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Recharge process of a dune aquifer (Roman coast, Italy)

Modalità di ricarica di un acquifero dunale (litorale romano, Italia)

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Riassunto: L'espansione urbanistica nel settore sinistro del delta del Tevere ha risparmiato circa 9 km^2 di area dunale caratterizzata dalla presenza di una pineta costiera monumentale (la pineta di Castelfusano), attualmente inclusa nella Riserva Naturale del Litorale Romano gestita da Roma Capitale. La pineta è stata ampiamente distrutta da diversi incendi, fra cui i più devastanti sono stati quelli di luglio 2000 e luglio 2017. Il progetto di riforestazione, approvato subito dopo l'incendio del 2000, prevedeva, fra i vari interventi di recupero ambientale anche la realizzazione di una rete di monitoraggio di 21 piezometri per il controllo del livello di falda e del grado di salinizzazione delle acque sotterranee. La ricerca in corso si propone di analizzare e quantificare gli effetti degli incendi del 2002 e del 2007 sui processi di ricarica dell'acquifero dunale, partendo dall'analisi ed interpretazione dei dati idrogeologici raccolti dalla rete di monitoraggio a partire dal 2002. Il primo risultato dello studio è stata la definizione di una modello idrogeologico concettuale sito-specifico in cui è stato distinto un acquifero freatico superficiale di acqua dolce al di sotto del quale sono presenti due acquiferi confinati caratterizzati da una marcata salinizzazione delle acque. Il confronto fra i valori della ricarica annua calcolata in alcuni specifici periodi, ha portato inoltre ad evidenziare un deficit di ricarica nel periodo 2002-2003 non ricollegabile al regime pluviometrico. Questa anomalia è stata messa in relazione con gli effetti del disastroso incendio del 2000. La ricerca è tuttora in corso al fine di verificare e analizzare nel dettaglio le eventuali variazioni nelle modalità di ricarica dell'acquifero indotte dagli incendi del 2000 e del 2017.

Keywords: *coastal aquifer; monitoring; Tiber River delta; groundwater recharge, conceptual model.*

Parole chiave: acquifero costiero, monitoraggio, delta del Fiume Tevere, ricarica, modello concettuale.

Abstract: *The urban development plan of left bank of the Tiber river Delta preserved a 9 km^2 stretch of dune belt with a monumental coastal pine forest (Castelfusano forest), which is nowadays portion of a natural reserve managed by Municipality of Rome. The forest was largely destroyed by a first huge fire in July 2000 and by another one in July 2017. A reforestation project involved the installation of a monitoring network composed by 21 piezometers to check the groundwater depth and its degree of salinization after the 2000 fire. By examining series of water head measurements and chemical -physical parameters carried out from 2002 up today, the current research aims to analyse the effects of 2000 and 2017 fires on the recharge process. The first result consists in the definition of the hydrogeological conceptual models of the dune aquifer: a shallow fresh aquifer overlapping two deeper confined salinized aquifers. The comparison between the amount of the yearly recharge, evaluated in different periods, showed a significant recharge rate decrease (about 36%) to be attributed likely at the 2000 fire effect. The research is still ongoing in order to verify and detail the changes of the recharge processes induced by the 2000 and 2017 fires.*

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Introduction

Coastal dunes are delicate systems highly sensitive to local environmental changes, highly exposed to a multiplicity of human and natural risks. This particular vulnerability has been frequently neglected in the development of urban plans in the coastal zones, where the priority has always been the growth of the residential and tourist urbanization.

Focusing on hydrogeological issue, the coastal dune represents a precious reservoir of fresh groundwater in a coastal system containing mostly brackish water. Thus, the fresh shallow dune aquifer is the best protection against the widespread groundwater salinization hazard. In addition, the natural dune vegetation growth and the survival of the maritime forests are regulated by the degree of groundwater salinization (Jones et al. 2006; Antonellini and Mollema 2010). The protection of the fresh shallow dune aquifer therefore guarantees the preservation of important "green lungs" having a beneficial effect on the quality of the air (Nowak et al. 2014), threatened by the proximity to metropolitan areas (Gratani and Varone 2005; Paoletti 2009).

The urban development plan of left bank of the Tiber river Delta (covering about 90 km^2) preserved a 9 km^2 stretch of dune belt with a monumental coastal pine forest (Castelfusano forest), nowadays part of a natural reserve managed by Municipality of Rome (Litorale Romano Natural Reserve) (Gasparella et al. 2017). It is bounded by the Castelporziano Presidential Estate, another natural reserve where the President of the Italian Republic has one of his dwelling homes. Even if moderate and not critical salinization processes characterize the Tiber River Delta aquifer (Capelli et al. 2007; Manca et al. 2014a; Mastrorillo et al. 2016a), the preservation of the dune environment must be one of the main aims of the future land-use planning in order to safeguard the quality of the water and air.

Despite Castelfusano dune is embedded in a natural reserve, the equilibrium of the dune environment has been strongly threatened by frequent and intense fires, occurred in last years. Two fires were largely destructive: the July 2000 fire, when more than 30% of the whole forest was burned and the July 2017 fire burned more than 10% of the forest.

The fire recurrence is very dangerous in the dune environment due to the loss of forest cover and the deterioration in the soil characteristics. These effects might affect the fresh dune aquifer recharge processes, particularly altering the fresh –salt water equilibrium (Teobaldelli et al. 2004; Antonellini and Mollema 2010; Werner et al. 2013). There are many works in literature dealing with the fire effects on soil properties, especially concerning the short – term variations (hourly – daily time scale) of the water repellency (De Bano 2000; Tessler et al. 2008; Malkinson and Wittenberg 2011; Jimenez-Pinilla et al. 2016). These studies focused on the increase of the erosion rate in a drainage river basin, after important fire events (Letey 2001; Badia et al. 2015), or on the evaluation of the reduction of the infiltration rate as a result of the fire effect on soil properties. The reduced water infiltration after a fire is used to be estimated by the post-fire assessment of the extent and degree of fire-induced soil water repellency (Pierson et al. 2001). Moody et al. (2009) found that hydraulic conductivity is inversely related to the degree of soil water repellency and Robichaud (2000) indicating that the after-fire water repellent soil conditions temporarily cause a 10–40% reduction in hydraulic conductivity values if compared to normal infiltrating soil conditions. Martin and Moody (2001) pointed out that the infiltration rates are less in the burned sites than in unburned sites. The volcanic soils showed in particular the greatest difference in infiltration rates in burned to unburned sites. The ratio infiltration rate ranges between 15% and 38%, depending on the forest cover type.

The long – term changes (yearly time scale) in groundwater recharge rate induced by fire, can be also related to the decrease in evapotranspiration as a result of vegetation losses in the forest (Ben-Hur et al. 2011; Inbar et al. 2014). Water balance can change therefore after a forest fire, and the reduction of one of the output terms (evapotraspiration) lead to an increase in infiltration rate (input term). It seem that increasing the burn frequency and removal of forest cover promotes the groundwater recharge processes (Silberstein et al. 2013), so that in a Adriatic coastal area the estimated recharge rates are increased in the partially and completely burnt areas (219 and 511 mm/ year, respectively) compared with the pristine pine forest area (73 mm/ year) (Giambastiani et al. 2018).

In the Castelfusano pine forest, after the 2000 fire, a municipal project aimed to the environment restoration, included the installation of a monitoring network to detect the groundwater depth and its degree of salinization. This section of the project has only partially been realized: the monitoring network was in fact completed but the monitoring activity never officially started. The monitoring network was only used for educational purposes by the geological degree course of Roma Tre University and the so far collected data are very discontinuous and heterogeneous. The current research aims to analyse the mechanisms of the recharge process and try to investigate the potential fire effects by examining the water head measurements and chemical – physical parameters carried out from 2002 up today. Anyway, the details of the aquifer recharge process have to be well known, in advance. For this reason, the present paper mainly focuses on the local hydrogeological conceptual model, looking further into the flow boundary conditions and on the groundwater flow path definition. In the second section of the paper, the amount of groundwater recharge was calculated yearly in order to estimate the system recharge evaluating the possible relationship between the recharge amount and fire events.

The achieved results constitute the benchmark of the subsequent studies, already partially ongoing, on possible changes of the recharge attitude of the Castelfusano dune aquifer, following fire events, with an emphasis on the environmental repercussions of the analized process.

Study area

The study area corresponds to Castelfusano dune, located 20 km southwestern of Rome (41°43' N; 12°19'E), along the Tyrrhenian shoreline on the left bank of Tiber River delta (Fig.1). The left bank of the delta is made up by Pleistocene and Holocene mostly sandy sediments (Milli et al. 2013 and references therein) hosting a fresh-brackish water multilayer aquifer (Mazza et al. 2015; Mastrorillo et al. 2016a; Mastrorillo et al. 2016b). The Pleistocene transitional mid-littoral deposits (sands, silty-sands, and clays interbedded with gravels), characterized the inland sector of the delta plain. The Castelfusano dune is located in the seaside sector of the delta plain, where only the Holocene deposits (coastal and aeolic sands) are present. Pleistocene and Holocene deposits show a heteropic contact, dipping towards the sea (SW), and buried under swamp deposits (peat, silt and clay), filling the drained wetland areas located behind the coastal dune ridge (Funiciello and Giordano 2008). The dewatering pumping activities, started in 1884 and still active today, influence the groundwater flow path of the regional multilayer aquifer. In the northwestern part of the plain, the current pumping activity leads to a depression level of the water table up to 3 m b.s.l. in order to keep the groundwater below the ground surface forcing the newlocal reference of the groundwater circulation. In the southeastern sector, the unhindered groundwater flows towards the sea. The Castelfusano dune is locate in the transitional area between the groundwater circulation affected and not affected by the pumping system. In addition, an important drainage canal flows parallel the northeast slope of the dune.

At regional scale, a high groundwater level (about 1 m a.s.l.) is shown (Fig. 1) in the Castelfusano dune, according to the typical dune hydrogeological model. A freshwater phreatic aquifer is hosted by wind-blown sands, accumulated on top of less permeable sediments which base of the dune system aquifer and usually host a deeper groundwater circulation (Stratford et al. 2013; Abesser et al. 2017).

The study area showed a typically Mediterranean clime, with a mean annual rainfall of 700 mm and a mean annual temperature of 16.5 °C. Most rainfall is concentrated in late fall and a 4-monthly dry period extended from June to September with July being the driest month (Mazza et al. 2011).

In the Castelfusano dune, a pinewood creates a wide crop layer with a subcanopy dominated by holm oak and other typical broadleaf maquis shrubs but in recent years hundreds of outbreaks of fires have devastated the pine forest. On 4 July 2000, 3.0 - 3.5 km^2 of pine forest and evergreen Mediterranean were burnt by fire, of which 2.8 km^2 were completely destroyed. Other serious fires that have decimated hectares reserve of Pinus pinea there were on 9 July 2002, from June to September 2003, 11 July 2004 and 1st July 2005. In July 2008, at least another 0.8 km^2 of pine forest have been destroyed by a series of arson fires. At the last, 27 July 2017, 1.0 km^2 of the pinewood were burned again.

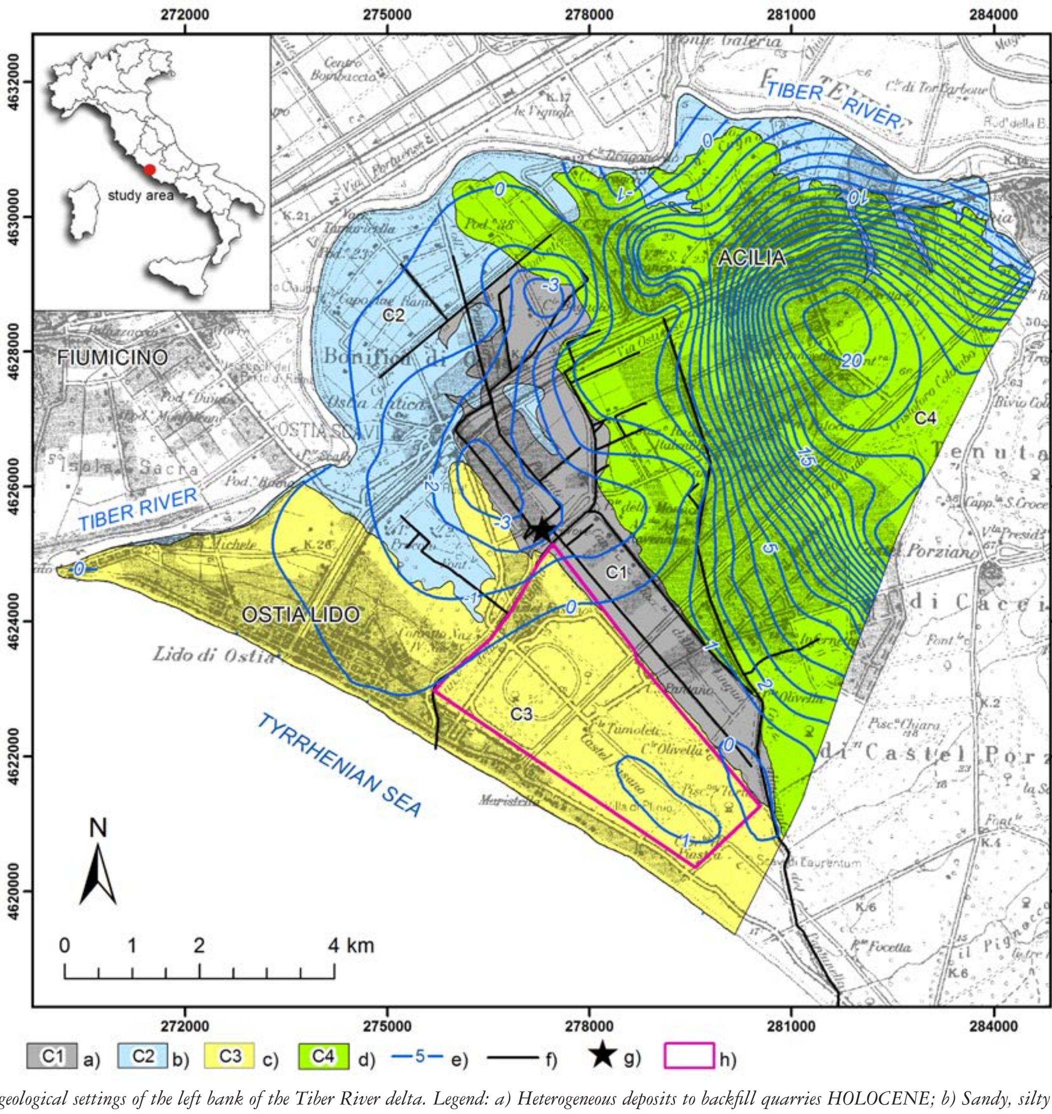

Fig. 1 - Hydrogeological settings of the left bank of the Tiber River delta. Legend: a) Heterogeneous deposits to backfill quarries HOLOCENE; b) Sandy, silty and clayey alluvial deposits HOLOCENE; c) Sandy beach deposits HOLOCENE; d) Heterogeneous clastic deposits (Sandy- silt and clay deposits interbedded with gravels) PLEISTOCENE; e) groundwater contour lines (1 m interval); f) drainage canals system; g) Ostia dewatering pumping station; h) study area.

Fig. 1 - Assetto idrogeologico del settore sinistro del Delta del Fiume Tevere. Legenda: a) Depositi di bonifica OLOCENE; b) Depositi alluvionali sabbiosi, siltosi e argillosi OLOCENE; c) Depositi sabbiosi di spiaggia OLOCENE; d) Depositi clastici eterogenei (depositi sabbioso-siltosi e argillosi intercalati con ghiaie) PLEISTOCENE; e) superficie piezometrica (equidistanza: 1 m); f) canali di bonifica: g) stazione di pompaggio delle Idrovore di Ostia; h) area di studio.

Data and methods

All available information concerning the geology and hydrogeology of the study area were collected and analysed. Most of data were detected from the piezometers of the monitoring network built in the pinewood area. Information about stratigraphic and groundwater levels were also taken from external points, neighbouring with the study area. The locations of main data points are shown in Fig. 2.

Collected data

Eight borehole stratigraphic data, available in the literature and including the data of monitoring network piezometers drilling, were selected to draw a SSE-NNE litostratigraphic cross-section, useful to understand the 3D aquifer geometry. The depth of the boreholes is between 8 and 30 meters, so the geometry of the deposits underlying the actual dune was also investigated.

Groundwater data collection consisted of water level measurements, physical-chemical characterization with temperature, pH and electrical conductivity (EC - 25 °C) measurements. All data refer to the groundwater monitoring network present within the Castelfusano forest and to three piezometers of the neighbouring monitoring system of Castelporziano Presidential Estate. The Castelfusano network includes 21 measurements point (piezometers), 17 of which

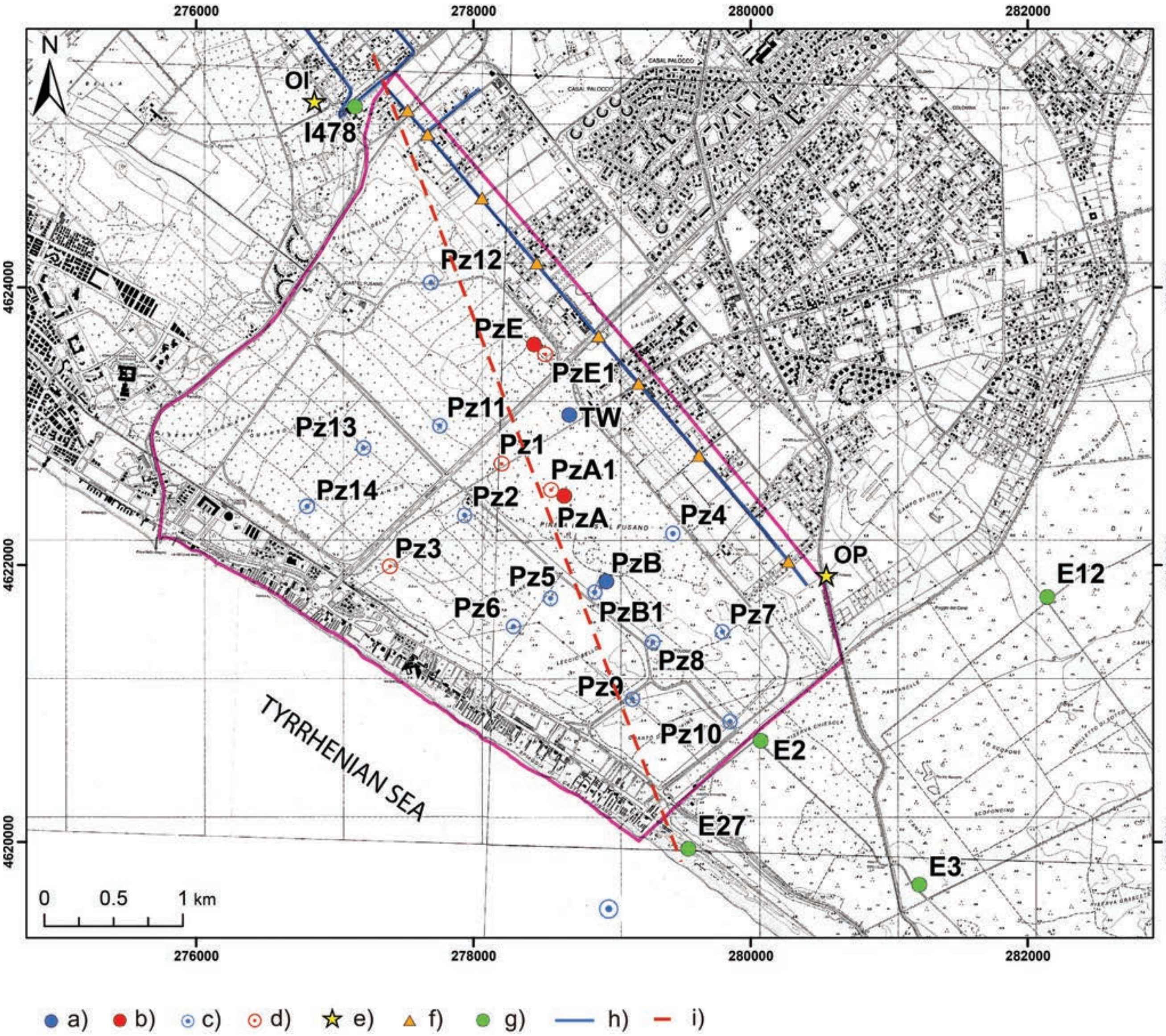

Fig. 2 - Spatial distribution of measurement points and their technical features. a) deep wells with manual measurements; b) deep wells with automatic probe; c) shallow wells with manual measurements; d) shallow wells with automatic probe; e) weather stations; f) measurements point of the bottom elevation along of the drainage Canale Primario di Levante (CPL); h) main drainage canals; i) location of lithostratigraphic cross-section.

Fig. 2 - Ubicazione dei punti di misura distinti sulla base delle loro caratteristiche tecniche. a) piezometri profondi con misurazioni manuali; b) piezometri profondi con sonda automatica di misura; c) piezometri superficiali con misurazioni manuali; d) piezometri superficiali con sonda automatica di misura; e) stazioni termo-pluviometriche; f) punti di misura della quota di fondo del Canale Primario di Levante (CPL); g) punti di misura esterni all'area di studio, h) principali canali di drenaggio; i) traccia della sezione litostratigrafica.

are 8 m deep (here named "shallow wells"), the other 4 piezometers reach the depth of about 30 meters ("deep wells"). The screens are located in the last 3 meters of each piezometer to prevent any possible mixing with overlapping aquifers.

Data were manually collected since June 2002, but monthly continuous datasets are available only for three periods (June 2002 – August 2003, April 2011 – May 2012, May 2016 – June 2017), with one measurement carried out at the end of each month.

Daily monitoring has been performed in 6 piezometers, 2 deep wells (PzA and PzE) and 4 shallow wells (PzA1, Pz1, Pz3, PzE1). Water-table depths, groundwater temperature and EC have been recorded by downhole data loggers with atmospheric compensation. The daily monitoring started in May 2016 and is still ongoing with a measurement frequency of 12 hours.

Thermo-pluviometric data were collected from local weather stations managed by Hydrographic Services of Lazio Region (Regione Lazio – Agenzia Regionale di Protezione Civile). Fosso di Pantanello station (OP in Fig. 2), placed at 5 m a.s.l. in the south-eastern boundary of Castelfusano dune, is the reference meteorological station from 2012; for the previous period (2002-2003) pluviometric data were acquired from Ostia_Idrovore station (OI in Fig. 2) (placed at 4 m a.s.l. in the northern boundary of dune) and thermometric data acquired from Roma Sud ACEA station (located at 10 m a.s.l and 8 kilometres due northeast of the dune).

In September 2002 and December 2015 chemical analysis of major ions were performed on water samples taken from all monitoring wells by ion chromatography (Dionex DX-120) on unacidified (Cl^-, and SO_4^{2-}) and acidified (Na^+, K^+, Mg^{2+} and Ca^{2+}) samples. The total alkalinity (as HCO_3^-) was determined in situ after collection by titration, with 0.1 M HCl against methyl orange indicator. All water analyses point out an error on the charge balance less than ±5%.

The elevation along of the drainage Canale Primario di Levante (CPL) was measured in 8 points, part of a geodetic survey carried out by network makers in order to dimension the monitoring network wellheads.

Methods of data processing

Data processing consisted in two main phases: i) the analysis of the geological and hydrogeological data in order to set up the local hydrogeological conceptual model; ii) the evaluation of the yearly groundwater recharge in periods differently affected by the forest fires.

The groundwater levels and EC data were elaborated with Natural neighbour triangulation in order to define the piezometric and EC distribution for all existing measurement campaigns. For this specific study, the minimum and the maximum water table surface elevations and the related EC spatial distributions were taken in account for each of three monthly continuous data sets available.

These elaborations were carried out only on the shallow wells data. The deep wells data were considered at a later stage, to obtain a comparison between the shallow and the deep groundwater circulations.

The annual groundwater recharge was calculated by two different methods and the results were compared to verify the differences (Sophocleus 1991; Jie et al. 2011), for the 2002-2003, 2011-2012, 2016-2017 and 2017-2018 recharge periods.

The applied methods are: Water Table Fluctuation (WTF) (Healy and Cook 2002) and Thornthwaite Groundwater Budget (TGB) (Thornthwaite and Mather 1957), both well-known from literature and easy to use.

The WTF method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table. If the water level rise and the specific yield are known, the recharge can be inferred:

$$R = \Delta h \cdot S_y$$

where: R is recharge, Δh is change in water table height and S_y is specific yield, defined as the volume loss or gain of water per unit area of aquifer associated with a corresponding unit drawdown or rise in water table (Freeze and Cherry 1979). In a water level hydrograph Δh is the difference between the peak of the rise and low point of the extrapolated antecedent recession curve at the time of the peak. Because rainfall is not the only factor that can cause the water table to rise, to estimate Δh, all other causes of the water table rising need to be filtered out to prevent an overestimation of the recharge (Healy and Cook 2002; Crosbie et al. 2005; Delin et al. 2007; Cuthbert 2010; Fan et al. 2014). The method is best applied in areas with shallow water tables that demonstrate sharp rises in water levels over short time periods, it is therefore well applicable in a coastal sandy environment like the Castelfusano dune aquifer. Experimental data about the local specific yield are not available, therefore it was estimated equal to 0.20 according to huge literature base (Prickett 1965; Johnson 1967; Celico 1986; Civita 2005; Fan et al. 2014). For the 2002-2003, 2011-2012 and 2016-2017 recharge periods, the mean Δh was evaluated as average of all Δh values of each shallow well. The mean Δh value was whereas calculated for 2017-2018 recharge period using only the four shallow wells equipped with automatic probes. For consistency with the previous periods, only the daily values recorded the last day of each month were considered.

The annual recharge of the same periods was also evaluated with TGB.

The monthly actual evapotranspiration and the water surplus (WS) (available water after the evapotranspiration process) were calculated according the monthly thermo-pluviometric dataset and using the Thorntwaite method. A mean soil moisture capacity of 40 mm was considered in order to estimate the WS, taking in account both the water depth (around 2 - 3 m b.g.l.) and the immature, sandy soils with not always dense vegetation (Carretero and Kruse 2012). The monthly effective infiltration (as the portion of the water surplus that can infiltrate) was calculated multiplying the monthly water surplus with a coefficient of potential infiltration of 0.80, mean value for the coastal sandy deposits in our latitudes (Celico 1988; Civita 2005).

The calculation of the effective infiltration was performed in the same periods considered in the WTF application.

Results

The elaboration of the collected data allowed to achieve two types of results, according to the different criteria of data processing. The first result concerns the local hydrogeological conceptual model. The second results are related to the evaluation of the yearly amount of groundwater recharge.

The lithostratigraphic reconstruction, from the boreholes data, (Fig. 3) shows an about 8 m thick continuous sand shallow layer, and a continuous clay deposit with a thickness at last 10 m, at a depth of about 30 - 35 m b.s.l. , 25 m of a very heterogeneous sequence are present between these two uniform deposits. The sequence consists of silty sand (mainly in the SSE sector) and sand with interbedded clay silt (mainly in the NNW sector). The sequence also contains several sandy gravel lenses at different depths. The local stratigraphic succession is in accord with the regional geological setting providing for Holocene deposits (dune sands) overlapping the Pleistocene transitional mid-littoral deposits, below which the Plio-Pleistocene marine shale bedrock was recognized (Funiciello and Giordano 2008).

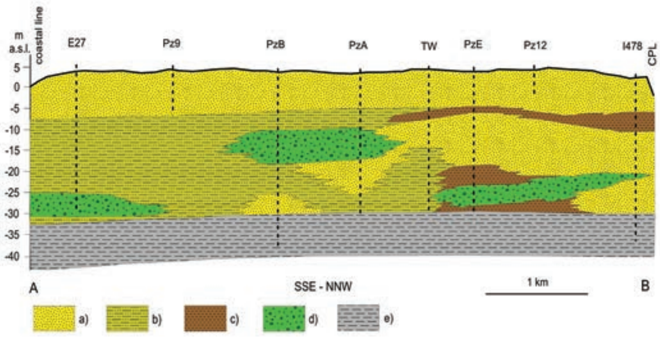

Fig. 3 - Lithostratigraphic cross-section. Legend: a) sand; b) silty sand; c) clayey silt; d) sandy gravel; e) clay. The section location is reported in Fig. 2.

Fig. 3 - Sezione litostratigrafica. Legenda: a) sabbia; b) sabbia limosa; c) limo argilloso; d) ghiaia sabbiosa; e) argilla. La traccia della sezione è riportata in Fig.2.

The water table maps of the three periods taken in account (Fig. 4), show similar shapes both in dry and wet seasons, with a mean groundwater level fluctuation of about 0.5 m.

A main groundwater divide runs parallel to the dune belt and divides the flow heading for the drainage canal (along the northeast slope of the dune) from the one towards the sea. A secondary divide, perpendicular to the dune belt, separates the dune aquifer circulation in Castelfusano to Castelporziano Presidential Estate.

Another significant result is the comparison between the piezometric data collected in the deep wells and the elaborated water table map realized using the data collected in the shallow wells. The groundwater levels of PzA and PzB matches the shallow groundwater table, on the contrary, the water levels of the PzE and TW are usually about 0.70 m lower and 1 m higher than water table, respectively (Table 1)

The chemical – physical characteristics of the aquifer are seasonally stable, and highlights a mild salinization of coastal sector (EC up to 3000 µS/cm) and certainly fresh waters (EC about 700 µS/cm) in the area located behind the coastal dune ridge (Fig. 5).The EC measured in the PzA and PzB deep wells is congruent with the values of shallow aquifer, whereas, PzE and TW are more salinized (more than 9000 µS/cm and about 1300 µS/cm respectively).

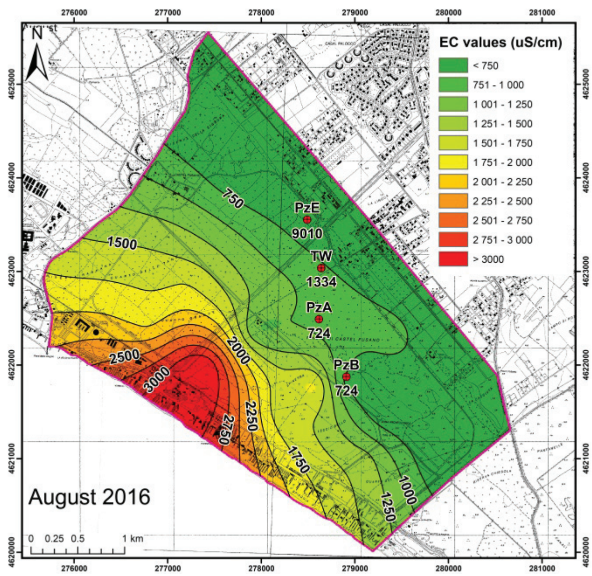

Fig. 5 - Electrical conductivity map of the shallow aquifer and comparison with the deep EC measured values. The deep wells are in red with the ID code and the measured EC value.

Fig. 5 - Carta della conducibilità elettrica dell'acquifero superficiale e confronto con i valori di conducibilità elettrica misurati nei piezometri profondi. I punti rossi indicano i piezometri profondi, con sigla identificativa e valore di conducibilità elettrica misurata.

In the Piper diagram (Fig. 6A) most of the water samples cluster around the Ca–HCO_3 field with a minority enriched in the NaCl composition up to the PzE sample, very similar to the sea water. The highest EC values correspond with NaCl water types confirming the marine origin of the mineralization. This process is clearly shown in the Na^+ vs Cl^- concentration plot (Fig. 6B), where all samples are aligned along freshwater - seawater mixing line.

Tab. 1 - Water levels in the deep piezometers. Elevation in m a.s.l.; n.a.: not available data.

Tab. 1 - Quote piezometriche dei piezometri profondi (m s.l.m.); n.a.: dato non disponibile.

Deep wells	Oct-02	Mar-03	Oct-11	Mar-12	Aug-16	Dec-16
PzA	0.02	0.57	0.85	1.32	0.06	0.76
PzB	0.26	0.63	0.97	1.40	0.27	0.96
PzE	n.a.	n.a.	-0.40	-0.05	-1.01	-0.44
TW	n.a.	n.a.	n.a.	n.a.	0.69	1.36

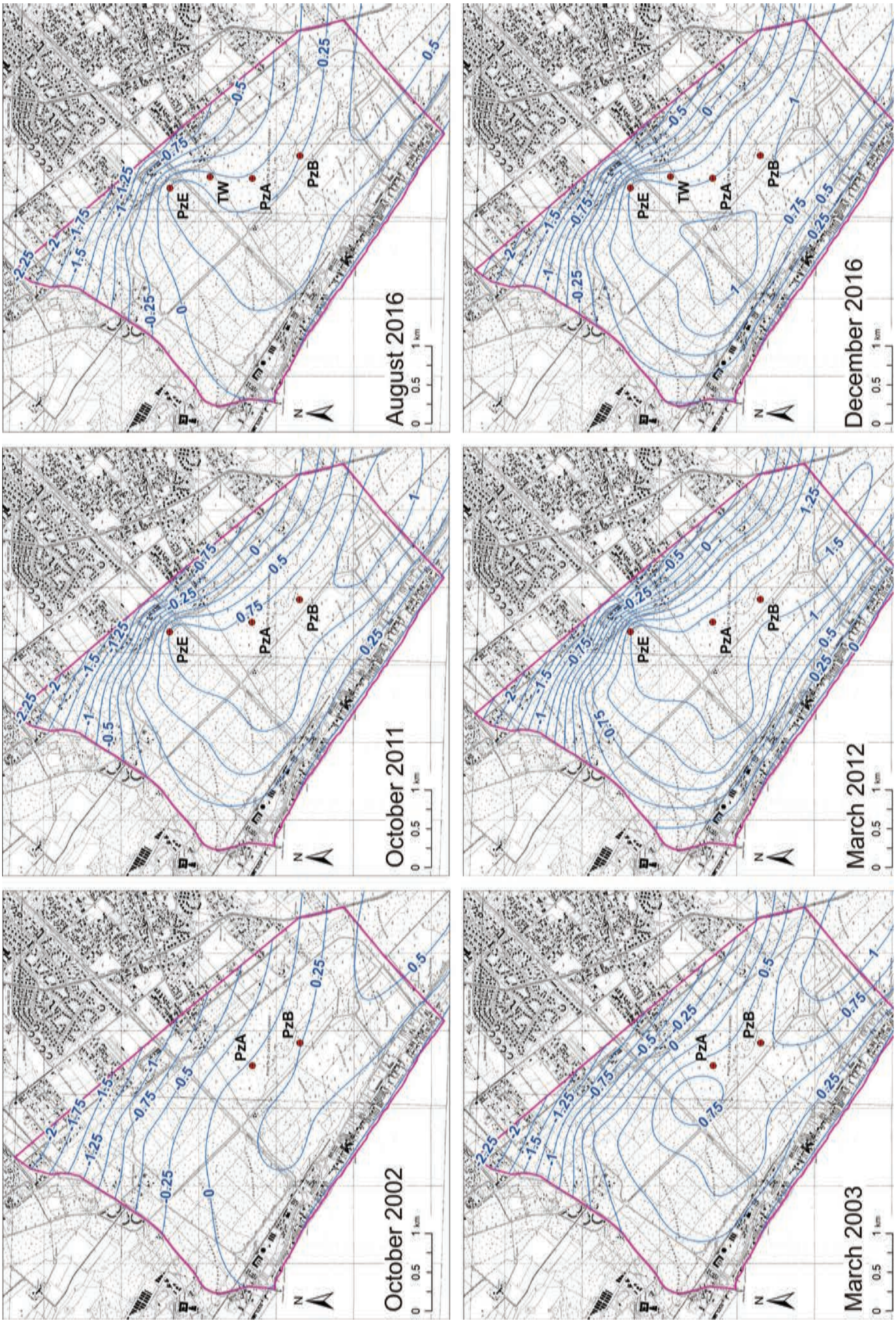

Fig. 4 - The lowest (on the first line) and the highest (on the second line) water tables in the three considered periods; the map was realized using only the shallow wells data. The deep wells (in red) are indicated and their groundwater levels are reported in Table 1.

Fig. 4 - Superficie piezometrica massima (in alto) e minima (in basso) dei tre periodi considerati, ricostruita con i dati dei piezometri superficiali. I punti rossi indicano la posizione dei piezometri profondi, le altezze piezometriche dei quali sono riportate in Tabella 1.

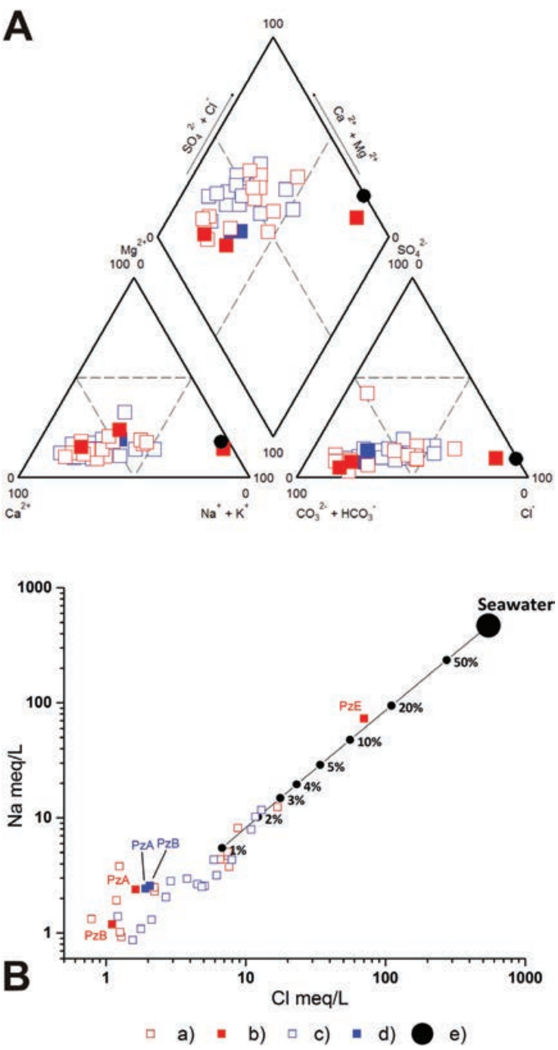

Fig. 6A,B - Piper diagram (A) and Na+ vs Cl- concentration plot (B) of the groundwater samples. Legend: a) 2015 shallow wells; b) 2015 deep wells; c) 2002 shallow wells; d) 2002 deep wells; e) seawater.

Fig. 6A,B - Diagramma di Piper (A) e grafico di correlazione della concentrazione degli ioni Na^+ e Cl^-. Legenda: a)campioni prelevati nei piezometri superficiali nel 2015; b) campioni prelevati nei piezometri profondi nel 2015; c) campioni prelevati nei piezometri superficiali nel 2002; d) campioni prelevati nei piezometri profondi nel 2002; e) composizione dell'acqua di mare.

Before outlining the results regarding the recharge, it is useful to analyse the trend of water level fluctuation against the rainfall and WS (Fig. 7).

It is clear that the same water level trend occurs in the shallow and deep (indicated with a red line) wells, showing an immediate response to the rainfall recharge at monthly scale.

Based on the assumption that the infiltration process is possible only when the WS is greater than zero, during the study periods, the recharge lasted for a minimum of three and a maximum of five months.

In detail, the total rainfall of 2002-2003 hydrological year was about 850 mm, about 20% more than the mean value of the study area (700 mm) (Mazza et al. 2011). The recharge of this period lasted only three months, starting in November 2002 and stopping in January 2003. Although it rained much in the summer months before (about 300 mm), the summer rainfall is not able to contribute to the recharge process.

The total rainfall of 2011 – 2012 and 2016-2017 hydrological years (both of about 640 mm) were similar to the average value, but while for the 2011- 2012 three significant recharge months were spread for five months (October 2011 - February 2012), for the 2016-2017 the recharge was concentrated in only two months (September and October 2016).

In the 2017-2018 hydrological year, total rainfall was about 800 mm (about 14% more than the average value) and the recharge was prolonged for five months, between September 2017 and March 2018.

The Δh values of each shallow well were calculated with WTF method for the four recharge periods considered and the results are reported in Table 2. The 2017 - 2018 Δh values are calculated only for the well equipped with the automatic probes, because the manual measurements of all piezometers were not carried out during this period. The last two lines of the Table 2 show average Δh values: in the "MEAN" line the average Δh values of all wells is reported; in "MEAN*" the average Δh value of only wells with automatic probes is presented. The average Δh values calculated for the 2011-2012 and 2016-2017 periods are very similar. It is therefore reasonable to consider that the 2017-2018 mean Δh value, calculated only from four wells, is representative of the overall trend.

Tab. 2 - Δh values (m) of each shallow well, calculated with WTF method. The asterisk indicates the wells with automatic probe and the related mean value of Δh. n.a.: not available data.

Tab. 2 - Valori di Δh (m) dei piezometri superficiali, calcolati con il metodo WTF. Con l'asterisco vengono distinti i piezometri con sonde automatiche e il relativo valore medio di Δh. n.a.; dato non disponibile.

Well	2002-03	2011-12	2016-17	2017-18
Pz1*	1.16	1.15	0.99	1.71
Pz2	0.69	0.96	0.81	n.a
Pz3*	0.88	1.26	0.89	1.21
Pz4	0.90	1.07	1.00	n.a.
Pz5	0.54	1.07	0.79	n.a.
Pz6	0.63	1.07	0.79	n.a.
Pz7	1.17	n.a.	n.a.	n.a.
Pz8	0.77	1.15	0.84	n.a.
Pz9	0.82	1.10	0.76	n.a.
Pz10	0.74	1.24	0.86	n.a.
Pz11	0.77	n.a.	n.a.	n.a.
Pz12	0.84	1.35	0.86	n.a.
Pz13	0.63	1.22	0.73	n.a.
Pz14	0.77	1.24	0.97	n.a.
PzA1*	n.a.	1.23	0.93	1.56
PzE1*	n.a.	1.08	0.78	1.95
MEAN	0.81	1.16	0.86	n.a.
MEAN*	n.a.	1.18	0.90	1.61

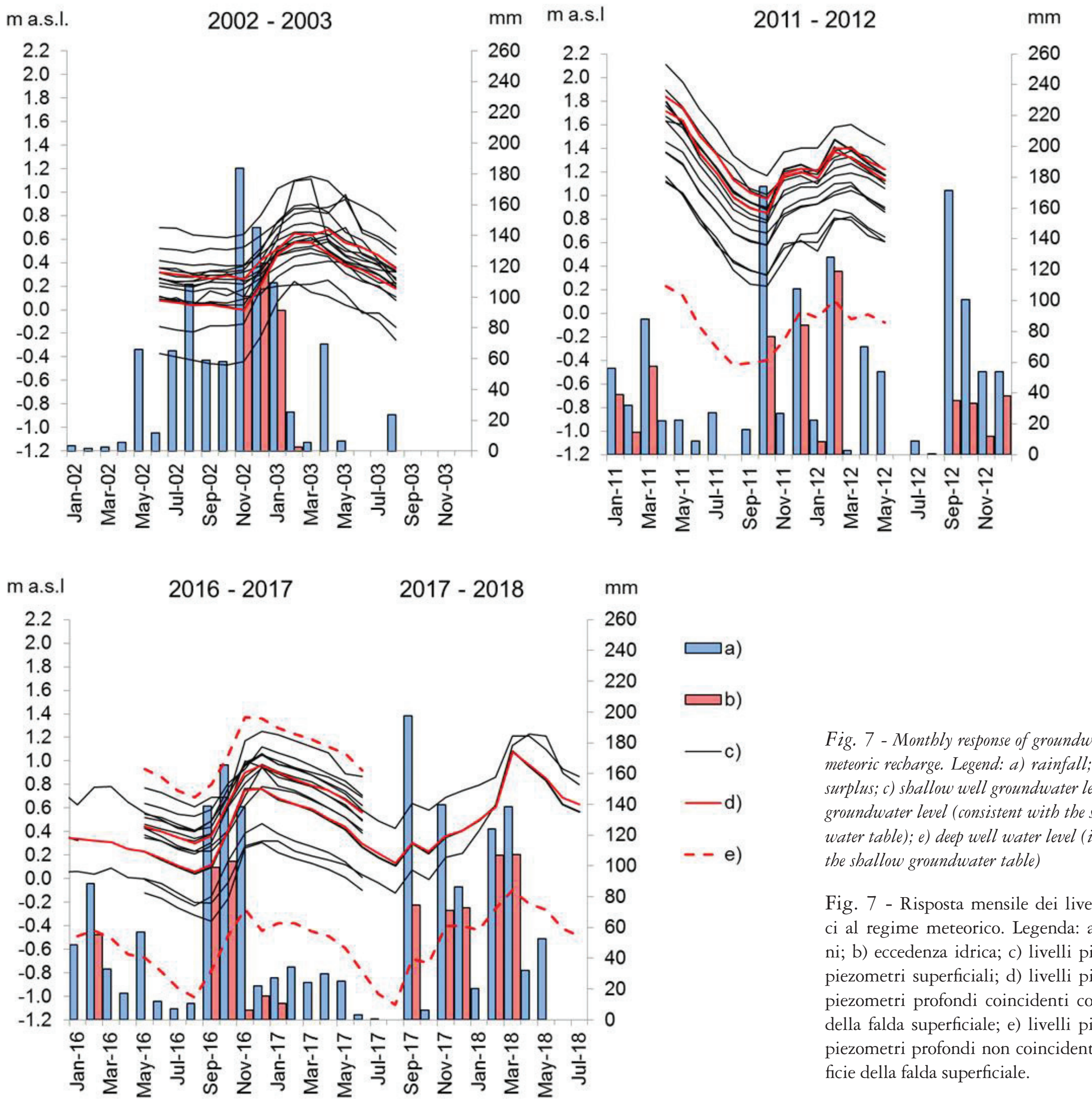

Fig. 7 - Monthly response of groundwater levels to the meteoric recharge. Legend: a) rainfall; b) WS - water surplus; c) shallow well groundwater level; d) deep well groundwater level (consistent with the shallow groundwater table); e) deep well water level (inconsistent with the shallow groundwater table)

Fig. 7 - Risposta mensile dei livelli piezometrici al regime meteorico. Legenda: a) precipitazioni; b) eccedenza idrica; c) livelli piezometrici dei piezometri superficiali; d) livelli piezometrici dei piezometri profondi coincidenti con la superficie della falda superficiale; e) livelli piezometrici dei piezometri profondi non coincidenti con la superficie della falda superficiale.

For the same observation periods the annual effective infiltration (EI) was evaluated from the monthly rainfall data with TGB. In Table 3 and in Fig. 8 the results of application of the TGB method and the next evaluation of EI are reported for the four considered hydrological years. The Table 3 reports both the total annual rainfall (AR) and the total rainfall of the only recharge months (RPR) in order to emphasize that the aquifer recharge is the highest (EI: 346 mm in 2017-2018 period) when the value of RPR is maximum (Fig. 8). As explained above, about the 40% of the highest value of AR (800 mm) measured in 2002-2003 period occurred during the summer months and therefore it cannot contribute to the recharge process.

Excluding the 2002-2003 data because of the anomalous rainfall seasonal distribution, the EI values correspond at about 35% of AR in 2011 – 2012 and 2016-2017 period, and at more than 50% of AR in 2017-2018 period. These rates are congruent with the literature that both suggests the maximum EI value of 470 mm against RA of 700 mm (Celico 1986) and identifies the 2011 – 2012 and 2016 – 2017 hydrological years as the most drought years of the last twenty years. (ABT and IRSA 2017).

Tab. 3 - Results of the application of the TGB method and the next evaluation of EI. All values in mm. AR: annual rain; RPR: recharge period rain; WS: water surplus; EI: effective infiltration.

Tab. 3 - Risultati ottenuti dall'applicazione del metodo TGB e dalla successiva procedura di valutazione dell'EI. Tutti i valori sono espressi in mm. AR: pioggia annua; PRP: pioggia cumulata del periodo di ricarica; WS: eccedenza idrica; EI: infiltrazione efficace.

Hydrological year	AR	RPR	WS	EI
2002-2003	847	463	316	253
2011-2012	638	432	288	230
2016-2017	637	493	234	188
2017-2018	797	686	433	346

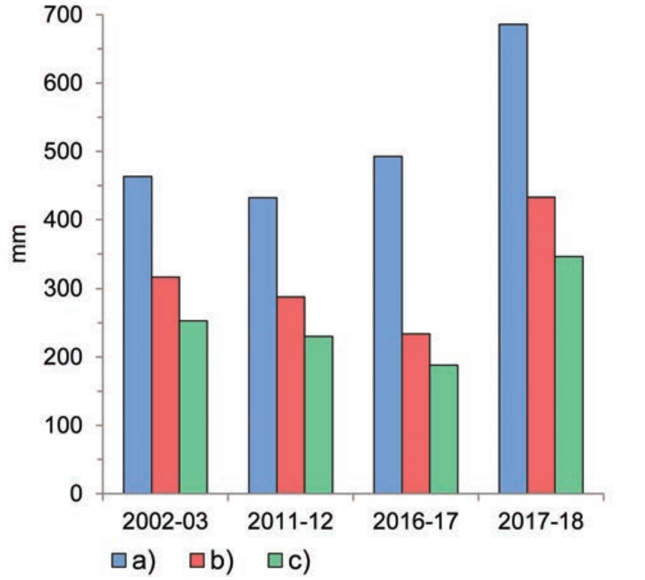

Fig. 8 - Results of the application of the TGB method and the EI evaluation. Legend: a) recharge period rain (RPR); b) water surplus (WS); c) effective infiltration (EI).

Fig. 8 - Risultati ottenuti dall'applicazione del metodo TGB e dalla successiva procedura di valutazione dell'EI. Legenda: a) pioggia del periodo di ricarica (RPR); b) eccedenza idrica (WS); c) infiltrazione efficace (EI).

Discussion

Castelfusano dune hydrogeological system

According to the regional hydrogeological setting, the site-specific hydrogeological model of Castelfusano dune provides a shallow unconfined aquifer, hosted by Holocene sand dune and two overlapping confined deep aquifers, hosted by Pleistocene heterogeneous clastic deposits. The whole groundwater circulation is sealed at the bottom by a clay basal aquiclude (Fig. 9).

This system, toward the sea, is in lateral contact with the saltwater - freshwater interface, reached at 24 m b.s.l. by a borehole drilled about 3 km further South East in close proximity (about 300 m) to the shoreline (Mastrorillo and Petitta 2009).

The shallow aquifer presents two main flow directions, one toward South West, with a basal level corresponding to the sea level and another toward North East, with a basal level between 0 and -2 m b.s.l., along of the drainage Canale Primario di Levante (CPL). According to the identified groundwater divide, the shallow aquifer hosted in the Castelfusano dune can be supposed a closed hydrogeological system, recharged only by the zenithal infiltration within its boundaries. This

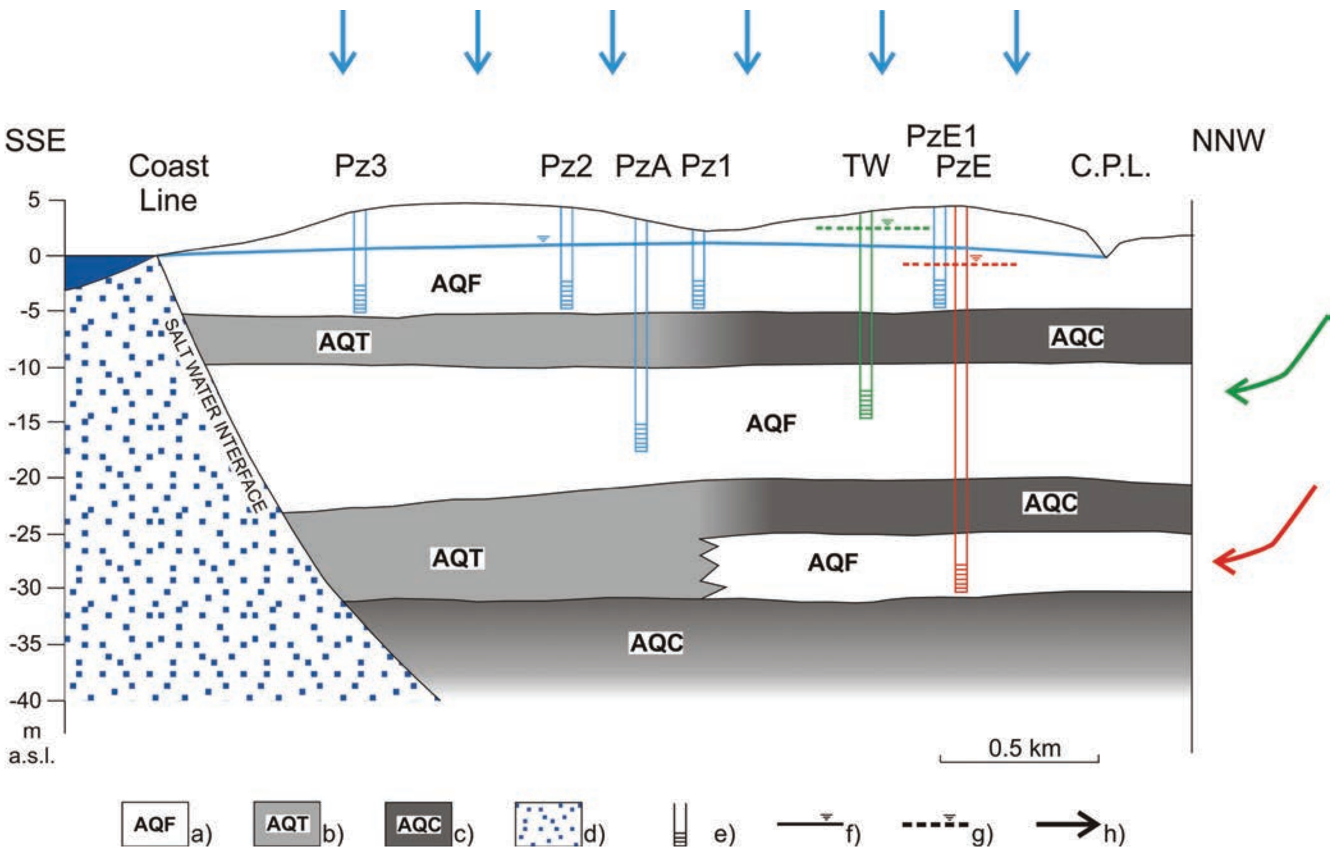

Fig. 9 - Simplified conceptual scheme of the Castelfusano dune hydrogeological system. Legend: a) aquifer; b) aquitard; c) aquiclude; d) sea water; e) well and screen position; f) water table of the unconfined aquifer; g) piezometric level of the confined aquifers; h) recharge of the aquifers. In cyan the elements referred to the shallow dune unconfined aquifer, in green and in red the elements referred to the deep confined aquifers.

Fig. 9 - Schema concettuale semplificato del sistema idrogeologico della duna di Castelfusano.
a) acquifero; b) aquitard; c) aquiclude; d) acqua di mare; e) piezometri e posizione dei filtri; f) superficie freatica dell'acquifero libero; g) livello piezometrico degli acquiferi in pressione; h) ricarica degli acquiferi. In celeste sono riportati gli elementi relativi alla falda libera, in verde e in rosso quelli attribuibili alle falde in confinate.

aquifer presents a moderate salinization (max EC of 4000 μS/cm) of marine origin, related more to the sea spray aerosol and to the canopy effect (Tuccimei et al. 2010; Manca et al. 2014b) rather than to the seawater intrusion.

At the mean deep of 5 m b.s.l. the shallow aquifer lies on a low hydraulic conductivity layer about 5 m thick. The hydrodynamic attitude of this layer goes from the aquiclude to aquitard, based on the lithological composition. Generally, the clay silt component seems gradually to increase moving towards East, so it is possible to hypothesize the presence of a real aquiclude only in the North Eastern side.

This particular setting implicates a likely hydraulic continuity between the shallow and deeper aquifer only in the West side of the dune system, where in fact, the shallow and deep wells present the same hydraulic head. On the contrary, in the Eastern sector the higher hydraulic conductivity contrast isolates the two overlapping aquifers and keeps different groundwater levels. Also the EC values of shallow and deep wells are the same in the Western side of the system, whereas they appear significant different Eastern sector, with higher EC values detected in the deeper aquifer.

The third and deepest aquifer was reached at about 30 m b.s.l in a gravelly layer, underlying another low hydraulic conductivity level that acts like an aquiclude in the East sector. In the Western side of the dune, the same deep drillings do not reach any aquifer. The third aquifer is a confined and salt aquifer, completely isolated from the other identified aquifers. It has been likely contaminated by salt intrusion, indeed, the aquifer depth corresponds to the position of salt water interface reached by the drilling in the shoreline (Fig. 9).

In the present state of the research the recharge area of the two deep aquifer is not yet identified exactly, but it is reasonable to suppose a groundwater recharge from inland areas, where the aquifer outcrop.

The evaluation of the annual amount of groundwater recharge in different periods

The present study focuses also on the recharge processes of the shallow fresh dune aquifer, without exploring the link between the three aquifers described.

The comparison of the results obtained from the different methods of recharge calculation (Table 4) allows to highlight the following considerations.

i. The difference between the WTF recharge and TGB recharge is less than 10% of the obtained results for three out of four periods (2011-2012; 2016-2017; 2017-2018). This difference is not significant, according to the structural errors, which characterize in the used methods. Given that the recharge is counted as a groundwater amount variation in the aquifer from the WTF method, and as a rate of rainfall from the TGB method, the convergence of the results can be interpreted as a proof of hydraulic sealing of the shallow aquifer. Therefore, any contribution from the underlying aquifers can be considered negligible.

ii. There are some uncertainties about the 2002 – 2003 period results. During this period the recharge amount evaluated from the rainfall (TGB method) is 36% more than actually stored in the aquifer (WFT method). This discrepancy could indicate a really EI decrease caused by the 2000 fire effect on soil properties. Specifically, an EI decrease of 36% seems be in according to an EI decrease in volcanic soils found by Martin and Moody (2001). To confirm this hypothesis it is necessary to develop a research on the relationship between EI rates, soil and cover forest types. It is important to remark that none EI decrease was observed after the 2017 fire, probably related to a smaller extension of the burned area (1.0 km^2) than the 2000 fire (3.0 - 3.5 km^2).

Tab. 4 - Comparison of the recharge values (in mm) obtained from the two different methods (WTF: Water Table Fluctuation; TGB: Thornthwaite Groundwater Budget).

Tab. 4 - Confronto fra I valori di ricarica (in mm) ottenuti tramite due differenti metodi di calcolo (WTF: Water Table Fluctuation; TGB: Thornthwaite Groundwater Budget).

	2002-03	2011-12	2016-17	2017-18
WTF	162	232	172	320
TGB	253	230	188	346

Conclusion

The analysis of the likely different responses to the zenithal recharge of the Castelfusano sandy dune aquifer following the large fires (as result of the loss of forest cover and the deterioration in the soil characteristics) was been preceded by the definition of a site-specific hydrogeological model.

A shallow dune aquifer was recognized, with a thickness about 8 meters, at the least five of them saturated by generally fresh water. The aquifer presents brackish water only in the closer to the sea sector, where the salinization was attributed to the sea spray aerosol and to the canopy effect. The dune aquifer overlaps two deeper confined aquifers; the deeper of the two is characterised by salt water, at a depth about 30 m b.s.l.

The study of fire effects was carried out only in the shallow aquifer, because it resulted recharged directly by the rain falling on the Castelfusano dune; whereas there is evidence that the deeper aquifers are recharged through external areas.

The application of two methods of annual recharge calculation (WTF and TGB) provided similar results for the all analysed periods, except for 2002-2003. In this period seems that the actual groundwater stored in the aquifer is less (about 36%) than the assumed recharge amount evaluated from the rainfall. This infers that the infiltration capability of the recharge area could be decreased, as a result of the 2000 huge fire.

Starting from this first result, the ongoing research aims to verify the local changes of the infiltration capability between burned and no burned areas. The 2016 – 2018 daily time series of both the groundwater levels of four shallow piezometers and rainfall are being analysed (cross correlation analysis) in order to identify likely differences of the rainfall responses between the piezometers located in burned and in no burned areas

A reliable response on two fronts is below reported :

a. Is it possible that the changes of soil features continue to cause a capability infiltration decrease two years after the 2000 fire? Generally, the long-term answers rather provide for an EI increase caused by evapotranspiration reduction for the forest cover decrease.

b. The 2017 fire, far less destructive than the 2000 one, did not seem to have detectable effects on the aquifer recharge processes at yearly scale. Is it possible to detect some short or long-term effects at daily scale?

The analysis of the distribution both in the space and in the time of EC and temperature values of groundwater, measured automatically every day in the piezometers, will also provide information suited to the purpose of this research.

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