POLITECNICO DI TORINO

Environmental and Land Engineering
Geoengineering

Master of Science's Degree Thesis

Application of the patented Idro Well System (IWS) to limit saltwater intrusion in a drinking water well in Reggio Calabria

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Academic year 2020/2021

Preface

Gli argomenti trattati in questa tesi sono il frutto di oltre trent'anni di lavoro e passione che mio padre e mio nonno mi trasmettono da quando ero bambino.
Con orgoglio in questo elaborato raccolgo i frutti di tale lavoro e nel solco delle esperienze raccolte provo a dare l'adeguato supporto scientifico ad una soluzione che nella sua complessa banalità ha dimostrato più volte la sua efficacia in diversi contesti geologici e per la risoluzione di diverse problematiche di salvaguardia della risorsa idrica sotterranea. In questo caso viene analizzata l'applicazione del sistema brevettato ideato nell'azienda di famiglia per la risoluzione del problema dell'emungimento di acqua salmastra in pozzi ad uso potabile.

Ringrazio il professor Rajandrea Sethi per avermi dato l'opportunità di trattare questo argomento a me molto caro, il professor Alessandro Casasso per l'enorme contributo fornito e l'ingegnere Paolo Mainieri per aver creduto in questo progetto ed avermi affidato il recupero del pozzo oggetto di questo elaborato.

Alla mia famiglia
Alla mia città: Reggio Calabria

Summary

Seawater intrusion (SWI) is one of the most challenging and widespread environmental problems that threaten the quality and sustainability of fresh groundwater resources in coastal aquifers.
This phenomenon is a global environmental problem that affects the chemical composition of the coastal aquifers worldwide. It´s mostly caused by human activities, in particular by groundwater over pumping that together with climate changes and population growth, are exacerbating the problem especially in arid and semi arid region all over the world.
In this thesis an innovative remediation technique is presented applied on a well located in the alluvial aquifer of Reggio Calabria, South Italy.
A detailed description of the IWS patented system, a tool developed by a water well drilling and rehabilitation company called Idromaty, and of how it has been used during the works is provided in this study with a particular focus on the results obtained thanks to the intervention.
To validate the results a numerical modelling has been performed creating a 3D finite element groundwater flow model of the area object of this study. A comparison between scenarios of non-pumping and pumping was conducted considering three different phases according to the stresses applied to the aquifer during the years.
The proof of a relevant saltwater upconing phenomenon below the well field and of the success of the IWS performance to generate an impermeable layer able to create a vertical separation between saltwater and freshwater, represents the major scientific contribution of this thesis. The theis in divided in five chapters as follows:

- Chapter 1: "Introduction", describes the saltwater intrusion problem worldwide, its main causes and the most applied and known countermeasures to the intrusion problem. The chapter describes also the evolution of the phenomenon in Reggio Calabria aquifer and the geological and hydrogeological framework of the area.

- Chapter 2: "Well rehabilitation", describes all the intervention performed on well number 3 in Calopinace well field, from air surging to well cementing and

in place screening with IWS patented tool.

- Chapter 3: "Results", the results of the intervention on the well are analyzed both from the hydraulic and chemical point of view
- Chapter 4: "Numerical groundwater flow model" , describes the numerical groundwater flow model developed to represent the aquifer, the conceptual model of the site, the tools and the related setup used for the groundwater modeling. The results of the simulation of the groundwater flow model are presented, discussed and analysed.
- Chapter 5: "Conclusions", the work of this thesis and what well rehabilitation has pointed out are resumed and evaluated. Pros and cons of IWS patent system are analyzed.

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Chapter 1

Introduction

1.1 Saltwater intrusion problem

Freshwater is a vital resource in sustaining ecosystems health [1, Bayart et al.] and the most universally required natural resource for human life. Despite its importance and its being renewable, fresh water is an extremely rare and vulnerable resource on Earth.
Even if our planet surface is covered 71 % by water, freshwater represents a little fraction of the total water reserves on Earth, in fact 97 % of the water is salt water found in the seas and oceans and only 3 % is freshwater, of which, however, most (68.6 %) is locked up in ice and glaciers, 30.1% in groundwater and 1.3 % in surface water [2, Igor Shiklomanov].
Freshwater availability and vulnerability are critical issues in all the coastal areas around the world, where coastal groundwater serves as major source for freshwater supply , especially in arid and semi-arid zones.
Freshwater in coastal aquifers is very susceptible to degradation, due to its proximity to the sea. If an undisturbed condition is maintained, a state of equilibrium is reached between freshwater and saltwater and a stationary contact between the two waters exists with freshwater flowing towards the sea but, if temporary or permanent perturbations of the system are applied, a saltwater intrusion problem can occur [3, De Filippis et al.].
Saltwater intrusion is the movement of water from the sea into the contiguous freshwater aquifer and its causes can be both natural or anthropic.
The boundary between saltwater and freshwater is not distinct, the interface is not found in the form of thin-sharp plane but is a diffuse zone with a progressive transition from freshwater to saltwater due to mixing and diffusion processes. This zone is referred to as the zone of dispersion or zone of transition and the higher the freshwater hydraulic head, the closer the interface to the sea.

This boundary between fresh groundwater and saline groundwater is dynamic and can often shift inland or seaward, depending on the aquifer and surface conditions. Saline water is the most common pollutant in fresh groundwater and saltwater intrusion is one of the most widespread and important processes that degrade water quality to levels exceeding acceptable drinking and irrigation water standards, and endanger future water exploitation in coastal aquifers.
Jacob Bear et al. [4] identified 7 main chemical indicators of saltwater intrusion (SWI):

1. Total dissolved solids TDS
2. Chloride
3. Sulphide
4. Hardness
5. Electrical conductivity
6. Cl/Br ratios: can be used as a reliable tracer because both Cl and Br behave conservatively (i.e., do not react with the aquifer matrix) except in the presence of very high amounts of organic matter
7. Ca/Mg $Ca/(HCO_3+SO_4)$ ratios: one of the most famous features of saltwater intrusion is the enrichment of Ca with respect to its concentration in seawater. High Ca/Mg and $Ca/(HCO_3^- + SO4)$ ratios (> 1) are further indicators of the arrival of saltwater.

The presence of dissolved solids in water affects its taste. According to World Health Organization,considering a TDS content of around 35000 ppm in saltwater, which are made up roughly 50% of Chloride, mixing of only 2% saltwater in a freshwater aquifer exceeds aesthetic objectives for the upper limit of chloride which is 250 mg/l (water begins to taste salty) [5, Custodio E.]. If mixing exceeds 4%, then the water becomes unusable for many uses, and if mixing exceeds 6% water becomes unusable except for cooling and flushing purposes [5, Custodio E.].
The taste of drinking water has been rated by tasters in relation to its TDS content, that is the sum of all the organic and inorganic dissolved particles in molecular, ionized, or colloidal form, as follows [World Health Organization 6]:

- excellent, less than 300 mg/l;
- good, between 300 and 600 mg/l;
- fair, between 600 and 900 mg/l;
- poor, between 900 and 1200 mg/l;

- unacceptable, greater than 1200 mg/l.

Water with extremely low concentrations of TDS may also be unacceptable because of its flat, insipid taste.
Salinity, that is the total of all non-carbonate salts dissolved in water, is comprised mostly by Cl^- and Na^+ ions and, even though there are smaller quantities of other ions in seawater (e.g., K^+, Mg^{2+}, or $SO_4^{2\check{}}$), sodium and chloride ions represent about 91% of all seawater ions. According to European Directive 98/83EC and the Italian Legislative Decree 31/2001, public drinking water standards require chloride level not to exceed 250 mg/l [7, 98/83EC],[8, D.Lgs 31/2001].

1.2 Natural and anthropic causes

Saltwater intrusion drivers can be natural or anthropic. Natural drivers of SWI include storm surges, drought, hurricanes, sea level rise and subsidence (figure 1.1).

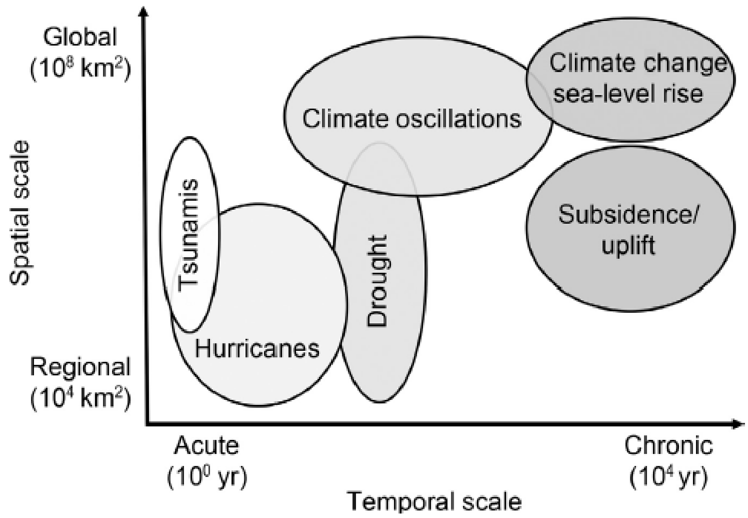


Figure 1.1: Schematic representation of the spatial and temporal scales of natural saltwater intrusion (SWI) drivers [9, Elliott White].

Natural drivers of SWI occur over different timescales and frequencies, varying from few minutes in the case of extreme meteorologic events to hundreds or thousands years in case of slow geologic events. At the shortest timescales, tsunamis can act as physically destructive forces on the coast and carry saline water far inland. At the longest timescales, sea level rise that acts in normal conditions over hundreds or thousands years. The rising water level is mostly due to a combination

of meltwater from glaciers and ice sheets and thermal expansion of seawater as it warms. Sea level rise rate is accelerating with global warming, it has more than doubled in the last century.
With climate change, according to the Intergovernmental Panel On Climate Change (IPCC) Assesment Reports, we can expect sea-level rise, more frequent extreme weather events, coastal erosion, changing precipitation patterns and warmer temperatures. All of these factors combined with the increased demand for freshwater, as a result of global population growth, could boost the risk of saltwater intrusion.
Anthropic SWI drivers include land drainage, depletion of coastal freshwater aquifers, reduction in freshwater discharge due to dam construction, hydraulic structures construction and land-use changes that affect recharge rates (lowered in areas with increased urbanization and thus impervious surfaces) [9, Elliott White].

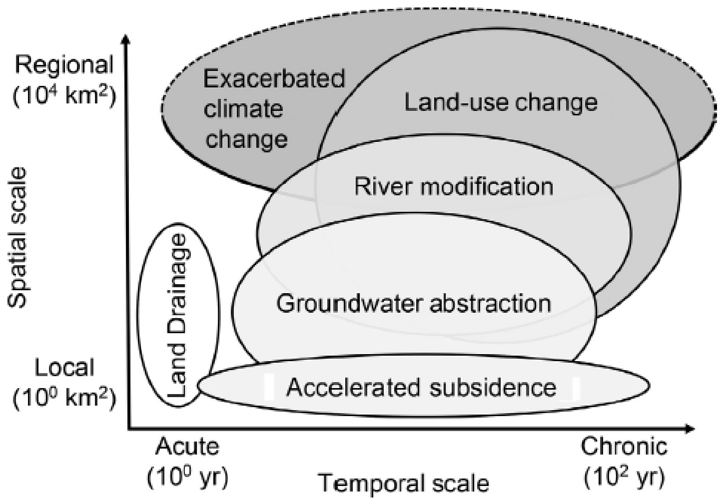


Figure 1.2: Schematic representation of the spatial and temporal scales of anthropic saltwater intrusion (SWI) drivers. Many anthropic drivers act over a wide variety of spatiotemporal scales as a function of development intensity [9, Elliott White].

According to the UN report, about 40% of world's population live within 100km from the coastline and a common source of drinking water for coastal communities is pumped groundwater. Groundwater extraction is the primary cause of saltwater intrusion because if the aquifer is overexploited the level of the freshwater table lowers, reducing the pressure exerted by the freshwater column and allowing denser saline water to move inland. This situation commonly occurs in coastal aquifers in hydraulic continuity with the sea when pumping of wells disturbs the natural hydrodynamic balance.

1.3 Saltwater-freshwater interface

Under natural conditions, the seaward movement of freshwater prevents saltwater from encroaching coastal aquifers and the interface between freshwater and saltwater is maintained near the coast. Marine intrusion is a dynamic process that depends on the periodic changes in the recharge-discharge balance of the aquifer. Any direct or indirect influence on the aquifer's water balance affects the position and movement of the fresh water-seawater interface and also the chemistry of the groundwater [10, Elena Giménez-Forcada].
At the interface between saltwater and freshwater the fluids mix together creating a transition zone (figure 1.3) due to the effect of molecular diffusion and kinematic dispersion created by freshwater flow.

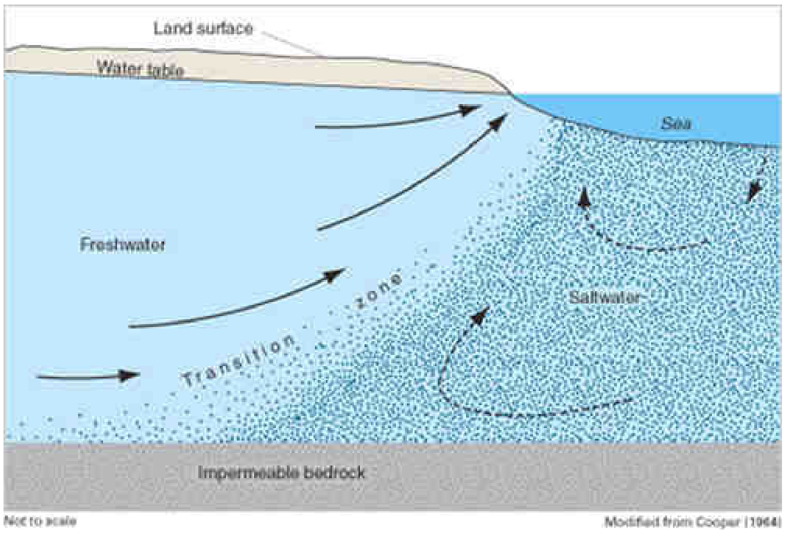


Figure 1.3: Saltwater-freshwater interface [11, William Sampson et al.]

This freshwater flow towards the sea limits the extension of the intrusion wedge that otherwise would extend indefinitely. The original salinity values in aquifers affected by saltwater intrusion can be restored naturally over decades or even centuries if the stress factors in the aquifer are removed because the restored seaward hydraulic gradient allows to push the saltwater wedge towards the coast. The flow of saline water through a porous medium is accompanied by reactions that alter the composition of the mixing water. One of the most important processes in alluvial aquifers is cation exchange, treated in detail by Appelo and Postma. According to whether the ion exchange is direct or reverse, we can identify the

phase of the intrusion process [10, Elena Giménez-Forcada].
Freshwater generally, but particularly in coastal areas, is dominated by Ca^{2+} and $HCO3^{-}$ ions derived primarily from the dissolution of calcite, or secondarily from plagioclase feldspar. Sediments in contact with seawater have Na^{+} as the most prevalent adsorbed cation.
In the intrusion phase, when saline waters enters the aquifer occupied by fresh water, a redox reaction occurs and Na^{+} replaces part of the Ca^{2+} on the solid surface. During freshening (or "refreshing"), when the fresh calcium bicarbonate water flushes the salty water seaward,the adsorption of Ca^{2+} with concomitant release of Na^{+} cations will occur. The following cation exchange takes place [12, Appelo and Postma]:

$$Na^{+} + \frac{1}{2}CaX_2 \iff NaX + \frac{1}{2}Ca^{2+} \tag{1.1}$$

As seawater intrudes coastal aquifers containing freshwater, the Na/Cl ratio increases and the $(Ca + Mg)/Cl$ ratio decreases.
The molecular diffusion occurring at the interface between freshwater and saltwater is a phenomenon due to the thermal motion of all solute particles present in the water mass. The movement is regulated by the impacts with the adjacent molecules that creates a mass flow from the zones with high concentrations to the zones with low concentrations. The final result is a pollutant flow in the direction of the mass gradient, whose mass flow rate is regulated by Flick's law [13, Rajandrea Sethi, Antonio di Molfetta]:

$$j_{M,x_i} = -D_d \frac{\partial C}{\partial x_i} \tag{1.2}$$

Where

- j_M mass flow rate per unit of time and surface $(kg/(m^2 s))$
- D_d molecular diffusion coefficient (m^2/s)
- C mass concentration (kg/m^3)

The mechanical (or kinematic) dispersion is a combination of the following phenomena due to the lack of uniformity at the microscale that have an impact on transport phenomena:

- non-uniform velocity distribution within a single flow channel;
- variation of velocity from pore to pore;
- transverse velocity components due to the matrix tortuosity.

The mechanical dispersion is responsible for:

- non uniform velocity distribution
- a transverse velocity component relative to the flow direction, which widens the area affected by the contamination

Mixing by dispersion is thus caused by spatial variations (heterogeneities) in the geologic structure and the hydraulic properties of an aquifer [13, Rajandrea Sethi, Antonio di Molfetta].

1.4 Saltwater upconing

In some cases, water in wells inland of the saltwater front may become degraded by increasing salinity. This is generally due to upconing rather than to lateral intrusion [4, Jacob Bear et al.]. In areas where saline groundwater is present below fresh groundwater (for example where the alluvial aquifer has a relevant thickness and no impermeable layer is present in the stratigraphic column), the interface between fresh and saline groundwater may rise when piezometric heads are lowered due to aquifer exploitation. This phenomenon is called upconing (figure 1.4).

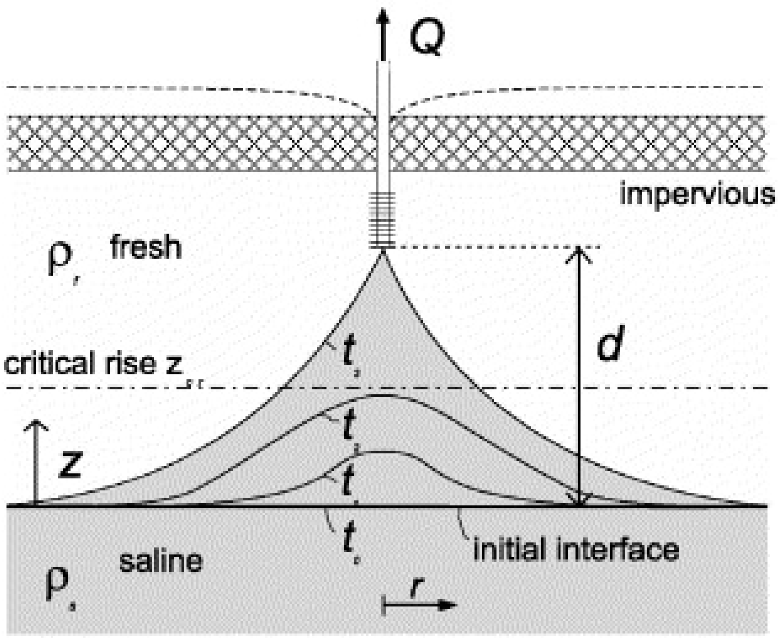


Figure 1.4: Saltwater upconing [14, Gualbert H.P Oude Essink]

The interface is horizontal at the starting time t_0 but, with prolonged pumping, it rises to successively higher levels until eventually it reaches the well. From that moment on, the quality of the extracted groundwater deteriorates. In order to

avoid or to limit these negative effects, the extraction rate, and so the lowering of the piezometric head, should be kept below a certain limit. After reducing the extraction, the interface may descend to a lower position, though this process occurs at a very slow rate [14, Gualbert H.P Oude Essink]. For water-supply wells that are close to the position of the front or close to the coast, it is difficult to determine whether a salinity increase is caused by upconing or lateral intrusion unless data are available from additional observation wells in the area. This distinction is important because different management actions, remediation solution and strategies would be chosen in the two different situation.
Although the regional groundwater system can be capable of providing the required water produced by a well, the local saltwater movement near discharging wells can make these wells produce salty water. This phenomenon occurs because the exaggerated drawdown near a well may cause a local, vertically-upward movement of saltwater into the well: the upconing [4, Jacob Bear et al.].

1.5 Remediation techniques

Remediation of brackish or saline groundwater using chemical, biological or physical techniques is a very expensive process and can take a long time, that depends on the source and level of salinity. For this reason a correct policy of exploitation of groundwater resources and monitoring campaigns are of paramount importance.
To control SWI problems, a seaward hydraulic gradient should be maintained, thus a part of the fresh water should be allowed to flow into the sea. [15, Hussain]

1.5.1 Reduction of pumping rates

Reduction of abstraction from pumping wells is the simplest, most direct and most convenient measure to maintain the groundwater balance in aquifers and control SWI problems. However, the possibility of reducing the abstraction collides, in some regions, with the water demand requirement, and of course a supplemental source of water should be provided to substitute the imposed reduction on the groundwater pumping plan.

1.5.2 Relocation of pumping wells

Pumping wells can be relocated far from the coast to provide a proper seaward hydraulic gradient. This approach could be limited in some cases due to unavailability of land and its costs due to the construction of new wells and transportation of water can be also a limiting factor. The spatial distribution of the new pumping wells should be carefully designed in order to control the problem rather than accelerating it.

1.5.3 Land reclamation

Coastal land reclamation is the artificial extension of the coastline towards the sea, new land is introduced by artificial filling of the appropriate type of soil creating the desired geometry and slope. Land reclamation is mainly designed to provide the land area required to meet growing urbanization and population increase [15, Hussain]. However, from a hydraulic point of view, coastal reclamation creates a new zone where a freshwater body may develop, helping to delay the advancement of saltwater wedge. To maintain the hydraulic equilibrium of the system, the freshwater body starts to penetrate into the newly reclaimed soil, and hence it delays the inflow of saline water.
The high costs of such a surface barrier at a large scale is the main limitation to this technique. In addition, the land subsidence that may occur due to the compaction of the reclaimed material in the areas that are underlain by soft layers, that is mainly due by the increased overburden pressure imposed by the mass of that material, is another concern.

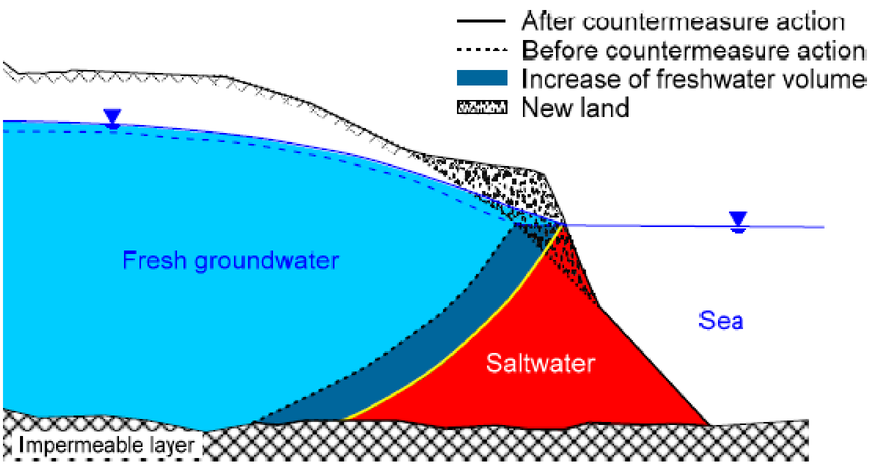


Figure 1.5: Land reclamation [15, Hussain]

1.5.4 Hydraulic barriers

Hydraulic barriers used to control saltwater intrusion are more popular than the other management strategies. Recharge, abstraction, and combination of abstraction and recharge are the three main types of hydraulic barriers. The main possible sources of water that can be used to recharge aquifers are: treated wastewater (TWW), desalinated seawater, and desalinated brackish water.
In artificial recharge (figure 1.6 (b)) the aquifer is recharged with surface water, rainwater, extracted groundwater, treated wastewater, or desalinated water to maintain the seaward gradient in the system by increasing the inland piezometric head. The main aim of artificial recharge of water is to store freshwater water in aquifers, raise groundwater levels, relieve over-pumping, and suppress the saline water body. This methodology is among the most popular techniques, which have been widely suggested and assessed in the literature.
Among the main limitations of recharge barriers using desalinated water there is the cost of providing high quality water (e.g. desalinated water) combined with the unavailability of such resource locally, especially in dry years or in dry regions that constitutes another restriction. Therefore, in recent years the use of renewable sources of water, such as treated wastewater, as the sources of recharge for seawater intrusion mitigation, has been evaluated.
In abstraction barriers (figure 1.6 (b)), the brackish or saline water is continuously pumped through abstraction wells located near the coast, the extracted water can be directly disposed of into the sea or it may be used as a water source for desalination plants.
In general, extraction barriers cause a drop in the piezometric head near the coast, which enhances the seaward hydraulic gradient and protects the aquifer.

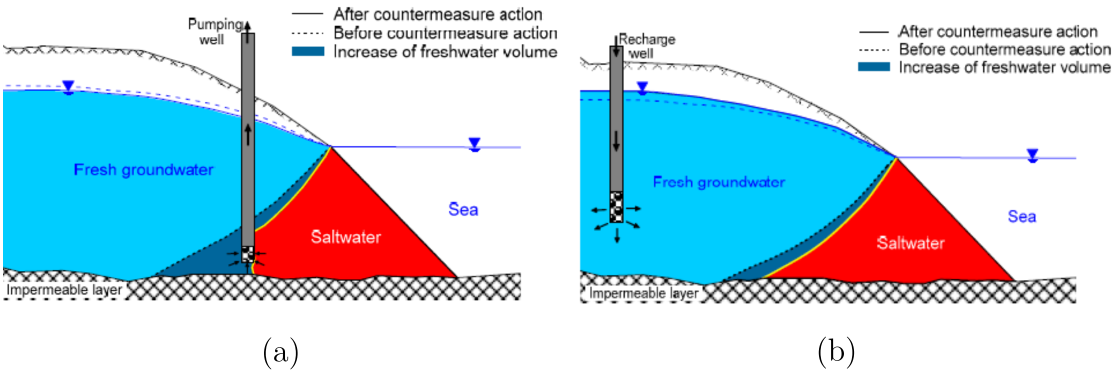


Figure 1.6: Abstraction barrier (a) and recharge well (b) [15, Hussain]

1.5.5 Physical subsurface barriers

In physical subsurface barriers, concrete, grout or bentonite-slurry walls, and sheet piles are commonly designed in front of sea along the coast in order to create a physical obstacle to seawater intrusion from the sea.
Although, the construction of such barriers has high initial installation and material costs, they do not require maintenance and repair activities over their life time [16, K.A. Allow]. The economic comparison between physical barriers and injection wells, taking into account the need to provide the source of recharge water and the maintenance costs of the injection process, make the construction of underground cut off walls more favorable in low depth aquifers with respect to injection wells [14, Gualbert H.P, Oude Essink].
A different technique working with the same aim was introduced by James et al. [17]. This method consists of a biological barrier to work against SWI based on the injection of bacteria or nutrient solutions to reduce the hydraulic conductivity of sub surface layers, and hence to reduce the risk of SWI. After the injection the bacterial biofilms grow with time and extracellular polymeric substances (EPS), that tend to clog the pores of the porous matrix and reduce its permeability, are produced . The application of biofilm barriers would reduce the economic cost by about 24% compared with the more traditional deep physical barriers [17, James et al.].

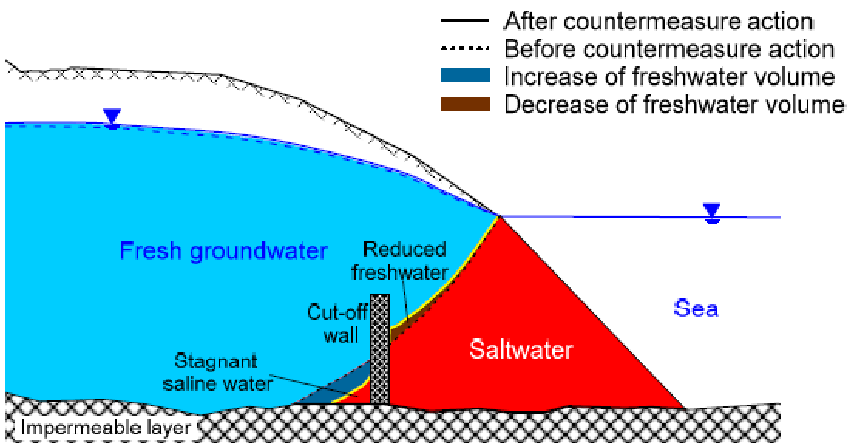


Figure 1.7: Physical subsurface barrier [15, Hussain]

1.6 Intrusion in Reggio Calabria aquifer

1.6.1 Geological setting

The study area is located at the extreme South of the Italian peninsula, on the Tyrrenian coast of the Calabria region in the Central-Southern part of Reggio Calabria city (figure 1.8).
Separated West from the Sicily island by the Strait of Messina, Reggio Calabria develops in alluvial plains created by the deposited sediments coming from the stream solid transport, streams that cross the territory in East-West direction rising in the heart of Aspromonte massif, watershed between Tyrrenian and Ionian Calabria that is located East of the city.
These plains are followed, towards East, by a hilly system constituted by plio-pleistocenic and miocenic sediments, most of all are sandy-clayey conglomerates with a mean incline up to the slopes of Aspromonte massif whose crystalline-metamorphic rocks originated during Paleozoic era.

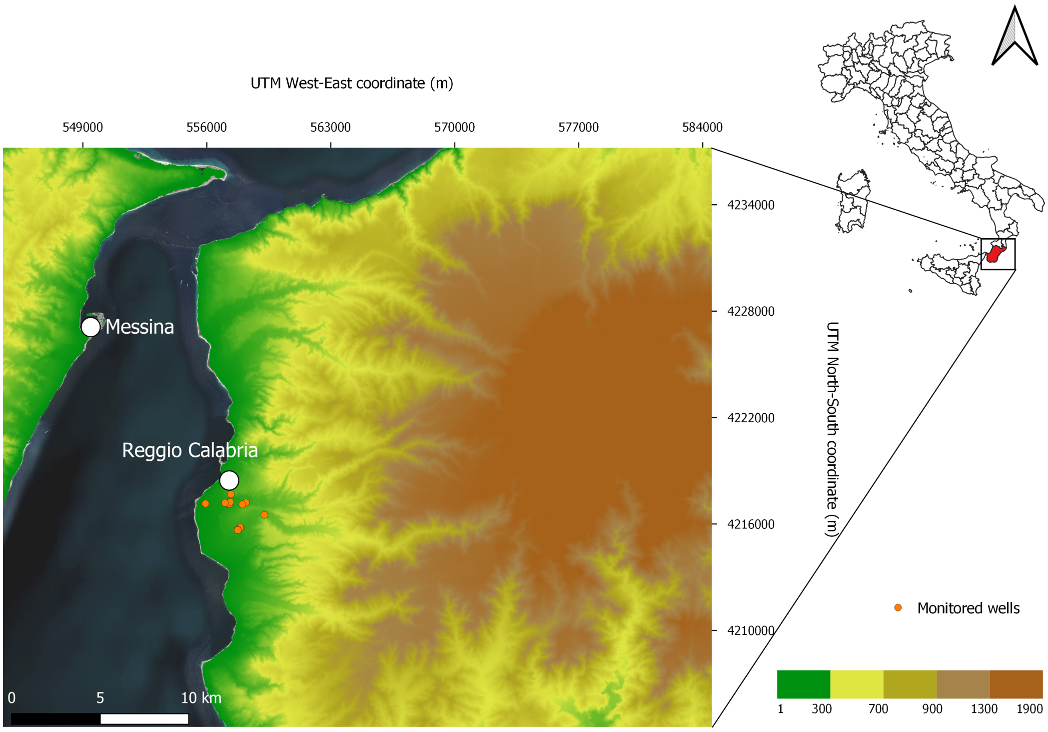


Figure 1.8: Location of the study area. The color map refers to the Digital Terrain Model (resolution of 20 m)

The area object of this study is part of the vast tectonic region characterized by the Strait of Messina Graben to which correspond, in the Calabrian emerged side, the South-Calabrian tectonic pillows delimiting the wide depression known as Reggio Calabria basin.
This territory is affected by severe vertical tectonic movements, still active, that gave rise to the rapid uplifting of Aspromonte in Calabria and Peloritani Mountains in Sicily. The Aspromonte Massif represents one of the four main sectors composing the Calabria-Peloritani Orogen (CPO). From North to South these sectors are: the Sila Massif, the Serre Massif, the Aspromonte Massif (figure 1.9) and the Peloritani Mountains.
The CPO is a composite segment of the western Mediterranean Alpine chain, mostly constituted by basement rocks deriving from a poly-orogenic multistage history which are currently merged in several Variscan, or possibly older, sub-terranes [18, Pezzino].

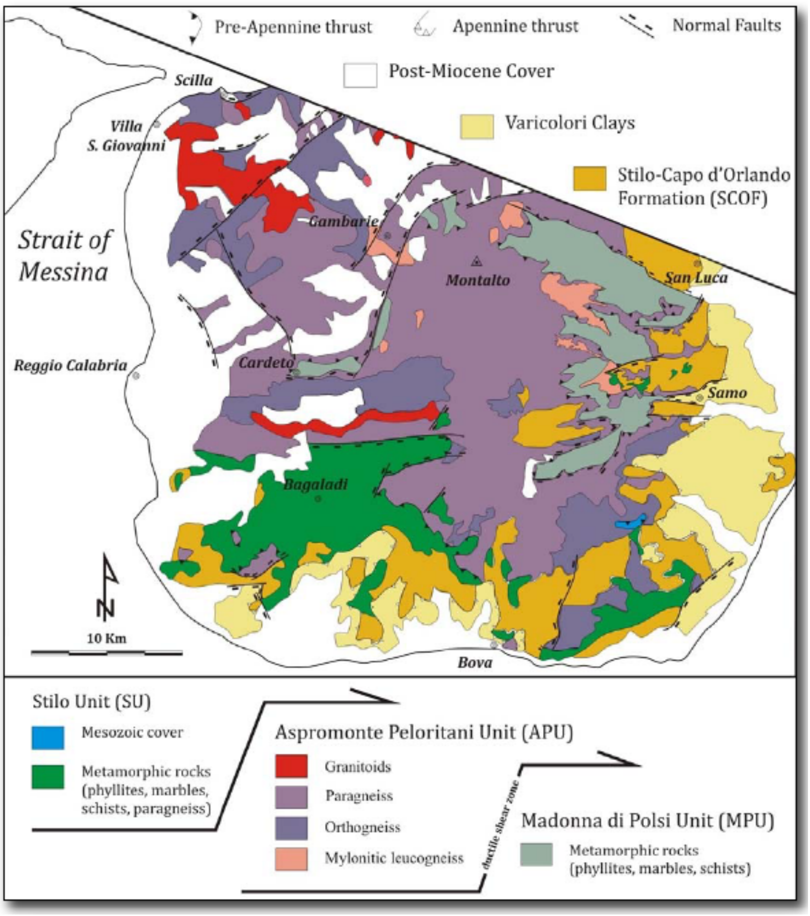


Figure 1.9: Geological map of Aspromonte massif [18, Pezzino]

The uplifting of the crystalline basement was discontinuous and generated the Pleistocene terraces sequence delimiting the eastern part of the basin that in Aspromonte massif can be observed up to 1600m above sea level.
The rapid tectonic uplifting shaped the form of the region, which looks like a platform bounded by steep terraces. Due to this shape, the drainage network consists mainly of ephemeral streams, named fiumara, which are widely observed in southern Italy. In fact, 55% of the regional area is covered by fiumara basins (which extend less than 200 km^2). These streams originate from the flanks of Aspromonte and reach the sea along steep, short and narrow beds that enlarge abruptly on coastal plains [19, Petrucci, O., Pasqua, A].

The geological formation present in the basin are listed in table 1.1.

Period	Epoch	Formation
Quaternary	Holocene	Recent sandy gravel alluvial deposits
	Pleistocene	Conglomerates and sands (random clay lenses)
Neogene	Pliocene	Gray-light blue clays with thin sand and sandstone layers
	Miocene	Sandstone and silty clays
Cambrian-Permian		Shale and gneiss

Table 1.1: Geological formations

Widespread subsidence phenomena characterized Reggio Calabria basin emphasizing its depression with respect to the mountainous hinterland and giving rise to cyclic sedimentation phenomena spaced out by uplifting phases.
The main geological formation called sand and gravel of Messina is constituted by gravel and grey-yellow sands of marine environment. This formation crops out in the hills located north-east of the city. Despite the lithotypes are mainly loosened sediments and the lithogenic processes are still at their initial phases, the diagenesis increased the relative density of the formation allowing the presence of steep slopes. The coarser components are represented by rounded cobbles of metamorphic origin whose size varies from few centimeters to few decimeters while the sand matrix is mainly a coarse quartz sand.
Near the streams the geology is mainly characterized by the sequence of irregularly arranged Holocenic sediments derived by the erosion of Aspromonte massif and transported by water (figure 1.10). This typical alluvial deposition forms thin strips along the valleys and enlarge to wide alluvial fans near the coast.
The grain size distribution is heterogeneous and goes from boulders and cobbles to fine sands and silts. The finer material is present as lenses of variable thickness

linked to the mechanism of alluvial deposition and the ancient stream channels path.
Sandy-clayey conglomerates and alluvial Pleistocene sands forms the alluvial terraces on the borders of the valleys that can be found again in the upper part of the basin above the crystalline formations.
The Paleozoic metamorphic rocks extend in the majority of the mountain basins while the clayey-arenaceous formations of Miocene and Pliocene appear in the hilly zone between the coast and the mountain.

Figure 1.10: Stratigraphy of the area corresponding to the Calopinace well field

The recent alluvial formations have a high hydraulic conductivity while the ancient Pleistocene alluvial conglomerates have a low hydraulic conductivity due to the presence of clay matrix. The Pliocene and Miocene formations are impervious (clays) or with a low conductivity limited to the weathered and fractured zones (sandstones). The conductivity of Paleozoic metamorphic rocks is linked to their fracture degree and is high in the upper weathered part while is low deep, where the weathering decreases [18, Pezzino].

1.7 Hydrogeological setting

The area object of this study is located in the alluvial fan between the streams Calopinace and Sant'Agata where the highest chloride concentration were recorded during the last thirty years.
The whole catchment basin includes also the streams Annunziata and Valanidi for an overall extent of 215 km^2.
The other streams of Reggio Calabria municipality are less interested by the saltwater intrusion phenomenon both for a lower pumping rate of the wells in the area, this happens for the streams located south of the city, and for a higher aquifer recharge of the streams, in the northern part of the city due to their greater extension.
In the table 1.2 are listed the fiumare of Reggio Calabria municipality from north to south represented in figure 1.11.

N	Name	A(km^2)	L(km)	H$_{max}$(m)	S(%)
1	Catona	6	20.2	1325	2.2
2	Gallico	38	21.2	1707	8.1
3	Scaccioti	14	6.7	601	8.9
4	Torbido	13	4.8	443	9.2
5	Annunziata	61	18.2	1349	7.4
6	Calopinace	26	12.8	1077	8.3
7	S. Agata	28	11.5	412	3.6
8	Armo	13	6.4	564	8.7
9	Valanidi	15	13.7	1024	7.4
10	Macellari	11	4.5	401	8.9
11	Lume	10	4.5	201	4.4

Table 1.2: Summary of Reggio Calabria river basins. N, number (from north to south); A, area; L, length; H_{max} maximum elevation above sea level; -S, slope of bed.

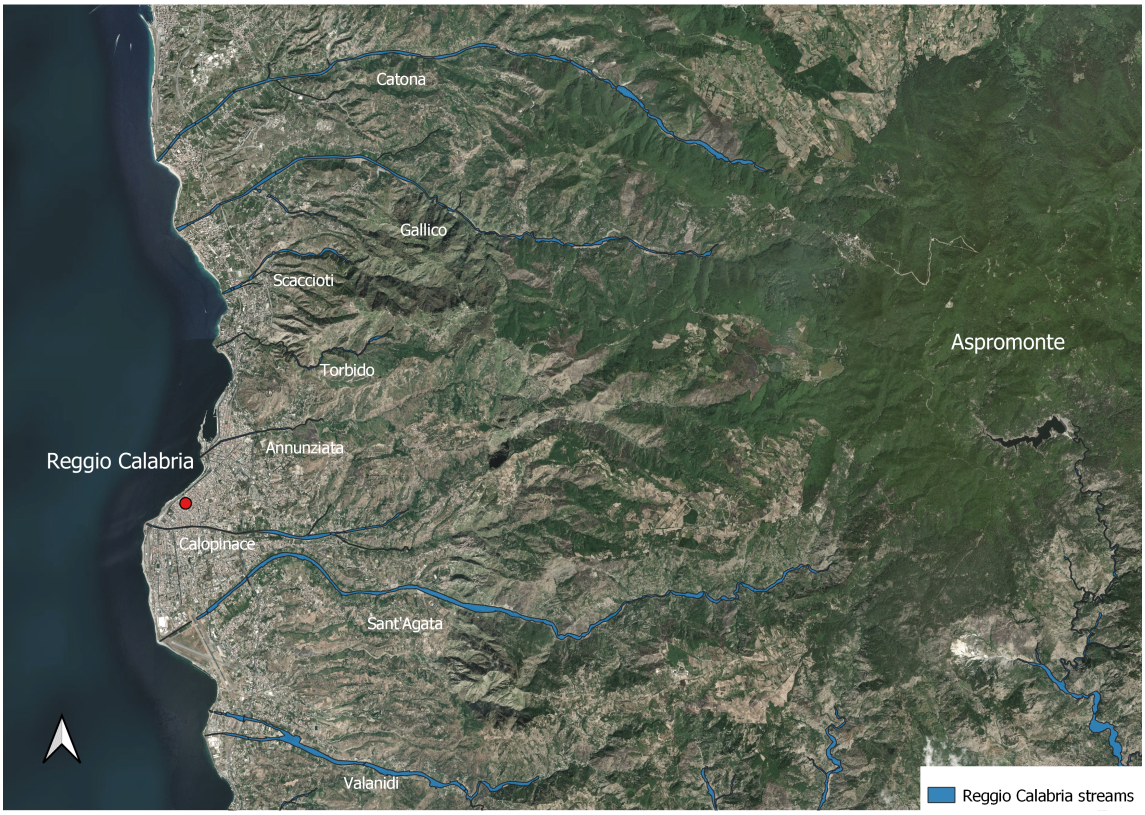


Figure 1.11: Reggio Calabria geomorphological setting

The thickness of the alluvial deposit that constitutes the aquifers varies from 30-60m in the upper part of the basins to more than 100m near the coast, at the mouth of the longer streams (Gallico, Catona, Calopinace, Sant'Agata).
Near the coast the streams Gallico and Catona, located North, and Annunziata, Calopinace, Sant'Agata and Valanidi, located in the Southern-Central part of the city, gather their alluvial fans and create plains where most of the human activities are organized. These plains create two separated aquifer systems: the north and the south one. The watershed between these aquifers is located north of Annunziata river, where the reduced thickness and yield creates an hydraulic division between the aquifers [G. Mandaglio, Italpros 20].

Chapter 2

Well rehabilitation

2.1 Calopinace well field

The saltwater intrusion phenomenon concerns mainly the well field located along the banks of Calopinace stream: Calopinace or San Giorgio Extra well field, so named after the neighborhood of Reggio Calabria where it stands.
The overexploitation of the aquifer has developed and progressively exacerbated the saltwater intrusion with a pumped water that has crossed the Italian legal chloride threshold in drinking water of 250 mg/l more than fifty times, reaching peaks of 22500 mg/l during the years.
The well field Calopinace is located 2.5 km far from the coast and consists of 7 wells distributed over an area of about 11000 m^2 all of them built during the last century, between the '60s and the beginning of the '70s.
In the area there are two other well fields (whose location is represented in figure 2.1) that have shown less or no saltwater intrusion problem, both due to a higher distance from the coast (in case of Prumo well field) and to a higher stream mean flow rate (in case of Sant'Agata well field).
The well field Prumo is located 3.5 km from the coast and consists of 2 wells built during the '60s and the '70s. The well field Sant'Agata, instead, is located 2.3 km from the coast and consists of 4 wells built between the '70s and the '80s.

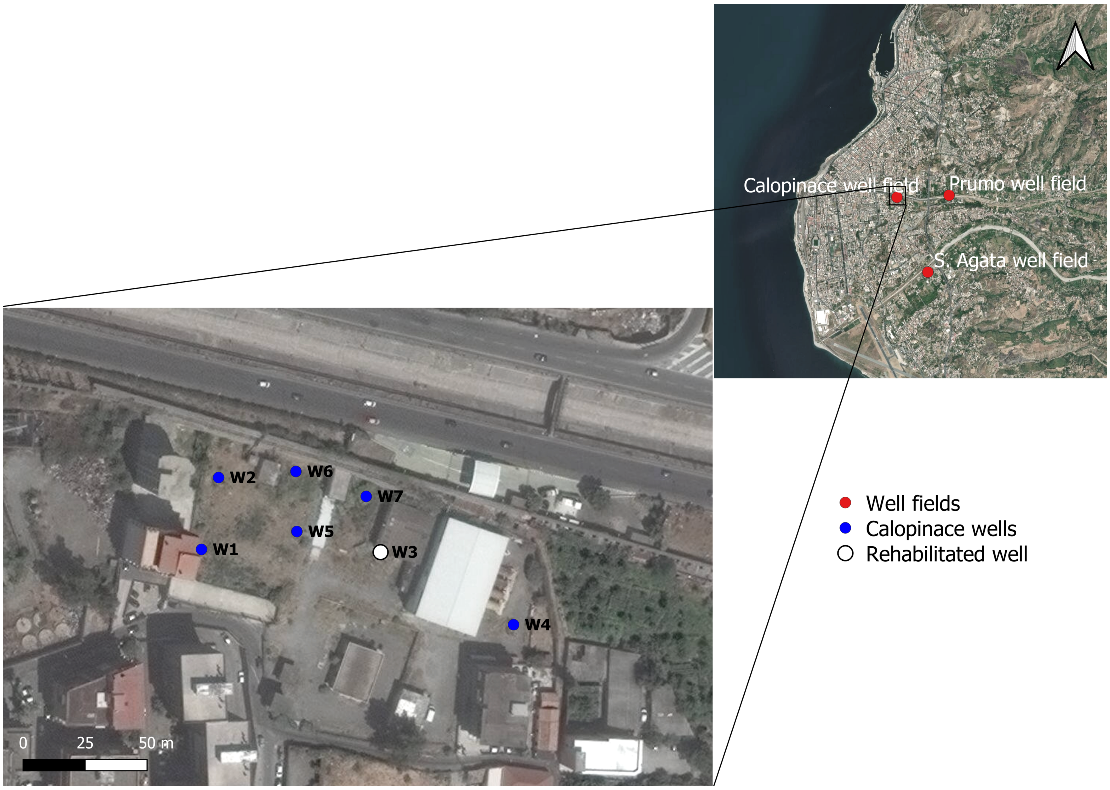


Figure 2.1: Spatial distribution of the wells in Calopinace well field

For more than 30 years Calopinace well field has provided 380 l/s to the main aqueduct of the city creating this problem of high chloride levels in pumped water and forcing the authority to construct a desalination plant in early 2000 with a treatment capacity of 280 l/s and an overall cost of more than 20.000.000 €. This plant has worked only few years not at its full treatment capacity and is now closed since 2017.

The reduction of precipitations during the years, due to climate change, has reduced the recharge of the aquifer thus intensifying the SWI phenomenon. This progressive reduction of rainfall height was already known at the beginning of the '80s when the first study financed by the Casmez (a public institution funded in 1950 to support the economic growth of South Italy) [G. Mandaglio, Italpros 20] to analyze the saltwater intrusion process in Reggio Calabria, highlighted the main causes of the process and through a wide measurement campaign of water chloride concentration and electrical soundings, reconstructed the likely interface between saltwater and freshwater as well as the approximate position of the saltwater front.

The electrical soundings realized during this study pointed out the raising of the conductive layer underlying the alluvial overburden. This raising is significant in the

area between the two streams analyzed in this thesis, Calopinace and Sant'Agata where between 1971 and 1988 it reached 20m. The raising has also been accompanied by the inland movement of the saltwater interface, with values between 400 meters along the Sant'Agata river, where the main river channel is more extended and so is larger the surface runoff and groundwater flow, and the Calopinace where the inland movement reached 800 meters.
In this area the seasonal runoff of the rivers and the geological features of the aquifer make the aquifer recharge more conditioned by the leakage form the streams than from the direct precipitations and the groundwater flow from the upper part of the basin. During the years these supplies reduced due to the increased exploitation in the upstream area and the waterproofing of part of the riverbeds with concrete at the end of the '70s, concurrent with the building sector growth, that has cancelled the contribution due to leakage in the cemented stretch.

2.1.1 Well 3 features

Well 3 (figure 2.1, well scheme on page 33) was built in 1962 with a depth of 75 m from the ground surface and a casing outside diameter $\phi = 500mm$. Excavated with cable percussion drilling technique, the well has been pumped 80 l/s until critical values of salt in pumped water where reached at the end of the '80s and chloride concentrations exceeded 10000 mg/l.
In order to restore the structural features of the well and its productivity Sorical, the company having the control of the water resources in Calabria, entrusted the contractor Idromaty to execute the necessary works required to restore the well.
The pump removed from the wellbore showed many signs of the chemical and physical alteration of the well and the first video-inspection of the well casing highlighted heavy clogging of the screen and structural impairment of the steel casing. This impairment was suffered after decades of corrosion accelerated by high chloride concentrations that reduced pipe original thickness provoking the collapse of the casing. A total collapse of the casing at 62.8 from the ground surface was preceded by a breakage with a partial section closure at 57.8m (figures 2.2, well scheme on page 33).

Figure 2.2: Collapsed casing at 57.8m

The casing has slotted screen starting from a depth of 52.8 m despite a water table depth of 41.98m. The completion technique adopted at those times provided for the covering of the external part of the casing with a brass mesh reps type that was a further filter to prevent the production of formation sand together with the gravel pack.
The fine net adopted to cover the outside casing screen has two long time negative effects:

- clogging of the mesh due to fine sediments accumulation and corrosion, caused mainly by microbiological iron bacteria activity and chloride adsorpion on steel surface.

- difficulties in well development with air surging to remove biofouling and impossibilities to use acidification to dissolve the incrustation due to the reduced thickness of the casing that could lead to further collapses of the wellbore.

2.2 Rehabilitation works

Rehabilitation treatments need to be tailored to fit the well that is being treated and its specific problems according to its construction details (types of screen openings, casing size, drilling size, type of formation and groundwater chemical composition).

Figure 2.3: Reduced casing thickness in the collapsed section along the welded joint

To recover the well extending its production phase and reduce the salt concentration in supplied water a series of well development activities have been designed and executed. The purpose of well development in water wells is to replace the physical characteristics of the gravel pack and alter the aquifer near the borehole removing the finer sediments in order to create a laminar flow toward the well increasing the hydraulic conductivity near the borehole.

2.2.1 Mechanical brushing

First of all to mechanically remove the fouling caused by ferric hydroxide precipitation linked to iron-oxidizing bacteria metabolism and chloride adsorpion, mechanical brushing has been adopted.
Brushing is an effective technique done with steel (figure 2.4) or plastic bristles attached to a tool that is moved vertically along the wellbore axis; to make more effective the treatment the tool can be also rotated through a drilling rig.
This approach is good as first step in rehabilitation because ensures that the following treatments, both mechanical and chemical, have a greater chance of reaching the deposits on the other side of the well screen, making it easier to attack the underlying materials. Scratching the surface with the wire rope the deposits are detached and collapse to the bottom. All the inner wall of the well below the water table has been treated, even the unscreened section from 41.5 meters to 52.8 meters.

Figure 2.4: Wire rope brushing tool

2.2.2 Airlift surging

Even though cleaning the inside of the well is a beneficial step, it will not work alone to replace the well productivity because much of the plugging occurs deeper out in the gravel pack and surrounding formation. It is important to be able to penetrate beyond the well screens and remove the deposits, even if it is more difficult due to the inaccessibility of this side, and this can be done with different technologies and techniques that must be chosen and adapted according to the problem to be faced and the well features.
To get good results the most effective methods of well development employ techniques which allow water to move in and out of the screen creating a bidirectional flow in the surrounding aquifer.

1. air lift surging
2. high pressure air impulse
3. mechanical surging
4. acidification

The listed well development methods can be combined to increase their effectiveness but only if the well allows it. In fact not all the techniques can be indiscriminately applied to all the works because the structural conditions of casing can be irretrievably compromised and the physico-chemical features of the formation can get worse. For this reason in this specific case invasive techniques like acidification, high pressure impulse or mechanical surge could not be adopted unless to compromise

the future structural integrity of the wellbore.
Mechanical surging is done through a plunger equipped with rubber disks that adhere to the casing wall; the alternate movement of the plunger nearby the screen creates a swabbing and surging action with a differential pressure able to develop a bidirectional water flow (towards the well and the formation).
The surging effect creates a positive pressure on the screen while the swabbing creates a negative pressure that carries into the well the finer sediments deposited in the gravel pack and in the surrounding formation and breaks the fouling. This differential pressure applied in the well could be really dangerous in a case like this one and provoking the casing collapse during the operations or increasing its damage. Only the installation of a smaller casing inside the wellbore could give the required safety factor to make mechanical surging and providing the required guarantees to extend the production phase of the well.
The impulse technique instead, uses a high-pressure shock developed by the rapid expansion of a compressed gas, which generates a vibration pulse that maximizes the inflow to the well from the surrounding aquifers by removing the physical, chemical, and biological clogging materials. The sudden change in volume creates a compression increasing the pressure on the screen and a subsequent cavitation effect resulting from air bubbles collapse that develops traction pressure wave. The pressure range between 50 and 250 bar of these systems would be too dangerous for well 3, for this reason also this technology was not adopted.
The technique adopted for well development after brushing was the reverse circulation air lifting. With respect to the other ones this technique allows to use compressed air in the range between 5-25 bars minimizing the risk to damage the wellbore. The high air flow rate (3000-28000 l/min) creates the required bidirectional water movement necessary to act behind the casing and to clean the gravel pack. The air bubbles act like in the impulse method but their action is less dangerous for the casing stability; the results are the same but the time required to get them is higher. The flow rate pumped with reverse air lift depends on the air flow rate and pressure, in this case was between 5 and 6 l/s. Alternating reverse circulation airlift to backwash is possible to remove the debris left in place after brushing and pump out of the well all the sand and fouling sedimented at the bottom because the specific weight of the water-air mixture is less than the specific weight of water and because there is a differential pressure between the injection and outlet points, so water rises in the discharge column up to the ground level.

Figure 2.5: First airlift executed, water rich of sediments and rust particles

2.2.3 Cementing with IWS patent system

To reduce salt upconing in the aquifer it was decided to cement the new bottom of the wellbore, located at 57.8 m from the surface after the collapse, and the annular gap between casing and formation occupied by the gravel pack, between 57.8 and 56.6 m (well scheme on page 33).
The approach presented is completely maintenance-free but the operation is not simple, filling the bottom creating a plug would be easier but alone not effective in order to stop the leaks between the upper and lower part of the aquifer severely polluted by saltwater upconing; according to oil and gas definitions we can call the bottom filling as plug cementing that consists of placing cement slurry in a wellbore and allowing it to set [21, Erik B. Nelson and Dominique Guillot].
In order to create a durable hydraulic seal in the wellbore that allows selective fluid production from subsurface formations and thus to plug the salt water raised due to the prolonged water table depression in more than 30 years of heavy pumping, it is necessary to extend as much as possible along the horizontal plane and behind the casing the waterproofing material otherwise the high permeability of the gravel pack but also of the interested formation would make the intervention ineffective allowing the vertical movement of water during pumping. In oil and gas industry this kind of cementing operation is called squeeze cementing.
To accomplish this kind of works Idromaty patented a multipurpose hydraulic tool called IWS (Idro well system) able to make many different recovery operations on existing wells such as:

- Repair partial sections of damaged casing wellbores through the installation of casing patches adherent to the existing casing and mechanically linked through punching.

- Reclaim the aquifers isolating the pollution source through sealing materials injection in wellbores artificially reducing the hydraulic conductivity of the formation

- Create new in place screen with six simultaneously activated pistons able to punch the steel casings leaving shutter shaped screen, that is half a bridge screen

This localized cementing is similar in purpose to squeeze cementing when it is used to shut off perforations in a depleted interval and both the perforation tunnels and the surrounding formation are filled with slurry cement. Squeeze cementing is generally performed using retrievable or drillable packers when the grout flow must be forced in a given perforated interval while IWS allows not to use the packers because perforation of the casing and injection are performed as a unique process and the perforation concave devices installed on the tool avoid leaks inside the casing (figure 2.6, 2.7). Although the processes are similar the pressure applied on the fluid during annular space injection is lower because lower is the formation pressure to be faced with shallow water wells in unconfined aquifers.

Figure 2.6: Image taken from IWS animation

To create a water tight layer it is necessary to fill the formation voids with cement allowing the permeation of a viscous slurry inside the porous media keeping the soil structure unaltered, avoiding any fracking (or claquage) that could make the overall intervention ineffective in preventing communication between the salt water and the fresh water along the vertical wellbore axis. The grout must remain in a fluid state, not only for proper placement, that is to have the widest treated volume, but also for the time necessary to complete the remedial operations.
To guarantee permeation without fracking the pumping rate must be low, in the

range between 10-20 l/min. At the beginning of injection the leak off pressure, that is the pressure required to force the cement in the formation, is low because no filter cake has formed; when the voids start to be filled with cement the pressure builds up and to not create fracture an intermittent pressure is applied with a procedure called hesitation pumping method [21, Erik B. Nelson and Dominique Guillot]. This hesitation procedure is a staged process characterized by the application of a pressure separated by intervals of pumping stop lasting several minutes during which pressure falls off. It can be decided to stop the injection when a predetermined maximum pressure or volume has been reached.
The main advantage of IWS is the possibility to divide the treated section in small slices and repeat the process for each slice creating rings of injected soil until the required volume has been pumped.

Figure 2.7: IWS cementing tools before running in

The grouting program is site specific and at present, there are no truly reliable small scale tests (i.e. <100mm in diameter) or laboratory methods which will accurately determine the injectability limits of soils characterized by a grain size distribution, as it is for the examined problem where the cobbles and gravels are spaced out by thin lenses of fine sand and silt. These tests do not accurately determine injectability limits into site specific soil conditions as they do not allow for injections to be performed in the same manner as they are in the field. [E. Landry, D. Lees, A. Naudts 22]
Grout permeation through soil voids is affected by many parameters that can be both physical and chemical such as:

- Grain size distribution

- Void ratio (affected also by the depth of the layer)
- Moisture content: dry soils absorb water from the mortar and increase its apparent viscosity while saturated soil cause dilution of the grout mix
- Chemical composition of the soil or formation fluid: the presence of contaminants may affect grout rheology or gel time, as in this case where the high chloride concentration reduces the gel time of the mortar

For these reason a proper design of the intervention should include the field tests in order to calibrate the injection and get the required result but in this specific case only one well was available and the time provided for the intervention was too low to make also the tests.
To design the intervention we based on the stratigraphy data available (page 33) and on the chemical data of the groundwater pumped by well 3.
There are three basic types of grout differentiated according to composition as follows :

- Suspension : small particles of solids are distributed in a liquid dispersion medium, e.g. cement and clay in water, having a Bingham's fluid characteristics.
- Solutions : liquid homogeneous mixtures of two or more substances, e.g. sodium silicate, organic resins, and a wide variety of other so-called chemical grouts. Their rehological behaviour is Newtonian with the shear stress directly proportional to the flow rate and their viscosity is constant until setting, within an adjustable period (nonevolutive.
- Emulsions : a two-phase system containing minute (colloidal) droplets of liquid in a disperse phase, e.g. sodium silicate based emulsions. They are evolutive Newtonian fluids, so called because the viscosity increases with time.

Neat cement and bentonite-cement grouts are the most commonly used particulate grouts with water/cement ratios ranging between 0.5/1 to 6/1. Low water/cement ratios provide less sedimentation and filtering and higher strengths but the grouts are harder to inject with respect to those with a higher water content. Chemical additives are sometimes used to facilitate penetration, to prevent cement flocculation and to control set times.
A cement grout is called stable if the sedimentation due to gravity is less than 5% after 120 min; unstable grout easily pressure filtrate, causing anisotropic characteristics in grouted soils [23, Deere]. Stability therefore indicates the ability of a grout to maintain its characteristics during the grouting process without sedimentation or increase in density.
Examples of stable suspensions are cement-bentonite mixes that behaves like

Bingham fluids and guarantee to have a stable suspension if the amount of bentonite is between 1-15%. The volume of grouted soil is directly proportional to the bentonite percentage as shown in figure 2.8. A cement-bentonite mix can be used if the percentage of small particles in the soil to be treated is low, in the order of 10% maximum of fine sand. Increasing the water/cement ratio increases the amount of bentonite necessary yo keep the suspension stable and so its influence on the properties of the mix in terms of reduced final strength, for this reason according to the purpose of the injection, the percentage varies. When it is required to reduce the hydraulic conductivity of the soil it is commonly used a bentonite percentage in the range 4-7%. If the suspension is not stable its injection is hampered from the increased thickness along the pores that reduces the influence volume of the treatment 2.8, this phenomenon is called pressure filtering and increases if the injection pressure increases (10-30bar) [T. G. Santhoshkumar et al. 24].

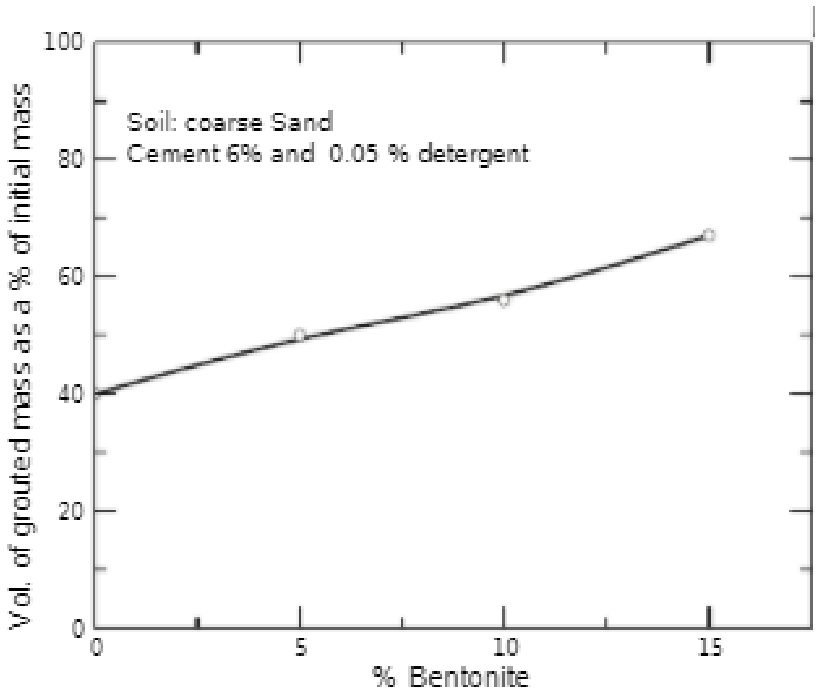


Figure 2.8: Volume treated increasing the bentonite percentage [T. G. Santhoshkumar et al. 24]

The permeation capability of a particulate grouting mix depends on the diameter both of the soil voids and cement particles and this concept is expressed by the groutability ratio [L.K. Mitchell 25]:

$$\text{For soils} : N = \frac{D_{15-SOIL}}{D_{85-CEMENT}} \tag{2.1}$$

Where:

- $D_{15-SOIL}$ is the diameter for which 15% of soil particles are finer
- $D_{85-CEMENT}$ is the diameter for which 85% of cement particles are finer

If:

$$\begin{aligned} &N > 24 \;\text{ grouting is possible} \\ &11 < N < 24 \;\text{ grouting must be verified with preliminary tests} \\ &N < 11 \;\text{ grouting is not possible} \end{aligned} \tag{2.2}$$

The grout penetrability can be improved by reducing the size of the cement grains and improving the grout's rheological properties,increasing the stability under pressure infiltration and reducing the yield stress values.
The cementing process in well 3 lasted 15 hours and was made with a cement-bentonite mix with 5% of bentonite and a water cement ratio 2. The final result as shown in fugure 2.9 was get pumping a total amount of cement of 1500Kg; this allowed to move the bottom of the well from 57.8 to 56.6m from well top, cementing the rest of the wellbore inaccessible to a direct intervention due to the casing collapse.

Figure 2.9: New well bottom resulting after the injection

There are different techniques to create this sealing but their cost is higher, for example install grouting pipe in the annular space and inject grout filling the gravel pack voids.

Figure 2.10: Injection pipes installed in the annular space to create the grout sealing [26, State of Nebraska Dept. of Health and Human Services]

Another technology to artificially reduce the hydraulic conductivity is the injection, in the upper part of selected areas, of a precipitate [O.D.L. Strack; et al. 27]. The installation of this plate shaped barrier is done by injection of an iron-oxide based precipitate to fill pores in the porous medium. The system is maintenance free, and requires horizontal extension in the upper part of the aquifer to create a barrier near the coast, downstream from production wells, to mitigate the effect of the groundwater withdrawal on the interface. This implies that the well field is in a zone where the aquifer is in its original state and the reduction of hydraulic conductivity does not affect the efficiency of the wells.

2.2.4 In place screening with IWS patent system

The partial completion geometry adopted in 1965 with the screened section starting from 52.8 m and a static level at 41.98 m reduced the slotted area with respect to the total potential available area thus increasing the water inflow velocity at the same flow rate.
To reduce the well losses and the total drawdown due to the undersized screened length and get the maximum safe yield from the well after the reduction of the available saturated thickness due to cementing, Idromaty found a solution creating new slots in the unscreaned section of the casing.
IWS multi purpose tool can in fact create new in place screen acting as a casing

perforator with six simultaneously activated pistons, having a 2.5cm stroke each, able to punch the steel casings leaving shutter shaped screen (figure 2.11.

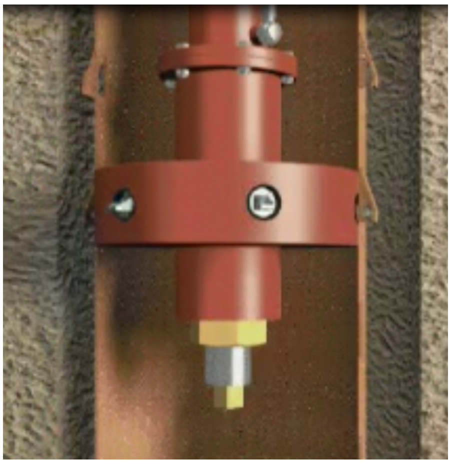


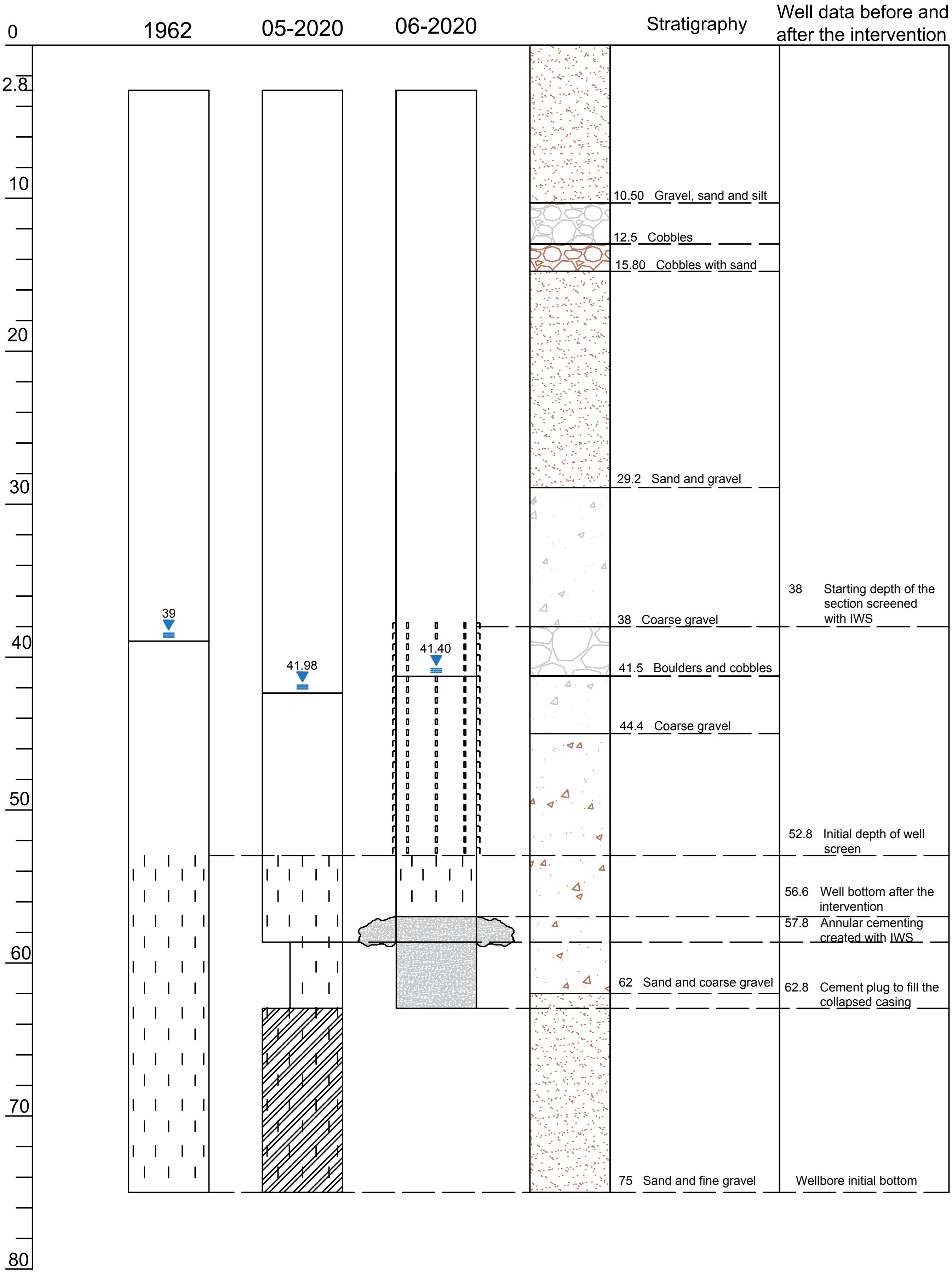
Figure 2.11: Image taken from IWS animation

The slots have been realized each 10 centimeters from 38 to 52.8 meters but the advanced state of casing deterioration didn't allow to get the desired results because in several casing stretches the limited punching tool stroke was not enough to fully penetrate what remained form heavy steel corrosion; the intact steel left in fact was not subjected to the required deformation necessary to punch the casing, thus reducing the effect of the designed intervention in terms of gained well yield.

Figure 2.12: IWS in punching configuration inside well 3

WELL N. 3

CALOPINACE WELL FIELD, REGGIO CALABRIA, ITALY



Chapter 3

Results

3.1 Step drawdown test

After the cementing operation a new airlift development was performed in order to clean the cement residuals left after the work at the bottom of the well.
To verify the outcome of the intervention a step drawdown test has been carried out. The step drawdown test is a single-well pumping test designed to investigate the performance of a pumping well under controlled discharge conditions. In this test the discharge rate in the pumping well is increased from an initially low constant rate through a sequence of pumping intervals of progressively higher constant rates. Water is pumped at the same rate until the drawdown stabilizes; each step is typically of equal duration, lasting from approximately 30 minutes to 2 hours. Water levels in a pumping well decrease with pumping duration as well as increased pumping rate. This water level decrease, or drawdown, is made up of two components: aquifer loss and well loss [Philippa Aitchison-Earl; Matt Smith 28];

- aquifer loss is head loss caused as water flows towards a well screen. Here the flow is assumed to be laminar, and the loss is proportional to the resistance provided by the material forming the aquifer.

- well loss is associated with non-linear head loss in turbulent water flow. Turbulent flow occurs when water passes rapidly through the well screen, and can occur in parts of the aquifer immediately adjacent to the screen. Additional turbulent losses can occur in the pump and rising column. The higher the flow the higher the inflow velocity and turbulence thus the percentage of non-linear well losses increases with pumping rate.

Step drawdown test data collected were analysed with stepmaster software that provides three options for matching the data:

1. Eden-Hazel (step-drawdown and recovery to estimate aquifer transmissivity linear well loss coefficients)

2. Birsoy-Summers (step-drawdown and recovery analysis to estimate aquifer transmissivity and storativity)

3. Hantush-Bierschenk (to estimate linear and non-linear well loss coefficients)

A summary of all data collected for the step-drawdown test is presented in table 3.1, raw data are represented in figure 3.1.

Step	Pump time (min)	Duration (min)	Flow rate (l/s)	Maximum drawdown (m)
1	30	30	2	0.62
2	60	30	5	1.64
3	90	30	12	4.3
4	180	90	18	10.22

Table 3.1: Test data summary from step drawdown test

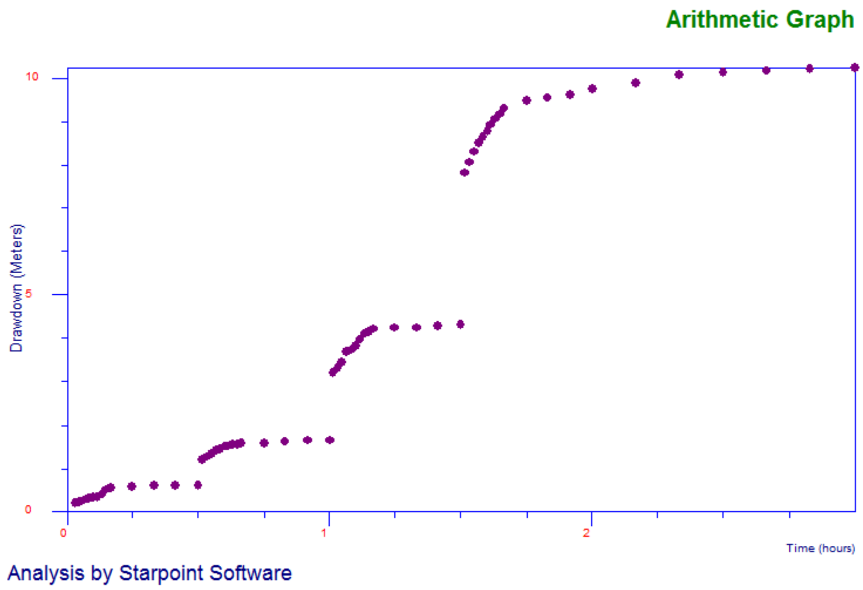


Figure 3.1: Step drawdown test data

To interpret the data of the step drawdown test the Eden-Hazel (1973) method has been used. This method is based on the Jacob straight line method to give an estimate of transmissivity and is adopted to combine the interpretation of the

turbulent well losses and the aquifer characterization. It is a graphical method, based on the application of superposition principle to large time logarithmic approximation in step drawdown test.
The Eden-Hazel procedure can theoretically be used if the following assumptions and conditions are satisfied:

- The aquifer has seemingly infinite areal extent.
- The aquifer is homogenous, isotropic, and of uniform thickness over the area influenced by the test.
- All changes in the piezometric surface are a result of the pumping well alone.
- Prior to pumping the piezometric surface of the aquifer is horizontal and unchanging over the area influenced by the test.
- The pumping well penetrates the entire thickness of the aquifer and thus received water from horizontal flow.
- The water removed from storage is discharged instantaneously with a decline in head.
- All flow is radial towards the well during pumping.
- The aquifer is pumped step-wise at increased discharge rates.
- The aquifer is confined.
- The flow to the well is in an unsteady state

The Eden-Hazel analysis can be displayed graphically in a plot (figure 3.2) of measured drawdown versus H_n (which is a function of pumping rate and time)

$$H_n = \sum_{i=1}^{n} \Delta Q_i \, log(t - t_i) \tag{3.1}$$

Where:

- $\Delta Q_i = Q_i - Q_{i-1}$ (m^3/min) is the discharge increment beginning at time t_i
- Q_n (m^3/min) constant discharge during the n-th step
- t (min) time since the step dradown test started
- t_i (min) time time at which the i-th step begins

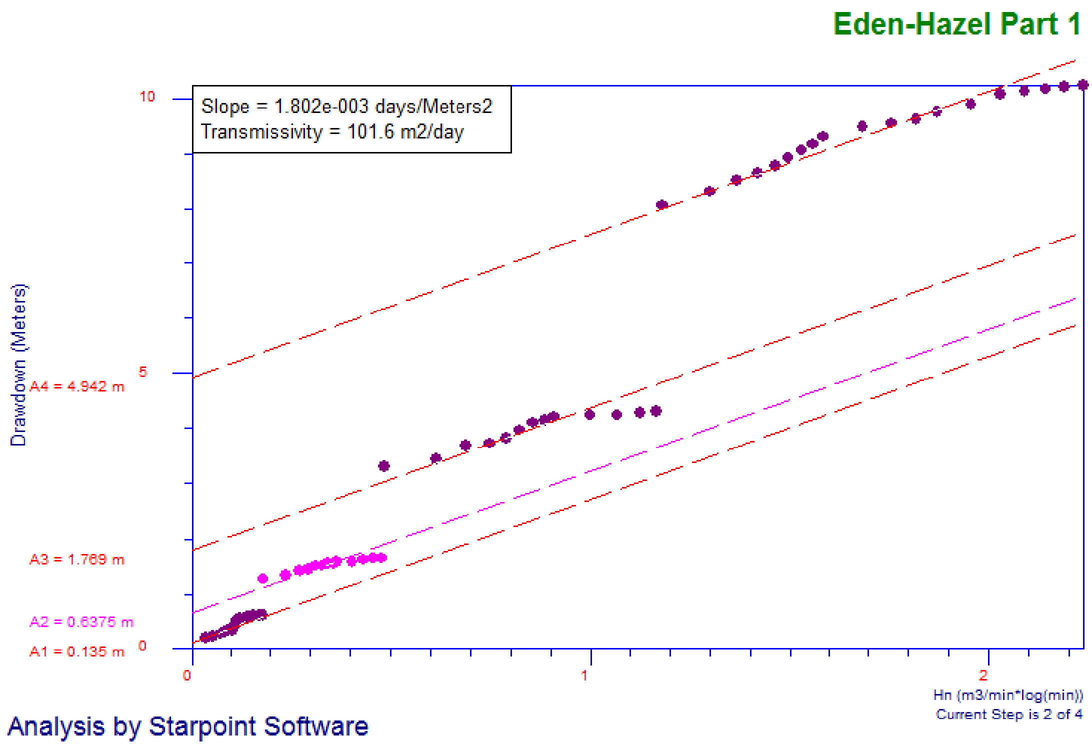


Figure 3.2: Eden-Hazel graphical solution

In the figure 3.2 the straight lines represent the line of best fit per each set of points relative to each step of the pumping test while the points represent the measured drawdown.
The slope of the lines $Drawdown - H_n$ gives the value of b while the interception point of these lines with the $H_n = 0$ axis gives the values of A_n.
Known the b values of the different straight lines it is possible to calculate the mean vale b_{mean} and use equation 3.2 to calculate the transmissivity of the aquifer, given by the product $K \cdot D$, where $D(m)$ is the aquifer thickness.

$$b = \frac{2.30}{4\pi KD} \tag{3.2}$$

The transmissivity value obtained is:

$$T = K \cdot D = 101.6 \; m^2/d = 1.13 \cdot 10^{-3} \; m^2/s \tag{3.3}$$

Calculating the ratio A_n/Q_n for each step and plotting each value versus the corresponding flow rate Q_n (figure 3.3) it is possible to get the C value that expresses the nonlinear well losses in the wellbore, this value is the slope of the straight line, representing the line of best fit between the points.

$$\frac{A_n}{Q_n} = a + CQ_n \tag{3.4}$$

$$a = \frac{2.30}{4\pi KD} log \frac{2.25KD}{r_{ew}^2 S} \tag{3.5}$$

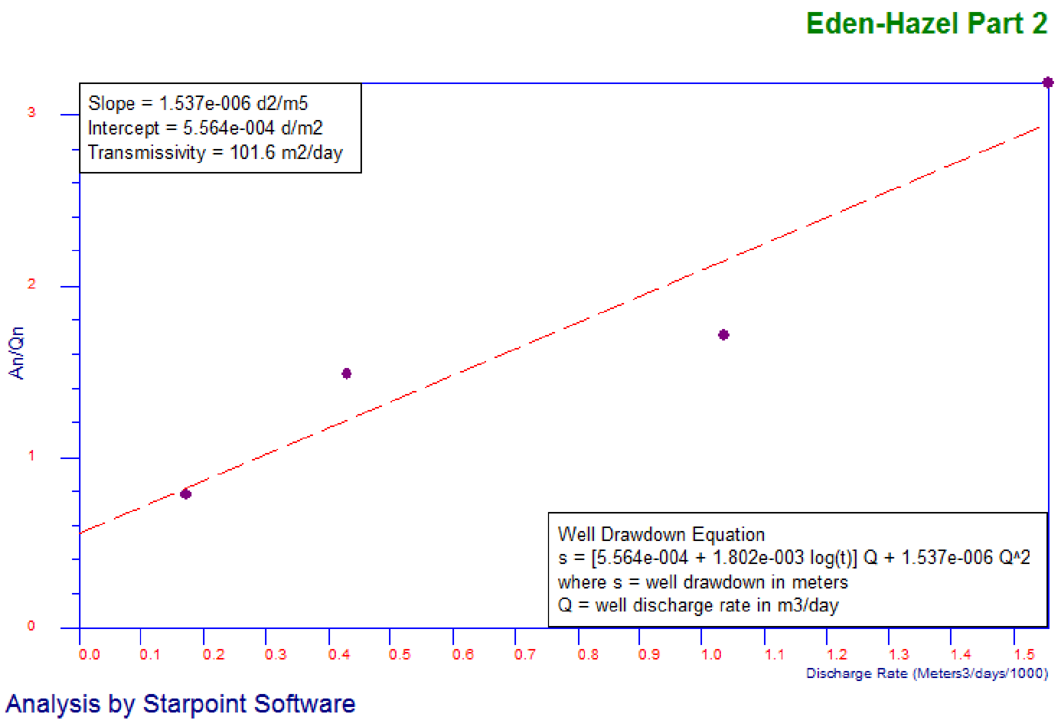


Figure 3.3: $A_n/Q_n \;-\; Q_n$ plot

$$C = 1.537 \ \cdot 10^{-6} d^2/m^5 = 11473.64 \ s^2/m^5 \tag{3.6}$$

The non-linear well-loss coefficient C is an expression of the well efficiency because is linked to the head losses due to turbulent flow created when water flows through the screen.
The value of C according to Walton [29] identifies the state of the well as shown in table 3.2.

C values s^2/m^5	Assessment
$C < 1900$	the well is properly developed and designed
$1900 < C < 3800$	the well has mild deterioration and clogging
$3800 < C < 15200$	the well has a severe clogging
$C > 15200$	difficult or impossible to restore the original yield of the well

Table 3.2: Walton criteria to asses well efficiency

The high value of C parameter obtained derives from the limited development works that could be performed and the cementing operation at the bottom of the well that have reduced the saturated thickness available for pumping.
Moreover the condition of well casing reduced in rust slices didn't allow to obtain an extension of the screened thickness as said in section 2.2.4.
Unfortunately no step drawdown test has been performed before the well rehabilitation to compare the C values prior and after the works but, a recovery test to compare the trasmissivity values has been done before well pump shut off.

3.2 Recovery test

The recovery test is a particular aquifer test done with null flow rate that is get when the pump is turned off after a constant discharge.
It is based on rising water levels (recovery) as a function of time and the analysis of recovered levels is used to determine aquifer transmissivity.
The recovery analysis uses the average pumping rate during the pumping period and, therefore, the recovery data are unaffected by short period flow variations during the pumping.
A recovery test starts at the moment the pump is turned off and continues until water levels recover to at least 80% of the undisturbed level. It is particularly useful for the following reasons:

- Constant discharge during pumping is sometimes difficult to achieve, particularly during the first few minutes of pumping. Recovery occurs at a constant rate, and can be used to independently verify results from early time data.

- If the pump unexpectedly fails, the subsequent recovery data can instead be used for the analysis.

- If test results for the pumping period appear anomalous, a recovery test can independently verify aquifer characteristics.

- Single well tests suffer from turbulence in the pumped well.

In this case the recovery test was performed before the development and restoration works in order to have a comparison between well data before and after the interventions.

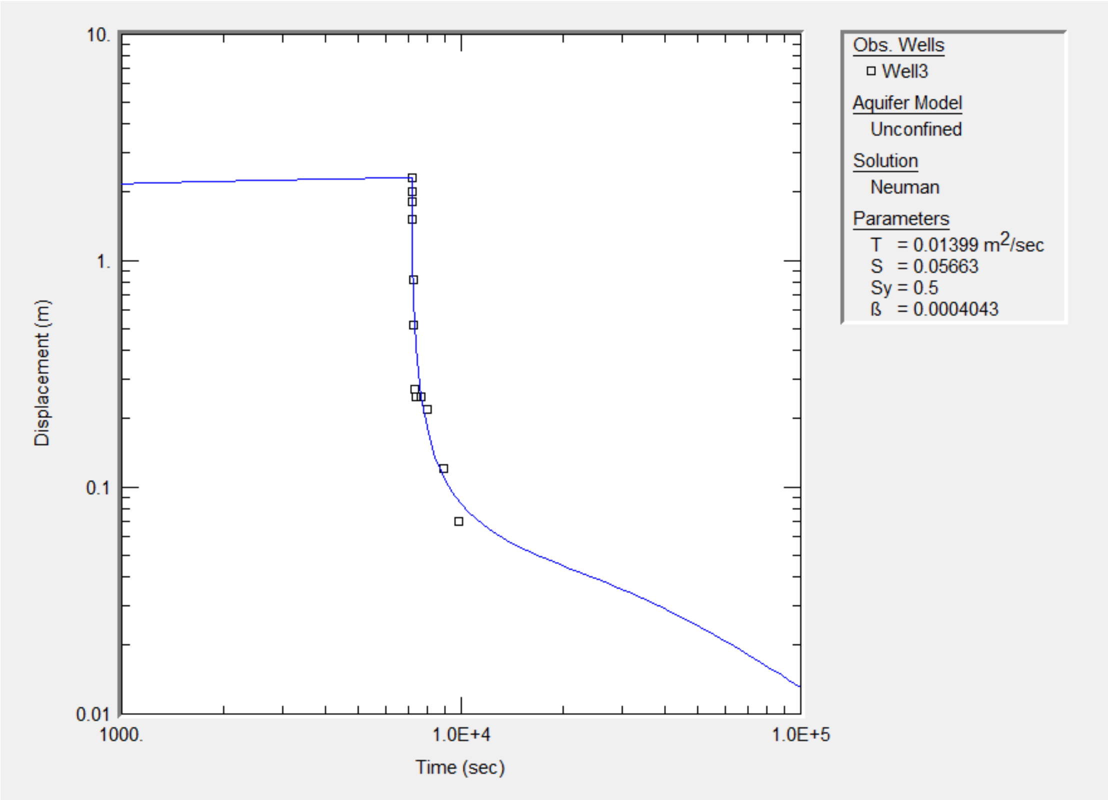


Figure 3.4: Recovery test plot

Data collected were interpreted using Aqtesolv, software for the interpretation of aquifer tests (pumping tests, slug tests, constant-head tests) in confined, leaky, unconfined and fractured aquifers. As can be seen in figure 3.4 the transmissivity of the aquifer before the works was $T = 1.4 \cdot 10^{-2}\, m^2/s = 1208.7\, m^2/day$. The order of magnitude of difference between the transmissivities before and after the operations can be explained with the reduction of the available penetrated thickness with cementing excluding the deepest part of the wellbore.

3.3 Chemical analysis

The main proof of the success of the intervention is given by the chemical analysis. Sorical analyzed the water pumped in the well field after the works and the results in well 3 compared to those of the same period in the previous year are amazing as shown in table 3.3.

Date		08-05-2019	27-05-2020	17-06-2020	
Parameter	Unit of measurement	Value	Value	Value	Legal limit
Flow rate	l/s	30	5	18	
Chloride	mg/l	958	234	53	250
Sodium	mg/l	460.7		16	250
Electrical conductivity	$\mu S/cm$	3060	1207	594	2500
pH	[-]	7.5	7.5	7.3	6.5-9.5

Table 3.3: Well 3 data before and after the intervention

Even if the flow decreased due to the introduction of a low conductivity grout layer, and so due to the reduction of saturated thickness form which the well pumped water, the 18 times chloride concentration decrease before and after the intervention testifies the success of the works.
It could be thought that the reduction of flow rate was the main cause of chloride concentration reduction but during the first surging (executed before cementing) the data collected (table 3.3 column 27-05-2020) testify a higher chloride content with a lower flow rate with respect to the last analysis. To reduce chloride content and respect the legal limit without cementing it is necessary to have a great reduction of pumped flow rate. Thus cementing allows to keep a good well yield with an excellent water quality.
The 94% chloride reduction is a proof of upconing interruption through cementing operation. The intervention performed on well 3 showed also another successful point: the recovery of static level before and after the works:

1. $41.98m$ from the surface, before

2. $41.4m$ from the surface, after

This phenomenon can be explained taking into account the non-uniform density distribution along the depth.
Let us assume the presence of fresh, brackish and saline water in the subsoil (figure 3.5) under hydrostatic conditions. If the screen of a well is positioned in the fresh water zone, the piezometric head as observed in the well, will be different from the observation in case the screen is in the saline zone.

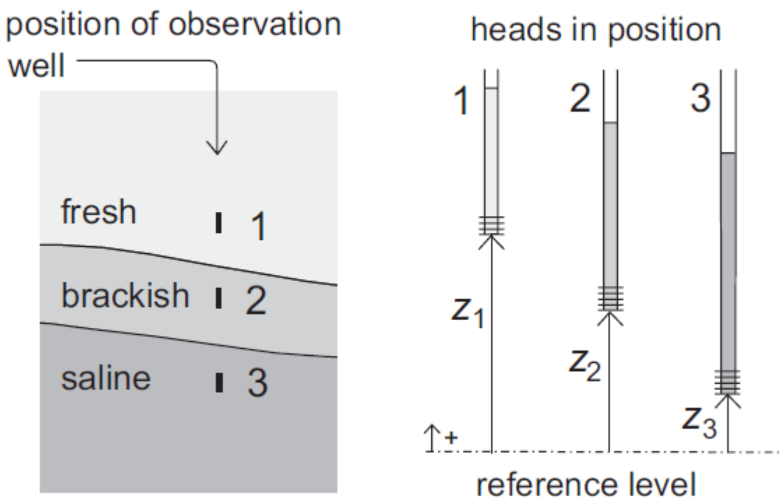


Figure 3.5: Piezometric heads at the same location, but at different depths with different densities [30, Gualbert Oude Essink]

The difference is due to the fact that in the first case the column of water in the well is fresh, in the second case the pressure at the screen is represented by a (shorter) column of saline water with higher density [30, Gualbert Oude Essink]. This condition does not change if we consider a well whose screened section crosses all the zones, in fact due to the different densities water will stratify along the vertical direction.
With cementing operation we have closed the deepest part of the well, pumping brackish water, obtaining a fresh water column above the cemented zone. Fresh water has a lower density with respect to the brackish one, so the same hydrostatic pressure is represented by a higher water column. The static water level recovery testifies the success of cementing operation. To make those levels with different densities comparable, they are generally expressed in a reference density, mostly of fresh water. Known the density of freshwater, the static levels before and after the intervention and the elevation of the surface point, it is possible to calculate the density of the brackish water mix. First, the length of the column of water in the observation well is converted into a column of fresh water:

$$H_s = 47.6m \implies \begin{cases} h_f = 6.2\ m \\ h_b = 5.62\ m \end{cases}$$

Where H_s is the surface elevation, h_f the fresh water head and h_b the brackish water elevation. The pressures applied by the fluid at the reference height (z=0 m a.s.l.) must be equal so the brackish water density is given by:

$$\begin{cases} P = z + \rho_f g h_f \\ P = z + \rho_b g h_b \end{cases} \implies \rho_b = \rho_f \cdot \frac{h_f}{h_b} \tag{3.7}$$

The resulting brackish water density, considering fresh water density equal to $1000 kg/m^3$, is equal to $1103 kg/m^3$ and surely this is not possible at the salt concentration and temperature measured, therefore the surging operation and the in place screening have also their contribution to the water level rise.
In unconfined aquifers like this, the inclination of the water table has important implications from a practical point of view 3.6: the piezometric level measured in a partially penetrating well completed in an unconfined aquifer depends on the depth of the screened section, in fact a partially screened well would provide a smaller hydraulic head value than if it were fully completed [13, Rajandrea Sethi, Antonio Di Molfetta]. This phenomenon is due to the deformation of equipotential flow lines that is not negligible in the well field area.

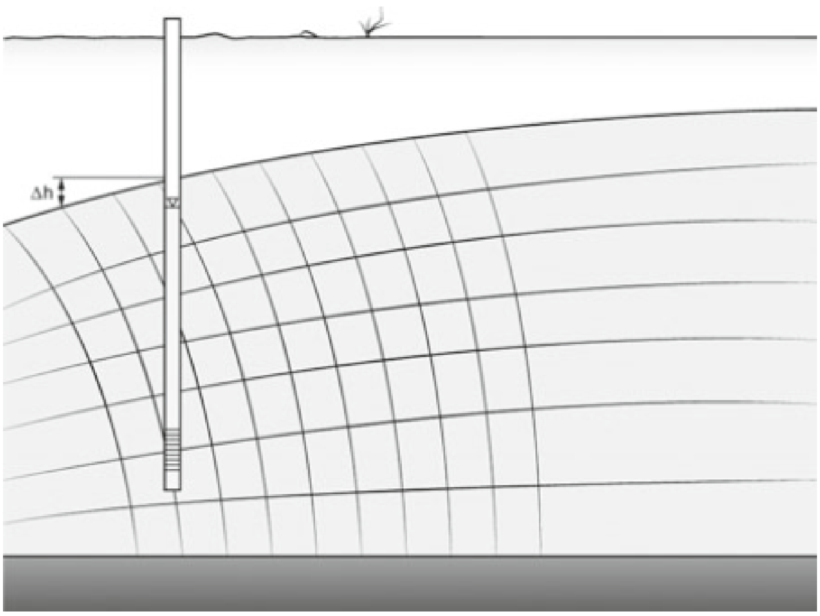


Figure 3.6: Influence of partial penetration of a well on the piezometric level reading in an unconfined aquifer [13, Rajandrea Sethi, Antonio Di Molfetta]

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Chapter 4

Numerical groundwater flow model

To validate the results obtained with the interventions on well 3 a numerical modelling has been performed to create a flow model of the alluvial fan created by Calopinace river and to focus on the well field area.
The model created must be considered a preliminary numerical model. The limited amount of data available allowed to build both steady state and transient model considering a unique hydraulic conductivity in all the domain. To have a more accurate model a series of data from the coast to the well field are necessary, in order to take into account the vertical anisotropy of the domain, especially near the coast where finer sediments can be expected with respect to the stratigraphic data previously reported.

4.1 Data acquisition and processing

The numerical model need intensive, accurate and complete data sets which cover the whole region of the modelled area.
The required data for a groundwater model are:

- DEM (Digital Elevation Model) for the area of interest.
- Geological settings and cross-sections of the aquifer layers.
- Water table contour map.
- Hydrodynamic parameters of the aquifer system.
- Thickness of each layer of the aquifer.

- Well pumping schedules.
- Chemical pollutant features and distribution.

To reproduce the geometry of the model, geo-referencing the available data maps and also preparing the layers related to hydro-geological information of this irregular model obtaining the files regarding the location of the wells that must be considered in the model, the open source software "Quantum GIS" (QGIS) has been used.
In this work, the software QGIS was used to:

- Build the boundary of the model domain, by creating the proper polygonal shapefile. The domain geometry was built considering the presence of a low conductivity area that acts as a physical limit to the groundwater flow and is constituted by clay matrix conglomerates in the eastern part that can be identified with the hills surrounding Reggio Calabria. On the western side the physical limit is represented by the Strait of Messina where Calopinace river flows into. The shape shown in figure 4.1 has been created to obtain a more detailed flow model of the Calopinace river and well field where most of the data have been collected and the well object of the intervention is located.

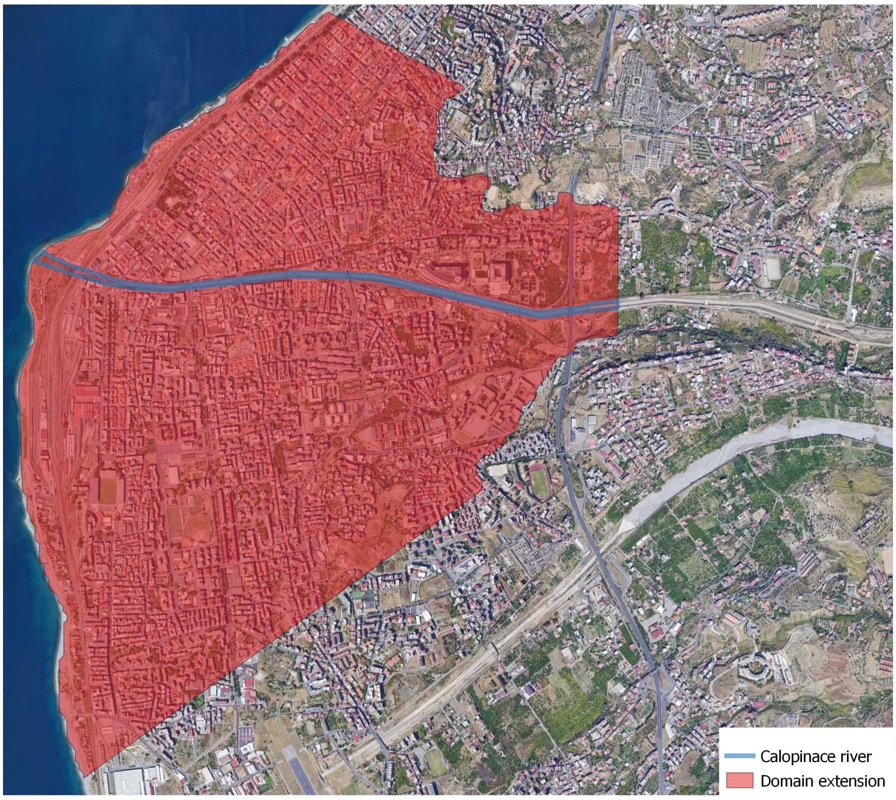

Figure 4.1: Model domain

- Define the location of the wells (active and abandoned) used to measure the water level necessary to create the groundwater contour map (figure 4.2) using Surfer and to calibrate the flow model.

In order to prepare the most possible completed data set, in all the available wells, two parameters have received special attention studying the evolution of the saltwater intrusion: the water level depth and the vertical distribution of the electrical conductivity.
The water head measured are reported in table 4.1

Well name	X (m)	Y (m)	Well depth(m)	Altitude (m a.s.l.)	Head (m)
W_Vilardi	1742326.42	4593603.65	46	42.395	4.39
W1_Calopinace	1742401.13	4593614.76	100	45.425	9.22
W5_Calopinace	1742441.11	4593621.428	75	45.425	4.42
W3_Calopinace	1742472.41	4593612.14	70	47.58	2.08
W4_Calopinace	1742526.12	4593584.07	60	47.58	3.7
W1_Prumo	1743660.52	4593675.54	92	74.2	3.205
W2_Prumo	1743696.66	4593679.98	92	74.2	7.205
W_Macello	1740794.13	4593623.39	38	10.7	-3.035
W_Miniera	1745015.92	4592780.12	36	112.2	97
W_Mili	1742624.8	4594276.93	80	75	5
W1_S.Agata	1743310.89	4591861.37	89	70	3
W3_S.Agata	1743092.26	4591703.82	87	64	2.5
W_Iannò	1743434.8	4593543	92	74	14.7

Table 4.1: Well location and water head

Figure 4.2: Piezometric surface contour map and well location

Figure 4.2 highlights a negative hydraulic head in the zone closer to the sea even if the well W_Macello has been abandoned thirty years ago and there is no pumping well near it. This negative water table slope was already known in 1980 when the study conducted by professor Mandaglio and Italpros [20] established that prolonged heavy pumping caused this phenomenon.
With the recent study this situation can be confirmed even if the overall pumped water decreased both for a reduction of well yields due to lack of maintenance and for the increased salt concentration that has lead to abandon the most polluted wells.
In the thirteen wells listed in table 4.1 the vertical profiles of electrical conductivity, measured after the intervention, pointed out a severe saltwater pollution mainly in the well field zone, where a relevant upconing phenomenon developed.

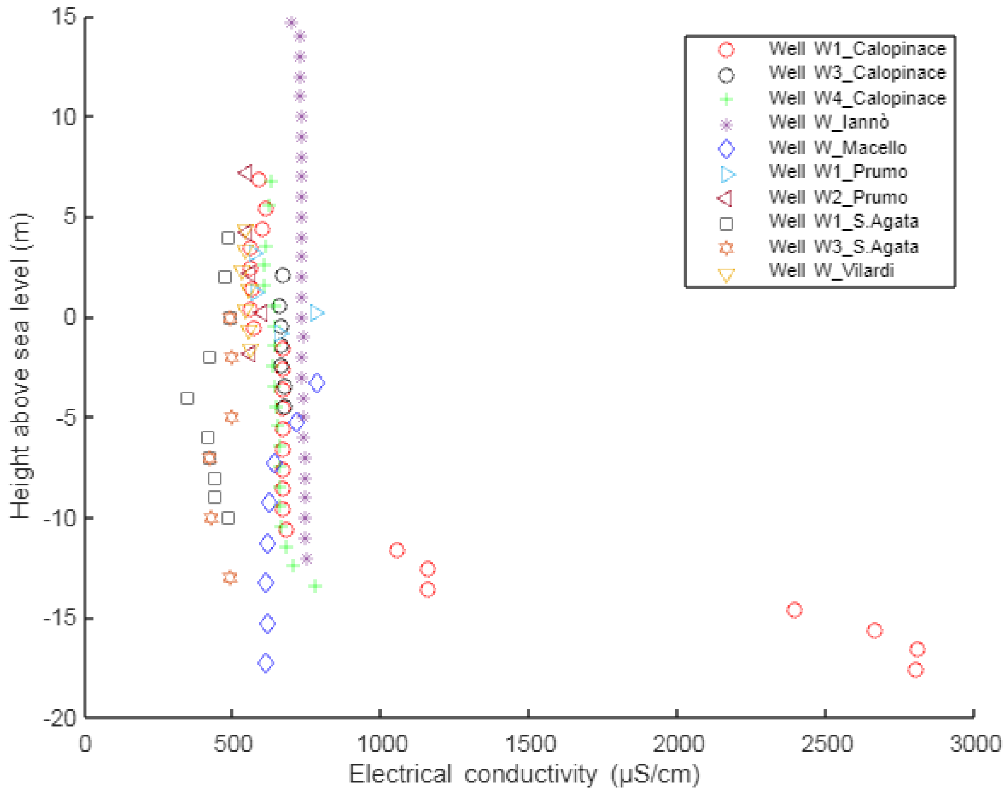

Figure 4.3: Vertical electrical conductivity profile of the main wells used in the simulation. The height has been limited to -17m a.s.l.. Data collected after the interventions

Figure 4.3 shows the electrical conductivities measured in the wells located in the studied area. As can be seen the electrical conductivity is in the range between 400-700 $\mu S/cm$ in the first part of the aquifer, until a height of -10 m a.s.l., then it abruptly increases especially in well number 1 of Calopinace well field. To point out the electrical conductivity variation in all the wells a relevant part of the vertical profile of well 1 has been removed and the entire profile is plotted in figure 4.4. The complete vertical profile shows an electrical conductivity that increases with depth and has three abrupt changes in the values:

1. -19 m -20m a.s.l. from 4600 to 18500 $\mu S/cm$
2. -26 m -33 a.s.l from 19500 to 58900 $\mu S/cm$
3. -33 m -35m a.s.l from 58900 to 45900 $\mu S/cm$

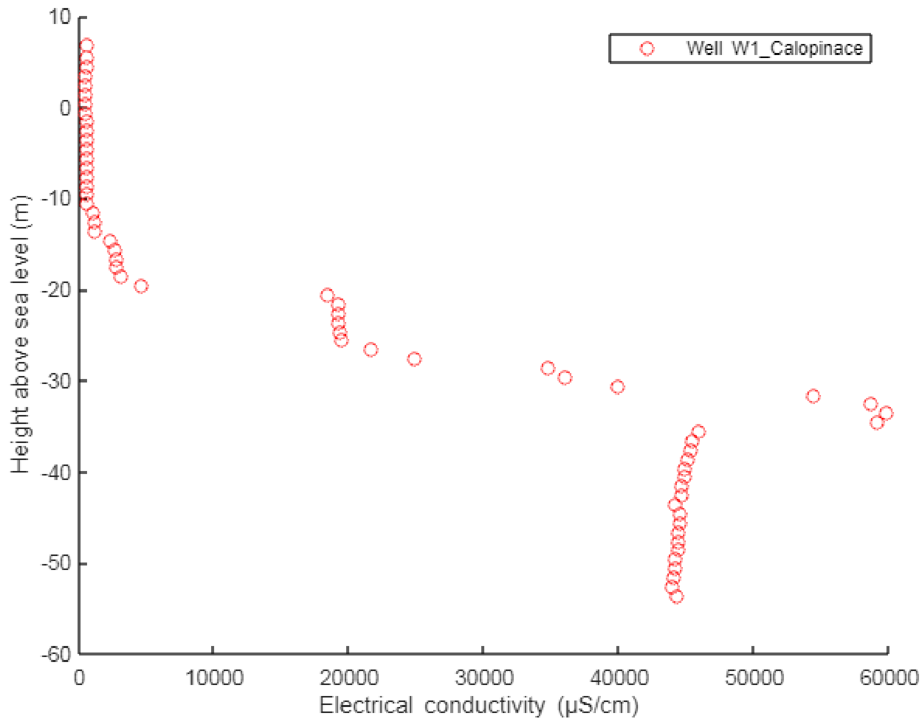

Figure 4.4: Complete vertical electrical conductivity profile of well 1, the deepest and most polluted

Electrical conductivity values are known to be strongly correlated to $[Cl^-]$ concentrations. Therefore, EC data can be converted to $[Cl^-]$ data if a relationship between the two can be assumed. Typically, electrical conductivity is more routinely and easily measured than chloride and thus an empirical relationship between EC and $[Cl^-]$ should be developed based on available pair measurements in the study area [31, Etienne Bresciani et al.].
The fitted function used to describe the relationship is

$$[Cl^-] = 0.04411 \cdot [EC]^{1.208} \tag{4.1}$$

Where $[Cl^-]$ and $[EC]$ are in units of milligrams per litre $(mg \cdot L^{-1})$ and microsiemens per centimetre $(\mu S \cdot cm^{-1})$, respectively.
Comparing the chloride concentration with depth in well 1, 1890m far from the coast, and well Macello (figure 4.5), 625m far from the coast is it possible to notice a concentration of the same magnitude order only up to -17m a.s.l., deeper in the well closer to the coast the salt concentration is more or less the same until its bottom at 38m (-27m a.s.l.). On the contrary in well 1 the concentration increases reaching 9018 mg/l at the same elevation -27m a.s.l., corresponding to a depth of 73m. Both the wells are abandoned for more than 20 years, for this reason

this difference in chloride concentration at the same depth can be explained only assuming a relevant upconing phenomenon below the well field.

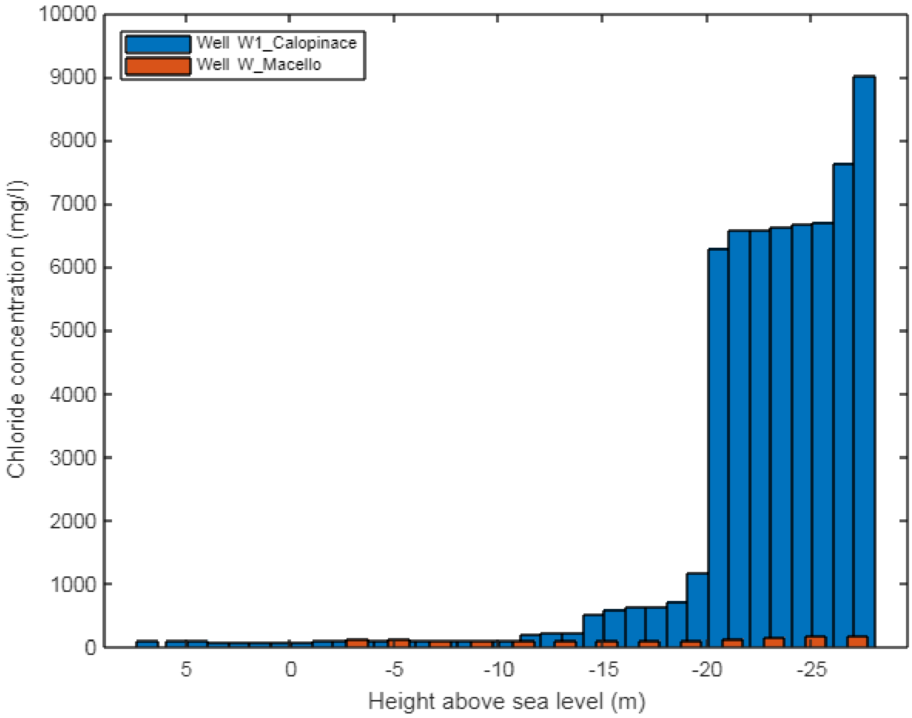

Figure 4.5: Comparison of Chloride concentration in well 1 and well Macello at the same height

In order to develop the model of the groundwater, the following information and data should be provided:

- the complete layer discretization and slice elevations over the whole interested area
- the aquifer parameters
- the boundary conditions

4.2 Model setup

4.2.1 Conceptual model

The conceptual model is a qualitative description of the aquifer domain in terms of its hydrogeological units, system boundaries (included time-varying inputs and

outputs), hydraulic and transport properties (including their spatial variability) [32, Anderson and Woessner] and can be considered as a summary of our current knowledge about a groundwater system describing the dominating processes and the overall geological structure.
The first step in the the development of the groundwater model is the design of a conceptual model that requires information on the geological formations, groundwater flow directions, recharge, hydraulic parameters, flow rate extracted or injected from wells, and the groundwater quality [33, Serguei Chmakov and Wayne Hesch].
A 3D unconfined coastal aquifer was used as model domain in this study, as shown in figure 4.6. The simulation model domain is divided into two geological regions according to the stratigraphic data of the wells in the area.
The system is in fact made up of several gravely and sandy layers which can be combined into a unique aquifer constituted, in the deepest portion, by fine gravel deposits with silt. This hydrogeological system overlies an impervious clayey basement whose thickness is several hundreds of meters.
The two geological regions are then the aquifer and the clay basement whose depth varies from 95m in the eastern part of the model to 130-150m near the cost. The aquifer is divided in two sections with different hydraulic conductivity due to the presence of the finer deposits in the deepest part of the domain, near the clay bottom.
Calopinace stream is an intermittent river dry from June to September, the river bed is cemented since 1970s in correspondence of the chosen model domain, for this reason its contribution to the groundwater flow is considered negligible.
The uncertainty associated with the estimation of the hydraulic conductivity, recharge or stratigraphy, should be taken into account in the analysis.

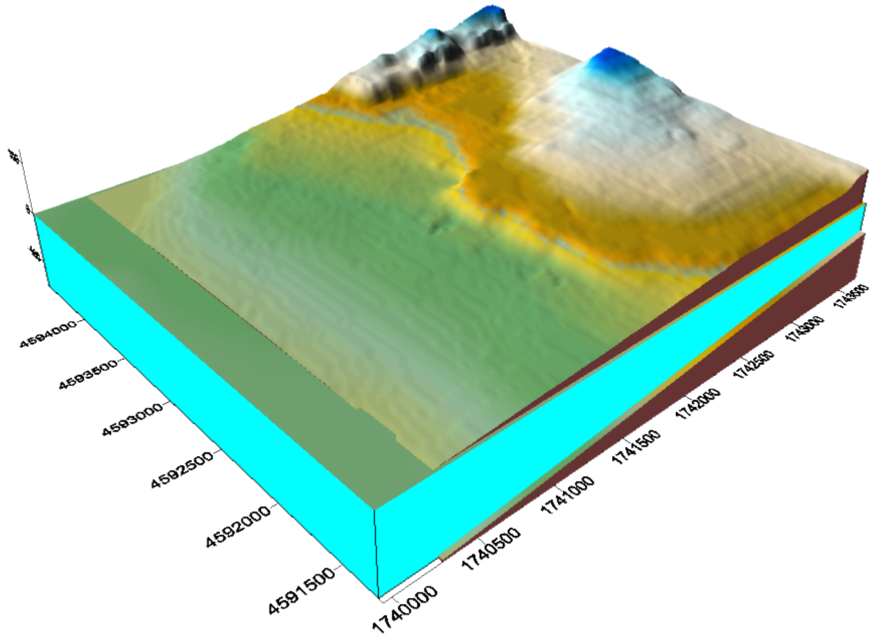

Figure 4.6: Conceptual model

4.2.2 Numerical model: Feflow

The conceptual model described in the previous section has been translated into a numerical Feflow model.
FEFLOW (Finite Element subsurface FLOW systems) developed by WASY Institute for Water Resources Planning and Systems Research Ltd., is a software for two (2D) and three dimensional (3D) modeling of water flow in saturated, partially saturated or unsaturated, isotropic or anisotropic domains.
Once created, through Qgis, the files containing the spatial information, it is possible to use them in order to build the 3D model assigning the proper information to the geometrical features and to the process variables.
The finite element method was adopted for its flexibility and capacity to simulate complex geometric forms and to refine the nodal grid around single points or lines (observation points, coastline, etc.).The groundwater numerical flow model was developed running simulations in steady-state and transient conditions.
FEFLOW, requires creation of the model in three different stages [34, 35, 36, Diersch HJG]:

1. Determination of geometric characteristics of modeled domain, generation of finite elements mesh, edition of problem class, method of solution, temporal and control data setting, determination of hydraulic properties of the domain,

characteristics of pollutants and of how they propagate, definition of initial and boundary conditions.

2. Main numerical calculations of water flow and mass transport in the studied domain.

3. Visualization of results and calibration.

The data set required are:

- physical and hydraulic parameters of soil: porosity, hydraulic conductivity, anisotropy ratio
- initial conditions for water flow: hydraulic head, saturation, moisture content
- mass transport parameters including porosity, longitudinal and transverse dispersivity, molecular diffusion coefficient and type and coefficients for decay reaction
- initial condition for mass transport: initial mass concentration.

To discretize the domain in FEFLOW is used the “Supermesh” operation, which is the fundamental framework for the generation of the finite element mesh since it contains all the geometrical information the mesh generation tool needs, information imported through external files.
The initial conditions and characteristics of soil may be assigned to model domain in several ways: to single nodes, to selected elements of FEM mesh, globally to the whole domain or to polygons, lines and points.
The introduction of the boundary conditions in FEFLOW is based on the selection of one of four types of boundary condition, definition of its value (constant of time varied) and assignment of the condition to FEM mesh.
The types of boundary conditions available for water and mass transport are:

1. First type (Dirichlet): hydraulic-head BC describing pressure head and mass-concentration BC for the given node.

2. Second type (Neuman): fluid-flux BC, mass-flux BC. Determine water flux or mass flux leaving or entering the modeled domain through the selected limit of the model.

3. Third type (Couchy): fluid-transfer BC, mass-transfer BC. Define the reference pressure head and concentration of the area located outside the modeled domain allowing inflow or outflow.

4. Fourth type: well BC, multilayer well BC. A single well allowing water and mass to be pumped out or in the domain through a single node (well) or a series of nodes aligned in the vertical direction (multilayer well).

. The process of assigning all the properties to run the numerical model can be summarized as follows:

1) Geometrical features	Supermesh operation 3D layer configuration
2) Problem setting	Problem class Aquifer definition Simulation time and time step size Numerical parameters Transport setting
3) Boundary conditions	Hydraulic head Mass
4) Initial conditions	Hydraulic head Mass
4) Material properties	Hydraulic conductivity Porosity Specific storage Longitudinal and transverse dispersivity Molecular diffusion
5) Observations	Hydraulic head and mass concentration observations

Table 4.2: FEFLOW flow chart

Meshing

To build the 3D model it is necessary to reconstruct the domain of the problem using the files developed in QGIS preprocessing. These files are used to create the framework for the meshing operation after the creation of the Supermesh as shown in figure 4.7.

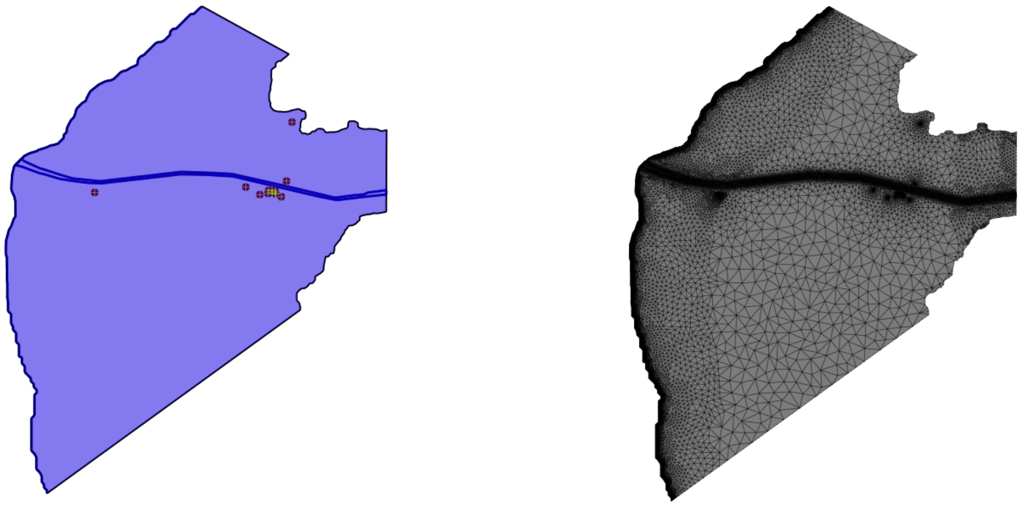

Figure 4.7: Supermesh elements and mesh generated

The area around the wells and near the coast has an higher meshing density of elements. The purpose of this local refinement is to improve the computational precision around the area where the most important points are located and thus the spatial and temporal discretizations must be higher.
The aquifer system was discretized using a grid of triangular elements made up of 341.750 nodes and 585.432 elements covering an area of about $9.2km^2$. A higher degree of refinement was adopted for the wells, for the stream, and along the seaside.
The three-dimensional grid (figure 4.8) consists of nine layers corresponding to the vertical discretization of mass concentration in the most polluted well according to different concentration ranges; each layer is therefore made up of nearly 65.048 prismatic elements with a triangular base, for a total volume of about $1.2km^3$.
The elevation of the upper layer has been defined using the DTM of the area and is included between 0 m a.s.l. and 82m in the area near the hills constituted by low conductivity sediments, excluded in the model domain.

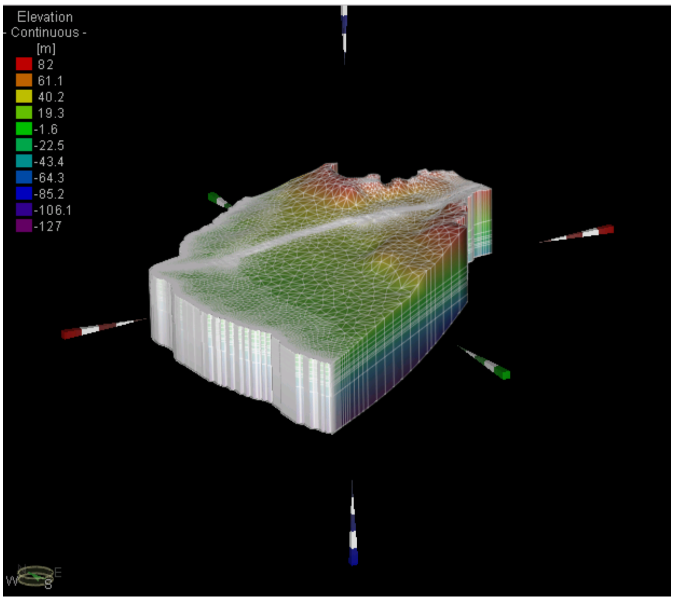

Figure 4.8: 3D grid and domain elevation

Problem settings

Once created the geometry of the domain the problem settings have been defined: flow was simulated, both in transient and stationary mode, the latter simulation was performed to obtain the initial hydraulic head distribution.
The flow simulation was performed considering the system as unconfined with the first slice as phreatic and the others dependent on the phreatic level.
Transient flow was evaluated over a period of 90 years with different phases corresponding to the stress applied in the aquifer system.

Boundary conditions

The choice of the boundary conditions represents an extremely important phase in the implementation of the model as the BCs influence the results obtained during the simulation.
The boundary conditions assigned to the numerical model derive directly from the conceptual reconstruction of the aquifer system.
A constant head boundary was assigned to nodes along the coastline, where groundwater is in contact with the free surface of the sea. A hydraulic head of 0 m a.s.l. was assigned to grid nodes coinciding with the shoreline while a hydraulic head of 14.7 m was assigned to the eastern part of the domain according to the hydraulic head value measured in the well closer to the boundary of the domain (figure 4.9).

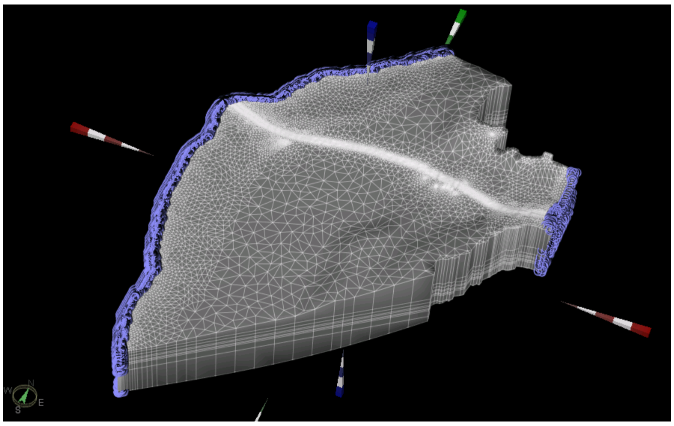

Figure 4.9: Hydraulic head boundary condition

Initial conditions

To allow the computation in FEFLOW it is necessary to assign Initial Conditions (ICs) as starting values of hydraulic head. This requires the reconstruction of the piezometry of the site at the starting time of the simulation. To define the initial condition of head distribution, according to the data available about the static levels in the wells drilled in 1960s, a stationary simulation was performed with no well active in the domain.

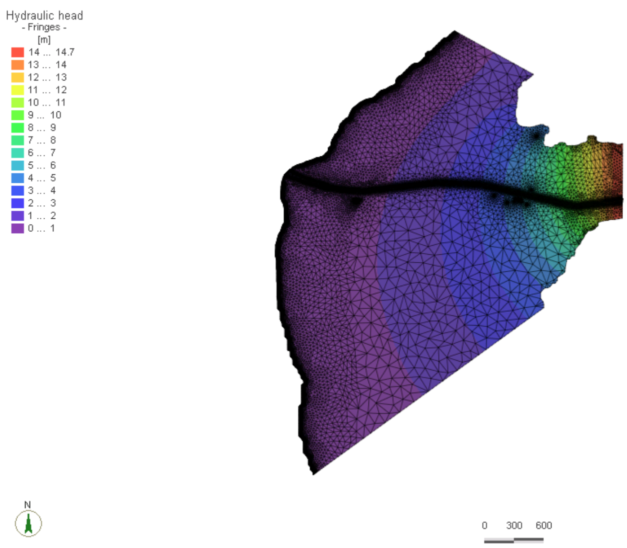

Figure 4.10: Initial hydraulic head distribution

The wells available in the area were set as multilayer wells, in 3D models multi-layer well boundary conditions can be used to simulate water injection/abstraction via a well screen. The screen extends over one multiple model layers and the pumping rate is assigned according to a pumping schedule varying over 60 years 4.11. The transient model simulation is set up with different phases, each lasting 30 years. In order to reproduce the variable pumping stress in the aquifer during time the phases adopted are the following:

1. A first phase with all the wells inactive in order to reproduce the unaltered hydraulic condition of the aquifer

2. A second phase with the wells pumping with the high rates recorded between 1960s and 1990s that caused the saltwater intrusion

3. A last phase with the wells pumping with lower rates due to the abandonment of the most polluted wells and a general reduction of the exploitation along the Calopinace stream.

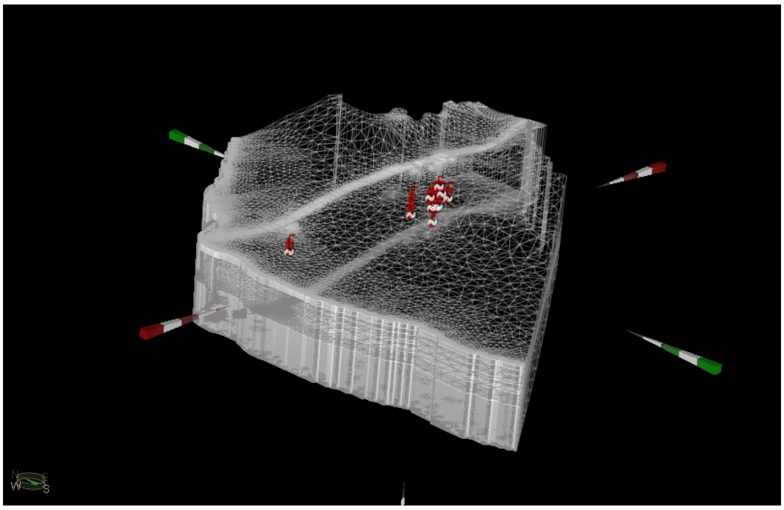

Figure 4.11: Multilayer wells distribution

Material properties

Defined the ICs and BCs needed in order to perform the simulation, the properties of the model layers were assigned. The hydraulic conductivity was applied according to the values provided by the study developed by professor Mandaglio and Italpros[20] In table 4.3 are reported the physical properties that were considered as uniform all over the domain.

Property		Measurement unit	Value
Hydraulic conductivity	k_{xx}	m/s	$7 \cdot 10^{-4}$
Hydraulic conductivity	k_{yy}	m/s	$7 \cdot 10^{-4}$
Hydraulic conductivity	k_{zz}	m/s	$7 \cdot 10^{-6}$
Porosity		[-]	0.3

Table 4.3: Model hydrodynamic properties

4.3 Model results and calibration

A common goal of modeling is to provide a tool to have a clear guidance for future planning. Thus, models can quantitatively test ideas about properties and processes in a way that is not possible for complex systems in any other method. Understanding which system features are likely to be important or not is of paramount importance in order to provide insights into model performance.

The model generally does not represent the system's behaviour adequately at the first attempt, for this reason it is necessary to adjust its parameters so that the model output matches related measured values. This process is known as calibration and allows to modify model inputs, such as the values of parameters used to quantify physical properties, initial and boundary conditions in order to make simulated data fit the observed ones. The model inputs that need to be estimated are often spatially and temporally distributed, so that the number of parameter values could be theoretically infinite.

Formal methods have been developed that try to estimate parameter values, given a mathematical model and a set of relevant observations. These are called inverse methods, and generally they are limited to the estimation of parameters as defined previously.

Calibration depends on observations but also on hypotheses and approximations introduced during the creation of the model, so that if calibration provides inconsistent outcomes the previous step should be revised.

To calibrate the model the software PEST has been used, this software aims to analyze the possible solutions and hence the uncertainty range associated with parameters and predictions. PEST (which is an acronym for Parameter ESTimation) is the most commonly used software for the calibration of groundwater models and with FEFLOW is possible to use FePEST that is a graphical user interface that links PEST with a FEFLOW model.

PEST engine uses the GLMA search algorithm (Gauss-Levenberg-Marquardt algorithm), that iteratively optimizes the model parameters to improve its fit to

observed data until a minimum objective function value is found.
The weight of an observation controls how much its residual (the deviation between computed and measured result) contributes to the measurement objective function: the larger the weight pertaining to a particular observation the greater the contribution that the observation makes to the objective function.
The model has been calibrated for steady-state conditions, taking into consideration the piezometric level measured in March 2021. The few known values of hydraulic properties were used as input parameters; by varying the hydraulic conductivity, simulations were carried out so as to achieve the best fit among estimated and measured piezometric values. The results of this calibration are plotted in figure 4.12, that shows the fit between measurements and calculations in the 7 observation wells inside the modelled area; the values of Calopinace well field have a good correlation, close to the perfect correspondence line.

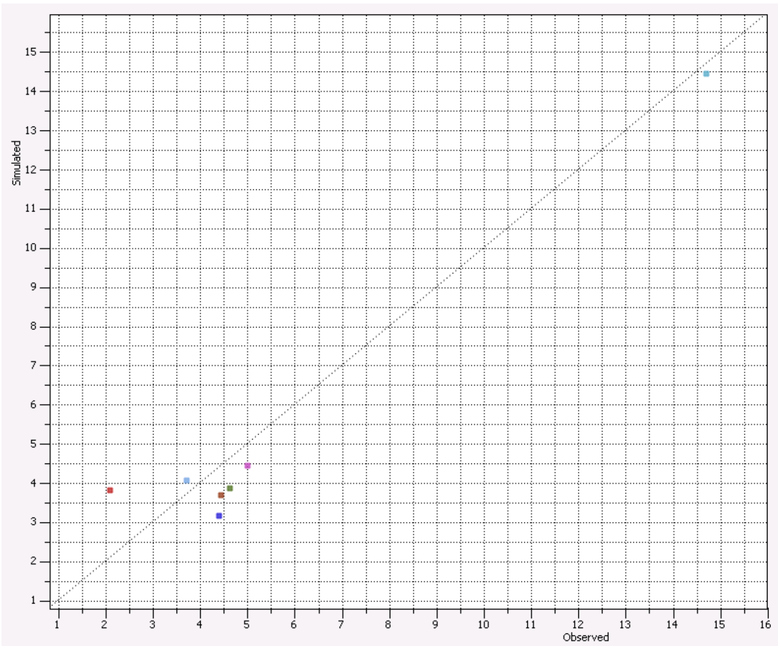

Figure 4.12: Hydraulic head calibration plot: discrepancy between simulated heads and observed ones

The fit to the observations is expressed through the Measurement Objective Function. In the simplest case, this will be the weighted sum of squares of the residuals between measurement and simulation results:

$$\Phi = \sum_i w_i (h_i^{obs} - h_i^{sim})^2 \tag{4.2}$$

where h_{obs} denotes an observation (typically from a field measurement), h_{sim}

is its related simulation result, and w the weight that has been applied to the measurement [37, FePest user guide].
The hydraulic conductivity increased during calibration, even if the starting value was measured on field during the study performed during the '70s, this can be due to the anisotropy of the model domain with respect to the assumptions which was not considered in the model. The values passed from $7 \cdot 10^{-4}\, m/s$ to $1.81 \cdot 10^{-3}\, m/s$, this change can be accepted considering the uncertainties in local hydraulic conductivity variations and the limited amount of measurement points available in the modelled area.
As can be seen in figure 4.12 the best fit between observed and measured data is in well field area. To get a better fit better data are required, for example the annual fluctuation of hydraulic heads in the wells and a better vertical distribution of hydraulic conductivity would help to build a model whose outputs are closer to the reality.
Standard Streamlines are the trajectories of the particles following the velocity vectors of the flow based on a steady-state flow field or at a specific time in transient simulations, thus represent the trajectory of a particle in a flow field assumed to be constant in time. If computed during a transient simulation, the trajectory will change with the flow field after each time step [34, Diersch HJG].
Streamlines can be calculated forwards or backwards from the starting point. Applying the backward option, they start from the seeding points, following the flow field in negative flow direction (up-gradient). The starting points (seeds) can be set at points, circles around points or distributed along lines.
In this specific case the computation of the streamlines backward from the seeding point was performed considering each well in the domain as seeding point. The trajectory of the particles was calculated each 30 years, at the end of each pumping phase (figures 4.13,4.14,4.15).

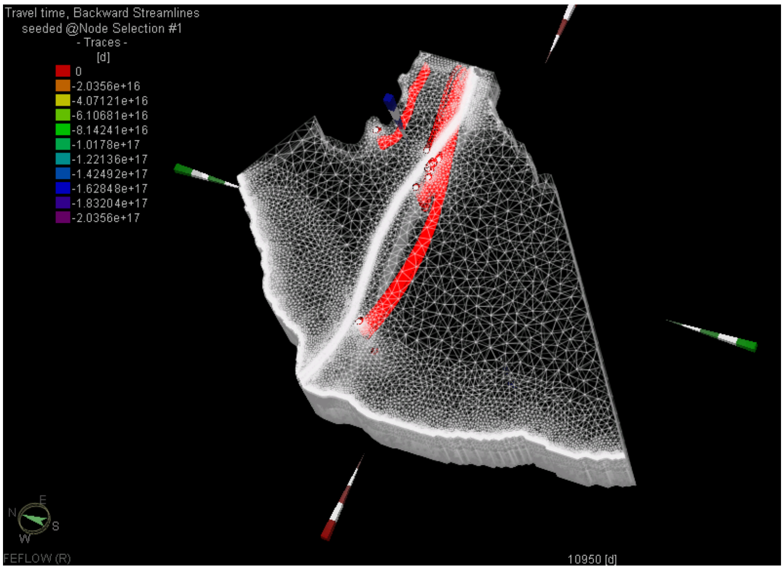

Figure 4.13: Streamlines after 30 years in undisturbed conditions

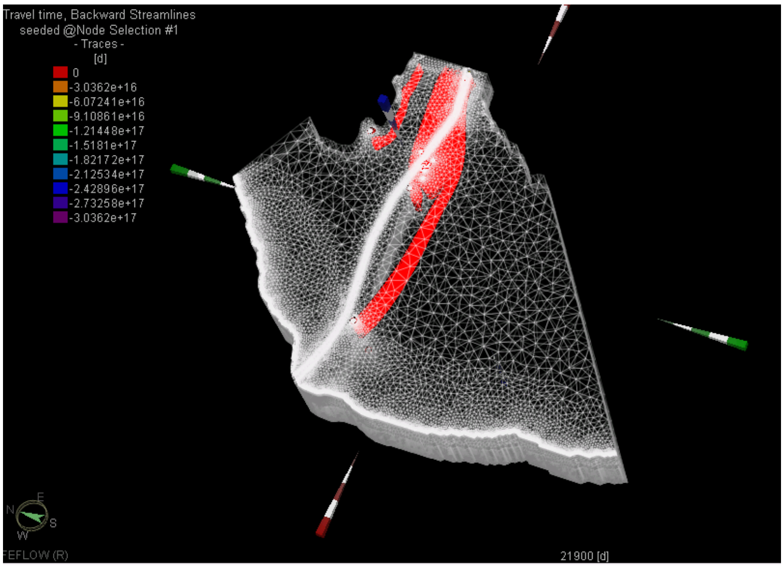

Figure 4.14: Streamlines after 60 years, 30 years with the high pumping rates of the second phase

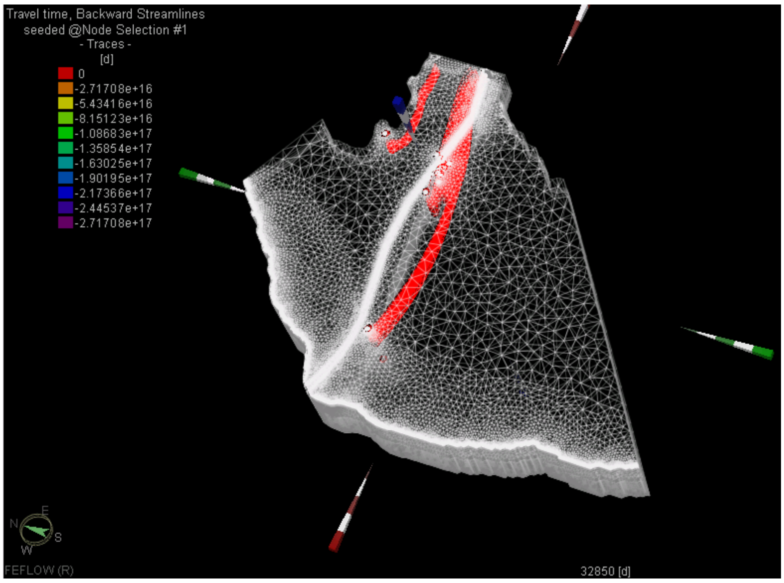

Figure 4.15: Streamlines after 90 years, from 60 to 90 years with the low pumping rates of the third phase

As shown by the figures, at the end of each phase the streamlines come from the uppermost part of the domain. This condition points out that chloride doesn't come directly from a lateral intrusion that has reached the hinterland coming from the sea, in fact water reaching the wells comes from Calopinace valley and not from the Tyrrhenian Sea.

The results achieved with modelling are a further proof of what the measurement campaign has pointed out (section 4.1), in fact the well closest to the sea shows a good water quality considering the same height above sea level with respect to well 1 in Calopinace well field that instead crosses the legal limit of salt concentration in drinking water below -15m a.s.l.. Due to the streamlines trajectories this condition can be explained only by a relevant upconing phenomenon caused by groundwater depression cone in the well field area that caused over the years saltwater rise from deeper layers.

Unfortunately, uncertainty and incompleteness of existing data limit the implementation of the model and the difficulty in characterizing subsurface heterogeneity limits the accuracy and realism of groundwater flow model. If more data would be collected in the future it would be possible to calibrate the model to represent the real condition of the alluvial aquifer in Reggio Calabria. To achieve this goal time series hydraulic head data automatically collected with data logger are necessary together with the time varying flow rate of each well and a better distribution of hydraulic conductivity to take into account the anisotropies of the domain.

The future development of this model should be the transport model to evaluate the actual position of the saltwater interface and its change with time, varying the stress condition of the aquifer. Saltwater intrusion is treated as a coupled flow and transport problem because flow and solute transport are linked processes, in fact groundwater flow causes the redistribution of solute concentration and this in turn alters the density field due to the high solute concentration, thus affecting groundwater movement. The transport simulations could be used to model the effect of a low conductivity layer with the properties of grouted soil below the pumping wells in order to further demonstrate the results achieved and simulate the behaviour of this layer below all the wells of Calopinace well field. To calibrate the transport model a better spatial distribution of electrical conductivity should be obtained because the data measured in the wells available are incomplete to create a complex coupled model.

Chapter 5

Conclusions

Seawater intrusion is a global environmental problem that affects the chemical composition of the coastal aquifers all over the world.
It´s mostly caused by human activities and especially by groundwater over pumping.
To act against the intrusion of salt from the sea a series of techniques have been analyzed, from hydraulic barriers to physical barriers.
The intrusion in Reggio Calabria (Italy) aquifer and the treatment to prevent the phenomenon in a well drilled in the alluvial aquifer have been analyzed.
To counteract the saltwater intrusion in a well pumping drinking water in Reggio Calabria alluvial aquifer the IWS (Idro Well System) patented tool has been used, showing the positive effect of the introduction of a low conductivity layer consisting of grout. Grouting the annular space and thus the gravel pack between the formation and the well casing it is possible to stop the rising of saltwater from deep layers.
The tests performed on the well showed a rising water table after the treatment due both to the presence of a lighter freshwater column in the well and the in place screening of the upper submerged part of the well, completed with blind casing when the well was built. The water table passed from $41.98\,m$ to $41.4\,m$ from the surface.
The chemical analysis performed before and after the interventions showed a reduction of chloride concentration from $958\,mg/l$ in May 2019 to $53\,mg/l$ in June 2020. The reduction of the available pumping thickness caused the reduction of the well flow rate from $30\,l/s$ to $18\,ls$.
The electrical conductivity values in the most polluted well and in the one closest to the coast show that saltwater intrusion is not due to the lateral movement of the advancing saltwater wedge but to the rising of brackish water from deeper layers.
A single well withdrawing the total flow rate from the aquifer can create large drawdowns that can cause the saltwater to move to the well, but the aquifer can still be in equilibrium on a regional basis [4, Jacob Bear et al.]. To validate the results

a preliminary groundwater flow numerical model has been developed considering three different pumping phases. The limited amount of data available did not allow to build a precise groundwater flow model or to perform the transport simulation to simulate the movement of the upconed saltwater below the main wells of the domain. The difficulty in characterizing subsurface heterogeneity and the limited hydraulic heads available limited the accuracy and realism of the groundwater flow model.
The Standard Streamlines, that are the trajectories of particles reaching the well, showed that in all the phases the groundwater pumped comes from the upper part of the domain and not from the coast, this can be considered a proof of the upconing below the wells more than an advancing saltwater front from the sea.
In order to avoid upconing of saltwater a greater number of small capacity wells, distributed over the alluvial fan where Reggio Calabria city stands, should be preferred over a few high capacity wells. The introduction of a grout layer in the well drilled in a uniform aquifer like this allows to pump only the freshwater in the upper part of the aquifer, interrupting the brackish water rise.
The punctual intervention performed with IWS has several advantages both in technical and economic terms: it allows fast intervention with limited equipment requirement and thus limited costs if compared to all the others remediation techniques adopted up to now for saltwater intrusion remediation operation.
A patent tool like IWS, able to perform cementing operation in the annular space creating holes in the casing, can also be used to restore the natural hydraulic seal between two different aquifers put in communication by drilling operations, avoiding the leaching of pollutants from the poor to the high quality one.
As disadvantage of IWS there is still no technique to control exactly the path of grout in the formation, for this reason a series of repeated steps with low amount of injected grout must be performed: the risk of threatening irreversibly the well is high.

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