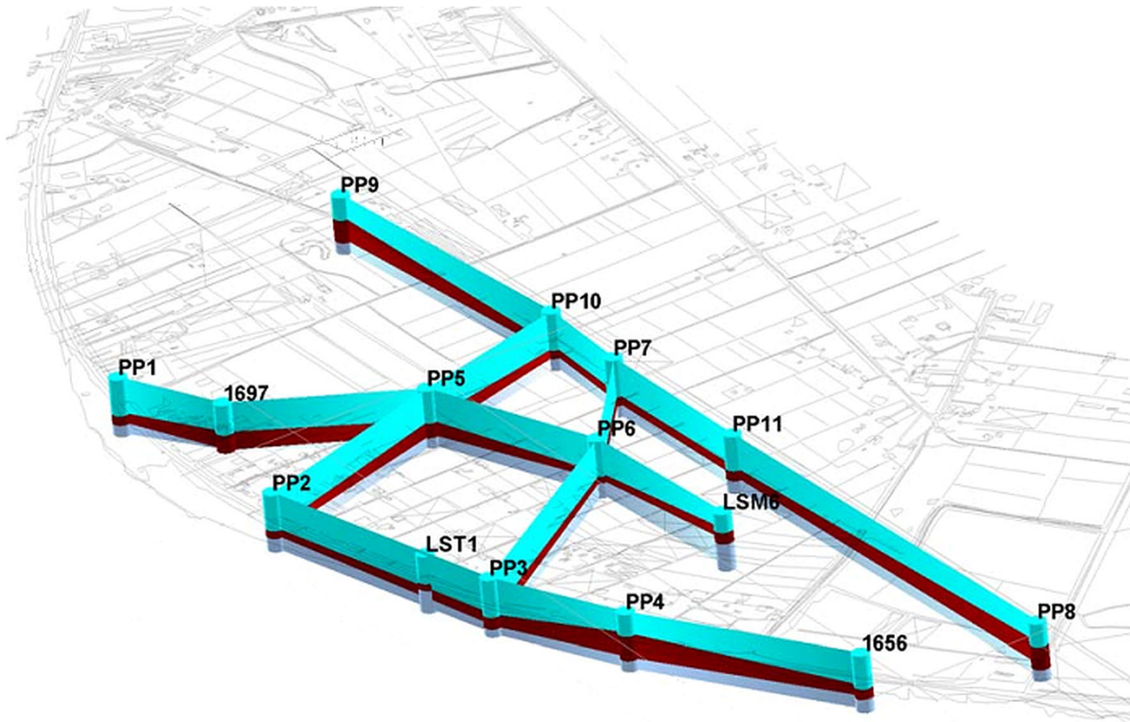

Fig. 3 Cross-sections of the shallow stratigraphy of Punta Sabbioni (0–29 m from the ground surface), deduced by core samplings acquired during the drilling of the deep piezometers (PP01/PP11) and by the Province of Venezia (1656, 1697, LSM6, LST1). Three layers are represented: the phreatic aquifer (layer A, *cyan*), the aquiclude (layer B, *brown*) and the shallow confined aquifer (layer C, *grey*)

time, vertical EC profiles are much cheaper and less time-consuming. In addition, they allow the vertical heterogeneity of groundwater salinity to be assessed, e.g. in order to monitor the freshwater lens on which most plants rely for their survival.

In order to assess the anthropogenic impacts on subsurface water, the data collected during almost 8 years of monitoring activity were compared with the natural driving forces (tidal oscillations, rainfall and evapotranspiration). The time series of sea-water levels are acquired from the "Diga Sud Lido" tidal gauge of ICPSM,[3] at a frequency of one measure per hour. The mean sea level amplitude in the Venice lagoon is 104 cm during spring tides and 46 cm during neap tides (Cucco and Umgiesser 2006), and their periods are, respectively, 6 and 12 h. Due to its small depth to water table, ranging from some 0.30 to 2.50 m, the dynamics of groundwater levels in the phreatic aquifer are strongly affected by the infiltration and the evapotranspiration. Rainfall data are registered on a hourly basis by the meteorological station "Cavallino Treporti" of ARPA Veneto,[4] at a distance of 5.5 km from the site. The climate of the Venetian lagoon is characterized by an average annual precipitation of some 800 mm, and monthly rainfall height is almost uniform during the year (Table 1), but storms are much more frequent during winter and spring, while few intense thunderstorms occur in May and September.

Table 1 Average climatic parameters in Venice meteorological station "ARPAV-Cavallino Treporti", years 1992–2012

Month	Total rainfall (mm)	Rainy days ($h > 1$ mm)
January	43.2	5/31
February	45.8	4/28
March	48.9	5/31
April	71.7	8/30
May	72.6	7/31
June	65.2	6/30
July	54.3	5/31
August	72.6	6/31
September	101.6	6/30
October	97.7	6/31
November	90.3	8/30
December	72.6	8/31
Total	836.5 mm	74/365

[3] ICPSM (Istituto Centro di Previsione e Segnalazione Maree) is the agency for the measurement and forecast of tides in the Venice Lagoon.

[4] ARPA Veneto is the regional environmental protection agency.

Monitoring results

The data acquisition at the Punta Sabbioni building site started on October 11th, 2005 and ended on April 30th, 2013. The *ante operam* situation was analysed during the preliminary works, in order to collect reference data which are essential for the assessment of groundwater control impacts (Attanayake and Waterman 2006). This phase lasted until March 2006, when a slurry wall and a series of cofferdams were dredged, thus modifying the subsurface water circulation. The dewatering of the *tura* lasted from January 2007 to March 2012 and, after the pumping cease, the *post operam* monitoring program was carried on for the subsequent 14 months, up to the end of April 2013, in order to verify the recovery to the pristine condition.

Hydraulic heads

The *ante operam* monitoring phase allowed two different types of groundwater level dynamics in the phreatic aquifer to be distinguished, depending on the distance of the piezometers from the coastline (Casasso et al. 2009). Along a narrow belt of less than 100 m from the coastline, sea tides are the strongest driving force acting on the phreatic aquifer. Forced oscillations are observed in PS01, PS02 (Fig. 4) and, in the *ante operam* phase (October 2005–March 2006), also in PS03 and PS04 (Fig. 5), with a slight delay of 1–2 h between the peaks of the sea and groundwater levels. The tidal efficiency factor (TEF), which is the ratio between the standard deviation of the hydraulic heads in the piezometer and of the sea levels (Erskine 1991), were calculated for the coastal piezometers in the phreatic aquifer (PS01–PS04) and in the confined one (PP01–PP04), differentiating between spring and neap tide periods (see Table 2). The values of this coefficient range approximately between 40

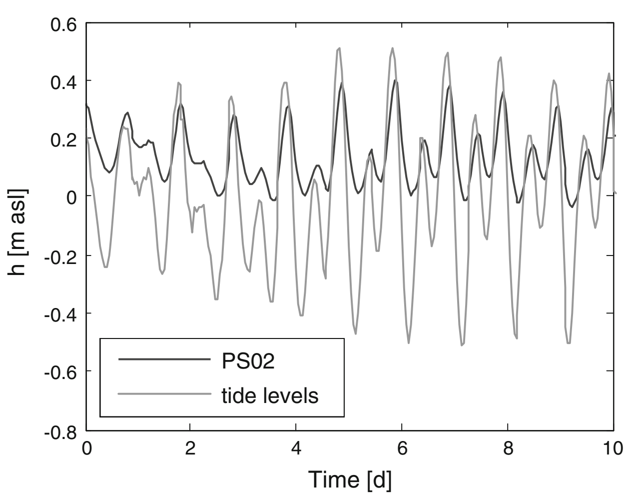

Fig. 4 Response of a coastal piezometer (PS02) to tidal oscillations

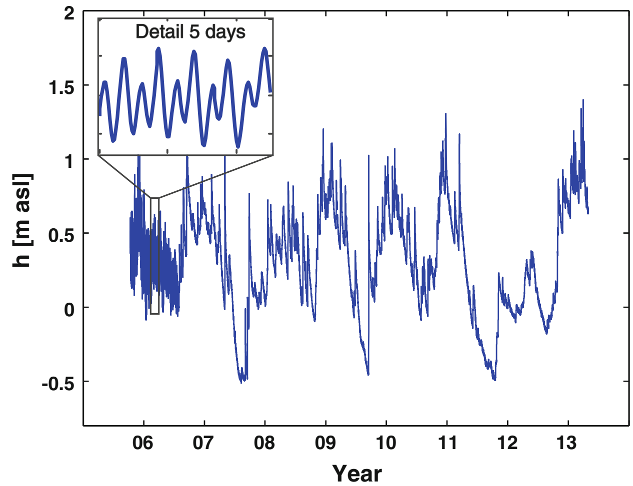

Fig. 5 Evolution of the hydraulic heads pattern in the coastal piezometer PS03: since March 2006, the emplacement of the slurry wall of the *tura* caused an abrupt interruption of tide-induced oscillations

and 50 % in the phreatic aquifer, and between 15 and 30 % in the confined one. The TEF values of PS03, PS04 (and, to a lesser extent, PP03 and PP04) experienced a strong reduction during the construction works, confirming that the tide-induced oscillations have been dampened, as shown in Fig. 5, due to the emplacement of the slurry wall of the *tura* on March 2006. Groundwater levels in these piezometers now show the same behaviour observed in the mainland (PS05–PS11, see Fig. 2b), where sudden level increases occur after rainfall events and a strong evapotranspiration is observed, especially in the summer season, due to the small depth to water table (i.e. 0.3–2.5 m) of the phreatic aquifer (Fig. 6). The influence of sea level fluctuations is negligible, since the amplitude of tide-induced oscillations exponentially decays with the distance from the coastline (Erskine 1991; Li et al. 2002).

The cross-correlation suggested by Song and Zemansky (2012, 2013) is a powerful tool to assess and compare the influence of different driving forces on groundwater levels, and it was applied to analyse the influence of rainfall and tides on the hydraulic heads during a wet month (March 2009, with a total rainfall height of 122.4 mm) and a dry month (July 2009, with a cumulative precipitation of 7 mm). Plots reported in the supporting information confirm that, in the phreatic aquifer, the most important driving force is rainfall, except for the coastal piezometers PS01 and PS02, where tidal oscillations are prevailing. On the other hand, in the confined aquifer, rainfall events exert an appraisable impact only for a mainland monitoring well (PP07), probably due to the formation of ponds, while tides are an important driving force for levels in PP01 and PP02. Close to the *tura* (PP03, PP04, PP12, PP13, PP14), hydraulic heads are almost insensitive to tides and

Table 2 Calculation of tidal efficiency factors (TEF) during spring and neap tides, before (*ante operam*) and during the construction works

Piezometer	Phase	x (m)	Tidal efficiency factors (–)	
			Spring	Neap
PS01	Ante operam	14	0.322	0.384
	During works	14	0.392	0.502
PS02	Ante operam	21	n.a.	n.a.
	During works	21	0.421	0.527
PS03	Ante operam	21	0.345	0.501
	During works	21	0.050	0.092
PS04	Ante operam	14	0.149	0.351
	During works	14	0.047	0.088
PP01	Ante operam	14	0.162	0.225
	During works	14	0.161	0.197
PP02	Ante operam	21	0.136	0.208
	During works	21	0.099	0.140
PP03	Ante operam	21	0.101	0.199
	During works	21	0.080	0.122
PP04	Ante operam	14	0.231	0.298
	During works	14	0.129	0.186

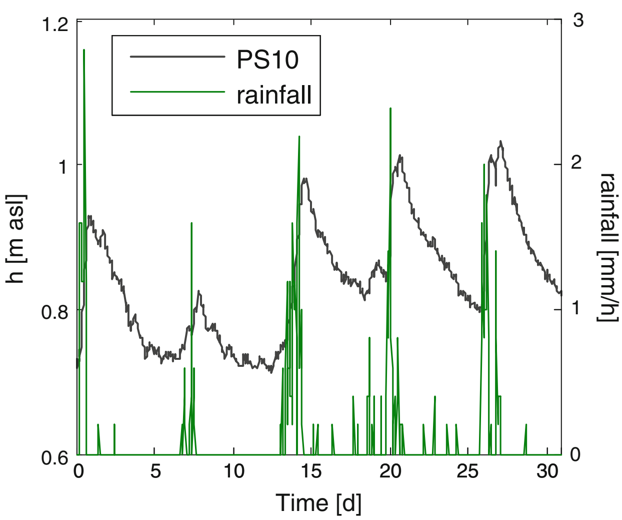

Fig. 6 Time series of the hydraulic heads in the shallow piezometer PS10, during January 2009: the level rise after rainfall events is almost immediate, due to the small depth to water table (<2 m)

precipitations, since the impact of dewatering pumping was dominating.

Forward Neural Networks (FNNs) carried out by Taormina et al. (2012) confirmed the deductions about the driving forces acting on the shallow aquifer, since a good fit was achieved when forecasting the hydraulic heads in the mainland piezometer PS10 only with climate data (rainfall and estimated evapotranspiration).

The shallow aquifer is characterized by a small depth to water table, and the cross-correlation plots reported in the supporting information confirm that a reduced time lag (i.e. smaller than 24 h) is observed between a rainfall event and a groundwater level peak. The level rises (Δh) against every appraisable rainfall event (cumulative height $h > 5$ mm) were calculated for all the monitoring year 2009, and their ratios (Table 3) give a good indication of the local effective porosity of the aquifer, which is deemed to be quite heterogeneous due to the recent formation of the phreatic aquifer layer.

In the monitored period, a strong depletion of the phreatic aquifer occurred during the summer droughts of 2007, 2009 and 2012. Further surveys demonstrated a strong correlation between groundwater levels and rainfall on a monthly and yearly basis (Fig. 7), but no direct effect of pumping was observed in the shallow aquifer, since the hydraulic heads in the phreatic aquifer and in the confined one in the most impacted monitoring position (PS04–PP04) do not show any correlation (Fig. 8).

Electrical conductivity (EC) vertical profiles

The strong evapotranspiration occurring during summer season also influences the seasonal evolution of the EC profiles, as shown in Fig. 9, due to the lowering of the water table and, to a lesser extent, to the reduced volume of groundwater in which the salts are dissolved. Indeed, the position of the saltwater wedge depends on the water table elevation and, according to the Badon–Ghyben–Herzberg formula (Bear 1999):

$$\xi = \frac{\rho_f}{(\rho_s - \rho_f)} h_f \approx 30\text{–}40\,\mathrm{h_f} \qquad (2)$$

where ρ_f and ρ_s are, respectively, the density of freshwater and saltwater, h_f is the water table elevation and ξ is the depth of the interface between the freshwater and the underlying saltwater. Using typical values of freshwater (1,000 kg/m^3) and saltwater (1,025–1,033 kg/m^3) density, one can easily understand that a small reduction of groundwater level results in a noticeable displacement of the saltwater wedge (i.e. 30–40 times larger).

In the inner area (PS05, PS06, PS07, PS09, PS10, PS11), where groundwater levels are usually higher than on the coastline, the conductivity is almost uniform along the well column, with low values (0.3–2 mS/cm) typical of fresh or slightly brackish water. Also coastal piezometers (PS01, PS02) have a uniform profile, but larger EC values are observed (10–15 mS/cm). In PS03, PS04 and PS08, the profiles show an abrupt EC variation from freshwater (1–2 mS/cm) to saltwater (8–25 mS/cm), which also occurs in PS09 and PS10 during summer due to the saltwater intrusion.

Table 3 Comparison of mean ratios between rainfall height (h) and level rises in internal piezometers (ΔH) after rainfall

Piezometer	PS03	PS04	PS05	PS06	PS07	PS09	PS10	PS11
$h/\Delta h$	0.096	0.143	0.126	0.080	0.090	0.163	0.162	0.129
R^2	0.856	0.875	0.863	0.826	0.800	0.729	0.880	0.855

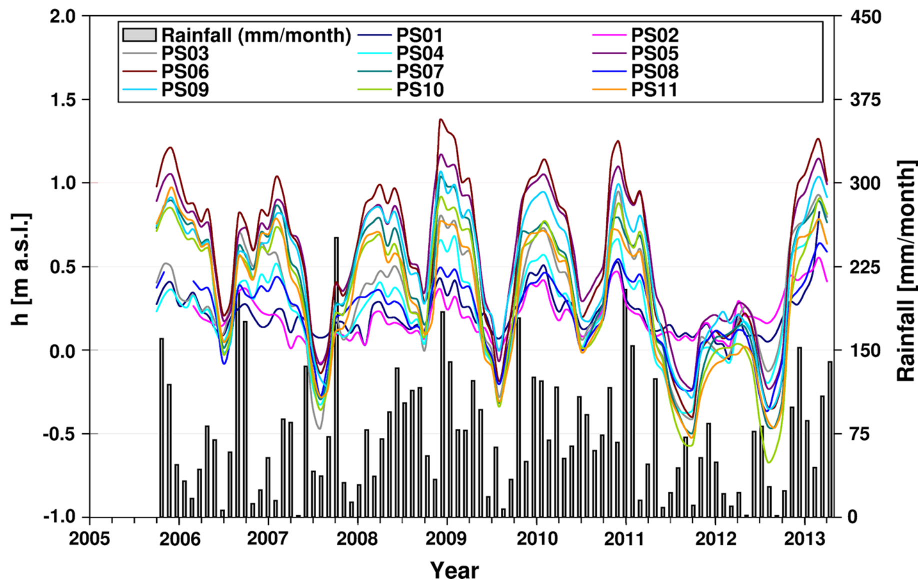

Fig. 7 Comparison between the monthly cumulative rainfall height and the monthly average hydraulic heads in the phreatic aquifer during the monitoring period (October 2005–April 2013)

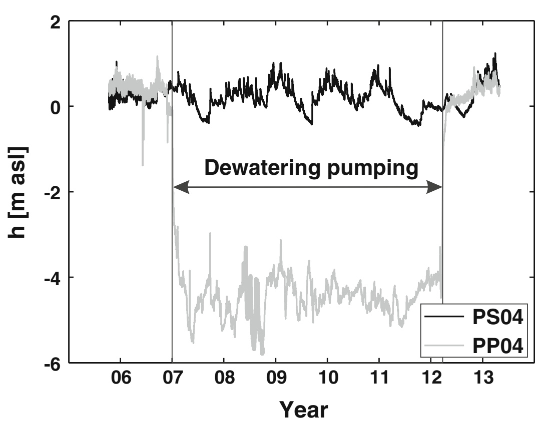

Fig. 8 Comparison between hydraulic heads in the deep piezometer PP04 and in its homologue in the shallow aquifer (PS04): no relation was observed comparing their dynamics, confirming the absence of any depletion of the shallow aquifer due to the construction works

The shape of the EC profile can vary during the year, generally with a temporary saltwater intrusion occurring in summer and autumn (Fig. 9) which sometimes involves the whole aquifer depth, e.g. in the piezometers PS05 and PS10. No permanent salinization trends were observed, while a clear desalinization trend was assessed for PS03 and PS04 (Fig. 10), due to the dam effect generated by the impermeable slurry wall of the *tura*, except for 2012 due to a severe summer drought (see Fig. 7) and a consequent strong water table level decrease.

The EC profiles are in good agreement with those of Rapaglia et al. (2010), who observed values between 1 and 14 mS/cm in two sites in the Peninsula of Cavallino, one in Punta Sabbioni (some 800 m northward from PS09–PP09) and one in Treporti (some 3 km from the monitored site). In particular, they found a shallow freshwater lens in Punta Sabbioni but not in Treporti, inferring that this is due to a smaller submarine groundwater discharge (and hence, a smaller saltwater supply from the sea side of the Peninsula) in this site.

Groundwater control in the tura

The EC monitoring in the shallow aquifer confirmed that no significant influence was exerted by the dewatering pumping in the tura, as one can also observe comparing the hydraulic heads in the piezometers PS04 (shallow) and PP04 (deep) in Fig. 8. On the other hand, the effects of this activity on the deep aquifer level are evident: the drawdown induced by dewatering pumping in the building site reached its maximum in piezometers PP04 (4–6 m) and PP03 (2.5–3.5 m), located behind the slurry wall, with a logarithmic decay with the increasing distance from the centre of the tura (Fig. 11). The radius of the depression cone induced by dewatering operations reached an extent

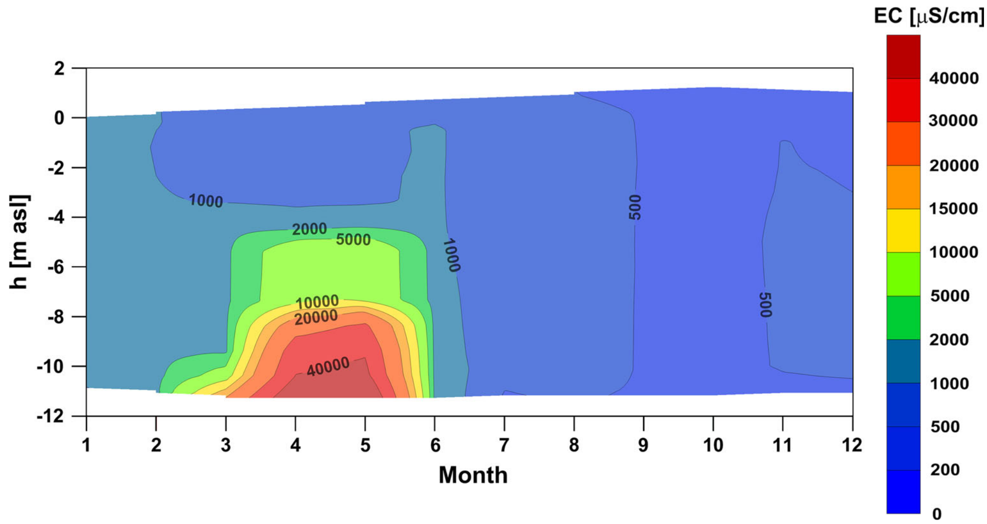

Fig. 9 Seasonal evolution of groundwater specific electrical conductivity (EC) vertical profiles in PS06 (June 2012–May 2013). Saltwater intrusion occurs in summer and autumn, while rainfall infiltration from autumn to spring results in a noticeable decrease of EC

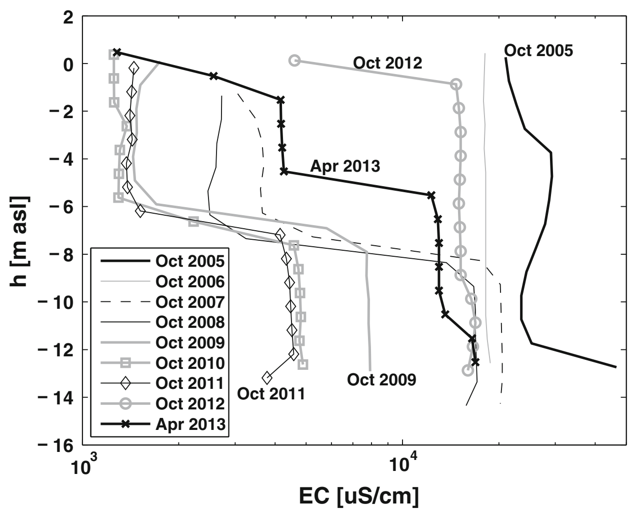

Fig. 10 Temporal evolution of groundwater specific electrical conductivity (EC) vertical profiles in PS04. The significant decrease in conductivity, and hence salinity, is due to the isolation effect of the slurry wall of the *tura*. An exception is observed in 2012, as the severe summer drought caused a strong saltwater intrusion, which was also observed in the other shallow piezometers

of about 1 km around the building site, which is not uncommon for dewatered basins of such a large dimension (Wang et al. 2013). The absence of any evident drawdown in the shallow aquifer is due to the presence of a confining clayey aquiclude (layer B) with no evident spatial discontinuities (Fig. 3), that prevents any vertical connection with the underlying dewatered confined aquifer, and the slurry wall of the *tura* also proved to be successful in preventing such a heavy environmental impact. The monitoring results were communicated monthly to CORILA and allowed the optimization of the discharge distribution of the dewatering wells and a reduction of the impact on the monitored mainland side. The oscillations of the hydraulic head were reduced through the years and a slight level recovery was also achieved (Fig. 8) due to the aforementioned variation of the safety threshold in the groundwater controlled basin, which was switched from 11 to 10 m below m.s.l. in October 2009. Nevertheless, the dewatering pumping caused some local settlements in the immediate vicinity of the building site (6–10 cm in PP03 and PP04, at less than 200 m from the centre of the tura), which have been quantified by periodic plano-altimetric surveys on the piezometers. These ground surface displacements are due to the compaction of the silty and clayey component of the aquifer and of the overlying aquiclude caused by the increase of the effective stresses induced by pumping operations. Minor displacements were found in the other monitoring wells. The extension of the major land settlements shows good agreement with the TerraSAR-X images interferometric analyses conducted by Strozzi et al. (2009) and Tosi et al. (2012).

The dewatering pumping in the building site of Punta Sabbioni was interrupted on March 3, 2012. The southern basin of the navigation lock was flooded, and the hydraulic heads in the deep aquifer definitely recovered to the *ante operam* spatial distribution in August 2012 (Fig. 11). In the phreatic aquifer, no significant variations were observed during the post-pumping recovery phase, confirming that it was not affected by the dewatering activity. The *post operam* monitoring phase ended on April 30, 2013. The hydraulic heads are still measured by the automatic acquisition network, although no reports are being published now.

Conclusions

In this paper, the results of the groundwater monitoring in the *MOSE* building site of Punta Sabbioni, in the Venetian

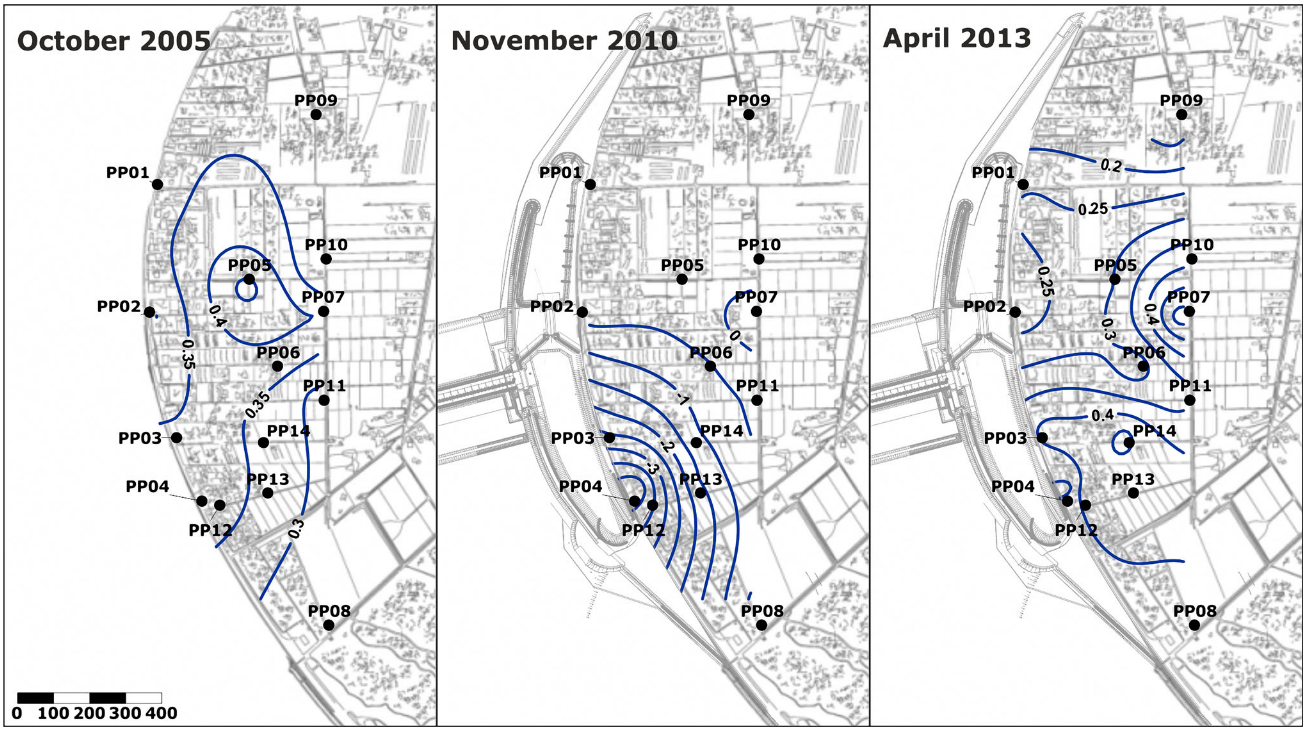

Fig. 11 Comparison between piezometric surfaces in the confined aquifer before the beginning of dewatering pumping (October 2005, *ante operam* phase), during the groundwater control activity in the *tura* (November 2010) and after it was ceased (April 2013, *post operam* phase)

Lagoon, are described. The impact of the construction work on the aquifer system is related to the dewatering operations conducted inside a wide basin, formerly occupied by the sea, that was used for the construction of the mobile gates and will later serve as a navigation lock when the barriers are lifted. The hydraulic heads in the surrounding area were monitored by a network of monitoring wells screened in the shallow and in a confined aquifer layer.

Although an impermeable slurry wall barrier was excavated to limit the impact on the aquifer system and proved to be successful in avoiding an impact on the phreatic aquifer, the monitoring network revealed a drawdown cone in the confined aquifer extending to 1 km from the southern basin of the harbour during a period of 5 years (January 2007–March 2012). After the interruption of the dewatering pumping, the hydraulic heads in the deep aquifer returned to the *ante operam* spatial distribution in 5 months.

During the 8 years of the monitoring program, no adverse effects were observed in the phreatic aquifer, which is mainly influenced by the tides on a narrow strip along the coastline and by the climate—precipitation and evapotranspiration—on the mainland. Droughts were observed in the summer seasons of 2007, 2009 and 2012, but the comparison with climate data confirmed the absence of a depletion induced by the construction works.

The slurry wall of the *tura* had a positive effect of desalinization in a portion of the phreatic aquifer, which is isolated from seawater intrusion, as confirmed by monthly EC measurement campaigns. Subsidence has been observed on a narrow strip along the *tura*, which has been confirmed by both GPS surveys and SAR interferometry (Strozzi et al. 2009; Tosi et al. 2012).

The monitoring activity proved to be successful in evidencing the impacts of construction work by ascertaining the effects of the natural driving forces influencing the hydrogeology of the area of the building site. In particular, continuous hydraulic head recording permitted a clear and rigorous representation of the groundwater flow field, especially in the phreatic aquifer, which is subject to rapid variations in response to natural driving forces. The monthly vertical EC profiles permitted the saltwater intrusion to be monitored with a simple, fast and inexpensive method with high spatial resolution. Periodic reports and a strong feedback procedure with the contractors of the worksite proved to be effective in reducing the groundwater impact induced by the construction of this infrastructure.

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