

# We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

186,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index  
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?  
Contact [book.department@intechopen.com](mailto:book.department@intechopen.com)

Numbers displayed above are based on latest data collected.  
For more information visit [www.intechopen.com](http://www.intechopen.com)



---

# **Irrigation Management in Coastal Zones to Prevent Soil and Groundwater Salinization**

---

Nicolas Greggio, Pauline Mollema,  
Marco Antonellini and Giovanni Gabbianelli

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/50534>

---

## **1. Introduction**

Soil salinization is one of the most widespread soil degradation processes on earth and, worldwide, one billion hectares are affected, mainly in the arid–semiarid regions of Asia, Australia and South America [1]. In Europe, soil salinity has effects on one million hectares mainly in the Mediterranean countries [1]. There are two types of salinization: primary salinization caused by natural events such as sea spray or rock weathering or seepage [2] and secondary salinization that is caused by human activities such as irrigation with salty water, groundwater overexploitation and excessive drainage [1].

Along the Adriatic coast of the Po Plain, freshwater resources are becoming increasingly scarce, because of irrigation and other intense water use, salinization and long periods of drought [3]. Custodio [4] underlines that, especially in southern Europe, the irrigation practices and the water requirements to sustain the coastal tourism industry exert a strong pressure on water resources.

The impact of groundwater salinization in coastal areas affects both natural vegetation biodiversity and agricultural production, through soil salinization and reduction of freshwater availability for irrigation. Salinization is closely associated with the process of desertification, because salinity may have direct negative effects on crop yields by reducing the ability of plant roots to take up water [5]. The most common salinity effect is a general stunting of plant growth, but not all plants respond in the same way. Grain and corn may reduce their seed production without appreciably plant dimensions reduction. Wheat,

barley, cottons seed productions, on the other hand, are decreased less than their vegetative growth [6]. The only agronomical significant criterion for evaluating soil salinization effects is the commercial crop yield decrease [6]. This encourages farmers in certain areas to cultivate salt resistant crops to adapt to high salinity of the soil and groundwater [5]. In our area fresh irrigation water until now was readily available and no salt resistant crops are grown, or other adaptation measures were taken against soil and groundwater salinization of the farmland.

An increase in water and soil salinity within a coastal habitat has direct effects on the natural vegetation and agriculture [5],[7], including decrease in plant species richness, decrease in wetland dry biomass, changes in plant communities, decrease in seedling germination, decrease in surface area of the leaves, decrease in stem length, N<sub>2</sub>-fixation inhibition, increasing mortality, and indirect effects such as habitat loss for some animal species [8],[9],[10].

In the Ravenna province, more than 68 square kilometers of farmland are at a risk for soil salinization (Figure 3). These are primarily the areas near the Pialasse lagoons and near the rivers open to sea (Figure 1). This agricultural land is at sea level and drained by pumping machines. Many of the pumping machines are located 5 km far from the shoreline and they maintain the water table at 2 meters below sea level during the year, creating hydraulic gradients land inwards and promoting salt-water intrusion from the Adriatic Sea [3].

High rates of anthropogenic and natural subsidence and artificial drainage, among others causes, have caused groundwater salinization in the coastal unconfined and semi-confined aquifer near Ravenna, [3],[11] and a subsequent loss of fertile soils and vegetation species richness in the natural areas [7].

In the Ravenna Municipality just about 35000 hectares are agricultural land, of these 30000 are arable land and 5000 are orchards. Irrigation is widely diffuse and more than 50% of farms are equipped for irrigation. Until two decades ago the main source of irrigation water was groundwater from the phreatic and confined aquifers, but the increase of subsidence rates, forced to change the water supply from groundwater to surface water [12],[13], mostly from the Po River and some from the minor rivers flowing from the Apennines.

The phreatic aquifer consists of sandy beach and dune deposits and is unconfined close to the sea and confined by a clay layer further inland (Figures 11 and 12). Two dune belts parallel to the coast covered by pine forests form the only topography above sea level. The area in between the dunes belts is used for irrigated and rain-fed farmland, as well as the land behind the older dune belt, 5 km from the coast (Figure 1).

Most of the coastal aquifer near Ravenna is very salty (above 10 g/l) [3],[11],[14] but, besides some small shallow freshwater lenses at the top of the aquifer, we found freshwater below an irrigated field. In some ways this result is worrying, because

irrigation water should not reach the groundwater, so that leaching of nitrates is avoided and waste of resources prevented. Mollema et al. ([15]) concluded from a water budget analysis over the *Quinto* basin watershed (south of the Ravenna urban area) that the amount of water used for irrigation was abundant but only looked at total volumes for the whole basin and did not quantify the contribution of irrigation to groundwater.

The objective of this study is to quantify in detail the effect of irrigation water on the groundwater hydrology with the help of geochemical analysis, geophysical profiling and infiltration measurements. We address, in particular, the mechanism of how excess irrigation water ends up in the aquifer and how that affects the salinity of the groundwater. By doing all this, we assess whether irrigation practices can help to counteract further groundwater and soil salinization.

## 2. Study area

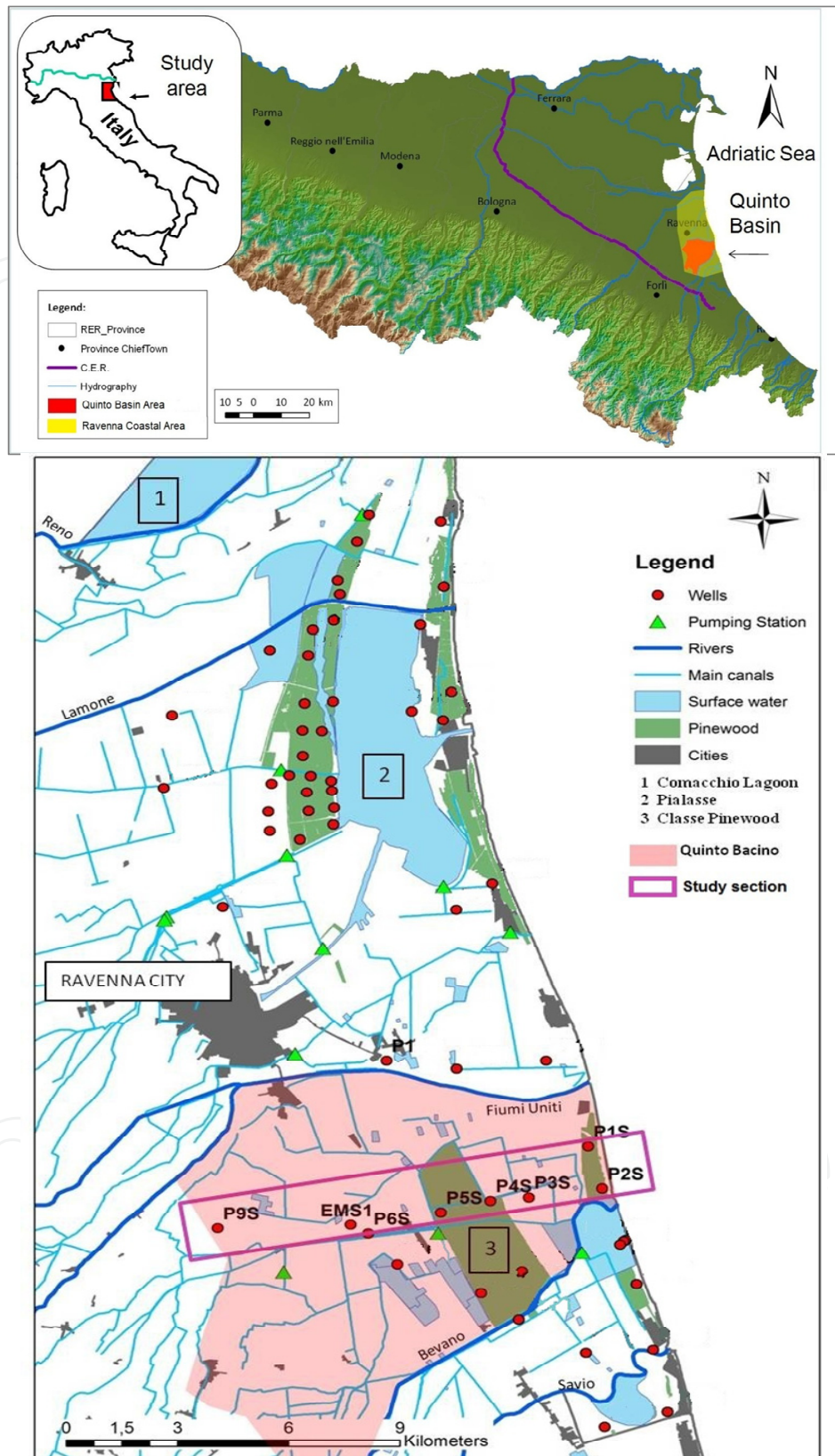
The study area (red rectangle in Figure 1) is part of the *Quinto* basin, the watershed that is confined between two rivers flowing from the Northern Apennines to the Adriatic Sea: the *Uniti* River in the north and the *Bevano* River in the south. The eastern border of the basin is the Adriatic Sea and the western border follows, in part, the *Ronco* River, a tributary of the *Uniti* River.

An east-west profile through the area starting at the shoreline sea includes a beach near the town of *Lido di Dante*, a recent dune belt covered by a coastal pine forest called *Ramazzotti*, planted at the beginning of the 1900's, agricultural land, an older dune belt (paleodunes) covered with a pine forest (*Classe* pine forest), a zone with many active and abandoned gravel quarries that form lakes and more agricultural land (Figures 1 and 5).

Our focus is on a plot of agricultural area (500 by 500 m) in the eastern part of the profile (Figure 2). The area is around a ditch (shown in red). The green dots are wells used to monitor the freshwater lenses, in particular P1S, P2S and P3S are fully penetrating the aquifer (-27m), the others are shallow piezometers (-6m).

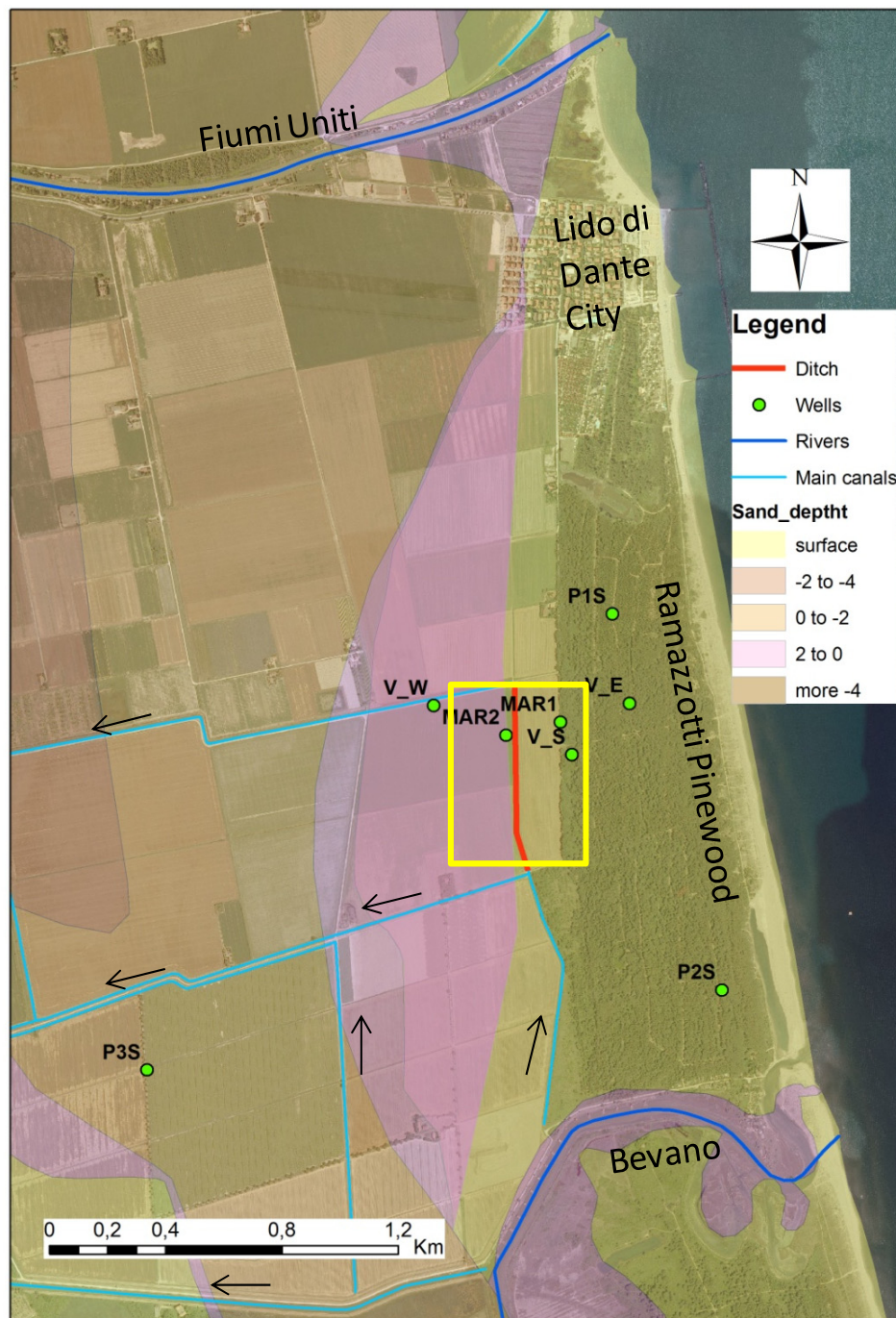
The ditch was dug in 1981 as a reservoir for irrigation water that was withdrawn from the *Fiumi Uniti* River. In 2008, the supply for irrigation changed and now it comes through an underground pipe from the *Po* River. The ditch is 500 m long, 5 m wide and 2,5m deep, resulting in a total volume of 6250 m<sup>3</sup>; it is completely disconnected from the drainage channels network.

In 2011, the planting schedule was as follows: in the east parcel tomato plants were grown from April to August; Alfa Alfa was contemporaneously grown in the west parcel. Because of the particularly dry 2011 weather conditions, tomato plants needed irrigation water from the early stage of growth onward.



**Figure 1.** Index map and detail of the Ravenna coastal zone and location of study area (*Quinto* basin); the map reports also monitoring wells, rivers, channels, pumping stations and main environmental features.





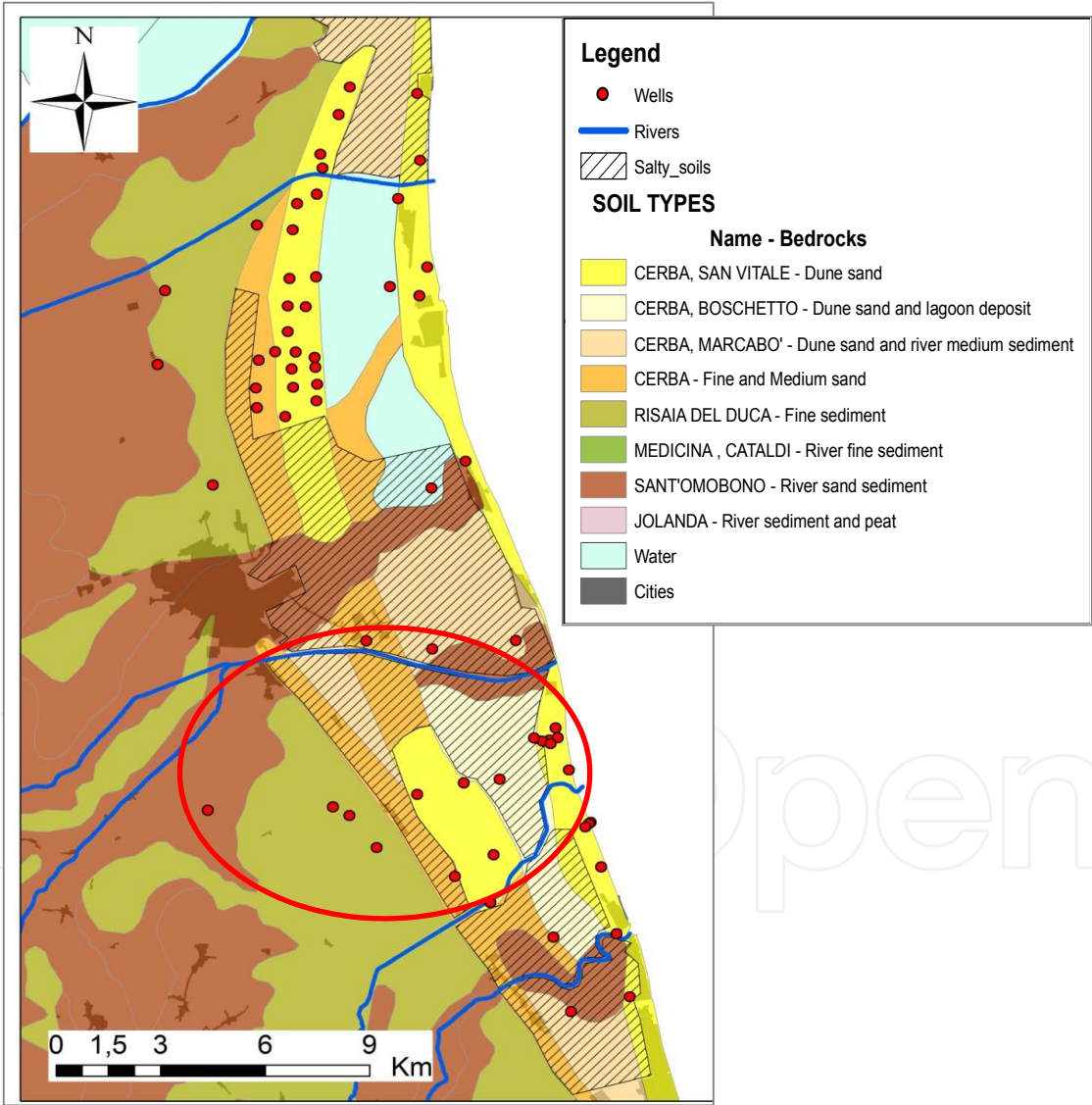
**Figure 2.** Detail of the study area with thickness of sandy top layer, main drainage channels, flux direction and wells used for water table monitoring.

### 3. Soil type and land use

In the coastal area, sediments at the surface are mainly sandy (Figure 3). The sand layers are parallel to the coastline and form paleo and recent dunes.

The sandy soils are called *Cerba* soils, and according to the FAO classification [16] for Soil Taxonomy, they are Calcaric Arenosols and Mesic Aquic Ustipsamments [17].

These soil types are mainly used as arable land or horticulture. Due to their high hydraulic conductivity, these sandy soils are most sensitive for salinization [18],[19]. The *Sant’Omobono* soils (Brown in Figure 3) represents river sand deposits; these soils were deposited along recent or paleo-rivers during flooding events. According to the FAO classification [16] for the Soil Taxonomy they are Calcaric Cambisols, Fine Sandy, Mixed, mesic Udifluventic Ustochrepts, [17]. These kinds of soils are cultivated with vineyards and orchards. Because of their sandy texture, also these soils are at risk of salinization. The *Medicina* (*Cataldi*) sediments (Green colors) are soils with fine texture, mainly created when rivers flowed in presently reclaimed areas. FAO classifies them as Eutric Vertisols [16] and for Soil Taxonomy they are Fine, Mixed, Mesic Ustic Endoaquerts. [17]. They are grown with arable crops only and they are not affected by salinization [18],[19],[20].



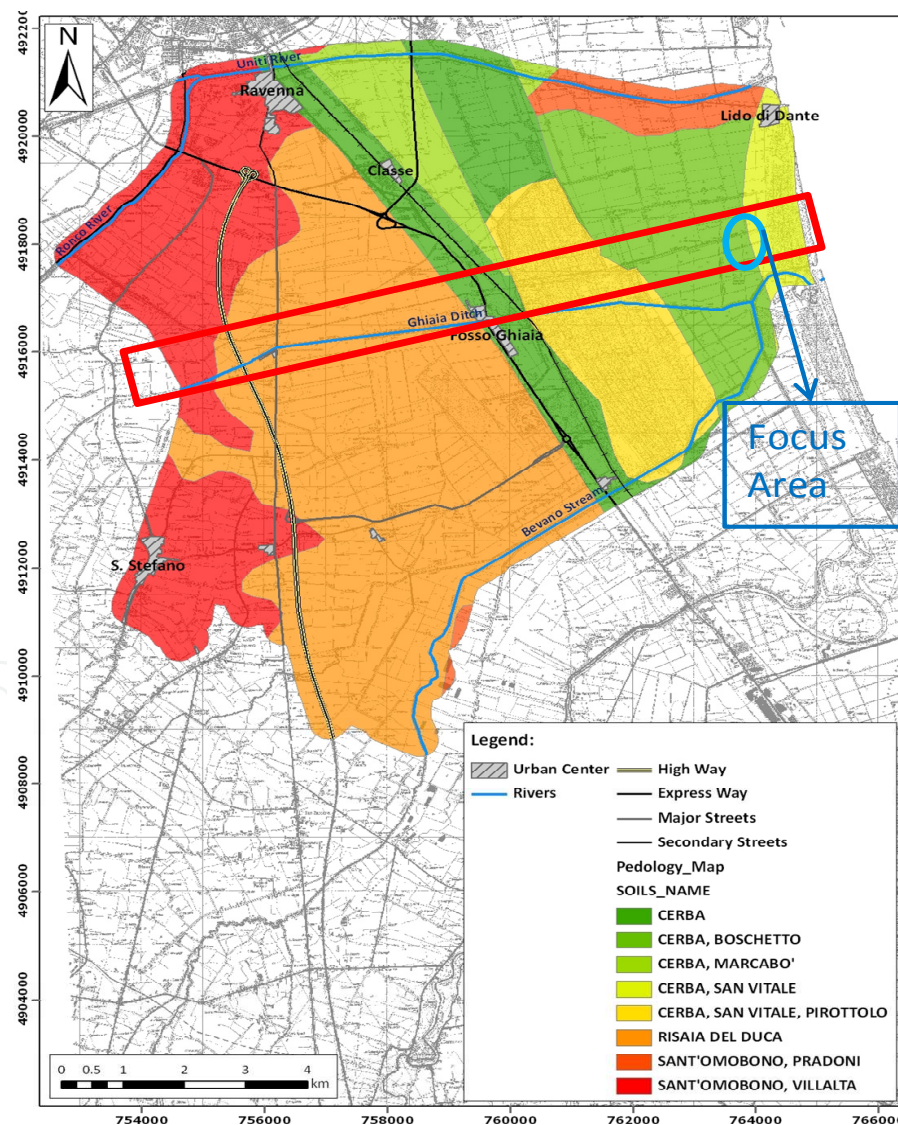
**Figure 3.** Soil types in the Ravenna area and soils at risk of salinization.

The area studied in detail has an extension of 12 ha consisting of two parcels of land of 6 ha on each side of the ditch. The western parcel lies on a 1-m-thick silty sand top layer (*Cerba*



*Boschetto* soil) that confines the sandy aquifer below, whereas the eastern parcel lies on the unconfined part of the aquifer that consists of beach sand (*Cerba San Vitale* soil; Figures 2 and 4).

The differences in soil and lithology, make the land suitable for different kinds of crops: in the last thirty years, on the sandy soil (eastern parcel), the crops consisted of horticulture (strawberries, tomatoes, potatoes, nursery sugarbeet); on the silty soil instead (western parcel), typical extensive arable crops were grown (barley, wheat, maize, alfa-alfa). At our Mediterranean latitude, horticulture crops need irrigation during all the growth phases [13]; arable crops, on the other hand, do not need irrigation during growth. To provide irrigation water for horticulture, the ditch is kept full of freshwater in the summer period. As a consequence, the water level in the ditch is higher than the water table level in the adjacent aquifer. During the winter, the water level in the irrigation ditch matches the adjacent water table level.



**Figure 4.** Quinto Basin soil types, with study section and focus area



Most of the land in the coastal zone near Ravenna is used for agriculture but urban and natural areas (pinewood and water surface body) are also widespread (Figure 1). Most of the natural environments are part of the Po Delta Regional Park. Irrigable crops are the most occurring culture in the province of Ravenna. Vineyards and orchards occupy a small percentage of the territory mostly further inland [12],[13].

The *Quinto* Basin covers a total of 10,355 hectares of which the largest part is used for agriculture (66%), 10% is covered by pine forests, 9% is urban area, and 9% is open surface water or wetlands (Figure 5) [15],[21].

The agricultural land is primarily devoted to arable crops as wheat, barley, alfa alfa, sorghum and corn and only 15% is grown with horticultural and orchards. Horticulture represents less than 5% of the *Quinto* basin and it is practiced on sandy soils (*Cerba* soil) (Figure 4). Orchards are grown in the western part, on *Sant'omobono* soils only that, being the deeper soils in the *Quinto* basin, are the most adapt for fruits and grapes, which are sensitive to water logging (Figures 4 and 5). The most common horticultural products cultivated in the *Quinto* basin are tomatoes, potatoes and nurseries of strawberries and sugar beets. The dominant fruit trees are peaches, apples and vine. For this basin, the data from the last general agricultural census shows that the entire surface cultivated with fruits and horticultural crops are equipped with irrigation systems [12].

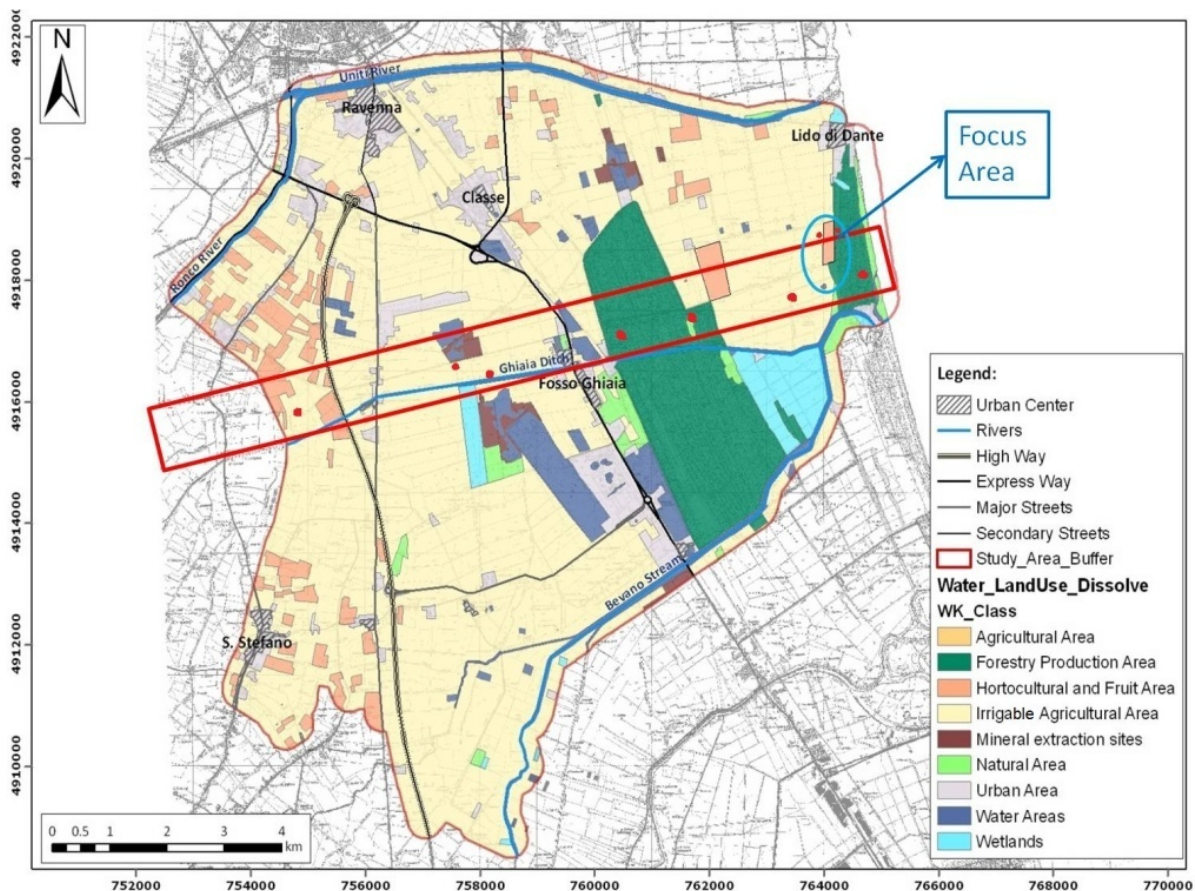
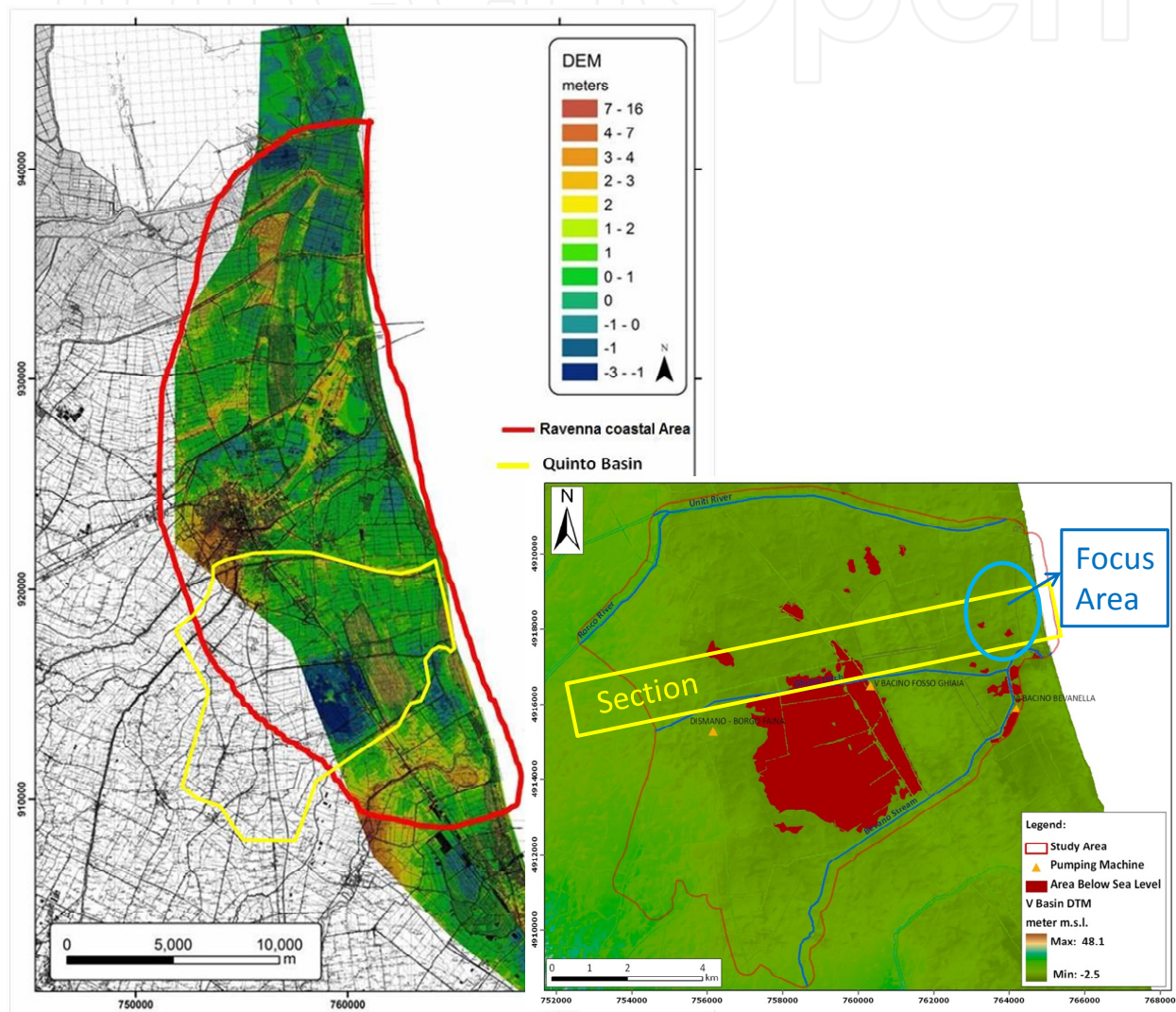


Figure 5. *Quinto* Basin land use map.

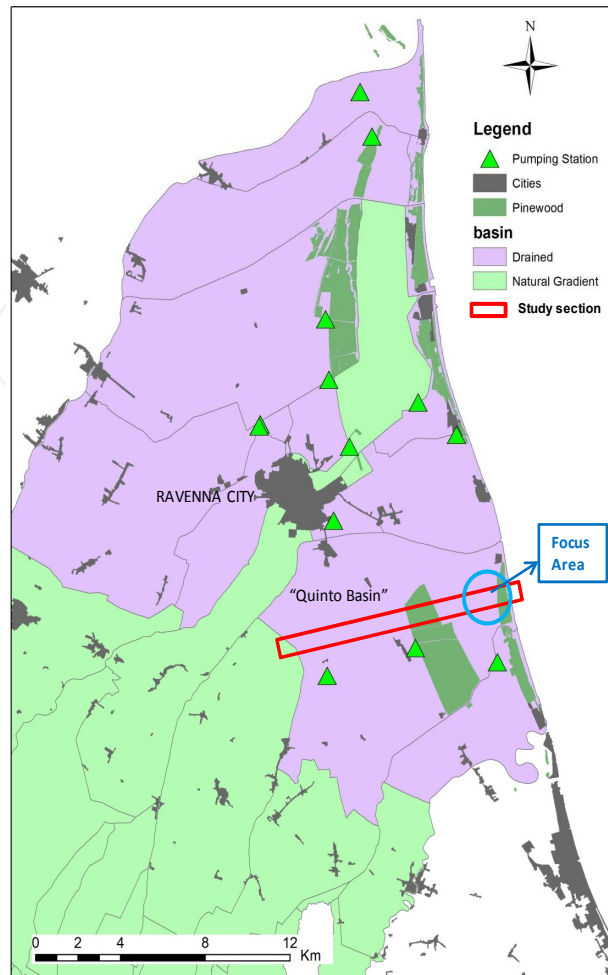
#### 4. Topography, drainage and irrigation

Most of the land near Ravenna is below or just a few centimeters above sea level. Only the recent dune belt and the paleo-dunes are up to 5 m above sea level (Figure 6). These dunes are covered by pine forests (Figure 1). The maximum elevation in the *Quinto* Basin is 5 m and it is measured in the most recent dune belts, whereas the lowest areas are near the gravel quarries 7 km from the coast at 2m below sea level (Figure 6). The farmland around the ditch of our study area is completely flat and lies at a few centimeters above sea level.



**Figure 6.** Topography of the coastal zone near Ravenna and area below sea level in the *Quinto* basin.

The whole coastal zone of Ravenna is drained mechanically to make agriculture possible despite the low topography. As a consequence, the areas of natural water infiltration are very small and localized along the dune belts. The entire district is divided into small watersheds defined by small topographic features such as rows of dunes, dikes, and levees [22]. Figure 7 shows the drainage basins in the Ravenna Municipality. Only one basin has a natural hydraulic gradient towards the sea (Figure 7).



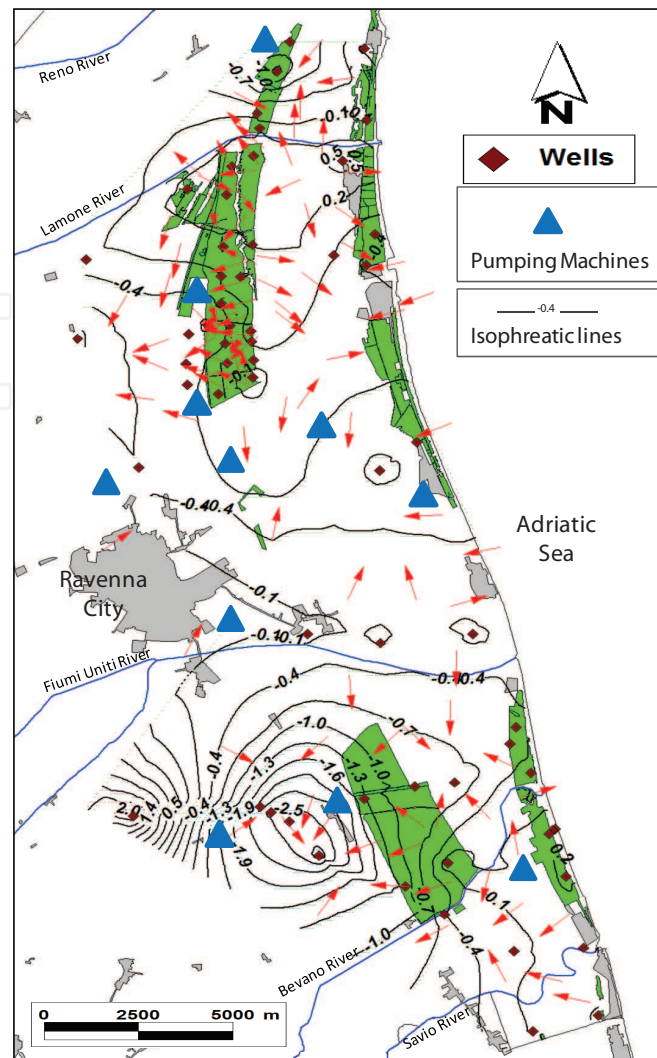
**Figure 7.** Drainage basins in the Ravenna Municipality. The light green color represents natural drainage basins; the pink color shows the mechanically drained basins.

A dense network of pumping stations and channels was built in the last century with the aim to keep the land from flooding and allow farming [23]. In the *Quinto* basin alone, more than 50 km of drainage channels reroute the water to the pumping stations [24].

The pumping stations are typically located inland, several kilometers from the shoreline (Figure 7). The drainage, therefore, creates a hydraulic gradient directed inland [3],[23]. Our study area is drained by two east-west oriented channels that collect the water between the two dune belts and convey it towards the *Fosso Ghiaia* pumping station (Figure 2).

The pumping stations are activated automatically when the water level in the drainage channels reaches a threshold, regardless of the soil water availability or the weather forecasts. As a consequence, the water table is everywhere below sea level with the exception of the dune belts where the water table may be above sea level in the wet periods of the year. The pumping station in the *Quinto* basin, (*Fosso Ghiaia*) causes a deep withdrawal cone down to -2.5 masl in the western part of the *Classe* pinewood (Figure 8). The flux vectors that were calculated based on water table measurements in the wells of Figure 1 are all directed inland showing that sea water flows into the aquifer.





**Figure 8.** Water table contour map and flux vectors indicating the direction of groundwater flow.

The main source of irrigation water is from river water; five rivers are tapped for irrigation, from north to south they are the *Reno*, *Lamone*, *Fiumi Uniti*, *Bevano* and *Savio* rivers. In the summer period, however, there is not enough water in these rivers and additional irrigation water is taken from the *Po* River by means of the *Canale Emiliano Romagnolo* channel (CER). The water from the CER is brought into the irrigation systems via the same channels that are used for drainage in the winter.

The most common irrigation systems are the sprinkler and the drip irrigation system. The first one is used for horticultural crops with a large volume of water distributed twice a week, whereas the second one is typical for orchards and it uses small volumes of water but with a daily treatment. The sprinkler method, therefore, needs a storage basin for the water (ditch, lake or basin). The drip system instead doesn't need a storage basin [25].

In our focus area, water for irrigation was taken for many years from the *Fiumi Uniti* River. Seawater, however, has encroached along the river and, therefore, it was necessary to change the water supply [3]. Recently, irrigation water comes through a pressurized



pipeline directly from the CER (Po river source). During the monitoring time, irrigation on tomato parcel started at an early stage of growth in April 2011 and ended at the harvest time in August 2011. The scheduling of irrigation has been rather regular: approximately twice a week. For each irrigation operation, 20 mm/m<sup>2</sup> were distributed on the tomato plants (Table 1). No irrigation was given to the alfa alfa in the parcel to the west of the ditch.

In the Ravenna Municipality, irrigation and drainage practices are managed by the same authority: the Land Reclamation Consortium for the *Romagna* Region and for both services the end users costs have recently increased [24],[25].

5. Climate

The climate of Ravenna is Mediterranean with generally warm summers and mild winters [26]. The average temperature is about 14°C varying from -5° to 10°C in the winter period and from 20° to 35° C in the summer months [27]. The average annual rainfall calculated on a long term database (1960-2011) is more than 650 mm and it is usually concentrated in the spring and autumn months.

In five of the last six years, total precipitation has been under the average; in particular 2011 was the driest of the last 23 years, with only 385 mm (Figure 9). Compared with the average monthly rainfall of 1960-2011, in fact, most of the autumn rainfall is absent (Figure 9). The same comparison for temperature shows that in 2011 the temperature was 3-4°C higher than the average of the last 51 years, especially in autumn and winter (Figure 10).

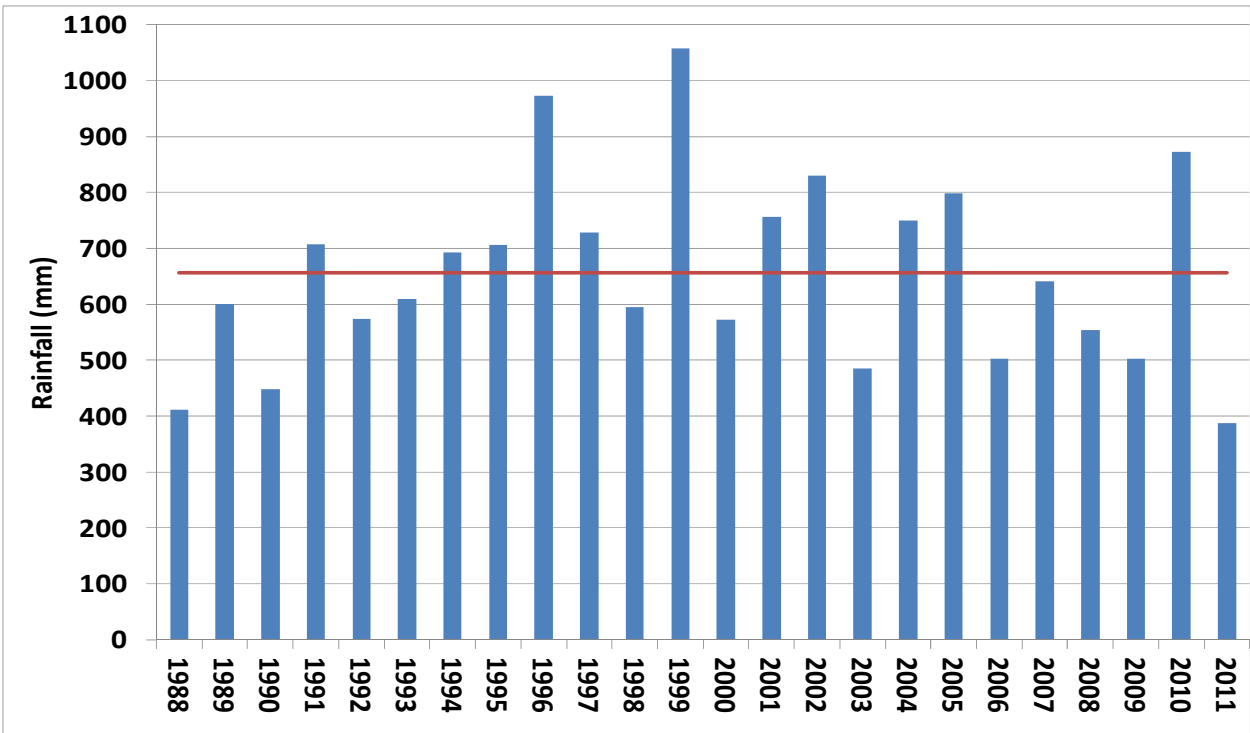
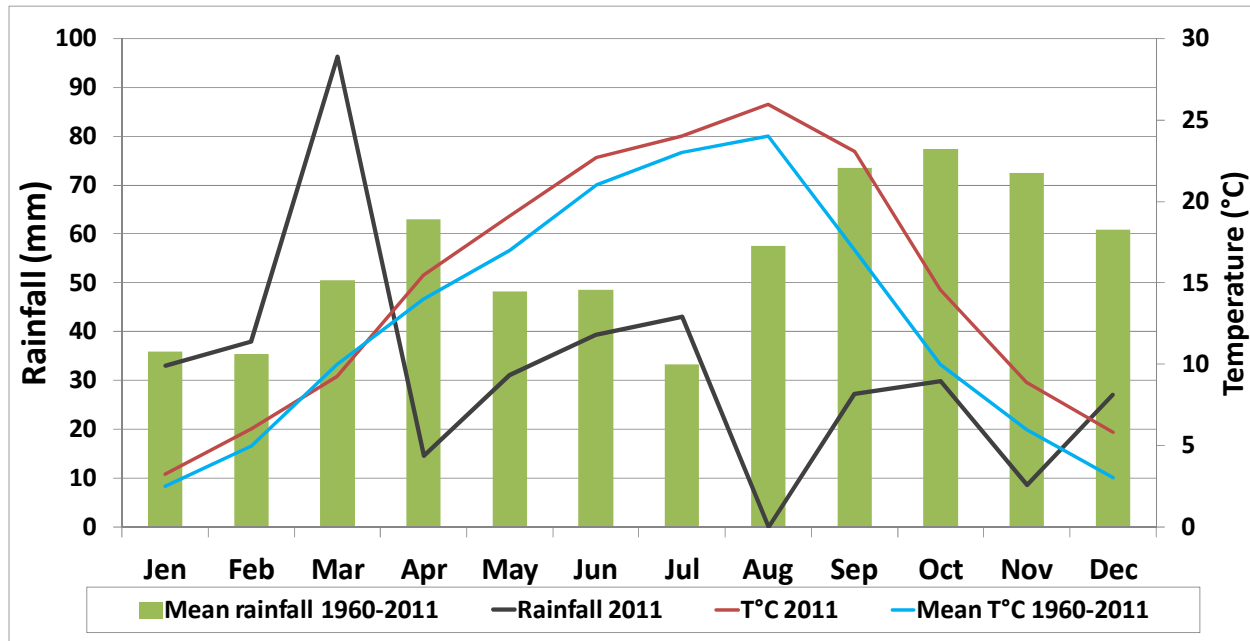


Figure 9. Annual precipitation in the city of Ravenna. Red line represents the long term mean value.



**Figure 10.** Monthly rainfall and temperature for the Ravenna Area.

One of the climate change scenarios proposed for the Mediterranean area [28] indicates a substantial change in the hydrologic budget by the end of this century. According to Antonellini and Mollema 2010 ([7]), evapotranspiration will increase as a result of an increase in temperature; rainfall will be concentrated in short periods, the winter will become more humid and the summer more dry compared to the present, and there will be an increase in extreme events (floods or droughts). Such a forecast for the coastal zone has a particular significance, because a shortage of fresh water in the area next to the sea will promote saltwater intrusion in the ground water and soil salinization. According to Magnan et al. 2009 ([28]), it is possible to mitigate some of these effects, but it is not possible to avoid them completely; it is, therefore, necessary to start the development of mitigation and adaptation strategies now in order to face these issues.

## 6. Geology and geomorphology

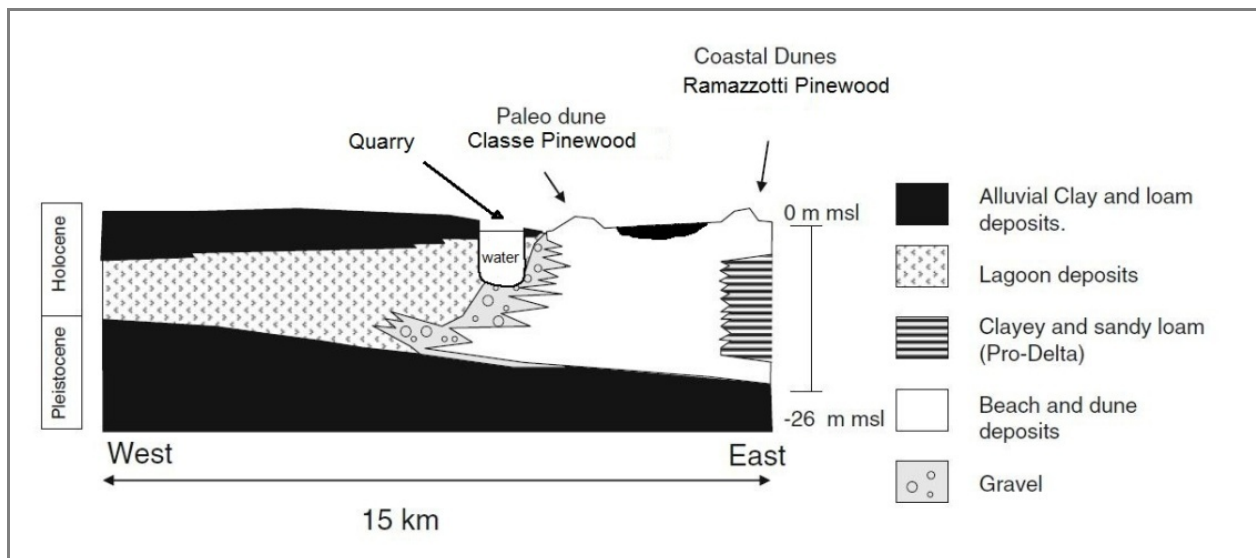
The study area is a small portion of the southern part of the wider Po delta plain. The surface aquifer sediments were deposited during the Late Quaternary (Holocene) sea-level fluctuations [29],[30]. During the last glacial maximum (19 kyr ago) the sea-level dropped about 100-120 m in the Adriatic basin and the North Adriatic Sea was became a deep alluvial plain [31][32]. During the optimum climatic period, about 5500 years ago, the paleo-shoreline was located 25-30 km west of its actual position. From the most landward position of the Holocene coast, a rapid migration of a barrier-lagoon-estuarine system was developed to create the Ravenna alluvial plain, especially from Roman age (IV cent. B.C.) to recent times.

The sedimentation in the study area turned from marine to continental only recently (XIX century). Most of the study area emerged during the last shoreline progradational phase

[33], which took place from 1851 to 1894 A.D at an average rate of 20 m/y and in the first half of the past century (4-12 m/y). Nowadays, although the Holocene glacial period with related sea level changes is finished [34], the movements of the coastline still occur: a large part of the coast is under active erosion and only a small part is prograding to sea. This is mostly due to human intervention: the subsidence due to water and gas exploration in combination with a lack of sediments transport by the rivers and the construction of various piers perpendicular to the coast near the harbors and breakwaters parallel to the coast that trap the sediments. These interventions have interrupted the natural process of long shore current and sediment transport [34]. Now beach and dune erosion and shoreline retreat are a major problem along the Adriatic coast [35].

The sandy aquifer consists of two main units: a relatively thick medium-grained sand unit (from 0 to -10 masl) and a lower fine-grained sand unit of small thickness (from -21 to -26 masl). These two sand bodies are separated by a clay-silt and sand-silt continental unit (from -10 m to -21 masl) called *Prodelta* (Figure 11). Lastly, the Flandrian continental silty-clay basement is at a depth varying from -20 m.a.s.l. in the west to -30 m.a.s.l. at the present shoreline [29],[36],[37].

The resulting picture of the aquifer is a wedge shaped dune and beach sand body pinching out in a westerly direction. It is enclosed at the bottom and top by clays and peat deposited in lagoons, marshes and alluvial plains. The only portion where the aquifer is phreatic are the paleodunes and the actual dune belt both covered by pine forests. At the tip of this wedge there are gravel deposits (Figure 11) [29][38].



**Figure 11.** Lithological cross section of the Ravenna aquifer in the study area (modified from [29][39])

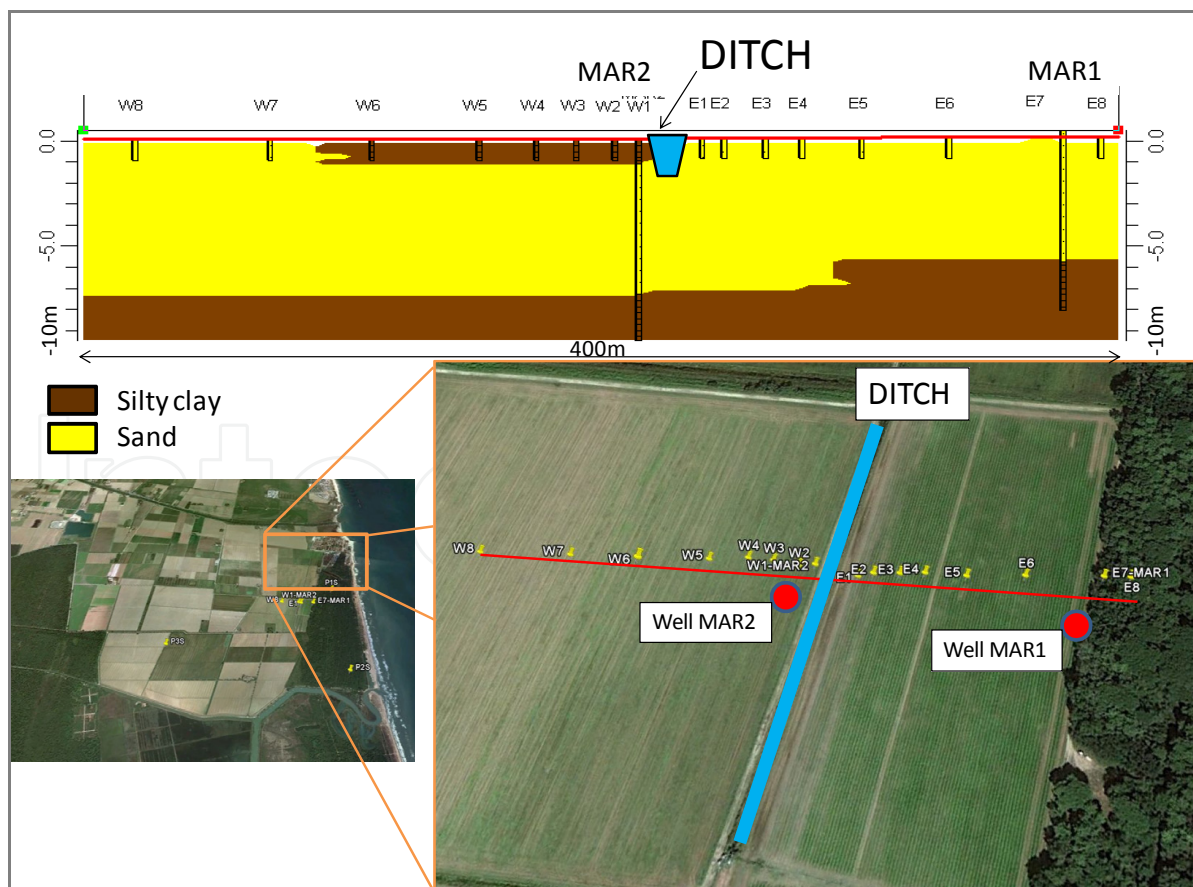
## 7. Monitoring

A groundwater monitoring campaign has been carried out in 8 wells along the section of Figure 1, in December 2010 and it was repeated in April 2011, with the aim to compare

salinity and chemical data in two different seasons. A monthly water table monitoring was performed for the whole transect with increased data density around the ditch, where we installed two shallow wells in February 2011. Overall, 8 wells near the ditch were monitored for water table analysis (Figure 15).

Rainfall was measured with 5 pluviometers located along the section. In the eastern parcel, within the tomato field, we were able to measure both rainfall and irrigation. To assess how much rainfall and irrigation from the surface reaches the groundwater, we buried in the same location a drain-gauge. Geo-electric vertical resistivity surveys (VES) in cross sections normal to the ditch (Figure 12) were carried out in order to determine the depth, shape, and evolution of the fresh water lens [40],[41],[42]. VES surveys were repeated twice: before the tomatoes were planted in February 2011 and during the maximum irrigation period in July 2011. The VES calibration was made using well salinity data, and apparent resistivity data obtained for the area by the process of inversion [43][44].

Groundwater with a salinity ranging from 0 to 3 g/l has been defined as freshwater, based on a study of the relationships between salinity and natural vegetation species richness [7]. Above the salinity threshold of 3 g/l, the species richness decreases dramatically. The brackish water has been defined as water with a salinity ranging from 3 to 15g/l and water with salinity above 15 g/l is considered saline.

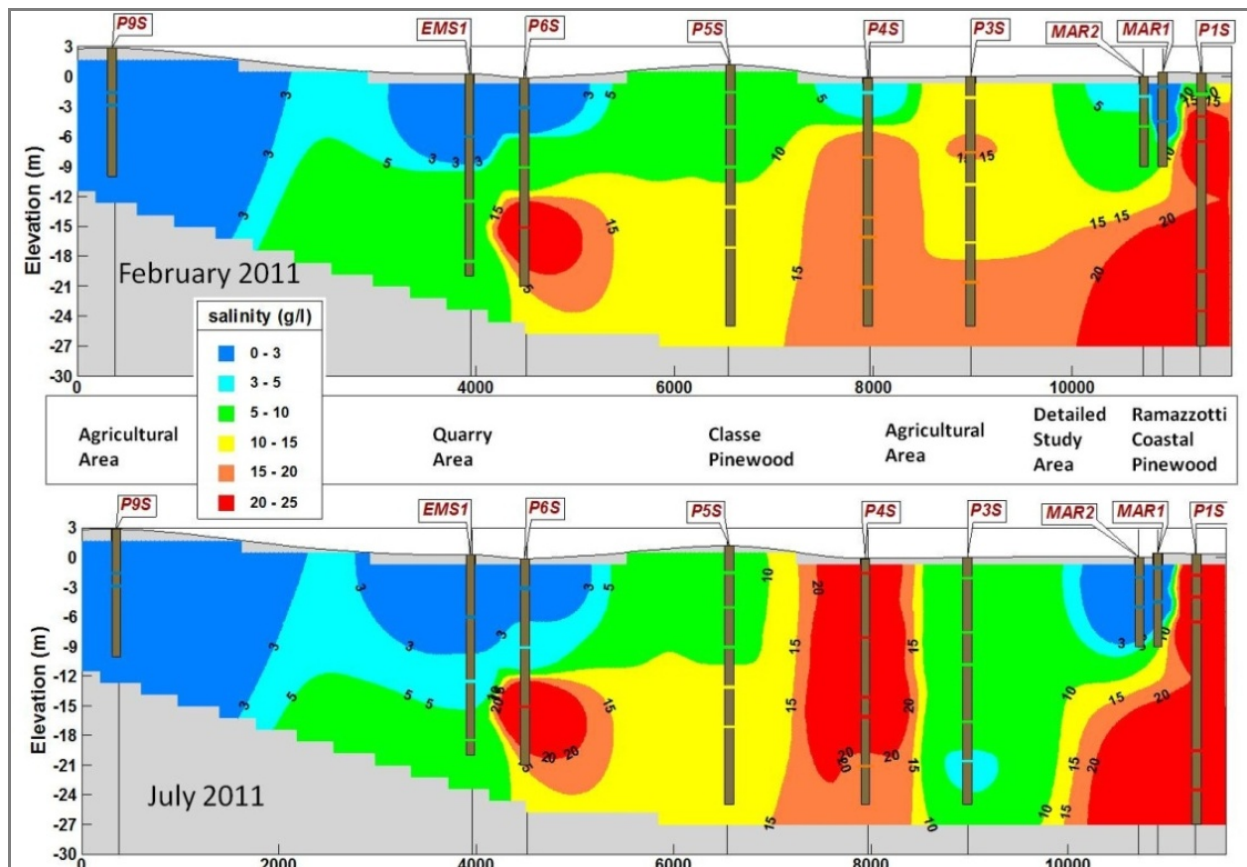


**Figure 12.** Small parcel, studied in detail, with simplified lithology, irrigation ditch (light blue), wells MAR1 and MAR2 (red circles), and 16 V.E.S. locations.



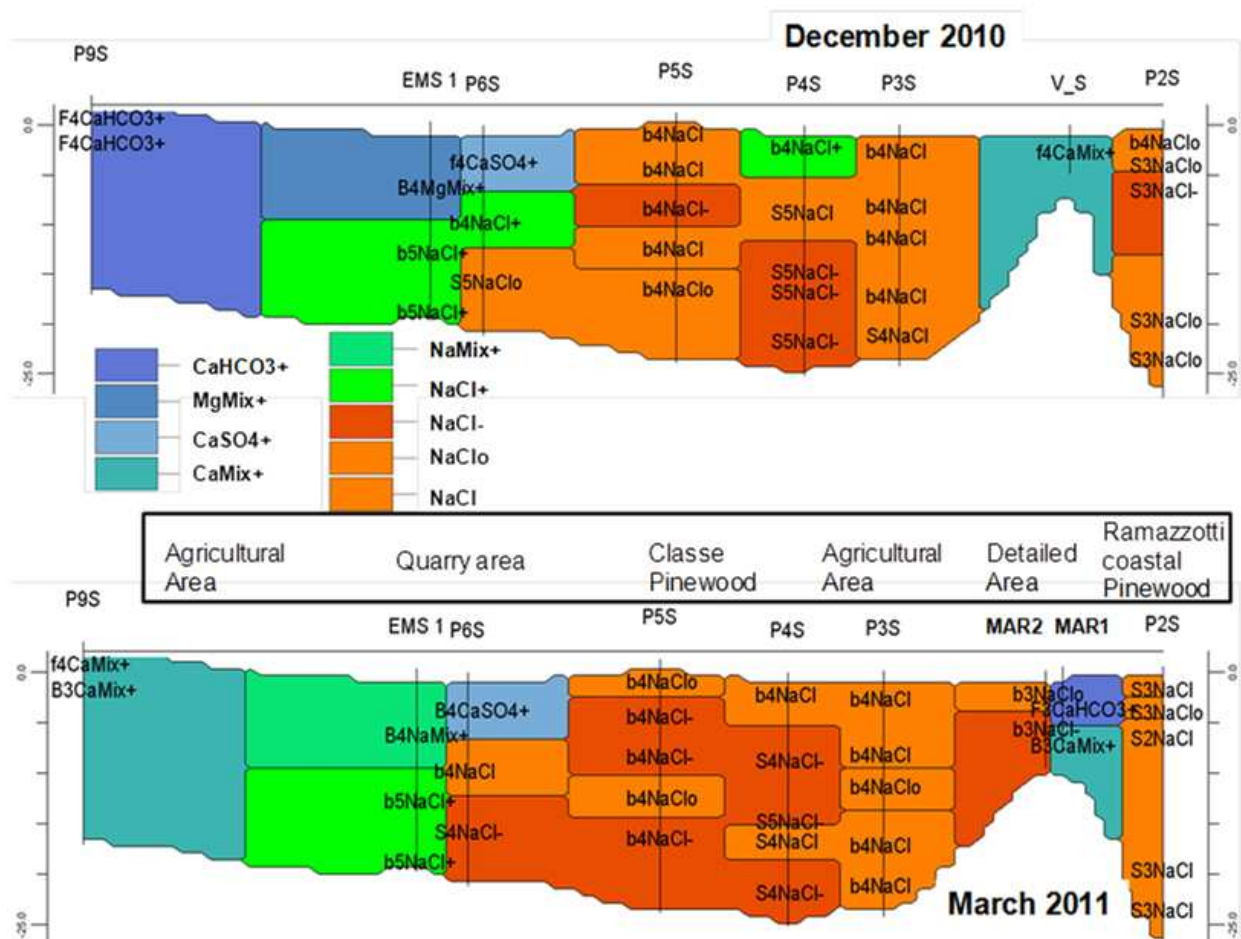
The salinity data show that the size of the freshwater lenses changes throughout the year (Figure 13). Below the coastal pine forest and close to sea, the aquifer is salty and there is a 0.5 m thick fresh-brackish water layer at the top of the aquifer, which disappears in summer. Salinity data indicate a counter-intuitive trend underneath the irrigated agricultural land at 2 km from the sea: in summer the salinity is lower than in the winter. Inside the historical *Classe* pine forest, at 4 km from the coast, the groundwater is mostly brackish (10 g/l) with a 1 m thick freshwater layer at the top of the aquifer that, in the coastal pinewood, vanishes rapidly. Fresh groundwater lenses within the quarry belt at 7 km from sea have a larger thickness (2 m) but at the bottom of the aquifer saltwater is also present. At a distance of 10 km from the coast, in agricultural land, there is fresh water throughout the whole thickness of the aquifer (Figure 13).

On the basis of the cations and anions analyses, alkalinity, and salinity, a groundwater type classification used by Stuyfzand [45] was obtained [11]. Seawater is typically of the S4NaClO type meaning a saline water with High Alkalinity, Na being the major cation, Cl the major anion and a zero BEX indicating a stable water without cation exchange taking place (for data see [11]).



**Figure 13.** Transect 10 km long from the Adriatic coast on the right towards the mountains on the left. Warm colors represent brackish-saline water whereas cold colors are for freshwater.

Apennine river water is typically of the type (g-F)3CaHCO<sub>3</sub> and (f-F)3CaMix, or in other words: fresh water, medium alkalinity and rich in Calcium and varying anions. Po river water coming through the CER is of the type g2CaHCO<sub>3</sub> and slightly less alkaline than Apennine river water [11]. The groundwater water type is diagnostic to evaluate if the river-irrigation water has replaced the saline groundwater. Figure 14 shows that the sodium-chloride water type is dominant in the whole section. It is important to note that there are differences between the winter and spring situations in the area studied in detail. This was caused by the addition of new wells in the second monitoring campaign (MAR1 and MAR2 were monitored in April 2011 only). Excluding this effect, two water type changes were observed in the western part of the transect: from calcium-carbonate in December 2010 to calcium-mix in April 2011 in well P9S and from magnesium to sodium in well EMS. The April water type for the area near the irrigation ditch shows, in MAR1 well, a calcium carbonate water type, which is the same chemical composition of river water. Otherwise, in well MAR2 despite its low salinity (Figure 13), the dominant water type is sodium-chloride (Figure 14).



**Figure 14.** 10-km-long transect from the Adriatic coast (on the right) towards the mountains (on the left). The different water types are indicated with different colors. Warm colors represent brackish-saline Na-Cl composition whereas cold colors are for typical freshwater composition.

The BEX index for dolomite-rich aquifers as reported by Stuyfzand [45] is used to study whether the groundwater is becoming more or less saline. The BEX is indicated in Figure 15 with a +, - or 0 character after the water type code. The groundwater samples at the top of the aquifer and in winter show a positive BEX index, which indicates freshening (Figure 14).

Rainfall from January to September 2011 recorded in the five pluviometers along the section has a fairly homogeneous value around 400 mm. Total irrigation of a tomato field in the area studied in detail was 600 mm, applied with a rate of 120 mm per month (April-August). The infiltration rate of water into the aquifer, measured from drain gauges located in the tomato field, was 8 mm/m<sup>2</sup> in May, 2 mm/m<sup>2</sup> in June and 0 in the other months (Table 1).

2011 (unit mm)	Months	January	February	March	April	May	June	July	August	September
	Rainfall	33	38	96	15	31	40	43	0	27
	Irrigation	0	0	0	150	120	150	180	90	0
	Infiltration	n.a.	n.a.	n.a.	8	2	0	0	0	0

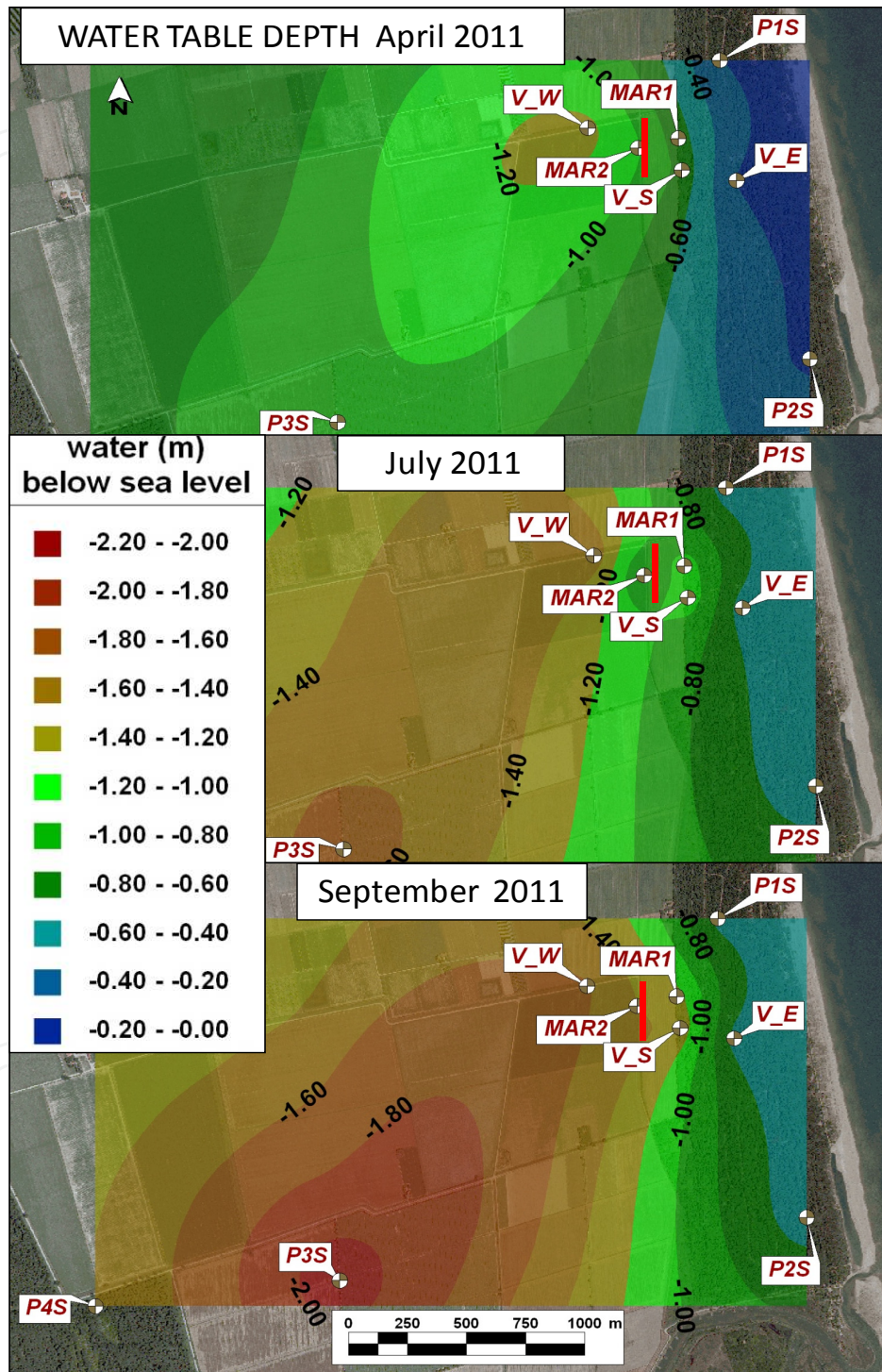
**Table 1.** Precipitations, irrigation and infiltration measured in tomato parcel from January to September 2011

Water table measurements in April 2011 show that the groundwater is at 0.2 m below sea level in the *Ramazzotti* pinewood and, moving landward, the depth linearly increases up to 1.2 m below sea level (Figure 15). The water level decreases rapidly everywhere during the summer, except for the area surrounding the irrigation channel (Figure 15) where an inverse gradient, with respect to the normal situation, is present during the whole irrigation time (from May to August 2011). As in winter the water level in the irrigation ditch is equal to the groundwater level, during the growing season the water level in the ditch is higher than the groundwater level, creating a hydraulic gradient in the phreatic aquifer that is directed to sea. At the end of the irrigation season (September for the year 2011), the inputs of freshwater end and the water level in the ditch returns to match the groundwater level (Figure 15).

The February 2011 survey results suggest that below the eastern parcel, where the aquifer is phreatic, a 4-m-thick freshwater lens is present before the irrigation season; freshwater is also present west of the ditch but its thickness is only 1,5 m. During both field campaigns in February and July 2011, VES profiles and the depth of the water table and the salinity of the groundwater at the water table were measured by drilling auger holes. The measurements made in February (Figure 16) show that the water level in the ditch is the same of the groundwater and that the whole system has a small gradient towards the pumping station. The freshwater lens vanishes below the *Ramazzotti* pinewood (E8 location) where the water is salty up to the surface (Figure 16).

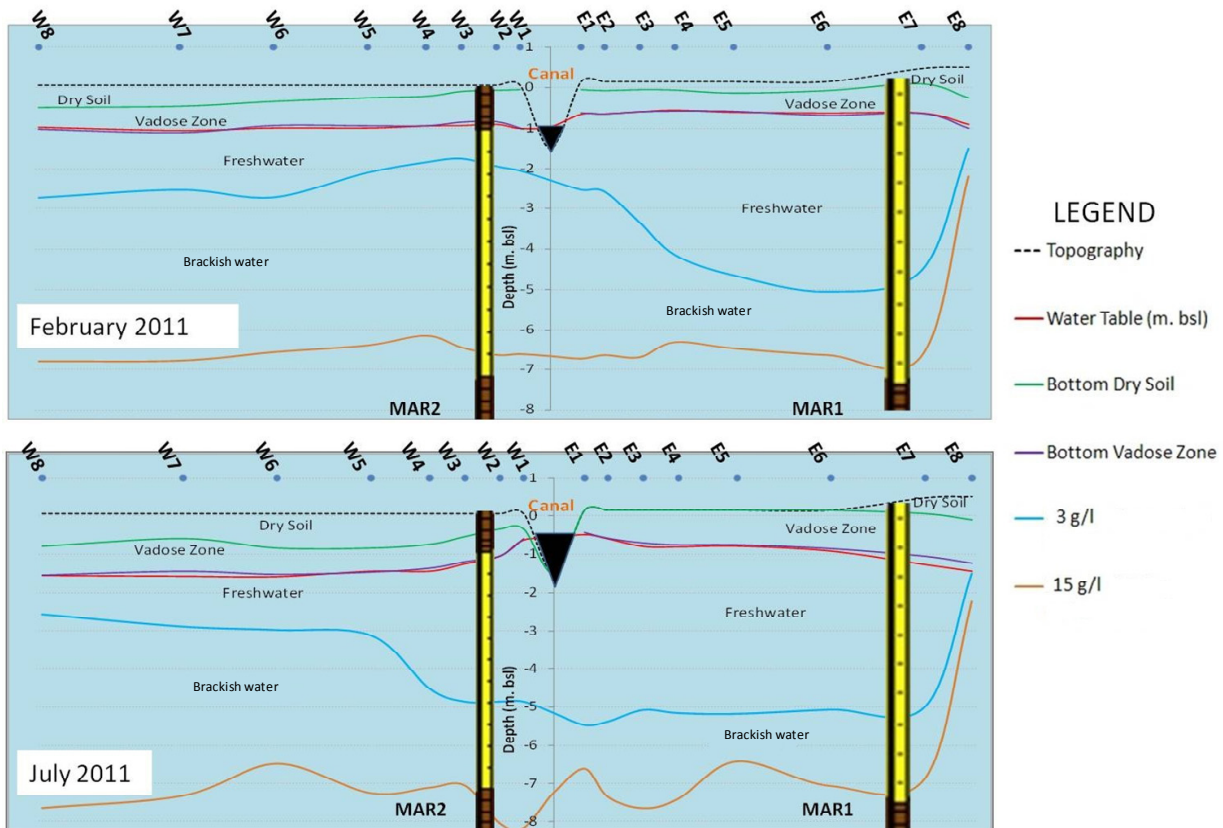
During the irrigation period (July 2011), the ditch is full of freshwater. The irrigation of tomatoes in the eastern parcel causes the whole soil profile to be moist. West of the ditch, where the Alfa Alfa was grown, the water table depth increases and also the bottom of the dry soil line becomes deeper (Figure 16). Comparing the VES profiles made in February 2011 with those made in July 2011 confirms the existence of a well-developed freshwater lens in the eastern part that grows in size during the irrigation season (Figure 16). The largest growth in thickness of the freshwater lens occurs under the ditch and in the western part where the semi-confined aquifer is present.





**Figure 15.** Study area water table map for April, July, and September showing also the irrigation ditch (red line).





**Figure 16.** Seasonal comparison of VES results for the agricultural land close to the freshwater storage ditch.

## 8. Discussion

As recently reported by IPCC [22] a reduction of freshwater availability and an increase of drought periods length is likely to occur in the Ravenna area during the next 100 years. An increase in temperature with a simultaneous increase of evaporation will cause soil salinization and loss of production. Near Ravenna more than 68 square kilometers are at risk for soil salinization caused by salt water intrusion in the coastal aquifer and along main rivers and channel. A stable isotope analysis shows that the ground and surface water near the city of Ravenna is a mix of sea, rain, and river water. The sea-water is, in part, inherited from the Holocene deepest marine ingressions [11]. The aquifer has the shape of a sandy wedge enclosed in clay and this inhibits an efficient flushing of the saline water that is in part left at the bottom of the aquifer from the optimum climate period. Deeper aquifers in the area receive underground recharge from water with a mountain or rainfall sources. Where present, freshwater is located in the recent and paleodune belts, because of their high infiltration potential [3],[22],[47]. Where channels and rivers flow on a sandy top layer, there is infiltration of freshwater into the aquifer as along the *Bevano* and *Fiumi Uniti* rivers as well as in the western part of the San Vitale pinewood [11]. There is a small area along the *Bevano* River, where the freshwater lens reaches the

bottom of the aquifer but in all other cases the freshwater lenses are floating on top of brackish groundwater. These freshwater lenses are thin (1m maximum), ephemeral (present only during winter) and strongly linked to the climate conditions [3],[22],[48],[49],[50].

Aquifer salinization in our study area is due to the combination of several factors such as low topography, natural and anthropogenic subsidence, mechanical drainage, destruction of the coastal dune belt, and scarcity of freshwater infiltration [11][43][51][52]). As shown in Figure 8, in the whole aquifer, the groundwater head is below sea level in winter also. This situation causes a sea-water encroachment promoted also by the high discharge water volumes of the pumping stations. Based on number of activity hours, we roughly calculated that in the *Quinto* Basin the volume of drainage water was 8 times larger than that of the total rainfall in same basin for the period.

In this contest, with low freshwater availability and poor natural recharge, it is important to look for some technique that is able to counteract soil and groundwater salinization and at the same time encourages water management practices that prevent nitrate leaching, safeguard the economics of agriculture, and save the freshwater resources.

Our attention was focused on a small agricultural area at a distance of 500m from the shoreline, where despite all previous studies [22][51][52][53], the presence of a freshwater lens throughout the year, was found. Although this area is affected by drainage, low topography, and subsidence as the rest of the Ravenna province, the presence of a sandy top layer, the horticulture with irrigation, and a ditch used for freshwater storage, all promoted aquifer recharge. The chemical analysis and electrical surveys showed that the size of the freshwater lens is larger during the summer period (Figure 13, Figure 14 and Figure 16).

In many other countries worldwide, managed aquifer recharge (MAR) is used to store fresh river or rain water in the underground of riverbanks or dunes for later use as drinking water [54].

Managed Aquifer Recharge or MAR is also used for re-pressurization of aquifers subject to falling water levels, declining yields, saline intrusion or land subsidence. Examples of these from around the world include different technologies such as aquifer storage and recovery (ASR), aquifer storage transfer and recovery (ASTR), bank and dune filtration, infiltration ponds, percolation tanks, rainwater harvesting , and soil-aquifer treatment (SAT) [55]-[61]. All above mentioned technologies have a cost that sometimes may be not sustainable by the local economy. In countries such as India, China, and Pakistan artificial recharge from ditches is affordable for the cultivation of rice, but this is usually done far from the coast ([61][62][63][64]). As reported by Gale 2000 ([61]), in many countries, the seepage from ditches or channels is considered a loss of water and they are studying systems to solve this problem. Irrigation ditches, on the other hand, may also play an ecological role: some authors report that ditches support the biodiversity and associated

ecosystem services ([65]) and that they promote retention and removal of agrochemicals, decrease soil erosion, and allow the early stage of development for fish, amphibians, and reptiles [66]. Another aspect to consider is the low cost for their construction and management (removal of excess vegetation to restore efficient drainage) [66]. In particular for our area a dense network of ditches is already present and their building costs could be very low or absent.

Irrigation practices tend to become more and more efficient by letting go less and less water into soil-evaporation. The driving forces for that are the scarcity of freshwater and economic incentives. One might say that the water left in the ditch to recharge the aquifer is water that is 'lost'. One of the main challenges in water resources and agricultural management in coastal Mediterranean zones will be to define priorities that may vary with the particular area. In one place it may be important to use as little water as possible for irrigation not leaving anything to waste or end up in the aquifer underneath the top soil. In other places instead, especially in the coastal zone, irrigation water may be left to seep from the ditches into the surface aquifer to create freshwater lenses that sustain the agricultural land as well as the natural areas and at the same time counteract seawater intrusion.

The high salinity of the coastal aquifer near Ravenna is in part inherited from its geological history. Therefore it is unlikely that the aquifer will be ever used as a source for drinking water. By infiltrating (excess) river water on purpose through ditches as the one studied in this paper, however, freshwater lenses can be created that may prevent soil salinization and serve agricultural crops as well as natural areas. Our studied ditch has the same dimension as the drainage channels in the area. The only difference is that it is a closed basin used for storage irrigation water during the summer. By using the existing hydraulic infrastructure for managed aquifer recharge in ditches, more freshwater would flow into the aquifer instead of being drained away by the pumping machines. This system of aquifer artificial recharge would be viable in similar coastal settings throughout the world.

## 9. Conclusions

Despite the fact that there are many technological, agricultural, economic, and water availability factors that are dependent on the local situation and farming practices (crop rotations, volume and timing of irrigation, tillage, economic forcing, etc.) and that the length of the study was of only one year, so that no long term trends can be captured by the analysis presented, some interesting observations have been made:

- The land use in the Ravenna coastal area is complex; natural areas (pine forests, lagoons and wetlands) and industrial activities are placed in a landscape dominated by agriculture.
- The Low topography, the high rates of subsidence, the salty phreatic aquifer require land drainage to allow for any activity. The result is that drainage allows for agriculture

but it decreases the recharge of the aquifer, removes freshwater from the top of the aquifer and increases up-welling of saline water from below.

- The surface hydrology is controlled by a high density network of channels used mainly for drainage but locally for irrigation.
- Due to different geological events, different kinds of sediments were deposited in the area; therefore special soils were developed and crops distribution as well as irrigation water requirements depends strictly from the soil characteristics.
- Irrigation is essential for horticultural crops, which are mainly located on sandy soil where the connection with the aquifer below is guaranteed.
- The water sprayed on the land for irrigation does not infiltrate into the aquifer and this is a good practice to avoid nitrate leaching and contamination of the groundwater. In the area studied in detail, the only irrigation water added to the aquifer is from seepage from the storage ditch.
- The case study shows that the presence of a ditch, full of freshwater for 5 months during the year, generates a permanent freshwater bubble 4 m in thickness, at 500 m distance from the sea. This shows that combined irrigation and drainage management, considering the dense network of existing channels and different types of soil, can be of benefit for the agriculture for soil protection, storage of freshwater resources, and to counteract sea-water intrusion.

## Author details

Nicolas Greggio, Pauline Mollema, Marco Antonellini and Giovanni Gabbianelli  
*Interdepartmental Centre for Environmental Science Research (C.I.R.S.A.),  
 University of Bologna, Ravenna, Italy*

## Acknowledgement

We thank the farmer of the “*Cooperativa Braccianti di Campiano*” for their helpfulness and kindness; we thank also University of Bologna, the *Autorità dei Bacini Romagnoli* and the Municipality of Ravenna for funding the several projects that form the basis of this chapter. Special thanks to Murugan Ramasamy and Sathish Sadhasivam for their fundamental support in field work.

## 10. References

- [1] Toth G., Montanarella L., Rusco E., 2008 Updated Map Of Salt Affected Soils In The European Union. Threats To Soil Quality In Europe, Office For Official Publications Of The European Communities, Luxembourg (2008), Pp. 61–74
- [2] Louw, P.G.B., De, Eeman, S., Siemon, B., Voortman, B.R., Gunnink, J., Baaren, E.S., Van And G.H.P. Oude Essink. 2011. Shallow Rainwater Lenses In Deltaic Areas With Saline Seepage, *Hydrol. Earth Syst. Sci. Discuss.*, 8, 7657-7707.



- [3] Antonellini, M., Mollema, P., Giambastiani, B., Banzola, E., Bishop, K., Caruso, L., Minchio, A., Pellegrini L., Sabia M., Ulazzi E., And Gabbianelli G., 2008. Salt Water Intrusion In The Coastal Aquifer Of The Southern Po-Plain, Italy. *Hydrogeology Journal* 16,1541-1556. Doi 10.1007/S10040-008-0319-9.
- [4] Custodio, E., 2010. Coastal Aquifers Of Europe: An Overview. *Hydrogeology Journal*, 18(1): 269 - 280 DOI: 10.1007/S10040-009-0496-1
- [5] FAO 2002 Agricultural Drainage Water Management In Arid And Semi-Arid Areas <Ftp://Ftp.Fao.Org/Docrep/Fao/005/Y4263e/Y4263e11.Pdf>
- [6] Maas E.V., Hoffman G.J. 1977 Crop Salt Tolerance, Current Assessment J. Irrig. Drain. Div., 103, Pp. 115–134
- [7] Antonellini, M. And Mollema, P., 2010. Impact Of Groundwater Salinity On Vegetation Species Richness In The Coastal Pine Forests And Wetlands Of Ravenna, Italy. *Ecological Engineering*. 236 (9), 1201-1211, Doi:10.1016/J.Ecoleng.2009.12.007.
- [8] Hutchinson, I., 1991. Salinity Tolerances Of Plants Of Estuarine Wetlands And Associated Uplands. Washington State Department Of Ecology Report, Washington, USA.
- [9] IPWEA, 2001. The Local Government Salinity Management Handbook. Institute Of Public Works Engineering Australia (IPWEA), Australia.
- [10] Lombardi, T., Lupi, B., 2006. Effect Of Salinity On The Germination And Growth Of *Hordeum Secalinum* Schreber (Poaceae) In Relation To The Seeds After Ripening Time. *Atti Della Società Toscana Di Scienze Naturali, Memorie, Serie B* 113, 37–42.
- [11] Mollema P, Antonellini A, Dinelli E, Gabbianelli G, Greggio, N, Stuyfzand P J. 2012 Identification Of Fresh And Salt Water Intrusion Types In The Upper Ravenna Coastal Aquifer (Italy) Via Hydrochemical Systems Analysis. Submitted to *Applied Geochemistry*.
- [12] Istat 2000 5° Censimento Generale Dell'agricoltura <http://www.census.istat.it>
- [13] Provincia Di Ravenna 2006 Piano Territoriale Di Coordinamento Provinciale
- [14] Marconi V., Antonellini M., Balugani E., Dinelli E.. 2011 Hydrogeochemical Characterization Of Small Coastal Wetlands And Forests In The Southern Po Plain (Northern Italy). *Ecohydrol*. Vol.4, 597-607
- [15] Mollema, P., Antonellini, M., Gabbianelli, G., Laghi, M., Marconi, V., Minchio, A., 2012. Climate And Water Budget Change Of A Mediterranean Coastal Watershed, Ravenna, Italy. *Environmental Earth Sciences*. 65:257–276 Doi: 10.1007/S12665-011-1088-7.
- [16] Fao. 1990. Guidelines For Soil Profile Description. Third Edition (Revised). Soil Resources, Management And Conservation Service, Land And Water Development Division, Fao, Rome.
- [17] Soil Survey Staff. 1996. Keys To Soil Taxonomy. Seventh Edition. United States Department Of Agriculture, Washington D.C.

- [18] Rose D. A., Konukcu F. & Gowing J. W. 2005 Effect Of Water table Depth On Evaporation And Salt Accumulation From Saline Groundwater. *Aust. J. Soil Res.* 43, 565-573.
- [19] Il'ichev, Andrej T. And Tsypkin, George G. And Pritchard, David And Richardson, Chris N. (2008) Instability Of The Salinity Profile During The Evaporation Of Saline Groundwater. *Journal Of Fluid Mechanics*, 614. Pp. 87-104. Issn 0022-1120
- [20] Filippi N (1994) Carta Pedologica (Soil Map) 1: 250.000. Stampata Dalla Regione Emilia Romagna, Italy
- [21] Corticelli S. 2003 Carta Del Uso Del Suolo (Land Use Map). Copertura Vettoriale. Stampata Dalla Regione Emilia Romagna, Italy
- [22] Giambastiani, B. M.S., Antonellini, M., Oude Essink, G.H.P., Stuurman, R. J. 2007 Salt Water Intrusion In The Unconfined Coastal Aquifer Of Ravenna (Italy): A Numerical Model. *Journal Of Hydrology* 340, 94-104.
- [23] Giambastiani, B.M.S., Mollema, P.N., Antonellini, M., 2008. Groundwater Management In The Northern Adriatic Coast (Ravenna, Italy): New Strategies To Protect The Coastal Aquifer From Saltwater Intrusion. In: *Groundwater: Modelling, Management And Contamination*. Authors: König L.F. And Weiss J.L.; Nova Publishers
- [24] Consorzio Di Bonifica Della Romagna 2002 Il Comprensorio E Le Infrastrutture <http://www.bonificaromagna.it/Cartografia.it/html>
- [25] Regione Emilia Romagna, Agip, 2009. Riserve Idriche Sotterranee Della Regione Emilia Romagna, Technical Report. Regione Emilia Romagna, Firenze
- [26] Giorgi, F., Lionello, P. 2008. Climate Change Projections For The Mediterranean Region. *Global Planet Change* 63,90–104.
- [27] Antolini G., Marletto V., Tomei F., Pavan V., Tomozeiu R. 2008 Atlante Idroclimatico Dell'emilia-Romagna 1961-2008
- [28] Magnan, A., Garnaoud, B., Billé, R., Gemenne, F., Iddri, Hallegatte, S., Cired-Météo, 2009. The Future Of The Mediterrenean. From Impacts Of Climate Change To Adaptation Issues. Institut Du Développement Durable Et Des Relations Internationals, Paris, France, 43 Pp.
- [29] Amorosi A., Colalongo M.L., Pasini G. & Preti D., 1999. Sedimentary Response To Late Quaternary Sea-Level Changes In The Romagna Coastal Plain (Northern Italy). *Sedimentology*, 46, 99-121.
- [30] Catalano, R., Di Stefano, E., Infuso, S., Sulli, A., Vail, P.R., Vitale, F.P. 1995 Sequence And Systems Tracts Calibrations On High Resolution Bio-Chronostratigraphic Scheme: The Central Mediterranean Plio-Pleistocene Record. In: *Mesozoic-Cenozoic Sequence Stratigraphy Of Western European Basins* (Ed. By P.C. De Graciansky Et Al.). Spec. Publ. Soc. Econ. Paleont. Miner
- [31] Rizzini, A., 1974, Holocene Sedimentary Cycle And Heavy Mineral Distribution, Romagna-Marche Coastal Plain, Italy: *Sedimentary Geology*, V. 11, P. 17–37.
- [32] Van Straaten, L.M.J.U. 1970 Holocene And Late Pleistocene Sedimentation In The Adriatic Sea. *Geo/. Runsch.* 60, 106-131.
- [33] Giambastiani B.M.S. 2003. Geomorfologia Del Litorale Ravennate: I Sistemi Dunosi. Unpublished Msc Thesis: University Of Bologna

- [34] Stecchi, F., Minchio, A., Del Grande, C.. And Gabbianelli, G., 2003. Historical And Recent Evolution Of The Reno River Mouth And Adjacent Areas. In. Gabbianelli G. And Sangiorgi F.(Editors). Volume 4 Of Proceedings Of The Sixth International Conference On The Mediterranean Coastal Environment, Medcoast 03, 7-11 October 2003, Ravenna Italy, P. 55-67.
- [35] Bondesan M, Castiglioni Gb, Elmi C, Gabbianelli G, Marocco R, Pirazzoli Pa, Tomasin A 1995b Coastal Areas At Risk From Storm Surges And Sea Level Rise In North-Eastern Italy. *J Coast Res* 11:1354–1379
- [36] Amorosi A., Colalongo M.L., Fiorini F., Fusco F., Pasini G., Vaiani S.C. & Sarti G., 2004 – Palaeogeographic And Paleoclimatic Evolution Of The Po Plain From 150-Ky Core Records. *Global And Planetary Change*, 40, 55-78.
- [37] Correggiari A, Roveri M, Trincardi F. 1996. Late-Pleistocene And Holocene Evolution Of The North Adriatic Sea. Late-Glacial And Early Holocene Climatic And Environmental Changes In Italy: *Il Quaternario: Italian Journal Of Quaternary Sciences* 9: 697–704.
- [38] Amorosi A., Colalongo M.L., Fiorini F., Fusco F., Pasini G., Vaiani S.C. & Sarti G., 2004 – Palaeogeographic And Paleoclimatic Evolution Of The Po Plain From 150-Ky Core Records. *Global And Planetary Change*, 40, 55-78
- [39] Marchesini, L., Amorosi, A., Cibin, U., Zuffa, G.G., Spadafora, E., Preti, D., 2000. Sand Composition And Sedimentary Evolution Of A Late Quaternary Depositional Sequence, Northwestern Adriatic Coast, Italy. *Journal Of Sedimentary Research* 70 (4), 829–838.
- [40] Bulter D. K. 2005 Near-Surface Geophysics, (Seg Investigations In Geophysics Series; N°13), Library Of Congress; Pag. 46
- [41] Burger H. Robert 1992, Exploration Geophysics Of The Shallow Subsurface. Prentice Hall Pagg. 291-295
- [42] Celico P.. 1998 Prospezioni Idrogeologiche. Vol I, Liguori Editore, V° Ristampa 1998 Pag 243
- [43] Capo D. 2011 Phd Thesis “Caratterizzazione Della Falda Freatica Costiera Ravennate” In Press
- [44] Loke, M.H. 2001 Electrical Imaging Surveys For Environmental And Engineering Studies – A Practical Guide To 2-D And 3-D Surveys. Residinv Manual, Iris Instruments; 67 Pp.
- [45] Stuyfzand, P.J., 1989. A New Hydrochemical Classification Of Watertypes. *Iahs Publ.* 182, 89–98.
- [46] IPCC Technical Paper Vi. 2008 Climate Change And Water - Intergovernmental Panel On Climate Change <http://www.ipcc.ch/pdf/Technical-Papers/Climate-Change-Water-En.Pdf>
- [47] Marconi V., Antonellini M., Balugani E., Dinelli E.. 2011 Hydrogeochemical Characterization Of Small Coastal Wetlands And Forests In The Southern Po Plain (Northern Italy). *Ecohydrol.* Vol.4, 597-607
- [48] Capaccioni B., Didero M., Paletta C., Didero L. 2005 Saline Intrusion And Refreshening In A Multilayer Coastal Aquifer In The Catania Plain (Sicily, Southern Italy): Dynamics

- Of Degradation Processes According To The Hydrochemical Characteristics Of Groundwater. *Journal of Hydrol* 307:1–16
- [49] Oude Essink G.H.P., 2001. Improving Fresh Groundwater Supply-Problems And Solutions: *Ocean And Coastal Management* 44: 429-449.
- [50] Chot Pp, Dekker Sc, Poot A. 2004. The Dynamic Form Of Rainwater Lenses In Drained Fens: *Journal Of Hydrology* 293: 74-84.
- [51] Marconi V. Antonellini M. Laghi M, Minchio A., Savelli D.. 2008. A Water Table Fluctuations Model In Sandy Soil Below A Coastal Pine Forest. *Geophysical Researches Abstract* 10: Egu2010-05761
- [52] Marconi V., PhD Thesis 2010 Hydrogeochemical Characterization Of Small Coastal Wetlands And Forests In The Southern Po Plain (Northern Italy).
- [53] Marconi V. 2011. Effetti Della Vegetazione E Del Drenaggio, Sull'intrusione Salina Nell'acquifero Freatico Costiero Della Zona Compresa Fra Foce Dei Fiumi Uniti E Foce Bevano (Ravenna). Dottorato Di Ricerca In Scienze Ambientali: Tutela E Gestione Delle Risorse Naturali, Ciclo XXIII. Università Di Bologna
- [54] Stuyfzand, P.J. 1999. Patterns In Groundwater Chemistry Resulting From Groundwater Flow. *Hydrogeology Journal* 7 P 15-27
- [55] Böhlke Jk 2002 Groundwater Recharge And Agricultural Contamination *Hydrogeology Journal* (2002) 10:153–179 Doi 10.1007/S10040-001-0183-3
- [56] Boonstra J., Bhutta M.N. 1996 Groundwater Recharge In Irrigated Agriculture: The Theory And Practice Of Inverse Modeling *Journal Of Hydrology* 174 357 374
- [57] Bouwer, H. 1997. Role Of Groundwater Recharge And Water Reuse In Integrated Water Management. *Arabian J. Sci. Eng.*, 22, 123–131
- [58] Bouwer, H. 1999. Chapter 24: Artificial Recharge Of Groundwater: Systems, Design, And Management. *Hydraulic Design Handbook*, L. W. Mays, Ed., McGraw-Hill, New York, 24.1–24.44.
- [59] Bouwer, H., Fox, P., Westerhoff, P., And Drewes, J. E. 1999 Integrating Water Management And Reuse: Causes For Concern? *Water. Qual. Internat.*, 1999, 19–22
- [60] Dillon P.. 2005 Future Management Of Aquifer Recharge *Hydrogeol J.* 13:313–316
- [61] Gale I., 2000 Strategies For Managed Aquifer Recharge (Mar) In Semi-Arid Areas International Association Of Hydrogeologists Commission On Management Of Aquifer Recharge Iah - Mar International Hydrological Programme (Ihp) Unesco Division Of Water Sciences [www.iah.org/recharge](http://www.iah.org/recharge)
- [62] Meijer, K.S., 2000. Impacts Of Concrete Lining Of Irrigation Canals, Uda Walawe, Sri Lanka. M.Sc. Thesis, University Of Twente, The Netherlands.
- [63] Meijer, K., Boelee, E., Augustijn, D., Van Der Molen, I., 2006. Impacts Of Concrete Lining Of Irrigation Canals On Availability Of Water For Domestic Use In Southern Sri Lanka. *Agric. Water Manage.* 83, 243–251.
- [64] Liqiang Yao, Shaoyuan Feng, Xiaomin Mao, Zailin Huo, Shaozhong Kang, D.A. Barry. 2012 Coupled Effects Of Canal Lining And Multi-Layered Soil Structure On Canal Seepage And Soil Water Dynamics *Journal Of Hydrology* 430-431, 91–102



- [65] Bradbury R.B., Kirby W.B., 2006 Farmland Birds And Resource Protection In The Uk: Cross-Cutting Solutions For Multi-Functional Farming? *Biological Conservation*, 129, Pp. 530–542
- [66] Herzon I., Helenius J. 2008 Agricultural Drainage Ditches, Their Biological Importance And Functioning *Biological Conservation* 141, 1171–1183

IntechOpen

IntechOpen