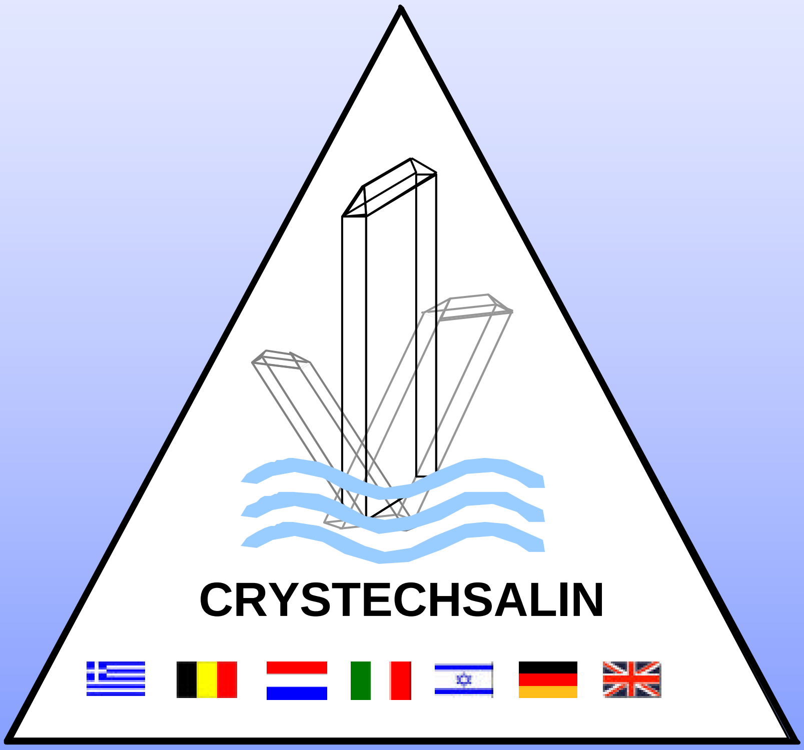
I.R.P.I.

IV MEETING
CRYSTALLISATION TECHNOLOGIES FOR PREVENTION OF SALT WATER INTRUSION

Scanzano Jonico, Italia
26-29 Settembre 2002



LA RICERCA EUROPEA PER LA RIDUZIONE DELL'INQUINAMENTO SALINO DELLE ACQUE SOTTERRANEE

Edito da M. Polemio & G. Gallicchio

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ISTITUTO DI RICERCA PER LA
PROTEZIONE IDROGEOLOGICA
Sezione di Bari

IV MEETING
CRYSTALLISATION TECHNOLOGIES FOR PREVENTION OF SALT WATER INTRUSION

Workshop: "La ricerca europea per la riduzione dell'inquinamento salino delle acque sotterranee"

tenutosi il 27 Settembre 2002 presso la Sala Consiliare
del Comune di Scanzano Jonico (MT)

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Con il patrocinio dell'Amministrazione Comunale di Scanzano Jonico (MT)

INDICE

INTRODUZIONE

***Maurizio Polemio*(1)**

Nel corso dell'anno 2001 ha avuto inizio l'attività di ricerca denominata CRYSTECHSALIN *CRYStallisation TECHnologies for prevention of SALt water INtrusion* (Tecnologie di cristallizzazione per la prevenzione dell'intrusione marina). Trattasi di un progetto di ricerca finanziato dall'Unione Europea della durata di tre anni, che rientra nell'ambito del V Programma Quadro (1998-2002), finalizzato a definire nuove tecnologie per la riduzione del rischio di degrado qualitativo delle acque sotterranee a seguito dell'inquinamento salino, dovuto al fenomeno dell'intrusione marina.

Al suddetto progetto partecipano unità di ricerca di sette nazioni (Germania, Regno Unito, Israele, Grecia, Olanda, Belgio nonché Italia). Il progetto di ricerca prevede la sperimentazione di una tecnica per realizzare barriere fisiche all'intrusione marina mediante la riduzione della permeabilità dei terreni per cristallizzazione. In sintesi, i vuoti presenti nel terreno, in cui penetra l'acqua di origine marina, vengono "intasati" mediante la precipitazione controllata di cristalli. La tecnica si prevede economica ed assolutamente eco-compatibile.

La sperimentazione in corso si svolge sia in laboratorio sia in sito. Sono previsti diversi siti sperimentali, tra cui uno in Italia. La sperimentazione in Italia vede protagonisti la Facoltà di Scienze della Terra dell'Università di Utrecht (Olanda), l'Istituto di Chimica Tecnica dell'Università Bergakademie di Freiberg (Germania), il Consorzio di Bonifica di Bradano e Metaponto, l'impresa RODIO e la sezione di Bari dell'Istituto di Ricerca per la Protezione Idrogeologica (IRPI) del CNR.

L'attività finora svolta in Italia ha previsto la caratterizzazione dell'acquifero costiero ionico lucano ed il monitoraggio delle relative risorse idriche sotterranee. Negli acquiferi costieri il degrado qualitativo è un fenomeno complesso particolarmente temibile in quanto spesso si manifesta con un lento ma progressivo deterioramento, difficilmente apprezzabile in quanto manifesta le sue conseguenze nel corso di alcuni decenni. Gli effetti negativi sono reversibili solo in tempi molto lunghi e con interventi costosi o che limitino fortemente l'utilizzo delle risorse idriche sotterranee.

Sulla base delle conoscenze del territorio, noto come *piana di Metaponto*, conoscenze tra l'altro ampiamente descritte in questo voume, è stata individuata l'area idonea ad "ospitare" la sperimentazione della proposta tecnologica in territorio italiano. In tale area, posta nel territorio comunale di Scanzano Jonico, a circa 500 m dal mare, è iniziato l'allestimento del campo sperimentale. All'iniziativa scientifica ha altresì aderito il Comune di Scanzano Jonico, in virtù della particolare valenza per il territorio delle problematiche connesse all'approvvigionamento idrico.

In attesa che le ricerche sperimentali in corso abbiano modo di maturare, questo volume riassume e raccoglie i risultati emersi nei primi diciotto mesi di attività del Progetto CRYSTECHSALIN, tesaurizzando

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(1) Responsabile scientifico per il Progetto CRYSTECHSALIN, CNR-IRPI sezione di Bari, Italia.

il dibattito svoltosi nell'ambito del convegno "*La ricerca europea per la riduzione dell'inquinamento salino delle acque sotterranee. Il caso della piana di Metaponto*" tenutosi nella Sala Consiliare dei Comune di Scanzano Jonico il 27 settembre 2002.

Seduta di lavoro tra i partners europei durante il IV Meeting del Progetto CRYSTECHSALIN, tenutosi a Scanzano Jonico (MT), Italia, nei giorni 26-29 Settembre 2002.

PREFACE

Gerald Ziegenbalg[1]

Seawater intrusion has been the subject of various investigations worldwide for many years. Numerous research groups are dealing with the development of numerical models describing groundwater and/or seawater movement in porous or fractured aquifers. The progress in computer techniques has allowed the construction of huge models simulating the process of seawater intrusion in dependence on the given geological and hydraulic conditions as well as the fresh water pumping rate. Large projects to reduce seawater intrusion by the creation of hydraulic barriers were realised or are under planning.

Investigations concerning precipitation or crystallisation processes occurring during seawater intrusion have been, however, only in some cases the subject of investigations. This is highly surprising because it is well known that precipitation or crystallisation phenomena play an important role in permeability changes of porous formations. Nothing is known if similar processes artificially induced can be used for the direction of groundwater flow and thus for the prevention of seawater intrusion.

A systematic research concerning the use of artificially induced crystallisation processes for the direction of groundwater flow in coastal areas has been started with the European project “CRYSTECHSALIN” in 2001. The project combines 11 research groups from 7 european countries. The research topics lead from fundamental subjects concerning crystallisation processes from oversaturated solutions to the description of geological and geochemical conditions in different costal areas as well as to the realisation of field tests in large scale. A new technology based on the in-situ formation of impermeable walls in costal areas shall be developed in order to reduce or stop seawater intrusion. This includes the development of numerical models describing groundwater flow in the areas in question as well as construction of monitoring systems allowing the detection of seawater intrusion. Mathematical models will be developed and used for the description of crystallisation processes from oversaturated solutions.

CRYSTECHSALIN is dated until March 2004. Three project meetings and many additional consultations between the partners took place since 2001. The book summarise main results obtained within the last 18 months and gives an outlook for the investigations that have to be realised within the next months. Many results have an “intermediate” status, however they are valuable for publication and public discussion.

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La ricerca europea per la riduzione dell'inquinamento salino
delle acque sotterranee, Ed. M. Polemio & G. Gallicchio, 2002

CRYSTECHSALIN – A EUROPEAN RESEACH PROJECT INVESTIGATING POSSIBILITIES TO REDUCE SEAWATER INTRUSION IN COASTAL AQUIFERS

CRYSTECHSALIN – UN PROGETTO DI RICERCA EUROPEO PER RIDURRE L'INTRUSIONE DI ACQUA MARINA NEGLI ACQUIFERI COSTIERI

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Abstract. The European project CRYSTECHSALIN combines basic and applied research in order to develop a unique technique for sealing soils in coastal aquifers. Impermeable walls shall be created by in-situ crystallisation processes from oversaturated solutions. These will act as barriers preventing seawater intrusion. The 11 partners from 7 states contribute to the project. Investigation concerning chemical, geochemical and geotechnical tasks are combined with geological and hydrological subjects as well as numerical modelling. The first results are show that copying natural processes can be a successful way in solving environmental questions. A wide area of potential applications is seen in areas outside the prevention of seawater intrusion, too. The most important are: a) reduction of the ground water level during the construction of fundaments, tunnels, during open pit mining etc.; b) construction of groundwater reservoirs; c) remediation of contaminated areas by immobilisation of dissolved contaminants or by encapsulation.

Keywords: progetto CRYSTECHSALIN, seawater intrusion, impermeable barriers, coastal aquifers.

Riassunto*. Il progetto europeo CRYSTECHSALIN combina ricerca di base ed applicata al fine di sviluppare una tecnologia unica per impermeabilizzare i terreni degli acquiferi costieri. Le barriere impermeabili saranno realizzate in situ mediante processi di cristallizzazione dovuti a soluzioni sovrassature. La geometria di tali barriere sarà tale da evitare l'intrusione di acqua marina. Al progetto contribuiscono 11 partners provenienti da 7 stati. Le indagini chimiche, geochimiche e geotecniche si fondono con gli studi geologici ed idrogeologici, nonché con i modelli numerici. I primi risultati mostrano che la riproduzione di processi naturali può essere un modo per risolvere con successo problemi ambientali. La tecnica di cristallizzazione proposta si presta a numerose altre applicazioni. Le più importanti sono: a) riduzione della permeabilità al di sotto del livello di falda durante la realizzazione di fondazioni, tunnel, e durante la coltivazione di cave, ecc.; b) realizzazione di riserve idriche sotterranee; c) messa in sicurezza di aree contaminate mediante immobilizzazione e incapsulamento di inquinanti.*

Keywords: *progetto CRYSTECHSALIN, intrusione marina, barriere impermeabili, acquiferi costieri.*

INTRODUCTION

Seawater intrusion in coastal areas has been the subject of investigations worldwide for many years. The most research deals with the development of numerical models to describe the connection between the rate of potable water production and aquifer pollution by sea water intrusion. Further points of interest are the geological and hydrological conditions, geochemistry and characteristics of the sediments. Mainly, the development of water management systems allowing a sustainable water production is in the centre of interest. Only few technologies do exist to influence the groundwater or sea water movement. Such technologies are:

- fresh water recharge into wells in order to create a hydrodynamic barrier;
- construction of impermeable subsurface barriers;
- extraction of sea water before it reaches wells.

On the other hand, many naturally occurring precipitation phenomena are well known leading to the closure of pores or fractures. Especially the formation of $CaCO_3$ from water with high hardness is well known. The same is true for blocking of flow paths by secondarily formed gypsum. In both cases, solutions which are only slightly supersaturated produce an effective, long time stable sealing. Drastic changes in the permeability of large areas can result. Such processes, however, need in nature a long time. If it becomes possible to synthesise solutions containing the minerals that will be formed in higher concentrations, the chance should be given to use processes similar to those occurring in nature for the directed reduction of the permeability of porous aquifers. "CRYSTECHSALIN" bases on that idea. Solutions leading to a directed crystallisation within aquifers will be used for the in-situ construction of impermeable walls in coastal zones. These walls shall prevent or reduce seawater intrusion. In the same manner it becomes possible to increase potable water recovery due to the reduction of fresh water migration into the sea. It is the aim of CRYSTECHSALIN to develop the fundamentals of such a technology and to carry out field tests in order to show the applicability under real conditions.

A co-operation of 11 partners from 7 countries was established. Chemical, geochemical and geotechnical research as well as numerical modelling and research in grouting are combined in order to develop a technology applicable in areas characterised by different geological and hydrological conditions. The paper gives an overview about the main subjects of research, the partners involved in CRYSTECHSALIN and first results.

MAIN SUBJECTS OF CRYSTECHSALIN

The investigations in CRYSTECHSALIN can be divided into five work packages:

1. chemical and geochemical investigations concerning the development of mineral forming solutions and characterisation of their interactions with different soils as well as the resulting change in permeability;
2. development of numerical models describing crystallisation processes from oversaturated solutions and to forecast the action of walls formed in porous rock sediments;
3. characterisation of the test sites in Greece, Italy and Belgium and development of numerical models describing the overall groundwater flow and seawater intrusion in these areas;
4. development and testing of different grouting techniques;
5. field tests to demonstrate the successful application of the technology.

The preparation of mineral forming solutions requires the prevention of spontaneous precipitation processes during mixing of the separate components. For example, the preparation of solutions leading to gypsum precipitation requires mixing of $CaCl_2$ and $MgSO_4$ containing solutions. Normally, spontaneous precipitation occurs if the solubility of gypsum is exceeded. In the presence of precipitation inhibitors, however, temporarily stable solutions are obtained. The selection of the most favourable inhibitor and fundamental research in describing crystallisation processes from oversaturated solutions are important subjects in CRYSTECHSALIN.

Stirring experiments will be used in order to determine the stability of differently composed solutions depending on nature and concentration of the used inhibitor. The interactions of oversaturated solutions with different types of sediments as well as the achievable permeability reduction are to determine in laboratory and batch scale. These investigations are part of the first work package. Results are expected that allow forecasting of crystallisation processes during the flow of the oversaturated solution through the soil.

Crystallisation processes are influenced by many factors. The project life time will not be enough to determine all parameters. Numerical modelling will be used in order to better understand the crystallization phenomena as well as to predict the influence of composition or inhibitor activity on the stability of the solution. A mathematical formulation at the micro-level of the crystallization process will be constructed. This requires numerical schemes able to solve a complex system of coupled partial differential equations governing such phenomena. A new free mesh numerical scheme based upon the collocation of Hermite interpolation radial basic functions for multiconnected domains is under construction. This approach was chosen due to the accuracy, simplicity and flexibility of its formulation, which is required in order to solve the present complex crystallization problem.

The effect of a wall with respect to the prevention of seawater intrusion depends on its geometry and the place of installation. Numerical modeling of the effects of the distance of the wall from the sea, its depth and length is the second task of work package two. It was mentioned already that the technology will be tested in different areas under real conditions. An assessment of the success of the technology will be possible only if the characteristics of the areas are known before starting with the grouting process. This requires geological, geochemical, hydraulic and hydrogeological characterisation of the areas and detailed characterisation of the test fields. Additionally, prior to carrying out the grouting process, there is a need for models capable of simulating the processes of flow and salt transport occurring during seawater intrusion into the test site areas. These models shall describe the density dependent groundwater flow as well as salt transport processes. The development of numerical models including all these aspects is the second task of work package three. The models will be used additionally for the development of water management plans for the test site areas.

The objective of work package four is the determination of technical relevant data necessary for the successful realisation of a grouting process. This is highly important because the action of oversaturated solutions differs from traditional grouts. Conventional grouts such as cements or polymers fill the whole pore space and a subsequent setting process leads to sealing. In contrast, oversaturated solutions produce a step by step sealing. Layers or single crystals are formed. These block up the flow paths and a permeability reduction results. To develop a favourable grouting strategy it is important to determine parameters such as injection pressure, distance between the boreholes or possible injection times. The investigations within work package four will answer these questions. Measurements on a special constructed laboratory apparatus and field tests in small scale will be carried out.

Field tests in three different areas are the final topic of the project. Essential steps are in all cases:

- borehole construction;
- borehole characterisation;
- construction of a grout plant;
- grouting;
- monitoring of the groundwater/seawater flow.

The obtained data will be used for further model development as well as model adjustment. Pumping tests and the observation of the overall groundwater chemistry will allow an assessment of the success of the technology. The project bases on a combination of fundamental and applied research, both within the work packages and between those. For example, the development of mineral forming solutions contains the task to find suitable inhibitors and inhibitor concentrations preventing spontaneous precipitation during the preparation of the solution as well as investigations to explain the activity of the inhibitor. While the first aspect is relevant for grout preparation, the second is of interest mainly from the scientific point of view. The explanation of the inhibitor activity, however, allows to determine its stability and to forecast the stability or instability during the flow through a rock formation. Additional, such investigations are the basis for the development of numerical models describing crystallization processes from oversaturated solutions. Other aspects related to the chemical investigations are geochemical considerations regarding interactions of oversaturated solutions with different types of sediments or the development of a small grout plant allowing the preparation of oversaturated solutions under field conditions.

It is important to mention that such interactions are given between all work packages of the project. As an example, the interconnections between tasks which are of importance to realise the field tests in Italy are given in Figure 1.

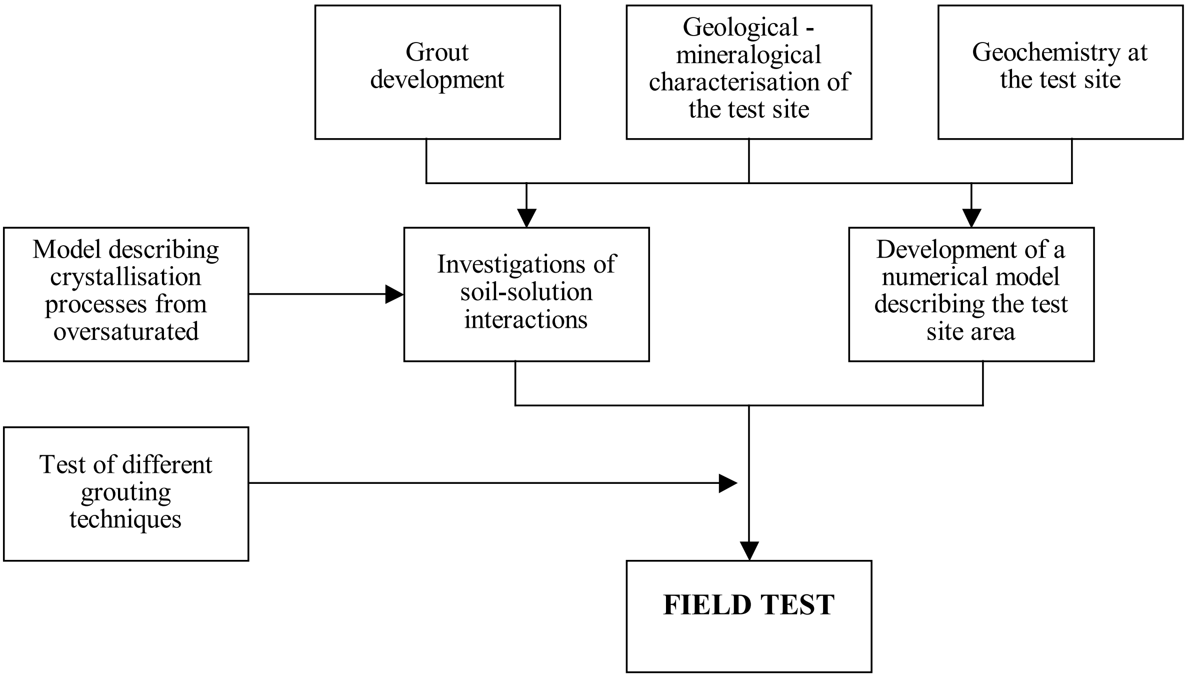

Figure 1: Investigations related to the field test at the Italian test site.

PARTERS

Due to the complexity of sealing soils affected by seawater it was necessary to establish an interdisciplinary research group allowing answering of questions important from the scientific as well as technical point of view. A co-operation of working groups specialised in:

- applied inorganic chemistry and the development of grout materials (Institute of Technical Chemistry, TU Bergakademie Freiberg; Germany),
- hydrology and monitoring of groundwater movement, description of changes in the ground water flow and chemistry caused by seawater intrusion (The Water Resource and Land Instability Research Center C.N.R. – CERIST, Italy),
- grouting and geophysical monitoring of seawater movement (RODIO, (Italy), Geoservice (Greece) and Geoservice-Pumps (Greece)).
- modelling of seawater intrusion and the sealing of porous formations by oversaturated solutions. (TECHNION, Israel),
- modelling of crystallisation processes from oversaturated solutions (Department of Mechanical Engineering at the University of Nottingham, United Kingdom),
- geochemistry (Universiteit Gent, Laboratory for Applied Geology and Hydrogeology, Belgium),
- modelling of the flow of solutions in porous aquifers (Hydrology Department of the Faculty of Earth and Life Sciences at the Vrije Universiteit Amsterdam, The Netherlands),

was created. Three potential users, Municipality of Eleftheron (Greece), RODIO (Italy) and Consorzio di Bonificia di Bradano e Metaponto (Italy), assess the process in respect to practical and economical aspects.

The tasks of the partners and the key persons are summarized in Table 1.

The project has started on March 1th, 2001. The overall duration of CRYSTECHSALIN is three years. The first 21 months are characterised by research to develop the fundamentals of the technology. The field tests will follow and the last step is summarising the results.

SCIENTIFIC ACHIEVEMENTS WITHIN THE FIRST YEAR

The scientific achievements of the first year of CRYSTECHSALIN can be summarized in the following points:

- solution compositions leading to Gypsum crystallisation between 24 to 120 hours were developed. The maximal achievable $CaSO_4$ concentrations are between 30 g/l and 40 g/l. The solutions can be used for sealing of areas polluted by sea water as well as sediments characterised by fresh water;
- $CaCO_3$ producing solutions can be synthesised by using precipitation inhibitors as well as by biocrystallisation processes. While precipitation inhibitors allow only the stabilization of $CaCO_3$ oversaturations up to 400 mg/l biomineralisation can be used for the preparation of solutions producing up to 10 g/l $CaCO_3$;
- the successful sealing of sand formations by gypsum crystallisation processes was proved under laboratory conditions by column tests;
- the formed gypsum produces a relative stable sealing. Increasing again of the hydraulic conductivity by flushing with pure water/sea water occurs much more slowly than the decrease realised by grouting;
- the Italian and Greek test site were characterised in detail. Geological, hydrological, and geochemical data are now available allowing the construction of numerical models describing ground water flow and seawater intrusion;
- a test site was prepared in Greece suitable for the small scale field test;
- first calculations regarding various configurations of a wall in a synthetic coastal aquifer at regional scale showed that the success will depend on the selection of a suitable place for the wall construction as well as on the geometry of the wall;
- the fundamentals of a hydrogeological model of the Greek test site were developed;
- the fundamentals of a numerical model describing crystallisation processes from oversaturated solutions were developed.

PARTNER	***KEY PERSON***	***TASKS IN CRYSTECHSALIN***
TU Bergakademie Freiberg, Institute of Technical Chemistry, Germany	Priv.-Doz. Dr. habil. Gerald Ziegenbalg	Co-ordinator, development of oversaturated solutions, testing of different grouting strategies
Geoservice, Greece	Geophysicist Klisthenis Dimitriadis	Characterisation of the test site area, Development of a water management plan for the basin of Eleftheres. Long term monitoring of seawater intrusion
Geoservice pumps, Greece	Eng. Yannis Dimitriadis	Small scale test to determine the most favourable parameters for grouting, Large scale field test
Consiglio Nazionale delle Ricerche, CNR-IRPI, Bari, Italy	Dr. Maurizio Polemio	Geochemical, hydrological and geological characterisation of the test site, Realisation of the field test
Technion - Israel Institute of Technology, Haifa, Israel	Prof. Jacob Bear, Dr. Jacob Bensabat	Development of a numerical model describing salt water intrusion in the Eleftheres Bay, development of a model describing the effects of walls within groundwater aquifers
The University of Nottingham, Great Britain Department of Mechanical Engineering	Prof. Henry Power	Development of a numerical model describing crystallisation processes from oversaturated solutions
Vrije Universiteit Amsterdam, Faculty of Earth and Life Sciences The Netherlands	Dr. Gualbert Oude Essink	Development of a numerical model describing groundwater flow and grouting processes at the Italian test site
Universiteit Gent Laboratory of Applied Geology and Hydrology, Belgium	Prof. Kristine Walraevens	Geochemical investigations concerning soil-water interactions, characterisation of the sealing capacity of oversaturated solutions, field test in Belgium
Ing. Giovanni Rodio & C. Impresa Costruzioni Speciali S.P.A, Italy	Eng. Vittorio Manassero	Field test in Italy, borehole construction and grouting
Municipality of Eleftheron, Greece	Agronomist Theodor Tsavdarides	Support of the field test
Consorzio di Bonifica di Bradano e Metaponto, Matera, Italy	Dr. Antonino Ferrara	Support of the field test

Table 1: Partners in CRYSTECHSALIN.

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AN OVERVIEW ON GROUTING TECHNIQUES

DESCRIZIONE DELLE TECNICHE DI GROUTING

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Abstract. The paper deals with different grouting techniques applied to soil improvement: permeation grouting, hydrofracture grouting, compaction grouting and jet-grouting techniques are discussed with reference to construction methods, drilling and grouting equipment, treatment geometry, grouting parameters and grout mixes. Some major case histories related to the discussed techniques are illustrated.

Keywords: grouting, permeation, hydrofracture, compaction grouting, jet grouting, grout mixes.

Riassunto. *L'articolo tratta le differenti tecniche applicate per migliorare le caratteristiche dei terreni, quali l'iniezione per permeazione e per idrofratturazione, tecniche di compaction grouting e di jet grouting, in riferimento ai metodi di esecuzione, alle attrezzature di perforazione e d'iniezione, alla geometria del trattamento, ai parametri di iniezione e alle miscele di iniezione. Vengono altresì illustrati casi di studio in riferimento alle tecniche discusse.*

Parole chiavi: *iniezione per permeazione, iniezione per idrofratturazione, compaction grouting, jet grouting, miscele di iniezione.*

INTRODUCTION

Soil improvement by grouting is one of the methods applicable to solve problems connected to foundations, open cut excavations and tunnelling.

The improvement of soils in terms of reduced permeability and increased strength can be achieved by various injection techniques, which may be summarized as follows (Figure 1):

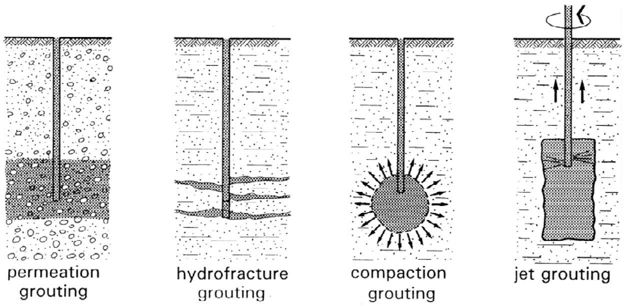


Figure 1: Typical grouting techniques.

- **permeation grouting**, in which the grout fills the voids without any essential change of the original soil volume and structure;
- **hydrofracture grouting**, in which the ground is fragmented by deliberate hydrofracturing (claquage) in order to increase total stresses by the wedging action of successive thin grout lenses, to fill unconnected voids and possibly to consolidate the soil under injection pressure;
- **compaction grouting**, in which a thick mortar-like mix acts as a radial hydraulic jack, creating bulbs or lenses and thus displacing and compressing the surrounding soil to some extent;
- **jet grouting**, in which the soil is mixed in place with a stabilizing mixture, delivered through radial nozzles under pressures much higher than usual (20 to 50 MPa), while revolving and drawing up the monitor from the bottom of a drilled bore; in alternative procedures soft fine grained soils can be removed to a great extent by air or air-water jetting and be replaced by grout.

PERMEATION GROUTING

Permeation grouting is a procedure which can not be strictly standardized because of the variability of the soil nature. It consists of a sequence of different operations:

- drilling a hole of an appropriate diameter in the established pattern and depth,
- preparation, proportioning, weighting and mixing of the selected grout suspension,
- injecting the prepared suspension into the designed section of the borehole from which the voids are filled.

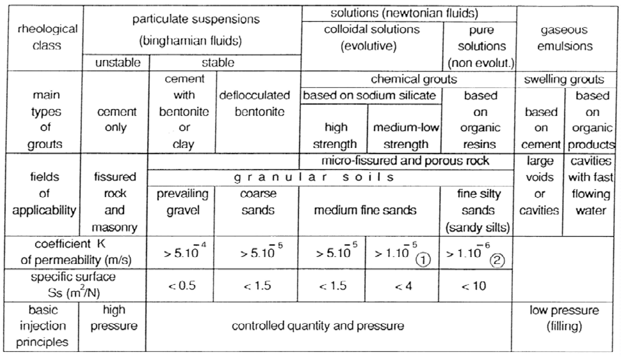
Permeation grouting is feasible with a wide variety of mixtures ranging from particulate suspensions to colloidal and pure chemical solutions, but both technical and economical hazards increase with decreasing soil permeability.

In an actual permeation treatment the flow rate and pressure at each injection level must be selected and adjusted in order to prevent hydrofracturing, particularly when chemical mixes are used.

In terms of the permeability coefficient the normal permeation limits are of the order of 10^{-5} m/s for silicate-based mixture and 10^{-6} m/s for the most expensive resin-based grouts.

In Figure 2 the grouting procedures by permeation are illustrated, with regards to:

- basic rheological classes and main types of grouts;
- fields of applicability related to groutable media;
- approximate groutability limits in terms of permeability coefficient and specific grain surface of soils;
- basic injection principles.



rheological class	particulate suspensions (binghamian fluids)			solutions (newtonian fluids)			gaseous emulsions	
				colloidal solutions (evolutive)		pure solutions (non evolut.)		
	unstable	stable						
main types of grouts				chemical grouts			swelling grouts	
				based on sodium silicate				
	cement only	cement with bentonite or clay	deflocculated bentonite	high strength	medium-low strength	based on organic resins	based on cement	based on organic products
fields of applicability	fissured rock and masonry			micro-fissured and porous rock			large voids or cavities	cavities with fast flowing water
		granular soils						
		prevailing gravel	coarse sands	medium fine sands		fine silty sands (sandy silts)		
coefficient K of permeability (m/s)		$> 5.10^{-4}$	$> 5.10^{-5}$	$> 5.10^{-5}$	$> 1.10^{-5}$ ①	$> 1.10^{-6}$ ②		
specific surface Ss (m^2/N)		< 0.5	< 1.5	< 1.5	< 4	< 10		
basic injection principles	high pressure	controlled quantity and pressure					low pressure (filling)	

① limit governed by viscosity/time evolution ② normal limit for uniform impregnation

Figure 2: Classification of grouts related to groutable media (After Tornaghi 1978).

CONSTRUCTION METHOD

Different grouting methods may be applied according to the different circumstances encountered.

In rock:

- Up-stage or down-stage methods
- Multipacker method (MPSP)

In soil:

- Sleeved pipe method or "tubes à manchettes" method (TAM).

The **up-stage stage method** is performed when the whole hole is drilled down to the required depth in one go, then grouted by placing the packer at the top of the deeper stage and grouting the hole from the bottom end up (Figure 3). The length of the stage is usually 3 m. If a total fluid loss occurs while drilling, a packer is installed at the top of the relevant stage, grouting is performed and drilling proceeds after re-drilling of the grouted stage.

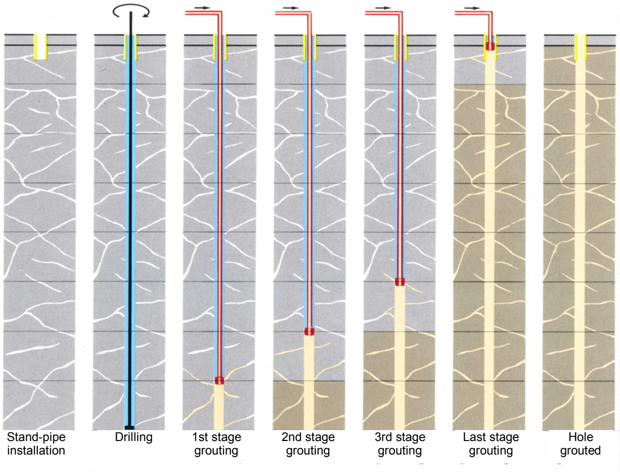


Figure 3: Up-stage method.

The **down-stage method** is performed by dividing the whole hole in stages of usually 3÷5 m in length. A borehole is drilled down to the bottom level of the first grouting stage and then permeability test and grouting follow. At a later time, the hole is extended down to the bottom level of the following stage to perform the next grouting step. This sequence is then repeated until the full depth has been reached (Figure 4). This method can be applied, as a rule of thumb, in presence of incompetent rock which requires stabilization, detected by the hole collapse during drilling or by the improper sealing of the packer at the required depth.

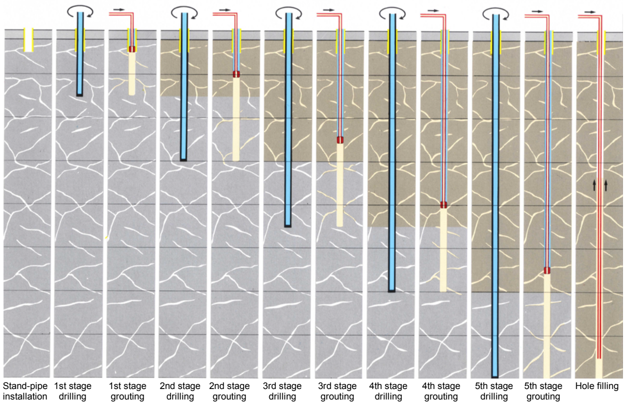


Figure 4: Down-stage method.

The **sleeved pipe injection by "tubes à manchettes" (TAM)** is a multiple phase process, which allows several successive injections in the same zone (Figure 5).

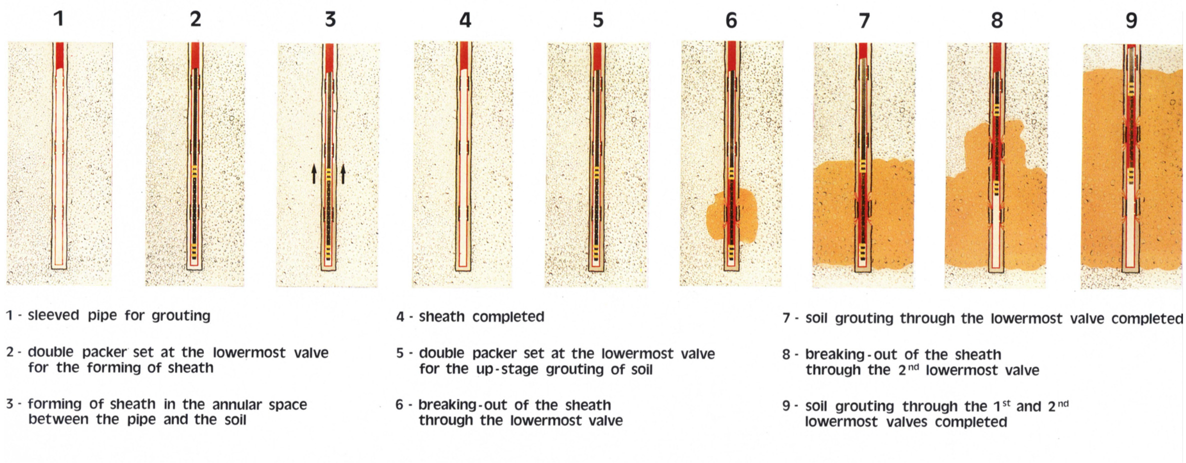


Figure 5: Up-stage method by sleeved pipe system.

This involves installing a sleeved pipe into a grout hole. This pipe is permanently sealed-in with a sleeve grout composed of a cement-bentonite-water mixture (usually C/W ratio by weight = 0,5).The sleeve grout seals the borehole between the pipe and the soil to prevent the injection grout from channelling along the borehole. This means that, under pressure, the injection grout breaks through in radial direction and penetrates into the soil. At fixed intervals, of the order of 0.5 m, small holes are drilled into the pipe to act as outlets for the grout. The holes are tightly covered by rubber sleeves (manchettes) which open only when under pressure. The holes and sleeves work as one-way valves.

Once the sleeve grout has set, pressure grouting can be performed. In order to inject through a sleeve, a double packer fixed at the end of a smaller diameter injection pipe is inserted into the sleeved pipe and centred around the sleeve to form a closed chamber with one-way valve outlets.This method presents numerous advantages. Firstly, there is the possibility of repeating the injection several times, which permits the use, at a different time, of different mixes with decreasing viscosities, to ensure the penetration of the grout in the fine voids, after the larger ones have been closed. More pervious soil layers may be sealed first regardless of the order of injection level, which prevents loss of expensive low viscosity grouts.

Moreover, it is to be noted that the grouting operations are carried out completely independently from drilling.

The **multipacker method (MPSP)** has been designed and lengthily experimented by Rodio, with laboratory and field trials, to improve grouting operations in those rock formations where:

- caving of the drilled holes and pronounced weathering prevent the sealing off of sections of holes to be grouted at the designed depths;
- where the downstage method is not capable of achieving a sufficient consolidation and stabilization of the rock.

The system consists essentially in the installation inside a borehole of a plastic or steel pipe fitted at regular intervals with rubber grouting sleeves. Bag packers, fastened to the grouting pipe at regular intervals (usually 3 - 5 m), seal off the hole between which the grouting is to be confined. The sealing action of the bag packers is obtained by expanding them against the hole walls through injection of grout into the bags.

After the packer grout hardening period, a water pressure test (if required) and, subsequently, upstage grouting by means of single or double packer are performed (Figure 6).

GROUTING PARAMETERS AND NOVEL GROUT MIXES

With regard to the practical selection of main injection parameters we can briefly remark on the followings:

- the planning of injection grid pattern is mostly empirical and based on previous experience; a theoretical approach may give useful hints only for chemical grouts;
- the hole spacing ranges usually between 1.5 and 2.5 m; closer spacing may be required for chemical grouting only;
- the flow rate and pressure at each injection level must be selected and adjusted in order to prevent hydrofracturing;
- most theoretical and empirical criteria for limiting pressure are unrealizable or conservative; the best method is based on

the direct determination of the hydrofracturing threshold in preliminary holes, by increasing the flow rate till the pressure tends to decrease;
- the rate of flow should be as low as possible, particularly when chemical solutions are used.

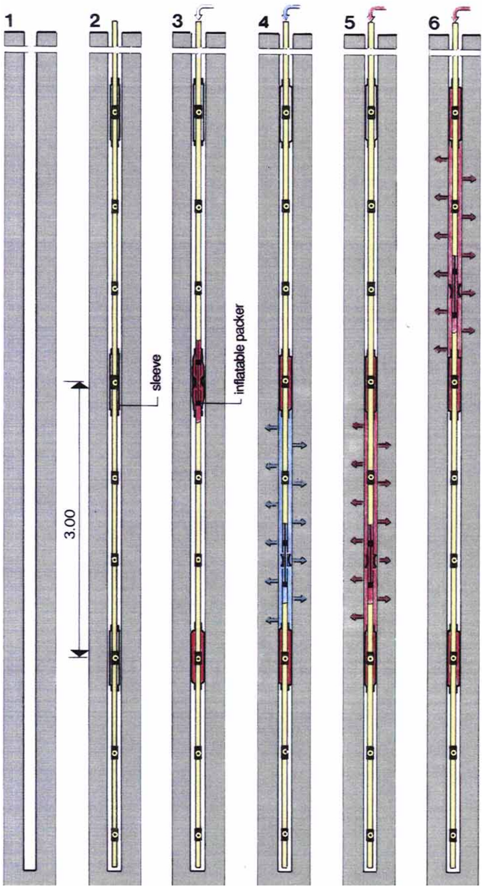


Figure 6: M.P.S.P. grouting system (Multiple Packer Sleeved Pipe).

Besides traditional grout mixes, new classes of cement mixes have been studied, developed and utilized in the last few years. The results obtained are extremely interesting and have made possible the proper improvement of fine soils, meanwhile increasing the safety factor in terms of environmental protection, and decreasing the costs.

Researches have been carried out to find additives capable of increasing the stability and reducing the cohesion of cement based grouts, thus increasing their penetrability. In Italy, Rodio developed the MISTRA grouts, a family of grouts which are stable suspensions (Figure 7) with enhanced permeation properties. This allows to grout finer soils, not permeable by cement mixes until now.

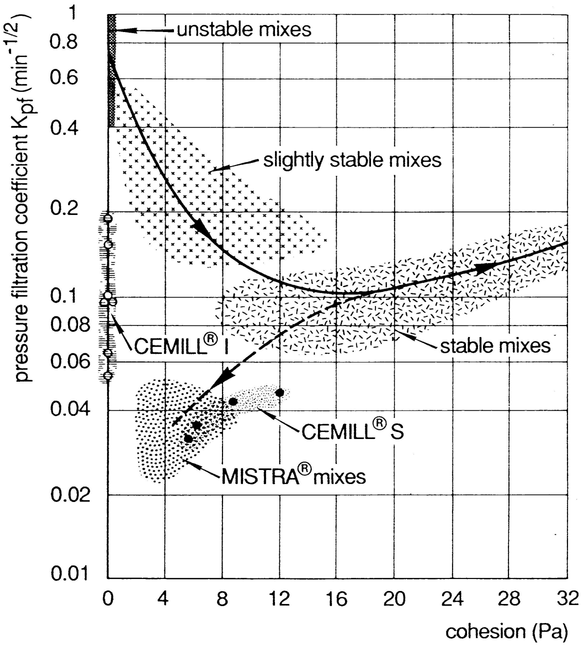


Figure 7: Relationship between stability under pressure and cohesion for different types of mixes (After De Paoli et al. 1992).

Most recently, concerns about the possible toxicity of chemical grouts have focussed the attention back onto cement based grouts which have finer granulometry. Microfine cements are produced on an industrial scale but, for various reasons associated with their availability, handling and price, they are seldom used. The alternative CEMILL manufacturing process has been developed by Rodio. This, starting from ordinary cement as raw material, produces stable mixes (Figure 7) characterized by a markedly fine grain size, able to permeate formations comprising medium-fine sands, thus approaching the penetrability limit of chemical mixes (Figure 8).

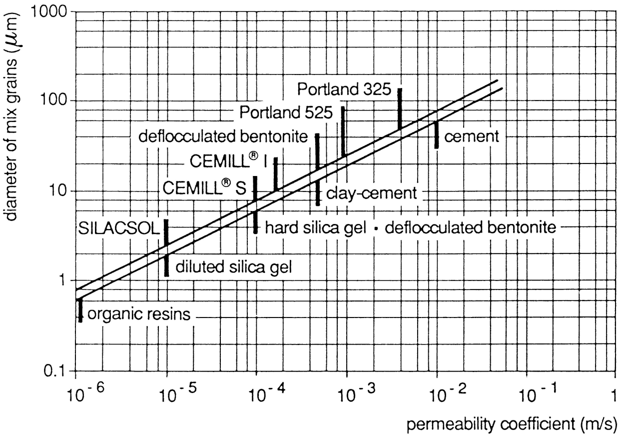


Figure 8: Permeability limits of grout according to Cambefort 1967 (lower) and to De Paoli et al. 1992 (upper).

Regarding high penetrability chemical mixes, the strict specifications and conservative prejudices against organic chemicals, especially as concerns urban areas and below the water table, have led to research and development of a new type of grout composed of a silica liquor and an inorganic reagent. This type of mix, SILACSOL, developed in France and Italy, and successfully used by Rodio in Italy, presents the same groutability range as common silica gels. The direct molecular scale reaction gives as a result a highly stable mix characterized by a crystalline structure quite similar to that obtained by hydration and setting of cement; the mix has the same stability of a cement grout, owing to the nature of resulting products (insoluble crystals of calcium silicate) and to the absence of aggressive by-products, thus being completely safe against pollution.

Case-history

The Turin railway junction crosses the town from South Northwards through several tunnels constructed either by tunnelling or cut and cover method. A critical section of tunnel, running underneath the double track Turin-Milan railway line with shallow overburden, has been excavated in an alluvial soil having widely variable mixtures and alternations of gravel and sand (Figure 9).

That soil was previously consolidated by permeation grouting. In a first phase a preliminary soil treatment ahead of the bore was carried out by successive series of 0.6 m dia. jet grouting columns, in order to excavate a 3.6 m dia. drift.

From the inside of this drift a series of sleeved PVC pipes has been installed radially. The permeation grouting by cement mix (MISTRA) and silica based mix (SILACSOL) has been performed through them, in order to create a 4.0 m thick arch of consolidated soil around the main bore.

In a second phase, during the excavation of the main bore, the treatment has been implemented by the installation, ahead of the excavation face, of successive series of steel driven reinforcements (forepoling).

Jet-grouting was also used for the consolidation of the side walls of the tunnel.

In spite of the 2.0 m thick overburden, the grouting treatment allowed the excavation to be carried out safely, meanwhile keeping the maximum surface settlements (1.5 mm) within the limits compatible with the requirements of the railway in service. Accordingly, the surface uplift has been kept to a minimum, during grouting treatment.

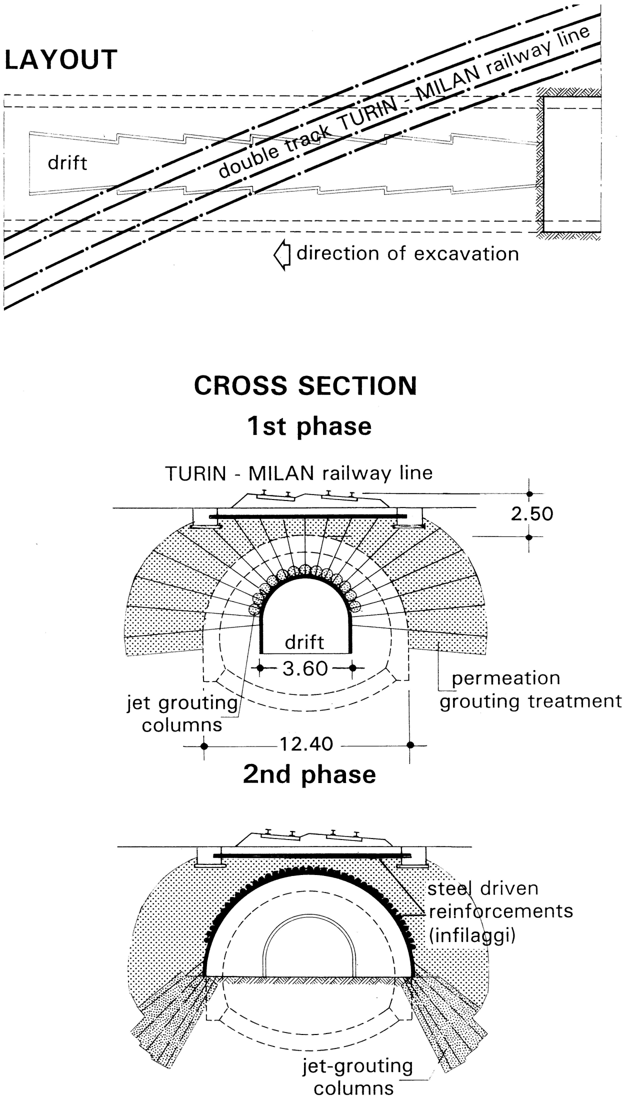


Figure 9: Turin railway junction. Soil improvement for a tunnel (critical section).

HYDROFRACTURE GROUTING

When the ground is too fine grained for a possible and convenient treatment by permeation, hydrofracturing may be a deliberate technique for soil improvement.

The ground is fragmented by hydraulic fracturing, injecting a grout with controlled rheological properties, which is generally a stable (non bleeding) cement suspension. The operational procedures are roughly the same as the above described permeation grouting, but grout characteristics, flow rate and injection pressure are selected with different criteria.

For a given injected volume the more viscous the grout, the thicker and shorter would be the fracture. On the other hand, too high pressure and too low grout viscosity may increase wastefully the extent of fissuring beyond any limit of reasonable control.

On the opposite, with very thick grout, bulbs or lenses can form around the injection point, displacing the surrounding soil (like in compaction grouting mentioned below).

In uniform soil, fractures occur on the plane of minimum principal stresses which is usually horizontal. Consequently initial fractures would be vertical with horizontal stresses increased and very little heave. When horizontal stress is greater than vertical, fractures tend to be horizontal producing heave only, without any further increase of stress, unless the extent of fracturing is small in relation to depth. Therefore a precise heave control is very important for shallow treatments. However, it is generally difficult to avoid potential danger of damaging nearby structures, owing to the high pressures applied.

Sometimes this method is used for the preliminary recompaction of decompressed soils, in order to guarantee the correct outcome of the subsequent consolidation treatment with other techniques, such as permeation grouting with high penetrability mixes or ground freezing.

In other cases the hydrofracturing has been applied to sedimentary soils to obtain a controlled surface uplift.

Case-history

An interesting application of soil heave by a combined permeation-hydrofracture grouting was carried out in 1972, as an experiment, for the uplift of an area of Poveglia island, in the Venice Lagoon.

The test area consisted of a 900 m^2 surface including two small old buildings, that were particularly interesting for the purpose of the test because of their extremely poor structural conditions (Figure 10).

After an exhaustive soil investigation by field and laboratory tests, soil uplift by grouting was carried out, by injecting at a pre-established depth a mix that caused a horizontal rupture of the soil with a resulting formation of a new layer and a consequent homogeneous uplifting of the overlying ground (Figure 11).

Grouting depth was about 10 m from surface where a thin sandy layer was sandwiched between two layers of clay.

The pre-established uplift of 100 mm has been achieved by the low pressure injection of about 1000 m^3 of mix in 75 days.

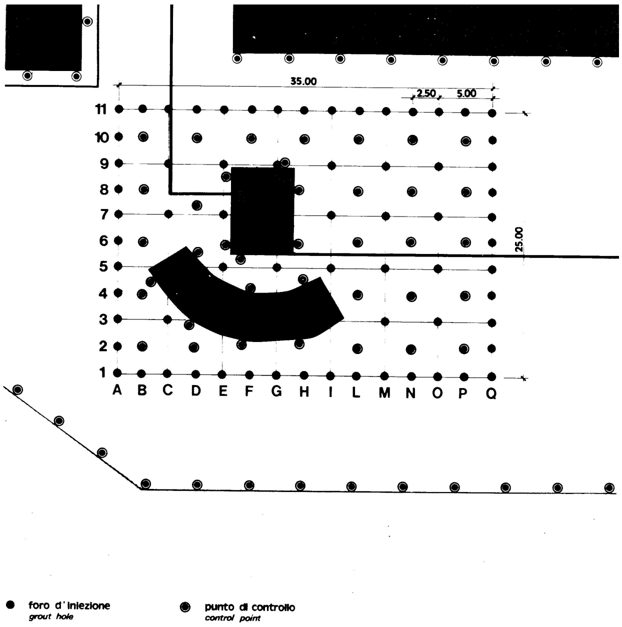


Figure 10: Poveglia. Lay-out of grout holes and control points of uplift (After Gallavresi 1984).

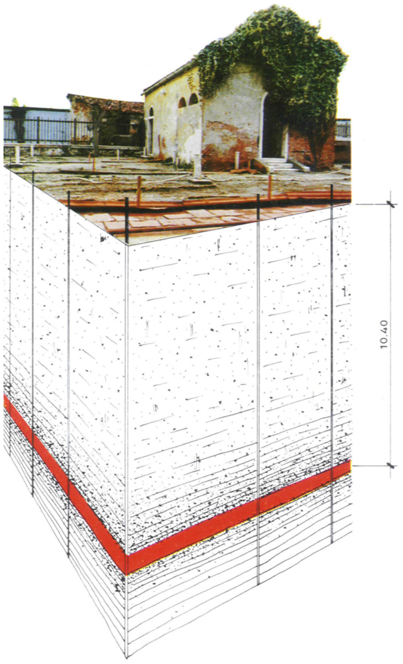


Figure 11: Poveglia. 3D view of the area undergoing the uplift treatment (After Gallavresi 1984).

Based on the design requirements, the magnitude of uplift could be increased by employing proportional quantities of grouting, as clearly shown in Figure 12, where injected volumes and results achieved are compared. In fact after the initial phase of the treatment, the average absorption for unit of surface area and uplift remained fairly constant.

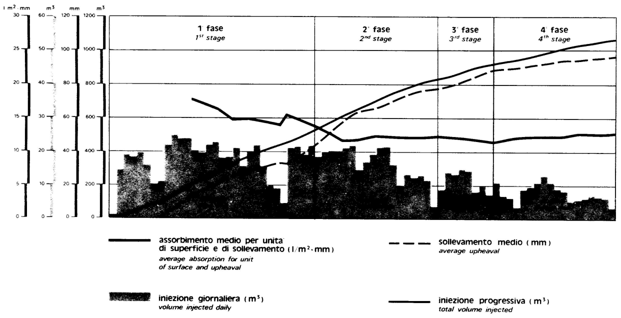


Figure 12: Poveglia. Maximum absorption and uplift diagram (After Gallavresi 1984).

COMPACTION GROUTING

The compaction grouting is a specialized technique used for the controlled densification of in situ soils at depth, by means of the extrusion of a viscous grout into a compactable soil mass. It is a very popular American method that has been in use since the early 1950's, but of no common use in Europe.

The basic concept of this technique is that of injecting a growing "bulb" of grout that acts as a radial hydraulic jack, displacing the surrounding soil particles and thus radially compacting the soil from the point of injection (Figure 13).

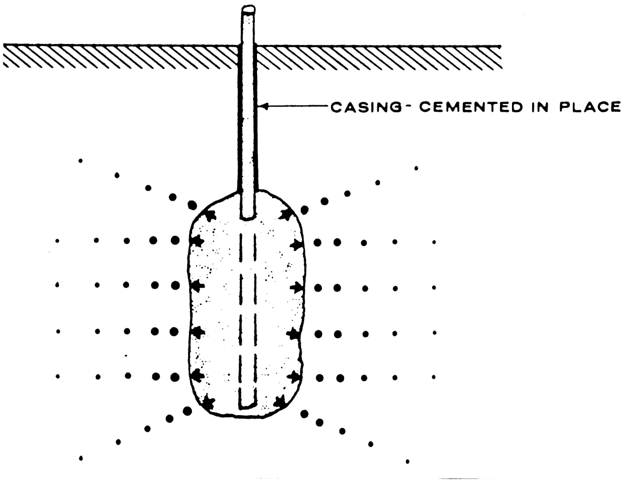


Figure 13: Increasing mass of grout displacement and compacting soil as it grows underinjection pressure (After Warner 1982).

Compaction grout technique is mainly used to underpin structures that have suffered differential settlements and to use the controlled bulbs of grout to lift the structure and the ground surface.

However, its application should be most carefully reviewed when dealing with tall structures or buildings that can tolerate only the smallest differential movements.

Grout holes are usually 50 mm or more in diameter. The spacing varies and must take into account structural restraints as well as soil conditions.

Normally, holes are spaced at about 2.4 to 3.6 m. As a rule, "primary" holes are grouted first and on their completion the grouting of "secondary" holes follows. "Secondary" holes are placed in between "primary" ones.

In practice, an oversized hole is drilled from the surface to the point at which stabilization is to begin. A full length steel casing is solidly cemented into the hole.

The hole is then extended, working through the casing and the first stage injection made. At a later time, usually the next day, the hole is extended through the same casing, for the next grout stage. This sequence is then repeated until the full depth of the treatment has been reached.

A different approach of the above procedure involves drilling the holes and simultaneously inserting a tight fitting steel casing to full depth. A standard deformed reinforcing bar is then inserted into the casing followed by grout injection.

The casing is withdrawn step by step as injection continues. Where proper performance is achieved, the result is a micropile that is effective in both compression and tension.

The grout material is a soil-cement mortar with sufficient silt sizes to provide plasticity together with sufficient sand sizes to develop internal friction.

The slump is normally less than 25 mm and the cement content is commonly around 12%.

The gradation of the sand material is probably one of the most important factors in successful application of the compaction grouting technique. An ideal sand material will be a natural, rounded material, having 100% passing through a No. 8 sieve, and not more than about 20% finer than 50 microns (Figure 14).

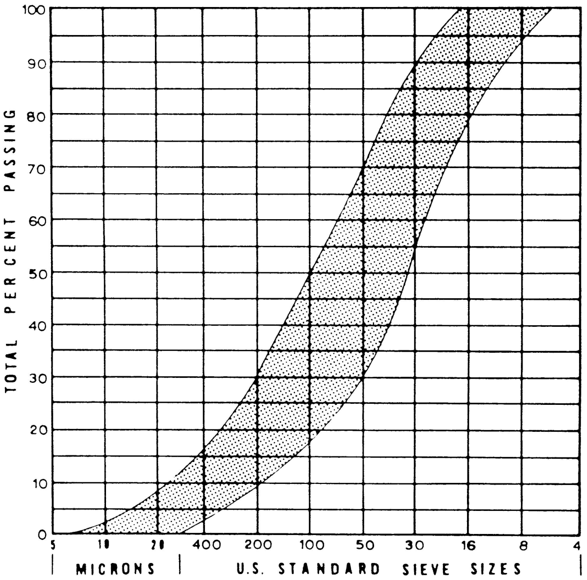


Figure 14: Preferred Gradation of Sand Material (After Warner 1982).

JET-GROUTING

The general basis of jet-grouting technique is a special high speed jet acting under a nozzle pressure up to 50 MPa or more.

The soil is fractured and simultaneously mixed in situ with a cement grout, or alternatively removed (to a certain extent depending on grain size and consistency) and replaced by grout jetting.

Hence the treatment may imply either the use of single fluid (the grout) as fracturing medium and stabilising agent or the use of 2-3 fluids (air + grout or air + water as fracturing media, and grout as stabilizing agent).

The sequence of operations related to the single fluid procedure (Rodinjet 1), consists of the main following phases (Figure 15):

- drilling down to the required depth by using a string of rods fitted at the bottom with a drilling and jetting tool (monitor);
- grout jetting through radial nozzles located along the monitor axis while revolving and drawing up the tool. In particular cases, the tool is only withdrawn (monodirectional jet-grouting).

According to soil conditions, a casing may be used or, quite frequently, uncased boreholes are drilled with direct circulation of water or bentonite mud. The size and mechanical properties of treated soil columns depend on the combined effects of the type of soil and composition of the grout, grout discharge and pressure related to the number and size of nozzles, rotational speed and lifting rate of the monitor.

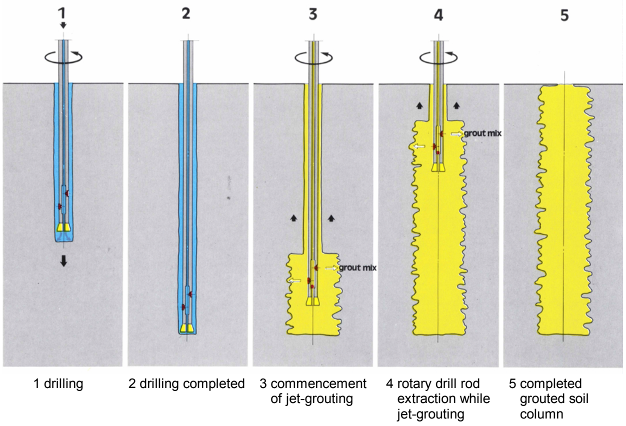


Figure 15: Single fluid system working phases.

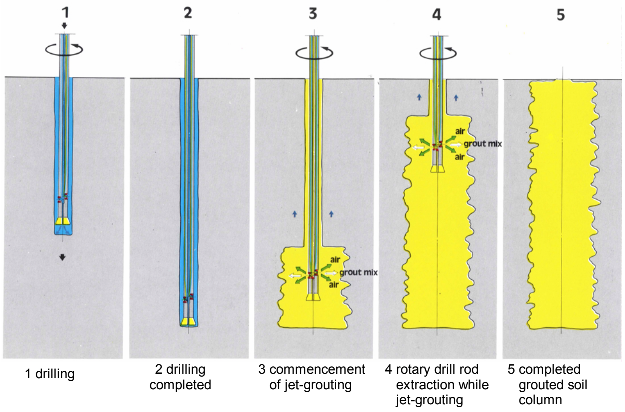


Figure 16: Double fluid system working phases.

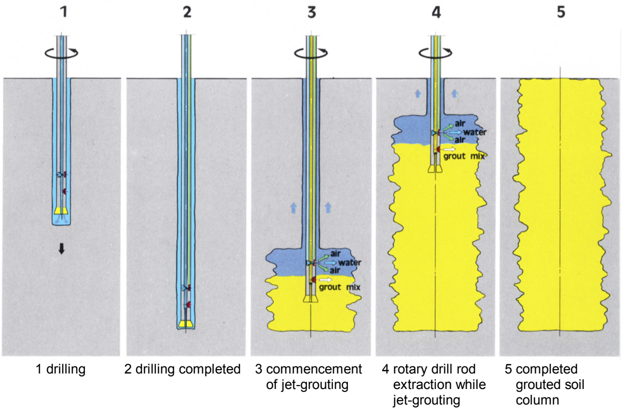


Figure 17: Three fluid system working phases.

The diameter of single columns (normally ranging between 0.5 and 0.8 m) may be increased to 1.5 m or more by alternative procedures:

- 2 fluids system, which involves air jetting through a coaxial nozzle placed around the grout nozzle (Rodinjet 2),

- 3 fluids system, which involves air-water jetting through coaxial nozzles placed just above the grout injection nozzles (Rodinjet 3).

The sequence of operations of 2 and 3 fluids system is shown on Figures 16 and 17.

Drilling and grouting equipment

The drilling mode is selected according to soil conditions, general features of the site and design specifications in regard to length and inclination of holes. Rotary drilling is preferred in medium to fine-grained soils. In coarse-grained soils, including cobbles and boulders, rotary percussion may be more suitable in terms of drilling speed.

When possible it is preferable to select a rig that enables operation with a single rod or very long elements, in order to speed up drilling and, more important, to minimize interruptions during the injection phase.

Jet-grouting equipment consists essentially of a drilling rig provided with a water/mud circuit, an automatic mixing plant that starting from water and dry products (bentonite and cement) supplies the drilling mud, if necessary, and the injection grout and a high-pressure pump (50 MPa or more).

In addition to the above units the 2 and 3 fluids system plant includes a compressed-air circuit. Only for the 3 fluids system a medium pressure pump (up to 10 MPa) is required for the cement grout injection, while the high pressure pump is used for the water injection.

Treatment geometry

The flexibility of the jet grouting method allows a wide range of problems to be solved by suitable geometrical patterns. These include:

- continuous strip treatment by one or more rows of vertical overlapping columns to form cut-off walls for ground-water control or earth-retaining structures;
- block treatment by vertical staggered columns (overlapping or not) to increase the bearing capacity of foundations or to improve mechanical properties of soils in tunnelling problems;
- sub-horizontal treatment ahead of the excavation face in tunnelling (cylindrical or conical), when operations from the surface are impossible or inappropriate.

Grout mixes and jet-grouting parameters

The grout mix constituents and composition can be selected to meet the specific requirements for soil improvement.

With respect to the initial rheological properties, viscosity and rigidity should be fairly low to allow an effective treatment to the greatest extent. When strength is the main design criterion a simple cement slurry is used, the cement/water ratio (mostly between 0.5 and 1.0) being selected according to various factors besides the required strength, i.e. the native soil characteristics and the estimated mean quantity of grout per unit volume of treated soil.

The influence of nozzle size, pressure, type and quantity of grout, monitor rotation and withdrawal speeds have been widely investigated for various soils and hydrological conditions.

Experience to date from several field trials and sites indicates that the main jet grouting parameters fall within the ranges indicated in Figure 18.

system	fluid	V_t (m/h)		V (m^3/m)		Q (m^3/h)		P (MPa)		E (MJ/m)	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
single fluid	mix	15	35	0.2	0.3	3.6	7.2	30	50	3	24
two fluids	mix			0.5	1.5	5	9	30	50	8	110
	air	4	18	10	90	150	360	0.7	1.2		
three fluids	mix			0.5	2	5	9	1	10	1	20
	water	2.5	18	0.5	2	5	9	30	50	8	180
	air			10	150	150	360	0.7	1.2		

V_t = withdrawal speed
V = mix volume
Q = grout mix flowrate
P = grout mix pressure
E = grouting energy

Figure 18: Ranges of jet grouting parameters.

In general, the radius of influence is mainly related to the waiting time between the drawing up steps, i.e. to the permanence of the monitor at the same level. An increase in pressure enhances the fracturing effects of the jet, reducing the time necessary to inject a given quantity of grout.

In each case the selection of operational parameters must be based on a reasonable balance of technical and economical factors that require practical experience and may demand site trials.

Figure 19 illustrates the result of statistical evaluation on five documented case records.

			controls on treated soil samples								
soil type	treatment systems	C/W mix	experim. data		statistical elaborations of the experimental data						
			γ	R	R_o	n	C	T	W	W_t	V_m
medium clayey silt	MF	0.5	1.60	0.55	5	2	216	727	659	31	505
low consistency peaty silty clay	MF	0.6	1.41	0.50	4	2	268	373	767	86	536
medium sandy clayey silt	MF	0.6	1.61	1.47	8	2	280	687	652	27	560
low consistency clayey silt	MF	1.25	1.72	6.52	7.5	2	596	487	640	33.5	664
peat	TF	1.4	1.34	0.8	1.5	3	297	255	790	227	311
										hypothesis of no drainage	

MF = single fluid three fluid
TF = three fluid

R = strength (MPa) $R_o = \frac{R}{(C/W)^n}$

treated soil composition (kg/cm³):
C = cement   T = dry soil
W = total water = $W_m + W_t$
W_m = water associated with mix = $C \cdot (W/C)_{mix}$
W_t = water associated with soil = $W - W_m$

W_t = 100 W_t/T = water content (%) of entrained soil

V_m = mix content by volume (litres/m³)

Figure 19: Statistical evaluation on treated soil samples.

Case-histories

The design of a new junction on the National road No. 1, near Genoa (Italy), required the construction of a new viaduct for the close by motorway A10, which goes from Genoa to France. Eight of ten piers of the viaducts, constructed on the Arroscia river bed, required shaft foundations built above improved soil. These were constructed following a jet-grouting treatment (Figure 20).

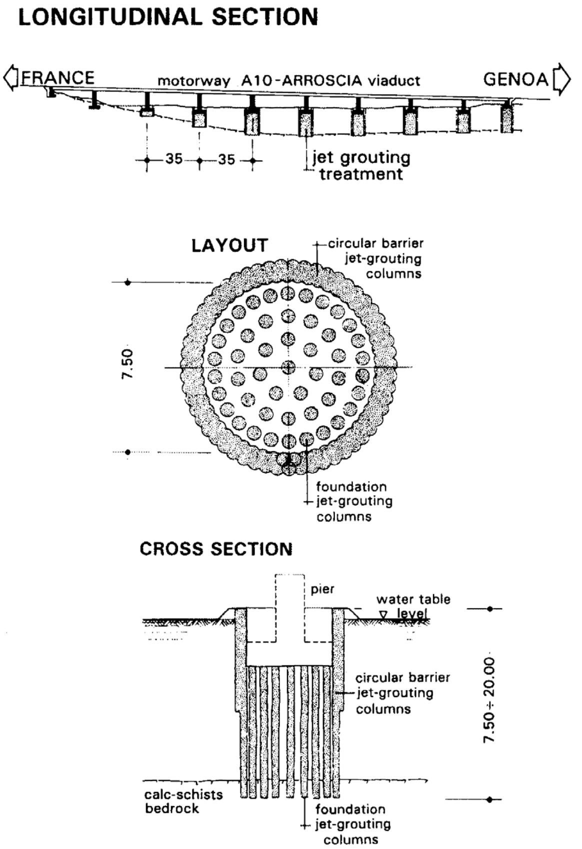


Figure 20: Motorway A10 from Genoa to France (Italy). Arroscia viaduct foundation.

For each pier a circular barrier consisting of two rows of vertical overlapping jet-grouted columns (0.6 m dia.) was constructed, both to protect the shaft excavation and to prevent seepage, since the water table level was approximately at ground level. These jet-grouted columns were drilled and jetted through about 18 m of gravelly alluvium and embedded on impervious calc-schists bedrock. Inside the above mentioned barrier, 48 jet grouted columns (0.6 m dia.) were carried out to reach the calc-schists, in order to improve the ground below the shaft base.

The jet grouting treatment proved very successful and the viaduct was completed well in advance of the scheduled construction time.

In the Turin Railway junction site, the same tunnel described in a previous paragraph, out of the critical section, was excavated in the alluvial soil, with 5.0 m overburden, underneath avenues and local parks. A preliminary soil treatment ahead of the bore was carried out by a successive series of 0.6 m dia. jet-grouting columns, implemented by the installation of some steel driven reinforcements (forepoling), on the lower surface of the consolidated arch (Figure 21).

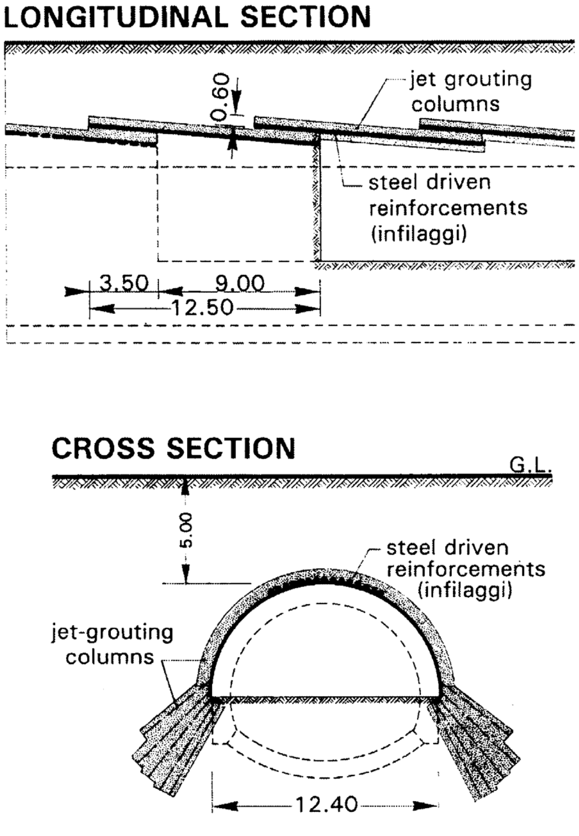
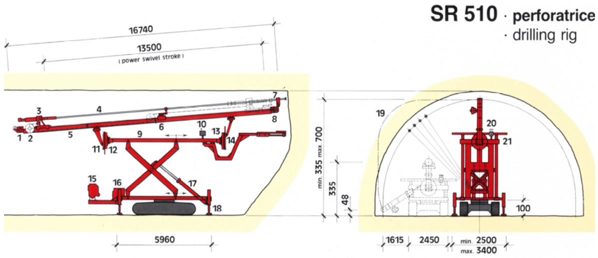


Figure 21: Turin railway junction. Soil improvement for a tunnel (standard section).

The treatment was achieved by a rig (SR 510) that was specially designed by Rodio for sub-horizontal rotary percussion drilling (Figure 22). A system of hydraulic jacks allows the mast to be rotated to within 180° and inclined up to 15° to the horizontal. By use of this rig all the holes necessary for the treatment of a tunnel section ahead of the excavation face can be drilled to a length of 15 m and with a single rod with no re-positioning of the equipment.



1	pull out winch and controlled extraction mechanism
2	hydraulic hose take-up reel
3	power swivel
4	drilling and jetting rod
5	mast
6	sliding rod guide
7	clamp
8	pull down winch
9	working platform
10	control panel
11	inclination mast slide
12	rear slewing ring
13	front slewing ring
14	inclination mast slide
15	power pack
16	hydraulic tank
17	working platform lifting device
18	stabilizer
19	border of allowed drilling area
21	slewing ring translation rail

Figure 22: SR 510 drilling rig.

Each series of jet-grouting and forepoling treatment, reaching a length of 12.5 m, allowed to excavate to a length of 9.0 m, so that the excavation proceeded by steps of 9.0 m, with a step completed every 5 days. Sub-vertical jet-grouting was also used for the consolidation of the side walls of the tunnel.

RIEPILOGO

Nell'articolo sono discusse diverse tecniche di iniezione applicate al miglioramento dei terreni: iniezioni per permeazione e idrofratturazione, compaction grouting e jet grouting. Sono inoltre illustrati alcuni "case histories" relativi alle suddette tecniche di iniezione.

L'**iniezione per permeazione** consiste nel riempimento dei vuoti presenti nel terreno mediante specifiche miscele, senza alcuna modifica sostanziale del volume e della struttura originale del terreno. Possono essere applicati differenti metodi di iniezione, in funzione delle diverse condizioni incontrate: in roccia si possono applicare i metodi up-stage, down-stage e MPSP, nei terreni sciolti il metodo dei tubi "à manchettes".

In alternativa alle sospensioni cementizie tradizionali, sono state sviluppate nuove miscele aventi caratteristiche di stabilità e di penetrabilità molto più pronunciate: la MISTRA' è una sospensione additivata di cemento e bentonite, mentre la CEMILL è una sospensione additivata di cemento microfine e bentonite.

In alternativa alle miscele silicatiche tradizionali, è stata sviluppata e messa a punto una miscela denominata SILACSOL, che presenta le stesse caratteristiche di penetrabilità dei comuni gel di silice, ma, a differenza degli stessi, risulta stabile nel tempo, poiché i prodotti di reazione costituiscono una struttura cristallina simile a quella che si produce nella idratazione del cemento.

La scelta dei parametri operativi è basata principalmente sull'esperienza, in funzione dei tipi di terreno interessati dal trattamento. Si può osservare che: la spaziatura dei fori varia generalmente tra 1.5 e 2.5 m; la portata di iniezione è mantenuta più bassa possibile, specialmente nel caso di iniezioni chimiche; la pressione di iniezione viene scelta in modo da evitare fenomeni di idrofratturazione. Il "case history" illustrato rappresenta un esempio di trattamento di iniezioni per permeazione, finalizzato al consolidamento preventivo allo scavo della sezione critica di una galleria per il Passante Ferroviario di Torino

L'**iniezione per idrofratturazione** può essere utilizzata per consolidare terreni aventi caratteristiche granulometriche troppo fini e di permeabilità troppo bassa perché sia applicabile l'iniezione per permeazione. Essa consiste nel provocare deliberatamente la rottura del terreno a mezzo di idrofratturazione (claquages), in modo da ricompattare il terreno mediante incremento delle tensioni totali; tale incremento è ottenuto a seguito dell'effetto martinetto creato dalla miscela in pressione in lenti e fratture. Le procedure operative sono simili a quelle dell'iniezione per permeazione, anche se le caratteristiche delle miscele, le portate e le pressioni di iniezione vengono selezionate con criteri differenti. Il metodo può essere utilizzato per la ricompattazione preliminare di terreni decompressi, per consentire successivamente la corretta applicazione di altre tecniche di consolidamento quali l'iniezione per permeazione mediante miscele ad altra penetrabilità ed il congelamento del terreno. Talvolta l'iniezione per idrofratturazione viene applicata per ottenere il sollevamento controllato del terreno, come ad esempio nel caso del campo prove sperimentale condotto sull'isola di Poveglia, nella laguna Veneta.

Il **compaction grouting** è una tecnica utilizzata per la ricompressione e l'addensamento di terreni mediante l'estrusione di una miscela molto viscosa all'interno di un terreno compressibile. Il concetto base della tecnica è la formazione di un bulbo di miscela che agisce come un martinetto idraulico radiale, spostando le particelle di terreno al contorno, conseguendo così una compattazione radiale a partire dal punto di iniezione.

Il compaction grouting è principalmente utilizzato per sottofondare strutture che abbiano subito cedimenti differenziali; può essere inoltre impiegato per provocare deliberatamente il sollevamento del terreno e di strutture. Di norma l'esecuzione comincia con la cementazione di un rivestimento nel terreno fino alla profondità da cui deve partire il consolidamento. Attraverso il suddetto rivestimento il foro viene prolungato per una certa lunghezza ed eseguita la prima fase di iniezione. Dopo un certo periodo di tempo (di solito il giorno successivo) il foro viene ulteriormente prolungato ed eseguita la seconda fase di iniezione. La sequenza suddetta viene ripetuta fino al raggiungimento della profondità di progetto.

Il **jet grouting** consiste nella disgregazione del terreno e nella simultanea miscelazione in sito dello stesso con una miscela stabilizzante iniettata ad altissima velocità attraverso speciali ugelli.

Il trattamento può implicare l'uso di uno o più fluidi: miscela cementizia per la tecnica monofluido, miscela cementizia + aria per la tecnica bi-fluido e acqua + aria + miscela cementizia per la tecnica tri-fluido. La sequenza tipo può essere sintetizzata nelle due fasi seguenti: 1) perforazione fino alla profondità di progetto utilizzando un "monitor" portaugelli autoperforante; 2) iniezione del fluido (o dei fluidi) di trattamento attraverso ugelli radiali installati sul "monitor", con velocità di rotazione e di estrazione predeterminate. Il diametro delle singole colonne può variare tra 50 e 80 cm per la tecnica monofluido, ma raggiungere 1.5 m e oltre con l'impiego delle tecniche bi-fluido e tri-fluido.

Il jet grouting può essere applicato per la realizzazione di paratie strutturali o impermeabili, per il trattamento massivo finalizzato all'incremento della capacità portante del terreno e per la realizzazione di trattamenti cilindrici o tronco-conici in avanzamento allo scavo di gallerie per ottenere un consolidamento preventivo allo scavo. Un esempio di barriere impermeabili e di consolidamenti di fondazione mediante jet grouting è rappresentato dall'intervento relativo alle fondazioni del viadotto Arroscia sull'autostrada A10 Genova-Ventimiglia. Un esempio di consolidamento preventivo allo scavo di una galleria, mediante jet grouting, è rappresentato dalla galleria a sezione standard per il Passante Ferroviario di Torino.

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La ricerca europea per la riduzione dell'inquinamento salino
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POSSIBILITIES TO PREPARE GYPSUM OR CALCITE FORMING SOLUTIONS FOR SEALING OF SEDIMENTS

POSSIBILITÀ DI PREPARARE SOLUZIONI DI GESSO O DI CALCITE PER DIMINUIRE LA POROSITÀ NEI SEDIMENTI

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Abstract. Gypsum or $CaCO_3$ forming solutions can be prepared by mixing calcium containing solutions with sulphate or carbonate containing in the presence of a suitable precipitation inhibitor. Oversaturations up 40 g/l gypsum and 1.1 g/l $CaCO_3$ are possible. The stability of the solutions depends on the used inhibitor and its concentrations as well as on the overall solution composition. Column experiments have demonstrated the successful sealing of sand packs by gypsum forming solutions. Further research will deal with the optimisation of the composition of the oversaturated solutions and the study of interactions with different types of sediments.

Keywords: gypsum, $CaCO_3$, solutions, inhibitor.

Riassunto. *Le soluzioni formanti gesso o $CaCO_3$ possono essere preparate dal mescolamento di calcio con soluzioni contenenti, rispettivamente, solfato o carbonato, in presenza di un idoneo inibitore. Sono possibili sovrasaturazioni superiori a 40 g/l di gesso e pari a 1,1 g/l di $CaCO_3$. La stabilità delle soluzioni dipende dall'inibitore usato e dalle sue concentrazioni, così come dalla composizione totale della soluzione. Gli esperimenti in colonne hanno avuto successo in quanto si è osservata l'occlusione dei pacchi di sabbia con le soluzioni di gesso. Ricerche successive tratteranno l'ottimizzazione della composizione di soluzioni sovrasature e lo studio di interazioni con i diversi tipi di sedimenti.*

Parole chiavi: *gesso, carbonato, soluzioni, inibitore.*

INTRODUCTION

The use of crystallisation process La ricerca europea per la riduzione dell'inquinamento salino delle acque sotterranee, Ed. M. Polemio & G. Gallicchio, 2002es for sealing of sediments in coastal areas requires the preparation of oversaturated solutions. These have to contain the minerals that will be formed in concentrations above their normal solubility. The oversaturation shall brake down during the flow of the solution through the sediments leading to an "in-situ" crystallisation and sealing. That means solution compositions are to develop which are characterised by a defined temporary stability. There are different ways to produce oversaturated solutions. Especially the use of precipitation inhibitors is promising. These are chemicals with the ability to stabilise supersaturations. The inhibitor increases the germination time and gives the solutions a temporary stability. For sealing of sediments in coastal areas it is essential that only non-toxic and environmental harmless minerals are produced. The formation of silicates should be the best way, however, crystalline compounds are not formed under conventional conditions. Amorphous precipitates of variable composition are found normally. Other minerals that are typical for coastal sediments are calcite and in some cases gypsum. While the solubility of calcite is small (15 mg/l under normal conditions) gypsum is characterised by a solubility of 2.5 g/l. A slight increase is found in sea water. The article summarises results of investigations to develop gypsum or calcite forming solutions. The stability of the solutions as well as the achievable permeability reduction will be discussed.

EXPERIMENTAL

The investigations concerning the selection of the most favourable inhibitor concentration and the determination of the timely course of crystallisation were carried out as isothermal stirring experiments at room temperature.

The preparation of solutions leading to gypsum precipitation is possible by:

- Mixing of $MgSO_4$ or K_2SO_4 or Na_2SO_4 solutions with $CaCl_2$ containing solutions in the presence of an inhibitor
- Mixing of a lime suspension with diluted sulphuric acid in the presence of an inhibitor

$CaCO_3$ forming solutions were prepared by mixing of $CaCl_2$ and Na_2CO_3 containing solutions in the presence of an inhibitor, too. Reagent grade chemicals were used in all cases.

The course of $CaCO_3$ or gypsum precipitation was determined by analysing the change in the calcium concentrations by means of complexometric titration with EDTA.

The inhibitor concentrations for stabilising $CaCO_3$ solutions were determined by simultaneous addition of a carbonate and a calcium containing solution to an inhibitor solution with known concentration. The occurrence of first precipitates was the sign that the capability of the inhibitor to stabilise the oversaturation was exceeded.

The apparatus shown in Figure 1 was used for column experiments to determine the change in permeability during and after penetration with gypsum forming solutions. Characteristics of the column are given in Table 1. The tests were carried out accordingly to following procedure:

- Permeability determination by measuring the time necessary for the flow of 50 ml water through the column at constant high.
- Injection of the gypsum forming solution from the bottom to the top of the column, replacement of one pore volume.
- The column was left standing for approximately 22 hours.
- Permeability determination as described.
- Injection of the gypsum forming solution from the top to the bottom of the column, replacement of one pore volume.
- The column was left standing for approximately 22 hours.
- Permeability determination as described and continuation of the experiment with injection of the gypsum forming solution from the bottom to the top.

RESULTS AND DISCUSSION

Preparation and properties of gypsum forming solutions

The stability of $CaSO_4$ solutions prepared by mixing of equimolar volumes of $CaCl_2$ and $MgSO_4$ solutions depending on the inhibitor concentration is shown in Figure 2. The start concentration was 26 g/l, which is more than 10 times higher than the natural solubility of gypsum.

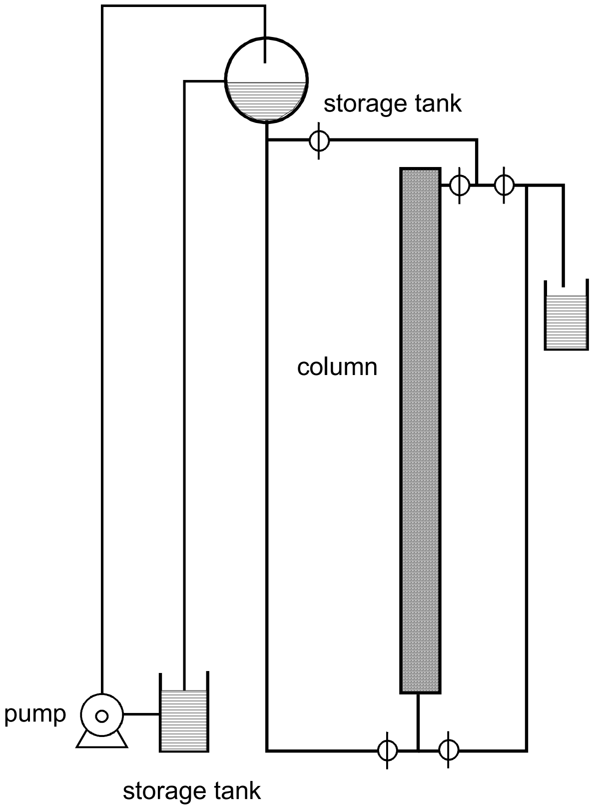

Figure 1: Apparatus used for the column experiments.

Length	0.98 m
Weight of sand	3.125 kg
Pore volume	0.830 litre
Concentration of used solution	0.25 mol $CaSO_4$/l
Inhibitor concentration	1.5 g/l

Table 1: Characteristics of the used column.

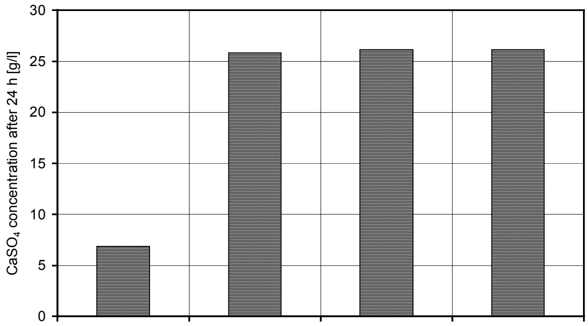

Figure 2: Stability of $CaSO_4$ containing solutions depending on the used inhibitor concentration.

It is visible that an inhibitor concentration of 20 mg/l does not prevent gypsum precipitation for 24 hours. Only little gypsum crystallises at an inhibitor concentration of 40 mg/l; no precipitation takes place in the presence of inhibitor concentrations of 60 mg/l or 80 mg/l. The solution containing an inhibitor content of 80 mg/l is stable for more than 72 hours.

Figure 3 summarises the course of gypsum precipitation at a constant inhibitor concentration depending on the degree of oversaturation. It is visible that higher starting concentrations result in a shorter stability of the solutions. The used inhibitor differs from that used for the investigations summarized already in Figure 2. Solutions containing 0.18 mol/l $CaSO_4$ have at an inhibitor concentration of 500 mg/l a stability of 24 hours. After that gypsum starts to crystallise. Gypsum crystallisation starts earlier with increasing $CaSO_4$ concentrations.

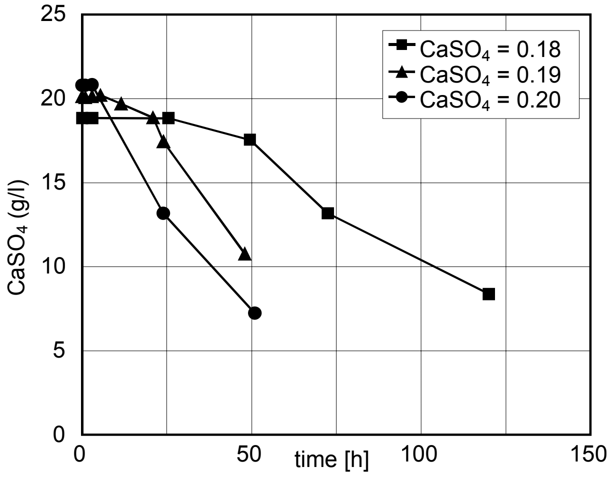

Figure 3: Course of gypsum crystallisation depending on the starting concentration at a constant inhibitor concentration of 0.5 g/l.

The same inhibitor concentration produces at a $CaSO_4$ concentration of 0.20 mol/l a delay in the start of the crystallisation of 4 hours only.

In general, the achievable degree of oversaturation and the stability of the gypsum forming solution depend on:

- the inhibitor and its concentration;
- the starting pH of the solutions;
- the overall solution composition.

The preparation of gypsum forming solutions by using $CaCl_2$ and $MgSO_4$ containing solutions can be carried out in stirred tank reactors, for example. The preparation procedure is simple but it has to be taken into consideration that the resulting solution contains $MgCl_2$ concentrations equivalent to the $CaSO_4$ concentrations. In the case of using Na_2SO_4 as sulphate source equivalent concentrations of NaCl result. Mixing of lime suspensions with diluted sulphuric acid offers the possibility to prepare "pure" $CaSO_4$ solutions. The timely course of gypsum crystallisation can be adjusted in the same manner by the concentration of the used inhibitor (Figure 4).

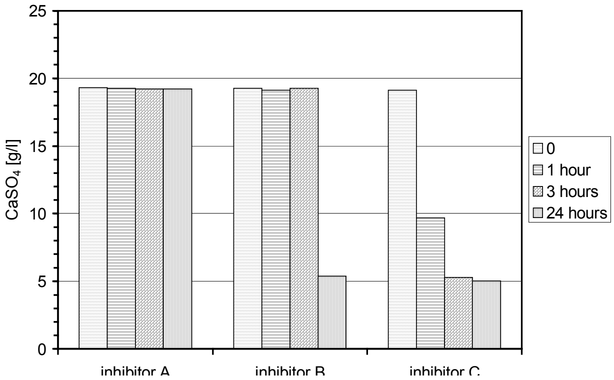

Figure 4: Stability of gypsum forming solutions prepared by mixing of $Ca(OH)_2$ and diluted sulphuric acid.

Preparation and properties of $CaCO_3$ forming solutions

Solutions supersaturated in $CaCO_3$ can be prepared by mixing of $CaCl_2$ solutions with Na_2CO_3 or $NaHCO_3/Na_2CO_3$ solutions in the presence of a suitable inhibitor. The final pH value of the resulting mixture depends on the characteristics of the inhibitor and the HCO_3^-/CO_3^{2-} ratio. Figure 5 shows the results of turbimetric titrations in which Na_2CO_3 and $CaCl_2$ solutions were added simultaneous into differently concentrated inhibitor solutions.

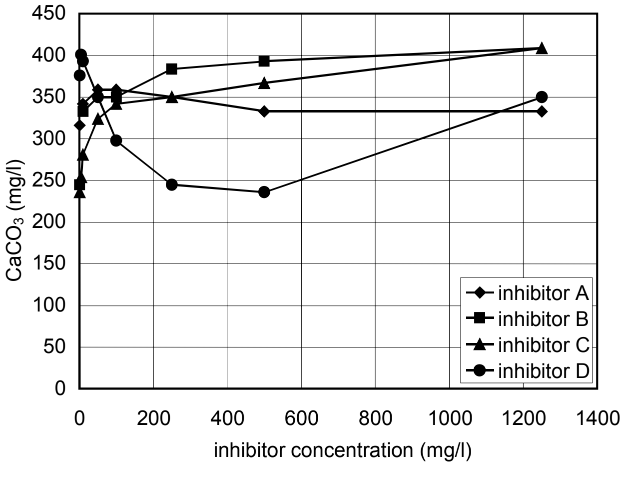

Figure 5: Stability of $CaCO_3$ oversaturated solutions depending on the used inhibitor and its concentration.

The diagram shows that an effective stabilisation of $CaCO_3$ oversaturations is achieved even at low inhibitor concentrations. Increasing inhibitor concentrations do not give in all cases the possibility to achieve higher oversaturations. In some cases only a small increase can be obtained, some inhibitors show a decreasing activity with increasing concentrations. Additional it is to regard that some inhibitors produce at high concentrations insoluble precipitates with calcium ions.

The absolute amounts of $CaCO_3$ that can be stabilized are low in comparison to gypsum forming solutions. If we regard, however, the ratio oversaturation to natural solubility it becomes visible that the degree of oversaturation is much higher in $CaCO_3$ solutions as in gypsum forming solutions.

The timely course of $CaCO_3$ precipitation depends on the used inhibitor, its concentration and the overall solution composition (Figure 6).

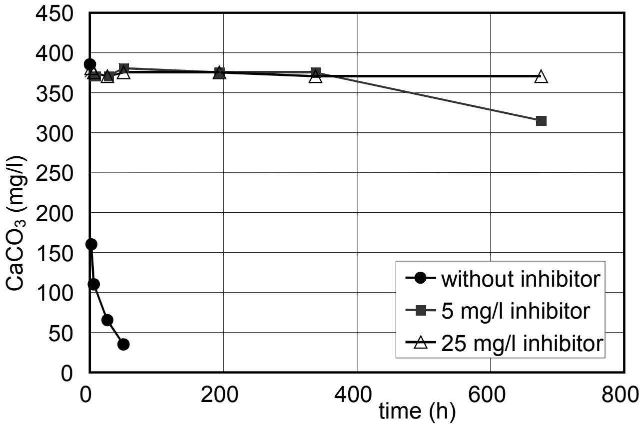

Figure 6: Course of $CaCO_3$ precipitation in a solution containing 0.5 g/l $MgCl_2$ depending on the inhibitor concentration.

For example, the presence of magnesium ions increases the stability of the oversaturated solution. Precipitation occurs later and slower. Another factor influencing the achievable absolute oversaturation as well as the timely course of precipitation is the HCO_3^-/CO_3^{2-} ratio. Slower precipitation takes place in the presence of HCO_3^- ions. Higher oversaturations are possible if HCO_3^-/CO_3^{2-} solutions were used instead of pure CO_3^{2-} solutions. Mostly Calcite is formed, in some cases the $CaCO_3$ modification Aragonite was found, too.

Change of permeability during the penetration with gypsum forming solutions

A column filled with sand was treated for 15 days with a gypsum producing solution containing 34 g/l $CaSO_4$. Sea sand was used for these investigations. The aim of the experiment was to demonstrate the high sealing capacity of gypsum forming solutions. One pore volume of gypsum forming solution was pumped each day through the column. Depending on the hydraulic conductivity a time between one and three hours was necessary to realise that. After 11 injections the k_f value was reduced from 23 m/day to 6.5 m/day (Figure 7).

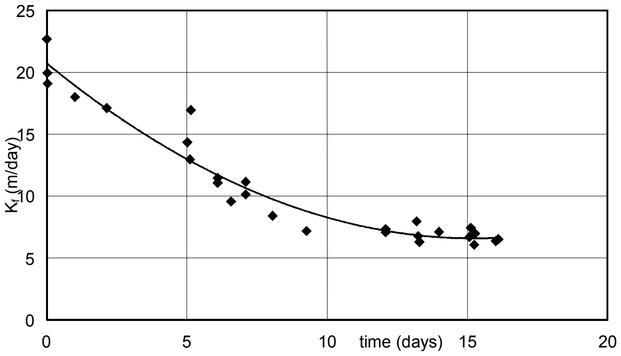

Figure 7: Change in permeability of a sand column during the treatment with gypsum forming solutions.

Approximately 350 g gypsum were precipitated within the sand pack. This resulted in filling of 18% of the pore space. It is visible that this reduction has resulted in a permeability reduction of 72%.

Apart from the possibility of sealing of sand packs by secondarily formed gypsum the experiment demonstrated that gypsum crystallisation takes place faster in contact with sediments than in pure solutions. This means it is of great importance to determine the sediment – solution interactions in order to select favourable solution compositions for large scale field testing.

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GEOLOGICAL AND GEOPHYSICAL INVESTIGATIONS OF THE GREEK TEST SITE

INDAGINI GEOLOGICHE E GEOFISICHE DEL CAMPO PROVA IN GRECIA

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Abstract. One field test of the CRYSTECHSALIN project will take place in the Eleftheres hydrologic basin, 15 km from Kavala, in East Macedonia, Greece. Purpose of the test is the application in true field conditions of the crystallization process in order to seal the underground flowpaths and therefore to prevent the saline water intrusion. The objectives for the first year of the project (March 2001-March 2002) were to determine the geological, hydrogeological and geochemical conditions of the test site in detail, in order to plan successfully the field test in true scale that will take place during the 3rd year of the project. Additionally to the geological works, a detailed geophysical survey was carried out in the basin area. The aim of survey was to acquire all possible information regarding the geometrical characteristics of the subsurface layers and the monitoring of the saline water intrusion front. Finally, for the long term monitoring of the saline water intrusion, one automatic (SCADA) measuring system has been designed by GEOSERVICE.

Keywords: geology, geophysics, GIS, telemetry, sensors.

Riassunto*. Il campo prova, inerente il progetto CRYSTECHSALIN, avrà luogo nel bacino idrologico dell'Eleftheres, a 15 km da Kavala, in Macedonia Orientale (Grecia). Lo scopo del test è verificare la fattibilità in sito del processo di cristallizzazione per creare barriere fisiche al flusso sotterraneo e quindi evitare l'intrusione di acqua marina. Gli obiettivi per il primo anno del progetto (Marzo 2001 – Marzo 2002) erano determinare, nel dettaglio, le condizioni geologiche, idrogeologiche e geochimiche del campo prova, per progettare con successo la sperimentazione che avrà luogo durante il terzo anno del progetto. Oltre lo studio geologico, un dettagliato esame geofisico è stato eseguito nel bacino. Lo scopo di ciò era acquisire tutte le informazioni possibili riguardanti le caratteristiche geometriche degli strati del sottosuolo ed il monitoraggio del fronte di intrusione marina. Infine, per il monitoraggio a lungo termine dell'intrusione di acqua marina, un sistema di misura automatico (SCADA) è stato progettato dalla GEOSERVICE.*

Parole chiavi: *geologia, geofisica, GIS, telemetria, sensori.*

INTRODUCTION

The hydrologic basin of Eleftheres, KAVALA, was selected from GEOSERVICE as a test site for the application of the crystallization methods, for the following reasons:

1. The U-shape of the basin and the relative shallow depth to the granite basement, offers easier and more promising initial conditions for the experiment.
2. The narrow and directional shape of the saline water intrusion front can be easily monitored with electronic instrumentation. As a result, any external intervention to the permeability of the groundwater aquifer system will be easily and measurable from the system.

GEOLOGICAL AND GEOCHEMICAL SURVEYS

Methodology

The methodology that has been followed in the project was based on:

1. A complete desk study of all the existing geological data concerning the Eleftheres basin.
2. Qualitative and quantitative analysis of the geomorphologic characteristics of the Eleftheres hydrologic basin. The processing and the management of the spatial information were performed using a vector GIS platform, while the analysis, the evaluation and the presentation was performed using a raster GIS platform. The major physiographic features of the basin

include mountain areas, alluvial fans and pediments, hydrologic basin lowlands and the flood plain of the Eleftheres stream.

3. Geological mapping in scale 1:20000 and 1:5000. Extensive field work points out that the Eleftheres hydrologic basin is composed of the Kavala plutonite and metamorphic rates. Geological cross-sections were drawn for certain locations of the basin.
4. Hydrological research. All the existing wells in Eleftheres basin were recorded using a GPS system and represented on the map using the latest GIS software platforms.

Geomorphology of the Eleftheres basin

The Eleftheres hydrologic basin is located 15 km SW from Kavala, in east Macedonia, Greece. The basin is bounded to the north, northeast and west by the Symvolon mountain ridge and extends towards the south and southeast reaching the coastal zone of the Aegean sea. The Symvolon mountain ridge dominates the greater area of Eleftheres and it has a long narrow NE-SW shape.

The major physiographic features of the Eleftheres hydrologic basin include mountain areas, alluvial fans and pediments, hydrologic basin lowlands and the flood plain of the Eleftheres stream. The study area encompasses 48.176 m^2 and is located at the southwestern part of the so called Rhodope massif.

The Eleftheres topography is characterized by land altitudes that range from about 100 to 670 m above the sea level. Near the coastal zone the topography is characterized by hills and lowlands that range from about 30-130 m above sea level. The longest axis of the Eleftheres hydrologic basin has a length of about 12 km, while its maximum width is approximately 10 km.

The major hydrographic features of the Eleftheres hydrologic basin include a well defined dendritic drainage system. The primary stream network drains the northeast, northwest and west parts of the mountainous area and also the alluvial fans as rejuvenated streams.

This hydrographic network is mainly composed of two major systems of streams, the form and the growth of which are only dependent on the geomorphologic relief. The northwestern one is called Asproneri and discharges into the Eleftheres main stream, while the Eleftheres stream discharges into the gulf of Eleftheres. The total surface area of Eleftheres watershed basin is 47.176 m^2.

Geology of the Eleftheres basin

Eleftheres basin occupies a small area that lies in the so called Rhodope massif. The Rhodope massif is a polymetamorphic terrain which extends along the Greek-Bulgarian border and covers in Greece regions of eastern Macedonia and Thrace. The Rhodope massif comprises of marbles, amphibolites, gneisses, schists and granitoid rocks.

The Eleftheres hydrologic basin is composed of plutonic rocks (the “Kavala” plutonite) and metamorphic rocks (Figure 1).

These units are overlain by sedimentary rocks of Tertiary through Quaternary age that consist of coastal sands, terrestrial deposits, and alluvian fans (Kronberg, 1970). The sedimentary units from oldest to youngest are:

1. **Terrestrial Deposits**: Units that consists of boulders, loose conglomerates, pebbles, fine-grained material and red clays. Terraces are formed, at places, in topographically areas of low elevation.
2. **Coastal Sands**: In the off-shore area a formation of coastal sands occurs as a result of the mechanical erosion of the Kavala pluton.
3. **Allouvian Fans**: Consisting of boulders, conglomerates, red-clays and pebbles

The metamorphic units are:

1. ***Gneiss and Gneiss schists:*** Fine to medium grained gneiss and gneiss schists, varying in color, from grey to brown and texture from gneissose to schistose, according to their individual mineral content.
2. ***The Falakron Marble series:*** composed of massive marble intercalated with amphibolite and metapelite layers bearing upper greenschist facies mineral assemblages.

The plutonic rocks (“Kavala” pluton) are mainly composed of granodiorite, and subordinate by diorite, tonalite and monzogranite according to the petrographic classification (Christofides et al. 1995). The granodiorite is light to dark colored and is characterized by a more or less gneissic texture. In many places of the pluton there are mylonitized zones from 5 to 10 mm wide. According to their mineralogy, the porphyroblasts are consisting mainly of K-Feldspar and plagioclase and less often of quartz. Based on the degree of deformation and the magmatic texture, the granodiorite can be varying from medium grained granodiorite to coarse grained granodiorite (Christofides, 1989).

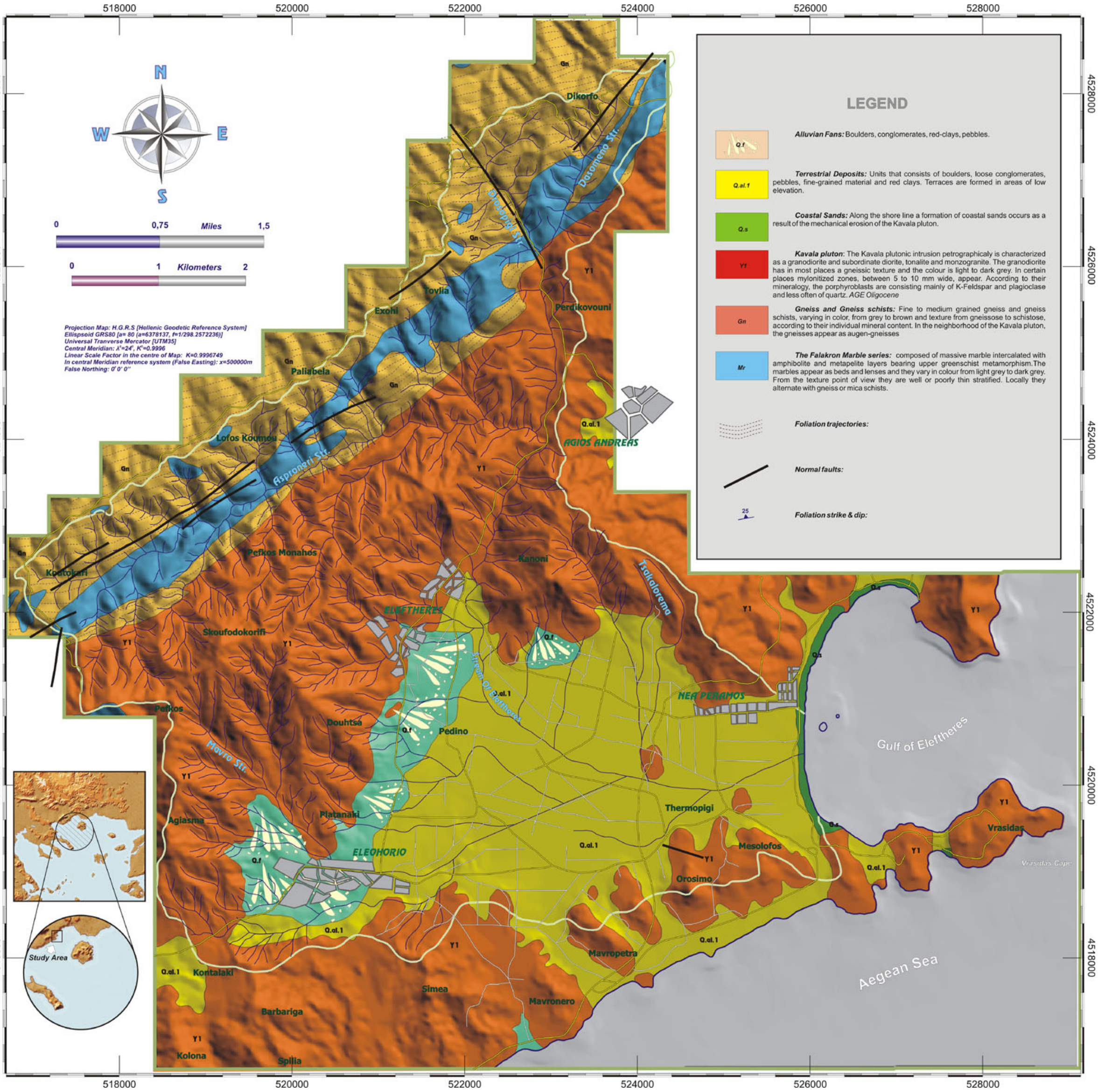

Figure 1: Geological map of Eleftheres basin.

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The transition between the two deformational plutonic types is gradual. The emplacement age of the Kavala pluton was a subject of dispute for many years but recent studies of Dinter et al. (1995), based on zircon and titanite U-Pb dates and hornblende $^{40}Ar/^{39}Ar$, showed a 20 Ma age of emplacement and a 13 Ma age of cooling. The Symvolon pluton is strongly mylonitic throughout most of its exposure (Kokkinakis, 1980). The margins of the pluton appear as mylonitic zones varying in width between 10 and 100 m. From our field work we observed that the Kavala pluton has been affected by hydrothermal fluids that have intruded the plutonic rocks along tectonic disconformities. In the Eleftheres basin, two fault systems has been identified. The major system has a NE-SW trend and comprises of parallel normal faults dipping northwest. These faults appear in the north and northwest part of the basin. The other fault system has a NW-SE trend dipping southwest.

Hydrogeology of the Eleftheres basin

The geological units of Eleftheres basin are classified in three hydrolithological units:

1. **Permeable** including alluvial fans and coastal sands.
2. **Semi-permeable** including the sedimentary cap of the quaternary deposits and
3. **Impermeable** including granodiorite, gneiss and massive marbles

Two types of wells are dominant, shallow and deep wells. The shallow wells are stone build dug wells from 2 to 6 meters deep, with diameters ranging between 1-2 meters. The average discharges of each shallow well is 20 m^3/hr. The deep wells with diameters 6 or 8 inches vary in depth between 10 and 200 meters. They are made of galvanized threaded steel pipes with bridge-slot screens. The average discharges of each deep well are 20 m^3/hr.

The pumping water of the wells is used only for the irrigation of the vineyards which is the only growing crop in Eleftheres basin. The total area for agricultural land is 15.433 km^2.

GEOCHEMICAL SURVEY

Measurements of Electric Conductivity (EC), Total Dissolved Solids (TDS) and Salinity (S) were taken in-situ from all the wells of the basin. Saline water intrusion front has affected the groundwater quality up to 1500 meters inland front me coastline (Figure 2).

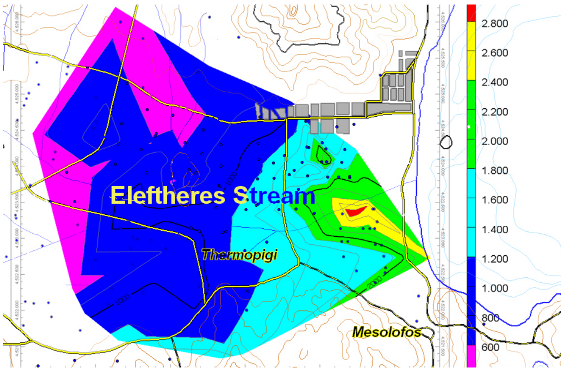

Figure 2: Saline water intrusion front in the basin.

Chemical analysis of water samples

Chemical analysis from 9 different locations was realized in order to study the quality of the underground water of Eleftheres basin. Three samples were taken (during the pumping season – June 2001) from wells located in the granite and 6 samples from wells in the sediments, 500 m inland from the coast. The samples were analyzed for: Ca, Mg, Na, K, NH_4, Cl, HCO_3, SO_4, NO_3, NO_2, F, B, Zn, Cu, Fe, and Mn. The results of the ions from the different samples were correlated using the following methods: Waterlot diagram, SAR diagram, B concentration, NaCl classification, Vertical bars diagram, Stiff diagram, Piper diagram, Durov diagram, Na/Cl ion ratio, Cl/SO_4 ion ratio, Ca/Mg ion ratio, Na/K ion ratio and Schoeller index.

GEOPHYSICAL SURVEYS

In order to acquire information from the subsurface layers, the following geophysical surveys have been carried out:

Geoelectrical survey

In this survey, the method of VES (Vertical Electrical Soundings) was used. Two separate geophysical crews, using special equipment have carried out 100 VES measurements, randomly spaced in all basin area. The depth of penetration of the method was kept greater than 150 m in each measurement, in other words greater than the depth of the granite basement. In all soundings the Schlumberger array of electrodes was used. For the synthetic interpretation of data, the non-linear least-square inversion algorithms Levenberg-Marquardt was used. One 3 dimensional model (3D) of subsurface layers was created using the results of one-dimensional models derived from the interpretation.

Electromagnetic survey (Very Low Frequency)

Additionally to the previous geophysical method, the Very Low Frequency electromagnetic method was used. This method is essential for localization of faults or fracture zones in rock formations.

The ABEM WADI electromagnetic instrument was used and 4 km of cross-sections have been realized with a measuring space of 10m.

Geophysical Well Logging survey

In order to achieve one additional quantitative interpretation of the subsurface layers characteristics, the geophysical well logging method has been applied in few abandoned wells in the area. Due to the fact that all abandoned wells were cased with well screens, only two probes have been applied:

1. The salinity log (SAL)
2. The natural gamma ray log (GR)

In the first case, one vertical profile of the conductivity variation was acquired up to the granite basement, in one cased well near to the sealing axis emplacement. In the second case the **shale content** of all layers up to the granite basement was measurement with high accuracy. Results of both geophysical runs are discussed below.

From the interpretation of gamma ray natural log records the **absence of shale layers** was noticed. Only one thin shale layer was found, near the granite basement. Most off the quaternary deposits are medium grained sands, therefore **permeability does not have significant variations from the surface to the bottom**. This fact has already been noticed from the interpretation of the conductivity-salinity log. Apart from a few centimeters from the water surface (40 cm), the rest of the water column in the wells has conductivity 2500 μS/cm rising to 3000 μS/cm at the bottom. The absence of shale layers must be considered as disadvantage for the sealing procedure.

Depth to the granite basement

Assuming that the granitic basement is impermeable is one inevitable condition for the purpose of this project. Under that assumption, the top of the granitic basement defines automatically the bottom of the aquifer. This assumption is certainly one approximation due to the fact that into the granitic basement, deep water circulations exist certainly into one deeper aquifer. The problem is that this aquifer cannot be modelled due to the fact that the water flows in very deep fractured zones. The localization of these zones is one very difficult task that is impossible to solve in the frame of this project.

It is noticed that the proposed assumption of an impermeable basement, covered with sediments is accurate enough for the purpose of CRYSTECHSALIN.

Due to this assumption, depth to the basement coincides with the bottom of the aquifer and varies from 0 to 90 m. Variations are smooth and match the low lands geomorphology. Near the coast line the basement acquires the highest depths (more than 80 m).

Between the UTM coordinates of

X_1 =271886 y_1= 4523976 (A) and
X_2 = 271958 y_2= 4523645 (B)

granite basement forms a ridge.

The depths to the basement along this axis (of a length of about 600 m) varies between 5 to 45 m.

Geological and geophysical results conclude that this axis can be used for the sealing process.

3D model of subsurface layers

During the second year of the project, works have been concentrated to the construction of one 3d model of subsurface layers derived from the geophysical data. For this reason, a total of 100 geophysical soundings (Schlumberger array of electrodes) have been interpreted using the Levenberg-Marquardt modeling algorithm. The stratigraphical model of layers derived from the interpretation is described below:

Layer1: Surface soil (sands + coarse gravels)
Layer2: Surface soil (shales)
Layer3: Coarse alluvium deposits, pebbles, coarse grained sands
Layer4: Fine alluvium deposits, fine grained sands
Layer5: Altered granodiorite
Layer6: Massif granodiorite

The above layers classification have been used to construct one numeric 3D model (50x50 nodes) of the subsurface layer's geometry. The numerical approach of the layers interfaces is essential for the hydraulic model in the basin.

LONG TERM MONITORING OF THE SALINE WATER INTRUSION

Water quality network

In order to monitor with accurate values the saline water intrusion of the Eleftheres basin, a Water Quality Network has been installed. For this purpose, 10 water points (deep or shallow wells) in critical locations of the basin have been selected. For all the above points, the following type of record is adopted:

- point coordinates (in GIS, UTM 35, North);
- point identification (Physical locations, and as-built descriptions of the wells monitored)
- depth to the Water Level;
- water Conductivity (in μS/cm);
- pH of water;
- salinity of water (ppm);
- Total Dissolved Solids (TDS);
- water Temperature.

The records are updated 3 months. Data collection has been started in June 2001.

Saline water intrusion monitoring system

During the second year of the project, GEOSERVICE's team, has realized one fully automatic electronic telemetry system for the long term monitoring of the saline water intrusion. This system will be installed in special monitoring wells and the measured parameters are:

1. aquifer piezometric level;
2. water conductivity and temperature;
3. rainfall;
4. atm pressure;
5. atm temperature.

The system uses submersible sensors and electronics to aquire data directly from the aquifer in three specific depths of the water column.In this way the vertical distribution and changes in the salinity will be recorded constantly for a long period of time, before and after the large scale test. All data are transmitted in regular time intervals to the main computer in Eleftheres city.

This computer server will be directly accessible (ON LINE) through Internet to all project partners. The latest software platform in data aquisition has been used for this purpose (SCADA systems).

RESULTS

Main results derived from the geophysical research

- Saline water intrusion has affected the groundwater quality up to 1500 meters inland from the coast line.
- The data were evaluated and indicated the existence of two aquifer systems: a phreatic aquifer, which exists due to the sedimentary deposits and a confined aquifer, which exists due to the fractured zones in the granodiorite bedrock.
- No faults or main fracture zones have been localized using the VLF electromagnetic method. This is an advantage for the sealing procedure.
- Although the two systems are separated with an impermeable zone of massive granodiorite rock, leakage between the aquifers may take place.
- Geometry of the granitic basement in the Eleftheres basin follows the topography of the basin. One favorable emplacement for the sealing axis has been selected between the coordinates: (X1,Y1) = (271.673, 4.524.303) and (X2,Y2) = (271.910, 4.523.601).

Main geochemical results

The results of chemical analysis have indicated that the water from the granite is different from the water coming out from the sedimentary deposits. The main conclusions for the water samples from sediments are:

- all wells are characterized by high concentrations of chlorine (Cl) and Sodium (Na);
- the very high values of SO_4 in one location denotes pollution;
- the very high values of nitrate (NO_3) and ammonium (NH_4) indicates the use of fertilizers and pesticides in the area;
- the predominance of Sodium (Na) with respect to Calcium (Ca) in certain areas denotes a low hydraulic conductivity of the aquifer system.

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La ricerca europea per la riduzione dell'inquinamento salino
delle acque sotterranee, Ed. M. Polemio & G. Gallicchio, 2002

ANALYSIS OF GROUTING PERFORMANCE

ANALISI DELL'EFFICIENZA DEL GROUTING

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Abstract. Seawater intrusion is an undesirable phenomenon that occurs in coastal aquifers. The extent of seawater intrusion can be controlled through pumping from the aquifer. The construction of a grouting wall parallel to the coast is a technique proposed to reduce seawater intrusion in conjunction with a proper aquifer management scheme. To facilitate the design of a grouting wall a model of seawater intrusion into coastal aquifers was constructed. To enable a solution of the mathematical model, a computer code was developed. As a first step in the model investigations, the effects of a wall on seawater intrusion in a synthetic aquifer were studied. The conclusion is that a grouting wall can control seawater Intrusion, but the effect in each case depends on the geometrical features of the wall.

Keywords: coastal aquifer, seawater intrusion, grouting wall, coupled flow and transport model, computer simulations.

Riassunto. *L'intrusione marina è un fenomeno indesiderato che si verifica negli acquiferi costieri. L'estensione dell'intrusione marina può essere controllata attraverso l'emungimento delle acque sotterranee. La costruzione di una barriera fisica o diaframma impermeabile, parallela alla costa, è una tecnica utilizzata per ridurre l'intrusione marina associata ad un idoneo schema di gestione dell'acquifero. Al fine di facilitare la progettazione di tale barriera, è stato realizzato un modello che descrive le modalità dell'intrusione marina nell'acquifero costiero. Al fine di ottenere la soluzione del modello matematico è stato sviluppato un programma opportuno. Come primo passo nella descrizione del modello è stato studiato l'effetto della barriera sull'intrusione marina per un acquifero schematico. Emerge così che il diaframma impermeabile può controllare l'intrusione marina, ma il risultato in ogni caso dipende dalle caratteristiche geometriche della barriera.*

Parole chiavi*: acquifero costiero, intrusione marina, barriera impermeabile, modelli di flusso e di trasporto, simulazioni numeriche.*

THE PROBLEM

One of the methods proposed for reducing the extent of seawater intrusion in coastal aquifers is the construction of an extended subsurface wall parallel to the coast. The wall may be impervious or semipervious. Grouting is a technique that can be used for creating such a wall..

The problem of in-situ grouting in aquifers is composed of two issues: 1) How to implement the in-situ grouting process, i.e., how to create a "wall " inside the aquifer, such the wall will have a desired size and hydraulic properties, and 2) How will a specific wall configuration affect the extent of seawater intrusion.

Accordingly, there is a need to design a grouting wall having a configuration (length, depth thickness etc.) and hydraulic properties (hydraulic conductivity and effective porosity) that will bests achieve the objectives of the grouting, i.e., the prevention of seawater intrusion.

In this paper, we attempt to evaluate the performance of the grouting, assuming that we have all the means to create a wall having desired geometrical configuration and hydraulic properties. By working under such ideal conditions, we shall be able to draw conclusions regarding the feasibility of the approach.

A useful tool, well suited for this kind of design, is a computational model that simulates groundwater flow and salt transport in the aquifer, taking into account the effects of density. Such a model should be capable of simulating processes of flow and salt transport occurring in seawater intrusion into coastal aquifers.

This phenomenon is characterized by coupled, density dependent groundwater flow and salt transport processes.

MATHEMATICAL FORMULATION

The mathematical formulation of this problem can be written as follows:

Three-Dimensional Flow Equation:

$$S_0 \frac{\partial \varphi_f}{\partial t} + \frac{\rho n \beta_c}{\rho_0} \frac{\partial c}{\partial t} =$$

$$\frac{\partial}{\partial x_i}\left[K_{ij} \left(\frac{\partial \varphi_f}{\partial x_j} + \beta_c c \frac{\partial z}{\partial x_j} \right) \right] +$$

$$\frac{1}{\rho_0} \sum_i \rho_i(t) I_i(t) \delta(x - x_i) -$$

$$\frac{1}{\rho_0} \sum_i \rho_i(t) P_i(t) \delta(x - x_i),$$

where:

t	Time
S_0	Aquifer's specific storativity
ρ	Water density
n	Aquifer porosity
β_c	Density coefficient due to salt concentration
ρ_0	Reference density (at zero salt concentration)
c	Salt concentration
φ_f	Reference freshwater head
K_{ij}	Tensor of hydraulic conductivity
I_i	Rate of water injection at well i at location x_i
P_i	Rate of water pumpage at well i at location x_i
$\delta(u)$	Dirac function $(= 0\ if\ u \neq 0, = 1\ otherwise)$
z	Vertical coordinate (positive upwards).
ρ_i	Density of the water injected or pumped at well i

The dependence of the water density on salt concentration is given by:

$$\rho(c) = \rho_0 (1 + \beta_c c).$$

The reference fresh water head is defined as: f

$$\varphi_f \equiv \frac{p}{\rho_0 g} + z,^{\cdot}$$

where, p denotes water pressure and g is the gravity acceleration.

Three-Dimensional Salt Transport Equation:

$$n\rho \frac{\partial c}{\partial t} + n\rho V_i \frac{\partial c}{\partial x_i} = \frac{\partial}{\partial x_i}\left[n\rho D_{ij} \frac{\partial c}{\partial x_j} \right] +$$

$$\sum_i \rho_i(t) I_i(t)(c_i - c)\delta(x - x_i),$$

where V_i is the ith component of the water velocity, given by:

$$V_i = -\frac{K_{ij}}{n}\left[\frac{\partial \varphi_f}{\partial x_j} + \beta_c c \frac{\partial z}{\partial x_j} \right].$$

This, the seawater intrusion problem is expressed as the solution of a set of two coupled, non-linear, partial differential equations, in whih the primary variables are the reference head, ,φ_f and the salt concentration, c. The two p.d.e.'s must be supplemented by appropriate initial and boundary conditions (Of the first, second or third type). Particular care must be devoted to boundary conditions along the interface between the aquifer and t the sea, where the conditions depend on the direction of the groundwater flow. The mathematical model was translated into a computer code written in the object oriented c++ language, and assembled into the **FEAS** (**F**inite **E**lement **A**quifer **S**imulation) platform. The construction of a model of this kind, particularly in three dimensions, is a tedious task. In order to facilitate the model construction, the **FEAS** platform has been adapted to a pre and post-processing software that allows us to perform all the operations associated with the model construction: mesh generation, definition of initial and boundary conditions, materials definitions and their spatial distribution, the geological structure of the model and the layer topography, assimilation of data etc..One of the major tasks of this project is the attempt to evaluate the performance of the grouting wall, once it has been constructed. By performance, we mean quantifying the impact of the grouting wall on the extent of seawater intrusion and on the shape of the seawater–freshwater interface zone. In other words, the objective of running computer simulations, using this model, are to understand and evaluate how the grouting wall can prevent or limit seawater intrusion.

TEST CASE

The grouting performance was first analyzed by using a model of a synthetic aquifer having regional size and properties. This simulated aquifer has the shape of a box of size 2km by 2km by 100 m. It was assumed to be composed of typical sandstone (having a horizontal hydraulic conductivity of 10 m/day, a vertical conductivity of 1 m/day, and an effective porosity of 0.20). The seawater is assumed to have a density of 1025 kg/m^3, meaning that the value of the β_c coefficient is 0.025. At the left boundary (opposite to the sea) a reference head of 4.0 m is imposed. On the right boundary (the sea) the reference head varies in the vertical direction, according to the salt concentration in the sea (the reference head varies from 2.5 m at the aquifer bottom to 0.0 m at the aquifer top). The aquifer is confined and no recharge takes place.

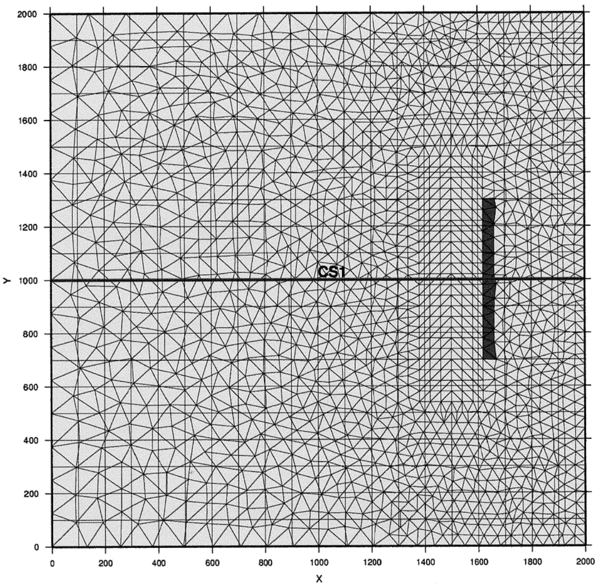

Figure 1: Plane view of computational mesh (1474 2D nodes, 2828 2D Elements), wall and cross-sections location.

An impermeable wall, produced by grouting, is parallel to the sea and has a length of 600 m. It is located 350 m from the sea (see Figure 1).

The hydraulic conductivity of the wall is 0.1 m/day, i.e., 1/100 of the horizontal hydraulic conductivity of the aquifer.

Five cases were considered (Figure 2):

1. No wall (case c1);
2. A wall with a height of 65 meters from the aquifer's bottom (case c2);
3. A wall with a height of 35 meters from the aquifer's bottom (case c3);
4. A wall with a height of 65 meters from the aquifer's top (case c4);
5. A fully penetrating continuous wall, which is an extension of the one shown in Figure 1.

In all cases the same initial and boundary conditions were applied. In each case, the model was run for 50 years.

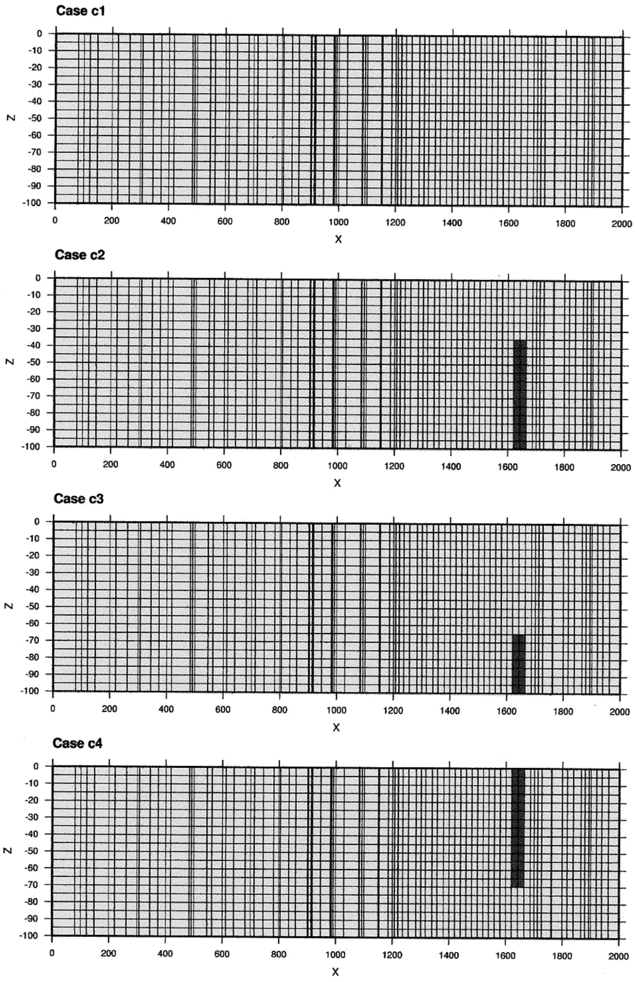

Figure 2: Model cross-sections for the wall configurations.

SIMULATION RESULTS

Results are presented through a cross-section passing through the wall. For each run the salt concentration, the reference groundwater head and the velocity field are plotted.

Case c1

This is the reference case for which there is no grouting wall. The simulation results for this case are presented in Figures 3. The extent of the seawater intrusion is 500 meters after 50 years. This compares well with the value of the seawater intrusion of approximately 550 meters that can be estimated using the Ghibben-Herzberg approximation.

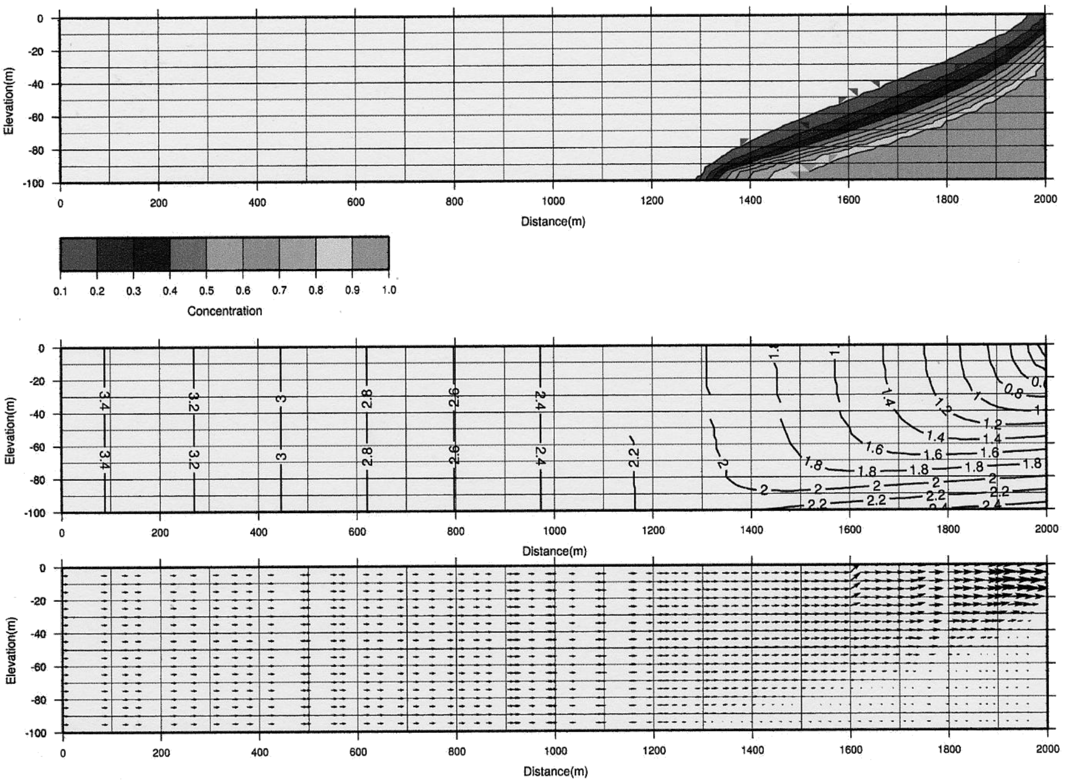

Figure 3: Salt concentration, reference head and flow field, Case c1.

Case c2

This case corresponds to the case of a grouting wall that occupies two thirds of the aquifer thickness from the bottom. We observe an accumulation of salt on the downstream side of the wall, meaning that the presence of a low conductivity wall reduces the intensity of the flow towards the sea. Results are illustrated in Figure 4.

Case c3

This case corresponds to a wall that is 35 meters high from the aquifer bottom. There is no notable difference in the horizontal extent of the seawater intrusion, as shown in Figure 5. However there is a clear difference in the vertical extent, as the height of the 0.1 concentration line is 10 meters lower in this case than in case c1.

Case c4

This case corresponds to a wall that penetrates two thirds of the aquifer from the top. Simulation results are presented in Figure 6. The results of this case are similar to those obtained in Case c2.

Case c5

This case corresponds to a wall that fully penetrates the aquifer from the top and extends over its entire length, parallel to the sea. Simulation results are presented in Figure 7. Here we observe that seawater intrusion is completely stopped on the upstream side of the wall

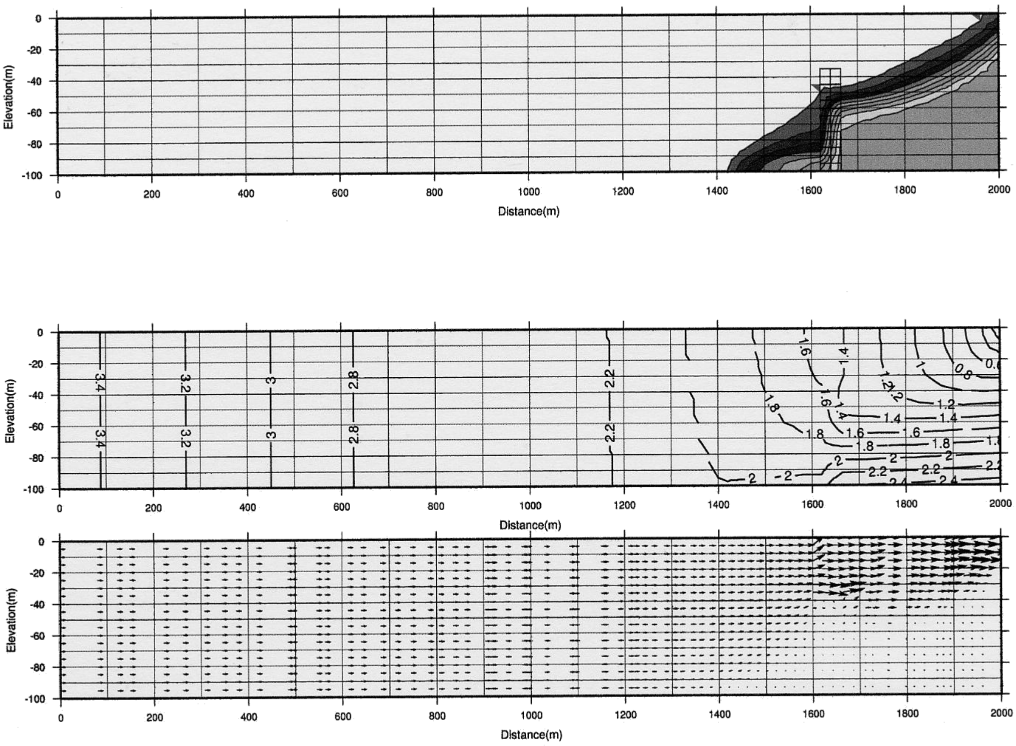

Figure 4: Salt concentration, reference head and flow field, Case c2

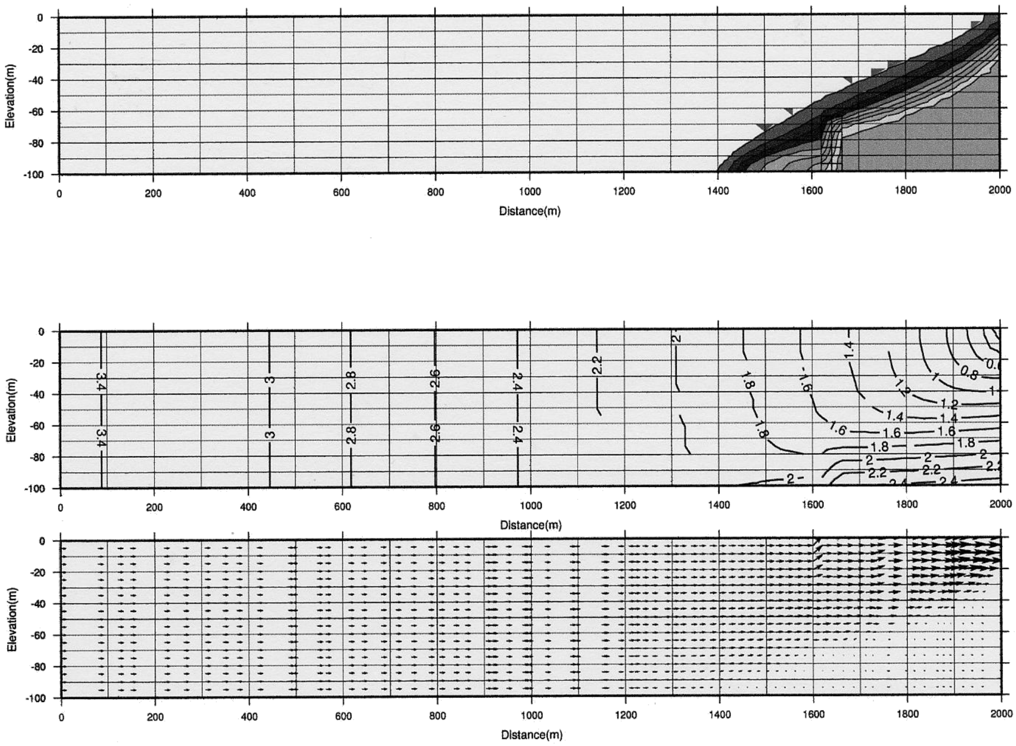

Figure 5: Salt concentration, reference head and flow field, Case c3.

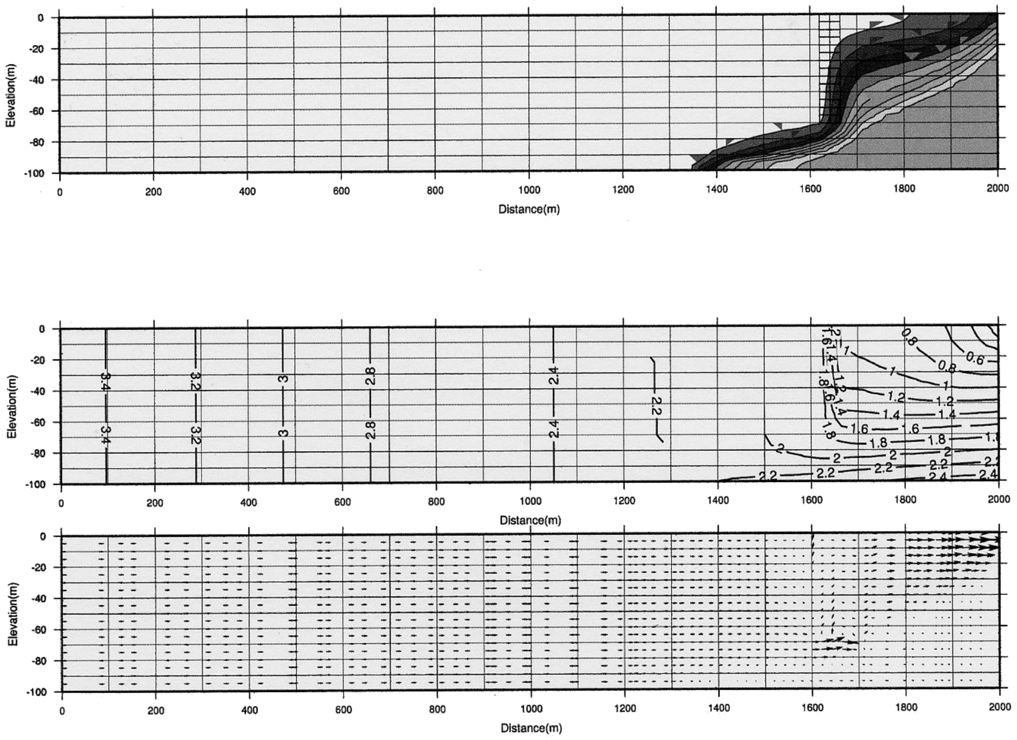

Figure 6: Salt concentration, reference head and flow field, Case c4.

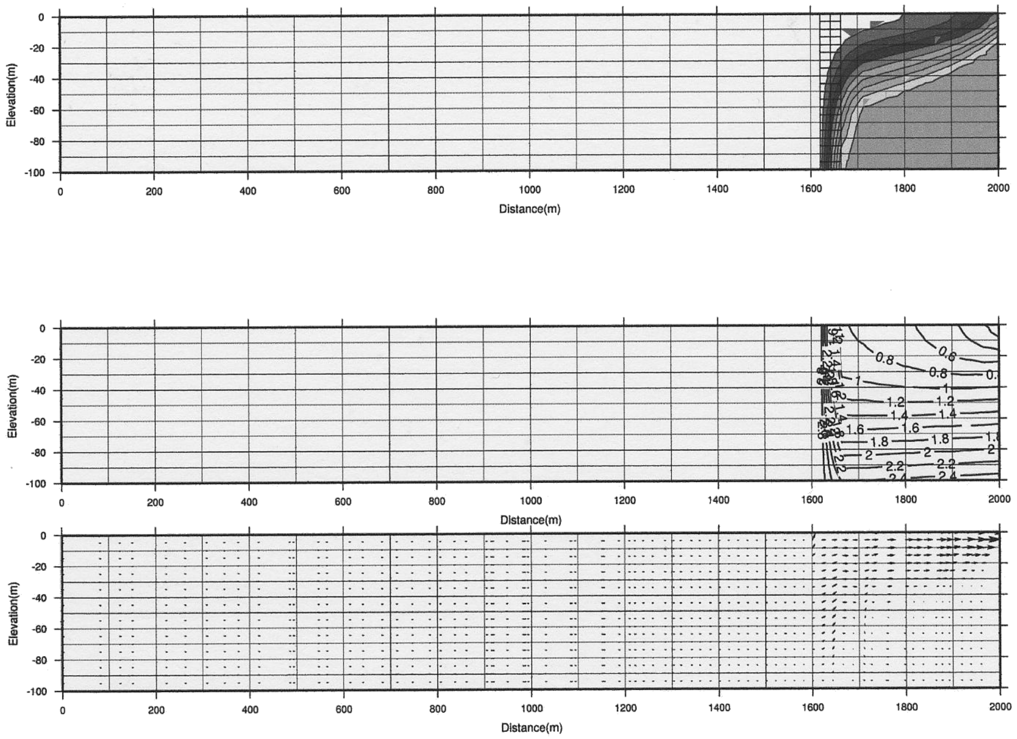

Figure 7: Salt concentration, reference head and flow field, Case c5.

CONCLUSIONS

The results obtained so far lead us to the following preliminary conclusions:

1. Under ideal conditions, it is possible to design a low permeability wall capable of controlling seawater intrusion process.
2. A partially penetrating wall, both in the horizontal and vertical directions can contribute to limiting the seawater intrusion process.

La ricerca europea per la riduzione dell'inquinamento salino
delle acque sotterranee, Ed. M. Polemio & G. Gallicchio, 2002

MICRO AND MACRO SCALE MATHEMATICAL FORMULATION OF GYPSUM CRYSTALLIZATION IN THE SEALING PROCESS OF THE CRYSTECHALIN PROJECT

MODELLAZIONE MATEMATICA DELLA CRISTALLIZZAZIONE DEL GESSO NEI PROCESSI DI IMPERMEABILIZZAZIONE NEL PROGETTO CRYSTECHSALIN

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Abstract. The mixture of an injected solution with the salt-water inside a porous media produces variety of reactions that can modify the water composition including crystallization and precipitation process. To describe the transport phenomena of this type of mixture, it is necessary to apply the mass conservation principle to each one of the chemical elements of the system. Although during the mixture reactive solutes are subject to a variety of processes such as convection, diffusion, precipitation and ion exchange the combined effects of all these processes on solute transport must satisfy the principle of conservation of mass. Therefore, in our case, the transport of species through the porous media can be described by a set of partial differential equations, which describe the conservation of the mass. Each of these equations needs to satisfy their corresponding boundary and initial conditions defined to each one of the species. In this work we present the mathematical formulation of such process, including the crystallization of gypsum, at the micros and macro scales of the porous media.

Keywords: mathematical formulation, crystal growth, cation exchange, porous media.

Riassunto. *La miscela di una soluzione iniettata ed acqua marina, all'interno di un mezzo poroso, determina una grande varietà di reazioni chimiche che possono modificare la composizione dell'acqua ed i processi di cristallizzazione e precipitazione presenti in essa. Al fine di descrivere i fenomeni di transporto all'interno di questa soluzione è necessario applicare il principio di conservazione di massa a ciascuno degli elementi chimici presi in considerazione nel sistema. Durante la loro miscelazione le sostanze reagenti sono soggette ad una varietà di processi (convezione, diffusione, precipitazione e scambio di ioni) che possono essere descritti attraverso una serie di equazioni differenziali e derivate parziali tali da soddisfare il suddetto principio. Ciascuna di queste equazioni deve, inoltre, rispettare le condizioni iniziali ed al contorno definite per ciascuna specie. Nel presente lavoro la modellazione matematica di tale processo viene introdotta includendo anche la cristallizzazione del gesso al livello dimensionale micro e macro del mezzo poroso.*

Parole chiavi: *modellazione matematica, crescita dei cristalli, scambio ionico, porosità media.*

INTRODUCTION

Saltwater intrusion can be defined as the migration of salt water into fresh water aquifers. Furthermore, the ground water system can be imagined as a conglomerate of soil and water. Basically, the subsoil consists of a porous matrix formed by sediment of different sizes. As a result, this porous media can be sealed to block seawater intrusion by inducing the formation of crystals inside the porous matrix, as showed in Figure 1, (Ziegenbalg and Crosby, 1997). The main objective of this chapter is to introduce the mathematical formulation of such crystallization process at the scale of the porous interstices (refereed here as the micro-scale) as well as the formulation of the problem at average scale of the porous media (refereed here as the macro-formulation).

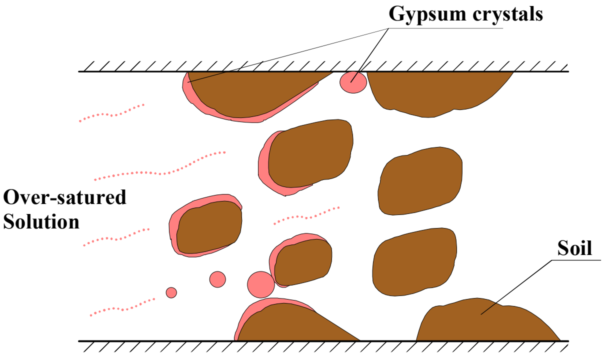

Figure 2: Definition diagram of the crystallization process.

In the present formulation, the creation of a crystal barrier in the subsoil will be induced by the injection of an over-saturated solution in gypsum. This solution mixes up with seawater and owing to the reaction of the sulphate ions with Ca^{++}, precipitation of gypsum can be observed.

The mixture of the solution with the salt-water produces variety of reactions that can modify the water composition. To describe the transport phenomena of this type of mixture, it is necessary to apply the mass conservation principle to each one of the chemical elements of the system. Although during the mixture reactive solutes are subject to a variety of processes such as convection, diffusion, precipitation and ion exchange the combined effects of all these processes on solute transport must satisfy the principle of conservation of mass (Appelo et. al., 1990). Therefore, in our case, the transport of species through the porous media can be described by a set of partial differential equations, which describe the conservation of the mass. Each of these equations needs to satisfy their corresponding boundary and initial conditions defined to each one of the species.

CHEMICAL RELATIONS BETWEEN ELEMENTAL CONCENTRATIONS AND CONCENTRATIONS OF THE DIFFERENT SPECIES

In the case of precipitation of gypsum due to the injection of an over-saturated solution, we will consider that the fluid phase can be identified by twenty species: Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, H^+, CO_3^{2-}, HCO_3^-, H_2CO_3, $NaSO_4^-$, KSO_4^-, $CaSO_4$, $MgSO_4$, $NaHCO_3$, $CaHCO_3^+$, $MgHCO_3^+$, $NaCO_3^-$, $CaCO_3$, and $MgCO_3$.

The above species can be grouped in the following seven elements Na, K, Ca, Mg, Cl, S and C, obtaining expression similar to:

$$Ca = Ca^{2+} + CaSO_4 + CaHCO_3^+ + CaCO_3$$

in which the stoichiometric coefficients in the chemical reaction of the twelve species are all identical to one.

In the solution the elements H and O have are not considered since the total concentration of hydrogen and oxygen greatly exceed all other elemental concentrations in the water of natural environments. We invoke electroneutrality to determine the hydrogen ion concentration in order to obtain the pH value

The chemical kinetic of such mixture is defined by 12 equations (Stumm, 1981), which correspond to the stability equilibrium of the ion considered. Owing to the effect of electrostatic shielding and the presence of aqueous complexes, the total molar concentrations of ions have to be corrected to the activities and consequently these equilibrium equations are given in terms of the activity of the species (see Appelo and Postma, 1996), as can be seen in eq(1) for the gypsum component of the solution.

$$\begin{gathered} Ca^{2+} + SO_4^{2-} \leftrightarrow CaSO_4^0 \\ K^1 = \frac{\left[CaSO_4^0\right]}{\left[Ca^{2+}\right]\cdot\left[SO_4^{2-}\right]} \end{gathered} \tag{1}$$

where [ ] means the activity of the specie.

To relate molar concentration to activities a correction term is used:

$$[i] = \gamma_i \cdot C_i \tag{2}$$

where $[i]$ is the activity of ion i, γ_i is the activity coefficient and C_i is the molality.

For dilute solution the activity coefficient becomes unity. Nevertheless, electrostatic interactions between the ions in solution increase as the concentration of ions increases; meanwhile, activity of ions becomes different than unit. Activities can be calculated using the extended electrostatical Debije-Hückel equation proposed by Davies (1962). Following such theory, first the ionic strength I have to be defined:

$$I = \frac{1}{2}\sum C_i z_i^2 \tag{4}$$

which takes into account the electrical charge that are present in the solution, and where z_i is the charge of ion i and C_i is the concentration in (mol/l).

Different equations have been proposed to derive activity coefficients from the ionic strength; for instance, if $I \approx 0.5$ the relation proposed by Davies could be applied:

$$\log\gamma_i = Az_i^2\left(\frac{\sqrt{I}}{1+\sqrt{I}} - 0.3I\right) \tag{5}$$

where A is a temperature dependent coefficient.

To find the hydrogen concentration the equation for the charge balance on the ionic species (electroneutrality) in the fluid can be used, (for more detail see Newman, 1991):

$$\sum^{J} z_j C_j = 0 \qquad (6)$$

where it is necessary to include the dissolution of water

$$H_2O \leftrightarrow H^+ + OH^- \quad K_w = [H^+]\cdot[OH^-] \qquad (7)$$

in order to obtain the correct value of the hydrogen concentration and consequently the pH. In this way knowing the total concentration of seven elements, we can obtain a non-linear algebraic system of equations of twenty equations to determine the concentration of each of the species at chemical equilibrium.

Besides, it is also necessary to consider that in soils and aquifer cation exchange occurs; that involves a replacement of one chemical for another one at the solid-liquid interface. Cation exchange acts as a temporary buffer in non-steady state situations, it tends to smoothen changes in water composition, and on the other hand can completely alter cation concentrations through a process known as ion-chromatography (see Robbins et. al., 1980). As cation exchange take place, 4 sorbed species (Na^+, K^+, Ca^{2+}, Mg^{2+}) will be considered.

Ion exchange can be described as a reaction with equilibrium constant. For the above four sorbed species, we can write three reaction equations similar to the following one:

$$\begin{gathered} Ca_{0.5-}X + Na^+ \leftrightarrow \frac{1}{2}Ca^{2+} + Na\_X \\ K_{e3} = \frac{[Ca_{0.5-}X]\cdot[Na^+]}{[Ca^{2+}]^{0.5}\cdot[Na\_X]} \end{gathered} \qquad (8)$$

where X indicates the soil exchanger.

Assuming that the system is in local equilibrium, it is no difficult to rewrite the cation exchange reaction equations in terms of the fractions of exchangeable cations βon the sediment and the activities of ions in the solution. In fact it is possible to express activities of exchangeable ions as equivalent fractions instead of molar fractions (for more details see Appelo and Postma, 1996). In this way the reaction coefficient in equation (8) can be rewritten as:

$$K_{e3} = \frac{[Ca^{2+}]^{0.5}[Na\_X]}{[Ca_{0.5-}X]\cdot[Na^+]} = \frac{\beta_{Na}[Ca^{2+}]^{0.5}}{\beta_{Ca}^{0.5}[Na^+]} \qquad (9)$$

where the equivalent fraction β_I for ion I^+ can be calculated as :

$$\begin{aligned} \beta_I &= \frac{\text{meq}\, I - X \text{ per 100g sediment}}{CEC} \\ &= \frac{\text{meq}_{I-X_i}}{\sum\limits_{I,J,K\ldots} \text{meq}_{I-X_i}} \end{aligned} \qquad (10)$$

here CEC is the cation exchange capacity of the sediment, which is often considered as a constant for a given sediment. The last equation that define the equilibrium of the four sorbed species at the soil-liquid interface is obtained by the condition of constant CEC, that is equivalent to:

$$\sum \beta = 1 \qquad (11)$$

In order to simplify the numerical solution of our model, only one mineral will be considered, i.e. gypsum. Using this assumption it is necessary to take into account in the formulation the following relation for the solubility product constrain of the mineral:

$$\begin{gathered} CaSO_4 \leftrightarrow Ca^{2+} + SO_4^{2-} \quad K_S = [Ca^{2+}]\cdot[SO_4^{2-}] \\ \text{if } \ C_{CaSO_4} \neq 0 \end{gathered} \qquad (12)$$

TRANSPORT PHENOMENA AT THE MICRO-SCALE

In the micro-scale process the analysis needs to be focused on the dissolved species. Basically, the mass conservation of each dissolved specie i is written as (see Bird et al., 1924):

$$\frac{\partial C_i}{\partial t} = D_i \frac{\partial^2 C_i}{\partial x_j^2} - u_j \frac{\partial C_i}{\partial x_j} + R_i \qquad (13)$$

here C_i is the aqueous phase concentration of species i, D_i is the diffusion coefficient of specie i, u_j is the flow velocity at the porous interstices, which is different to the average seepage velocity at the porous media (see Bear, 1988), and R_i is the production rate of flux of an ion (positive or negative) due to reactions in the solution, considered here as homogeneous reactions defined by the chemical kinetic of the process.

The R_i term can be written using the reaction rate constants of the forward and backward reactions (for more detail see Levenspiel, 1972). For instance, considering the bimolecular reaction:

$$A + B \overset{k_1}{\underset{k_{-1}}{\longleftrightarrow}} C \qquad K = \frac{k_{-1}}{k_1} \tag{14}$$

the homogeneous reaction term takes form:

$$R_i = \left(k_1 c_A c_B - k_{-1} c_c \right) \tag{15}$$

for all ions involved in the above reaction.

In this type of analysis it is assumed that the characteristic time scale of the transport process is significantly longer than the characteristic time scale of the chemical process and consequently the above reaction relation can be considered to happen instantaneously. The twelve chemical reactions relations, similar to equation (1), define the reaction coefficients in the mass conservation equation (13) for each of the species. In this way, the analysis of the transport of the different species is defined by a set of coupled differential equation (mass conservation for each species).

Although, in principle the set of governing equations appears to be linear, due to the non-dilute condition of the mixture the reaction terms are given in terms of the activity coefficient of the species involved in the chemical kinetic leading to non-linear complex relations. For the twenty species considered in this work, a set of nineteen partial differential equations of the following type are obtained:

$$\begin{aligned} \frac{\partial C_{Ca^{2+}}}{\partial t} = D \frac{\partial^2 C_{Ca^{2+}}}{\partial x_j^2} - u_j \frac{\partial C_{Ca^{2+}}}{\partial x_j} + \\ k_{-1}^{1} \left(\left[CaSO_4^0 \right] - \frac{1}{K^1} \left[SO_4^{2-} \right] \cdot \left[Ca^{2+} \right] \right) + \\ k_{-1}^{8} \left(\left[CaHCO_3^+ \right] - \frac{1}{K^8} \left[HCO_3^- \right] \cdot \left[Ca^{2+} \right] \right) + \\ k_{-1}^{11} \left(\left[CaCO_3^0 \right] - \frac{1}{K^{11}} \left[CO_3^{2-} \right] \cdot \left[Ca^{2+} \right] \right) \end{aligned} \tag{16}$$

where for simplicity we assumed that the diffusion coefficients D_j are equal for all species j.

The above mentioned transport partial differential equations for the species Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, CO_3^{2-}, HCO_3^-, H_2CO_3, $NaSO_4^-$, KSO_4^-, $CaSO_4$, $MgSO_4$, $NaHCO_3$, $CaHCO_3^+$, $MgHCO_3^+$, $NaCO_3^-$, $CaCO_3$, *and* $MgCO_3$ define a set of couple initial-boundary value problems.

To find the hydrogen concentration the equation of electroneutrality, eq. (6), is used, where the dissolution of water needs to be taken into account to obtain a correct value of the PH.

As cation exchange take place the four sorbed species (Na^+, K^+, Ca^{2+}, Mg^{2+}) develop a concentration jump across the soil liquid interface defined by the chemical relations of the type given by equations (9),(10) and (11).

According to the double diffusion boundary layer model (see Coulson et al., 1991), these differences in concentration induces a flux across the surface proportional to the such concentration difference between the surface and the surrounding medium. In this type of analysis it is considered that the difference in concentration between the bulk fluid and the external soil surface is confined to a thin layer of poor conductivity $K_A^{'}$.

Adsorbate is transferred to an adsorbent at a rate that depends upon the concentration difference across the boundary layer of thickness δ. The rate flow though it, per unit area per unit time, is

$$\frac{K_A^{'}}{\delta} (C_{A\_X} - C_A) \tag{17}$$

This is equivalent to the following boundary condition for the adsorbate specie at the fluid medium:

$$D \frac{\partial C_A}{\partial n} + \frac{K_A^{'}}{\delta} (C_A - C_{A\_X}) = 0 \tag{18}$$

In the above relation it is necessary to express the concentration at the soil, C_{A_X}, which is usually given in meq/g of sediment, in term of mol/l of pore water in order to be consistent with the equations in the solution.

For each of the sorbed species we have a boundary condition of the type given by equation (18), in which the concentration at the soil phase, C_{A_X}, is related in a nonlinear form with the concentration of the other sorbed species at the solution by the cation exchange equations, were it have been assumed that the adsorption takes place in perfect chemical equilibrium conditions. This implies that there is no resistance to the transfer of molecules of adsorbate from the bulk fluid to the adsorption size.

For all the other species in the solution, except for gypsum, we will prescribe zero flux at the soil-liquid interface.

The boundary condition for gypsum needs to be determined by the crystallization process as explained in the next section.

CRYSTALLISATION PROCESS

Homogeneous nucleation is the spontaneous nucleation of crystals in a solution. The nucleation occurs because the driving force for crystallization is greater than the increase in the interfacial energy caused by the formation of a three-dimensional nucleus in solution. Homogeneous nucleation does not require an existing surface to occur but results from the cluster of growth units (sometimes called embryos) growing to sufficient size that a critical nucleus is formed, which is stable and able to grow. From highly supersaturated solutions, homogeneous nucleation leads to spontaneous precipitation (see Mullin, 1997).

In contrast, heterogeneous nucleation requires a surface on which nucleation may occur. The term, "heterogeneous", is derived from the fact that the surface is of a different material from the crystallizing phase and is usually uncharacterized, e.g. dust particles within the solution or the material of the containing-vessel walls.

At sufficiently high supersaturation, homogeneous nucleation occurs. In some instances a precursor phase may form which subsequently recrystallises to a more stable crystalline form of the substance. At lower supersaturation, heterogeneous nucleation occurs accompanied by the slow loss of lattice ions from solution. Exactly how a stable crystal nucleus is formed within a homogeneous fluid is not known with any degree of certainty. A stable nucleus could hardly result from the simultaneous collision of the required number of molecules since this would constitute an extremely rare event. More likely, it could arise from a sequence of bimolecular additions.

The overall excess free energy between a small solid particle of solute and the solute in solution is equal to the sum of the surface excess free energy; the excess free energy between the surface of the particle and the bulk of the particle, and the volume excess free energy i.e. the excess free energy between a very large particle and the solute in solution. The surface energy is a positive quantity, the magnitude of which is proportional to r^2, been r the characteristic diameter of nucleus. In a supersaturated solution the volume energy is a negative quantity proportional to r^3. Thus the overall excess free energy posses a maximum value that correspond to a critical nucleus size $r_{c,}$ which dependent on the saturation state. As the saturation state increases the critical nucleus decreases (Mullin, 1997).

The behavior of a newly created crystalline lattice structure in a supersaturated solution depends on its size, it can either grow or redissolve, but the process that it undergoes should result in the decrease in free energy of the particle. The critical size r_c, therefore, represents the minimum size of a stable nucleus. Particles smaller than r_c will dissolve because only in this way can the particle achieve a reduction in its free energy. Similarly, particles larger than r_c will continue to grow.

For entirely diffusion-controlled or surface reactions controlled crystallization process, where the diffusion in the solid can be neglected due to the difference in magnitude between the liquid and solid diffusion coefficient, the molecular flux *J* (mol/s cm^2) at the crystal surface is related to the concentration gradient as (House, 1989):

$$J = -D\frac{\partial C_{CaSo_4^0}}{\partial n} \tag{19}$$

Besides from the solubility product equation of the mineral and the equilibrium constrain at the solution, it is possible to define the concentration of gypsum at the liquid-solid interface, corresponding to the equilibrium concentration of the mineral in the solution at the crystal interface.

From the equilibrium between gypsum and water the solubility product can be written as

$$K_S = \left[Ca^{2+}\right]\cdot\left[SO_4^{2-}\right] \tag{20}$$

or in term of the molal concentrations:

$$K_S = \gamma_{Ca^{2+}} C_{Ca^{2+}} \gamma_{SO_4^{2-}} C_{SO_4^{2-}} \tag{21}$$

Since equal amount of Ca^{2+} and SO_4^{2-} are released during gypsum dissolution, $C_{Ca^{2+}} \equiv C_{SO_4^{2-}}$ and since $\gamma_{Ca^{2+}} = \gamma_{SO_4^{2-}}$ the solubility of gypsum is simplified to

$$C_{ca^{2+}} = \frac{(K_S)^{1/2}}{\gamma_{ca^{2+}}} \tag{22}$$

where $\gamma_{Ca^{2+}}$ is obtained from the electrostatical theory as explained before.

The above concentration needs to be corrected by taking into account the aqueous complex *$CaSO_4$*. The stability constant of this complex can be rewritten as

$$\left[CaSO_4^0\right] = K^{11}\left[Ca^{2+}\right]\cdot\left[SO_4^{2-}\right] \tag{23}$$

Substituting in the previous equation the solubility product of gypsum, we obtain:

$$[CaSO_4^0] = K^{11} \cdot K_S \qquad (24)$$

Since the uncharged species the activity coefficient is one, this also the molal concentration of the complex. Thus the total solubility of gypsum is (see Appelo and Postman 1996):

$$C_{CaSo_4^0} = K^{11} \cdot K_S + \frac{(K_S)^{1/2}}{\gamma_{ca^{2+}}} \qquad (25)$$

The crystallization process cannot progress at those surface points of the solid-liquid interface in which the concentration is smaller than the above solubility value. Therefore at those points, the boundary condition for the aqueous complex *CaSO₄* is defined by a non-flux condition. On the other hand, points that reach this value of the concentration will remain at this value and the crystallization process progresses on such surface point.

In those points of the liquid-solid interface, $z=\xi(x,t)$, where the crystallization process takes place, the mass balance equation establishes that molar rate of diffusion into the crystal is proportional to the molecular flux. In this way, taking into account the molar volume, v, allows to define the crystal growth rate as:

$$V_n = vJ = -Dv\frac{\partial C_{CaSo_4^0}}{\partial n} \qquad (26)$$

where V_n is the normal growth velocity at the crystal surface and J denotes the diffusion flux. Therefore, we need to obtain from our set of transport equations the local flux of gypsum at the crystal surface in order to obtain the corresponding crystal growth rate.

EFFECTS OF INHIBITORS

The presence of impurities in a system can have a profound effect on the growth of a crystal. Some impurities can suppress growth entirely; some may enhance growth, while other may exert a highly selective effect, acting only on certain crystallographic faces and modifying the crystal habit. Some impurities can exert an influence at very low concentrations, less than 1 part per million, whereas others need to be present in fairly large amounts before having any effect. In some systems, there is a range of solution compositions, which are supersaturated but remain stable in composition over long periods. This can be achieved by adding to the oversaturated solution a precipitation inhibitor (House, 1989), which reduce the rate of growth of homogeneous nucleus inhibiting them to grow to their critical size and consequently inducing the dissolution of such initial crystals, as long as the effect of the inhibitor is present. On the other hand, lager crystals formed by heterogeneous nucleation around large impurities (as are the soil grain in our case) will continuously grows but at a slow rate. The important role played by inhibitors is clearly illustrated in the Figure 2.

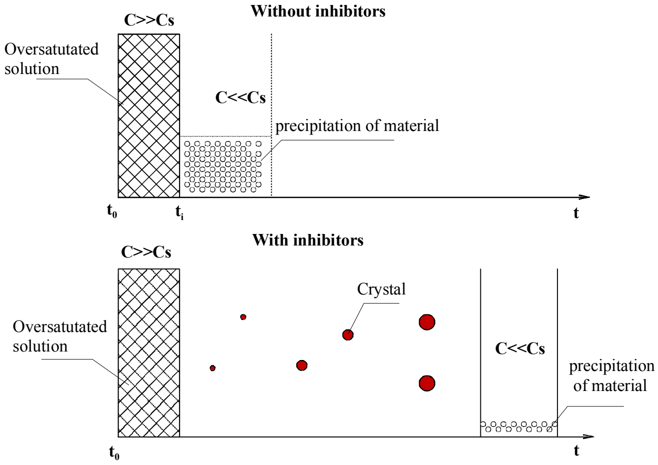

Figure 2: Schematic representation of the effect of the inhibitor in the crystallization process.

In the case of absence of inhibitors, owing to over-saturated solution, gypsum starts to precipitate as small particles instantaneously. Instead when inhibitors are added to the system, the growths of small homogeneous nucleus are suppressed allowing the slow growth of large heterogeneous nucleus.Any substance other than the material being crystallised can be considered an "impurity". Impurities can influence crystal growth rates in a variety of ways. They can alter the characteristic of the adsorption layer at the crystal-solution interface and influence the integration of growth units. They may be built into the crystal, especially if there is some degree of lattice similarity. Impurities are often adsorbed selectively on to different crystal faces and retard their growth rates. To effect retardation, it is not necessary for the impurity to achieve total face coverage.

In the literature it is generally assumed that the inhibition of growth occurs by the blocking of surface sites ("active growth sites") by adsorbed molecules or ions of the additive (Meyer, 1984). The adsorption may be described by the Langmuir-Volmer isotherm. This isotherm is given by the equation

$$\frac{\theta}{1-\theta} = K^{*}C_{inh} \tag{27}$$

where θ is the fraction of occupied adsorption sites (coverage) which may be, e.g. terrace, ledge, or kink sites, C_{inh} the concentration of additive in solution, and K^{*} a constant. With the further assumption that the relative decrease of the growth rate *$(v_0-v)/v$* or of the dosage rate *$(j_0-j)/j$* proportional to it is equal to the coverage θ the following equation is obtained:

$$\frac{J_0 - J}{J} = K^{*}C_{inh} \tag{28}$$

or

$$J = \frac{J_0}{(1+K^{*}C_{inh})} \tag{29}$$

The above Langmuir-Volmer correction needs to be taken into account in both the crystallization and dissolution rate. It is important to point out that according to the natural boundary conditions of the transport equation a modification on the flux at the solid-liquid interface will corresponds to a modified surface concentration, resulting from the solution of the new Neumann problem.

The reduction of the growth rate of the crystal obtained by substituting the above corrected diffusion flux into equation (26) persists for a finite time due to inhibitor adsorption. Although the problem is complex in nature, a general description of what is likely to occur at the inhibitors is useful. For the purpose of the present work, it is sufficient to give the above description of such phenomenon. Generally, the inhibition action of some compounds is through their presence in solution, thus, if the inhibitor concentration decreases such action come down. During crystal growth adsorption of chemicals by the new crystal occurs, therefore inhibitor concentration reduces in the course of crystallisation.

In fact, inhibitors allow crystal growth and scale deposition even thought block precipitation phenomena. Nevertheless, precipitation will occur in the subsoil due to gradual reduction of inhibiting effects.

Soils and aquifer contain abundant materials with are able to sorb chemicals from water. Adsorption indicates that a chemical adheres to the surfaces of the solid. In a dilute solution the adsorbed concentration can be related to the concentration in the solution by Henry's law for gases (see Appelo and Postma, 1996), In the case of the inhibitor this law implies

$$(C_{inh\_}X) = K_d C_{inh} \tag{30}$$

where K_d is the distribution coefficient and as before X indicates the soil concentration.

This above single linear relation cannot be expected to work correctly in all cases. The relationship between solute and sorbed concentration, at a constant temperature, is termed sorption isotherm. The linear adsorption isotherm stems from Henry's law. Other isotherm which are often used are:

Freundlich isotherm

$$(C_{inh\_}X) = K_F C_{inh}^{n} \tag{31}$$

and *Langmuir isotherm*

$$(C_{inh\_}X) = (C_{inh}^{\max}{}_{\_}X) K_L C_{inh} \big/ \left(1 + K_L C_{inh}\right) \tag{32}$$

As can be observed Langmuir formula has a maximum $(C_{inh}^{\max}{}_{\_}X)$. In this work to be consistent with our formulation of the rate of crystal growth, we will use Langmuir isotherm formula to relate the solute and the sorbed concentrations in the rate of adsorption of the inhibitor specie.

As in the case of cation exchange, the above adsorption relations represent a jump condition on the concentration of the inhibitor across the liquid solid interface, which implies a flux across the soil surface given by a radiation condition

$$D\frac{\partial C_{inh}}{\partial n} + \frac{K_{inh}}{\delta}(C_{inh} - C_{inh\_X}) = 0 \tag{33}$$

The above relation together with the appropriated adsorsion isotherm defines the boundary condition of the inhibitor at the soil liquid interface, in which the inhibitor is assumed to satisfy the following transport equation:

$$\frac{\partial C_{inh}}{\partial t} = D\frac{\partial^2 C_{inh}}{\partial x_j^2} - u_j \frac{\partial C_{inh}}{\partial x_j}$$

In this way the complete crystallization process is defined by a set of 20 partial differential equations in the solution, including the inhibitor, plus the condition of electroneutrality. This set of governing equations need to be solved simultaneously according with the corresponding boundary and initial conditions including cation exchange, adsorption and solubility, given before, at a moving interface, i.e. the growing crystal.

MACRO-SCALE FORMULATION

At the macro level where no boundary between the soil grain and the solution is considered, due to its average sense, it is possible to simplify substantially the mathematical formulation of the problem. In this approach we will use a set of partial differential equations based on the conservation of mass of each element instead of species as we did before. In such way the R_j term will be eliminate because of its definition. Indeed, considering elements instead of species, R_j is zero since the reaction terms are included in the invariant total mass of an element (Rubin, 1983).

Following our previous approach, at this scale we can also express a series of partial differential equations for the transport of the species similar to those given in section 3, were instead of having the diffusion coefficient and the flow velocity at the porous interstices, the equations will be defined in terms of dispersivity and the seepage velocity. However, as we are considering both the solution and the porous matrix as a single entity in the average sense, the effect of the cation exchange of the sorbed species (Na^+, K^+, Ca^{2+}, Mg^{2+}) needs to be considered all over the problem domain. These species at the solution (mobile participants) react with the solid associated species, *Na_X, K_X, Ca_X* and *Mg_X*, (immobile participants) according to the cation exchange equations. In this way four additional reaction terms, to those previously considered in section 3, need to be included in the transport equations of such species in the solution, for example in the case of the specie Ca^{2+}, we need to include the following reaction terms

$$\begin{aligned} &k_{-1}^{e2}\left(\left[Mg^{2+}\right]\cdot\left[Ca\_X\right]-\frac{1}{K_{e1}}\left[Mg\_X_2\right]\cdot\left[CA^{2+}\right]\right)\text{-}\\ &k_{-1}^{e3}\left(\left[Ca^{2+}\right]^{0.5}\cdot\left[Na\_X\right]-\frac{1}{K_{e3}}\left[Ca_{0.5}\_X\right]\cdot\left[Na^{+}\right]\right)\end{aligned} \qquad (34)$$

Simultaneously it is necessary to consider four new time evolution equations for the immobile species *Na_X, K_X, Ca_X* and *Mg_X* of the type:

$$\frac{\partial C_{Ca\_X_2}}{\partial t}=-k_{-1}^{e2}\left(\left[Mg^{2+}\right]\cdot\left[Ca\_X_2\right]-\frac{1}{K_{e1}}\left[Mg\_X_2\right]\cdot\left[Ca^{2+}\right]\right) \quad (35)$$

Grouping the governing partial differential equations of the seven different elements, as defined in section 3, in terms of the equations of the corresponding species, in which it is necessary to include the above reactions terms for the mobile participants of the cation exchange and the evolution equations for the immobile participants, we obtain a set of seven couple transport equations of the type:

$$\frac{\partial C_{Ca}}{\partial t}+\frac{3}{2}\frac{\partial C_{Ca-X_2}}{\partial t}-\frac{\partial C_{Cgypsum}}{\partial t}=D\ \frac{\partial^2 C_{Ca}}{\partial x_j^2}-u_j\ \frac{\partial C_{Ca}}{\partial x_j} \quad (36)$$

As expected the element equations are free from the reaction terms, which results from the requirement that a component (element) is reaction invariant. The above seven elements equations can be used to solve the problem in terms of the total concentration of the elements only in those cases in which the boundary conditions for each of the species contained in an element are of the same type.

In the above equations the concentration of the immobile participants needs to be given in mol/l of pore water in order to be consistent with the dimensions of the equations. The relation between the mobile and immobile sorbed species are given by the cation exchange equations, in which the concentration of the immobile participants are defined in terms of the fraction of exchangeable cations, $\beta_j, j=1,2,3,4$. When including the effect of the immobile participants Ca_X_2 and $Ca_{0.5}\_X$ into the element equation of *Ca*, we have taking into account that Ca_X_2 and $Ca_{0.5}\_X$ are two different conventional ways to represent the same structure of adsorbed ion-clay. It is assumed that their exchanger activities are identically and equal to equivalent fractions (for more details see Gomis et al., 1996).

It is important to point out that is necessary to include in the equations for the elements S and Ca (see for example equation (36)) an additional sink term corresponding to the losses in the solution of such elements due to the crystallization process, which is consistent with the mineral dissociation reaction relation given by equation (12).

As mentioned before, the existence of heterogeneous nucleation leads to a slowly loss of lattice ions from the solution. In these conditions, Nancollas and Reddy equation (see House, 1989) can be used to obtain the net rate of crystallization

$$\frac{d}{dt}\left(C_{Cgypsum}\right)=KA(1-SR) \qquad (37)$$

where *KA* is the rate of the reaction and *SR* the saturation ratio

$$SR = \frac{\left[Ca^{2+}\right]\left[SO_4^{2-}\right]}{K_S} \tag{38}$$

with $\left[Ca^{2+}\right]$ and $\left[SO_4^{2-}\right]$ the activity in the solution.

In similar way it is possible to obtain a transport equation for the inhibitor at the macro-scale including the retardation effect due to the adsorption process (see Bear, 1988), i.e.

$$\frac{\partial C_{inh}}{\partial t} + \frac{\partial C_{inh-X}}{\partial t} = D\frac{\partial^2 C_{inh}}{\partial x_j^2} - u_j\frac{\partial C_{inh}}{\partial x_j} \tag{39}$$

where the relation between the mobile, C_{inh}, and immobile, C_{inh-X}, inhibitor concentration is given by the adsorption isotherm defined in section 4.

In this way, we have a system of seven differential equations for the elements, with their corresponding initial and boundary conditions obtained from the initial and boundary conditions of the twenty species. These seven equations can be solved to find the elements at the bulk of the domain. Knowing the values of the elements in the domain, the concentration of the twenty species can be found by completing the system with the chemical kinetic relations defined in section 2, including electroneutrality to find the hydrogen concentration.

In this way, it is found a non-linear system of twenty-one equations for the variation of the concentration of the original species in the solution at each time interval. Besides, the time variation of the inhibitor concentration is found from the solution of equation (39).

The changes in the variation of the coefficient of permeability needs to be defined in terms of the reduction of the porosity due to the crystallization of Gypsum given by equation (37). It is important to point out that it is necessary to find how the crystal growth rate defined by equation (37) is affected by the present of the inhibitor according to the Langmuir-Volmer theory given in section 4. This last point is one of the major research objectives of the present research project.

Acknowledgments

Financial support from the European Commission, research project CRYSTECHSALIN, Grant No. EVK1-CT-2000-00055.

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La ricerca europea per la riduzione dell'inquinamento salino
delle acque sotterranee, Ed. M. Polemio & G. Gallicchio, 2002

CARATTERIZZAZIONE IDROGEOLOGICA DELLA PIANA DI METAPONTO, QUALITA' E RISCHI DI DEGRADO DELLE ACQUE SOTTERRANEE

HYDROGEOLOGICAL CHARACTERISATION OF THE METAPONTO PLAIN, QUALITY AND POLLUTION HAZARD OF GROUNDWATER

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Riassunto. La Piana di Metaponto si estende per circa 40 km lungo la costa ionica lucana, tra i fiumi Sinni e Bradano. L'assetto geologico e idrogeologico dell'area e i caratteri chimico-fisici delle acque sotterranee ivi circolanti sono stati dedotti dall'analisi dei dati censiti, rivenienti da 1130 pozzi. Diversi acquiferi, collegati tra loro, caratterizzano l'idrogeologia dell'area. Il flusso delle acque sotterranee è principalmente freatico nell'interno, dove affiorano i depositi marini terrazzati e i depositi alluvionali, ed essenzialmente confinato nella piana costiera alluvionale, a causa della presenza di uno strato argilloso, posto a tetto dell'acquifero costiero sabbioso, caratterizzato da una conducibilità idraulica media pari a 2,3 10^{-4} m/s. A fronte di una ricarica naturale bassa per infiltrazione, la ricarica dell'acquifero costiero è garantita prevalentemente dalle acque provenienti dagli acquiferi a monte che dalle perdite del reticolo fluviale. L'analisi dei dati chimico-fisici delle acque circolanti nell'acquifero costiero ha evidenziato che il fenomeno dell'intrusione marina sembra coinvolgere un tratto della piana costiera per una larghezza di 1÷1,5 km, area in cui il letto dell'acquifero costiero giace al di sotto del livello medio del mare. Infine, l'inquinamento caratterizzante le acque sotterranee è risultato essere un reale problema ambientale. Il degrado quantitativo e qualitativo costituiscono quindi un rischio concreto che minaccia le risorse idriche sotterranee della Piana di Metaponto.

Parole chiavi: risorse idriche sotterranee, intrusione marina, parametri idrogeologici, Italia meridionale.

***Abstract.** The study area falls within the Ionian coastal plain (Southern Italy), bounded on the West by the Sinni River and on the East by Bradano River. It covers 40 km along the coast and 6 km inland. The geological and hydrogeological features of the study area and the chemical-physical groundwater characterisation have been inferred from the data analysis of 1130 boreholes. Some aquifers, connected among them, constituted by soils of different geological origin, exist in the area also if the coastal plain aquifer is the most interesting for practical utilisation. Groundwater flow is mainly unconfined inland, where the aquifer is constituted by terraced deposits and confined in the alluvial coastal plain. An upper clayey layer overlies the sandy coastal aquifer characterised by a mean hydraulic conductivity value equal to 2.3* 10^{-4} *m/s. Being the direct natural recharge extremely low, the recharge of this coastal aquifer is mainly guaranteed by the discharge from upward aquifers and from the river leakage. The bottom of the aquifer is a silty-clayey bed which lies under the sea level permitting so the seawater intrusion. This phenomenon involves the studied coastal plain for a width of 1-1.5 km on average and it is less evident moving inwards where the altitude of the clayey bottom of the aquifer becomes progressively higher than the sea level. Other chemical-physical data, studied to determine the quality of the waters, showed that the pollution of the groundwater is considered a grave environmental problem for the studied area.*

Keywords: groundwater resources, seawater intrusion, hydrogeological parameters, Suothern Italy

INTRODUZIONE

Da alcuni anni la Sezione di Bari del CNR-IRPI è impegnata in ricerche a carattere idrogeologico nell'area metapontina (Polemio & Ricchetti, 1991).

Di recente l'attenzione è stata rivolta alle risorse idriche sotterranee dell'intera Piana di Metaponto grazie ad un recente progetto di ricerca, dal titolo "*Crystallisation technologies for prevention of salt water intrusion*", finanziato dall'Unione Europea (V Programma Quadro, 1998-2002). In particolare, il suddetto progetto prevede la realizzazione di barriere fisiche per contrastare l'intrusione marina, attraverso la riduzione della permeabilità degli acquiferi mediante la cristallizzazione controllata di sostanze naturali. L'intrusione marina costituisce un fenomeno particolarmente dannoso in ampie porzioni delle pianure costiere dell'Italia meridionale, dove, nel tempo, si sono concentrate le popolazioni nonché le attività agricole e industriali più pregiate, tutte utenze che richiedono acqua di buona qualità. Tale fenomeno di degrado qualitativo delle acque è particolarmente temibile in quanto spesso si manifesta con un lento ma progressivo deterioramento, difficilmente apprezzabile per l'uomo comune in quanto le sue conseguenze si evidenziano solo nel corso di alcuni decenni (Polemio & Limoni, 2001).

La caratterizzazione geologica e idrogeologica degli acquiferi presenti nell'area metapontina e quella chimico-fisica delle acque sotterranee ivi circolanti, unitamente all'individuazione degli effetti delle modificazioni naturali e antropici del ciclo idrologico sulla disponibilità delle risorse idriche sotterranee sono state perseguite, in tale contesto, al fine di effettuare la scelta ottimale del sito sperimentale previsto in Italia, appunto nella Piana di Metaponto, nonché la dettagliata valutazione degli effetti dell'intervento sperimentale previsto, mediante modelli di calcolo numerici.

Il presente articolo riporta sinteticamente le conoscenze emerse fino ad oggi, sia sulla base degli studi pregressi che alla luce di nuovi approfondimenti, maturati con un approccio interdisciplinare in merito ai caratteri idrogeologici degli acquiferi costituenti la Piana di Metaponto nonché alla qualità e ai rischi di degrado delle relative risorse idriche sotterranee (Polemio et al., 2002a; 2002b; 2002c; Polemio e Dragone, 2002).

L'area di studio corrisponde alla piana costiera che si estende dalla foce del fiume Sinni a quella del Bradano (Figura 1). Durante il ventesimo secolo, i lavori di bonifica, la costruzione di oltre una decina di dighe o traverse nelle porzioni poste a monte dei bacini idrografici che attraversano la Piana nonché l'introduzione di reti irrigue servite da acque addotte dagli invasi, hanno modificato profondamente il ciclo dell'acqua lungo la pianura costiera. L'area, già notevolmente antropizzata, è soggetta ad una crescente espansione turistica e ad un potenziamento delle pratiche zootecniche e agricole di pregio. La crescita socio-economica di un'area è funzione anche della disponibilità di acque di buona qualità, la quale diminuisce nei periodi di siccità. Allo stesso tempo lo sviluppo economico, non opportunamente pianificato o gestito, crea condizioni potenzialmente rischiose per la salvaguardia delle risorse idriche, con particolare riferimento a quelle sotterranee.

L'assetto geologico ed idrogeologico dell'area in esame e le caratteristiche chimico-fisiche e qualitative delle acque sotterranee ivi circolanti sono state studiate sulla base di conoscenze pregresse e alla luce di nuovi dati desunti da accurati rilievi e indagini in sito svolte in occasione del progetto, in precedenza citato.

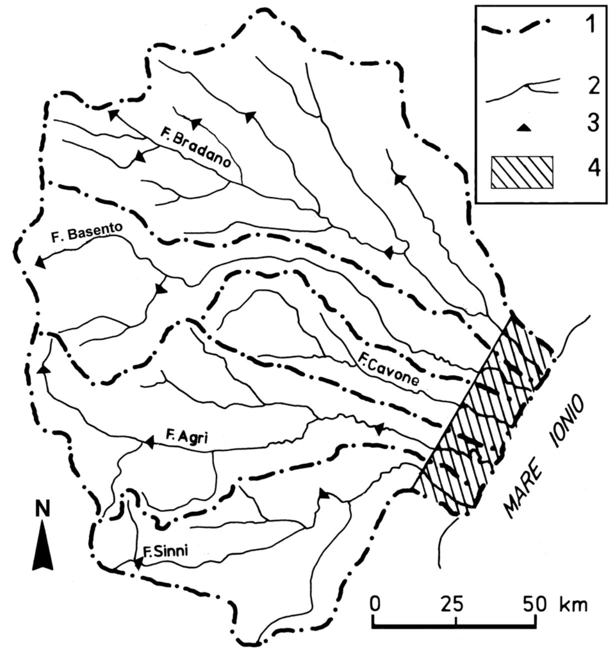

Figura 1: Area di studio, bacini imbriferi e opere di invaso e derivazione: 1) limite di bacino imbrifero, 2) reticolo idrografico, 3) diga o traversa, 4) area di studio.

A tale fine, sono stati esaminati i dati provenienti da 1130 perforazioni, eseguite da diverse istituzioni pubbliche (Ente per lo Sviluppo dell'Irrigazione e la Trasformazione Fondiaria in Puglia e Lucania, Regione Basilicata, Provincia di Matera, Ministero dei LL. PP., Ministero dell'Ambiente, Comune di Policoro, ANAS e Ferrovie dello Stato), realizzati principalmente per approvvigionamento idrico e secondariamente a fini geognostici. Dopo una complessa lavorazione di validazione e un'attenta analisi dei molteplici dati raccolti, si è provveduto a georeferenziare i diversi pozzi censiti e a creare data base relazionali, contenenti le diverse informazioni acquisite. In sintesi, le informazioni stratigrafiche ed idrogeologiche hanno riguardato il 71,9 % dei pozzi censiti, mentre i dati chimico-fisici e geotecnici sono stati disponibili rispettivamente per il 13,9 % e per il 5,4 % dei pozzi.

L'analisi dei diversi dati raccolti ha permesso sia di ricostruire l'assetto litologico e idrogeologico dei diversi acquiferi presenti nell'area di studio che definire i caratteri chimico-fisiche delle acque ivi circolanti. In particolare l'esame della distribuzione degli ioni principali dissolti nelle acque sotterranee ha permesso di definire i caratteri chimici principali delle stesse acque. Altresì, sono stati definiti gli andamenti areali della salinità, della conducibilità elettrica, del pH e della temperatura delle acque sotterranee circolanti nei diversi acquiferi. Inoltre, sono state analizzate le relazioni esistenti tra precipitazioni meteoriche, temperature atmosferiche, deflussi fluviali, prelievi dai principali invasi lucani e quote piezometriche, attraverso elaborazioni statistiche dei diversi dati su un intervallo ampio diversi decenni dell'intero ventesimo secolo. Si è operato ad una scala "regionale", considerando anche gli effetti derivanti dalla costruzione di numerose dighe e traverse, avvenuta fra gli anni '60 e '80, all'interno dei bacini idrografici sottesi dai fiumi che solcano la piana (Figura. 1).

Infine, nel corso dell'attività di ricerca in esame, l'attenzione è stata principalmente focalizzata sull'acquifero superficiale esistente nella piana costiera, intensamente sfruttato, come già evidenziato da Radina (1956). L'assetto litologico di questo acquifero, la sua posizione rispetto al livello mare, il suo spessore e quello della zona non satura, l'andamento della superficie piezometrica, la variabilità nello spazio della sua conducibilità idraulica, i caratteri fisico-chimici sono stati quindi attentamente studiati.

Sulla base delle analisi svolte, l'acquifero costiero è risultato soggetto al fenomeno dell'intrusione marina ed al rischio di degradazione qualitativa per effetto delle attività antropiche presenti sul territorio (Polemio et al., 2002a; 2002b; 2002c). La contaminazione chimico-fisico-batteriologica delle sue acque sotterranee, legata agli eccessivi emungimenti, alle pratiche agricole, zootecniche e al non sempre corretto smaltimento delle acque reflue e dei rifiuti, costituisce già, per quanto emerso, un serio problema ambientale. Inoltre, a causa della recente siccità e dell'aumento delle attività agricole, il rischio di intrusione marina nell'acquifero del litorale metapontino costituisce un concreto problema per lo sviluppo sociale ed economico di questa zona.

INQUADRAMENTO GEOLOGICO

L'area di studio ricade nella porzione meridionale della Fossa Bradanica, lo stretto bacino di sedimentazione plio-pleistocenico, compreso tra il margine esterno della catena appenninica meridionale e l'avampaese apulo, allungato in direzione NO-SE (lungo 200 km; e ampio da 15-20 fino a 50-60 km), colmato da una potente successione sedimentaria del Pliocene-Pleistocene, spessa fino a 2-3 km. La porzione superiore di questa successione (Pliocene superiore ?-Pleistocene superiore), caratterizzata da uno spiccato trend regressivo, affiora estesamente a causa dell'intenso sollevamento neotettonico che ha coinvolto l'avampaese pugliese e la Fossa Bradanica, a partire dal Pleistocene inferiore-medio, indotto da una resistenza alla subduzione della spessa litosfera continentale pugliese (100-110 km; Doglioni et al., 1996). Il suddetto sollevamento neotettonico ha coinvolto quindi prima i settori settentrionali e successivamente quelli meridionali della fossa, inoltre, esso è stato maggiore lungo i settori occidentali rispetto a quelli orientali della fossa, determinando un conseguente basculamento regionale della successione plio-pleistocenica verso il Mar Adriatico (Ciaranfi et al., 1983; Tropeano et al., 2001; 2002).

A questo progressivo sollevamento si sono sovrapposte oscillazioni del livello marino di tipo glacioeustatico che hanno interferito e complicato il meccanismo di regressione. Infatti sia pure con modalità intermittenti e con periodiche inversioni di tendenza, durante il Pleistocene il mare è regredito fino a quote di 100 m sotto il livello marino attuale (Cotecchia & Magri, 1967; Cotecchia et. al., 1971), quota raggiunta durante l'acme della glaciazione würmiana alla fine del Tirreniano (circa 15.000 anni B.P.), per poi risalire progressivamente all'attuale livello medio del mare in seguito alla deglaciazione post-würmiana. In particolare, tra i fiumi Basento e Bradano, l'ubicazione dell'antica Metaponto indicherebbe che 2500-3000 anni B.P. la linea di costa correva sicuramente ad una distanza inferiore a 2 km da quella attuale (Cotecchia et al., 1971). Inoltre, l'allineamento delle torri marittime quadrangolari, costruite nella seconda metà del XVI secolo, mostrerebbe come 400 anni fa la linea di costa non avesse ancora raggiunto quella attuale. Variazioni della linea di costa, connesse a fattori naturali e antropici, sono avvenute anche in tempi recenti: graduali accrescimenti e progressive riduzioni sono stati stimati rispettivamente in corrispondenza della foce del fiume Cavone e lungo i tratti costieri comprendenti le foci degli altri fiumi lucani (Guerricchio e Melidoro, 198; Spilotro et al., 1998).

La porzione superiore della successione sedimentaria della Fossa Bradanica, con carattere regressivo e spessori massimi intorno a 600 m (Pieri et al., 1996; Tropeano et al., 2002) è costituita dalle emipelagiti argilloso-limose delle Argille subappennine (tardo Pliocene- Pleistocene medio), passanti verso l'alto ai depositi regressivi costieri del Pleistocene inferiore-medio (Sabbie di Monte Marano e Conglomerato di Irsina) e a quelli del Pleistocene medio-superiore (Depositi Marini Terrazzati).

In particolare, nell'area di studio affiorano estesamente le Argille subappennine, i sovrastanti Depositi Marini Terrazzati, i depositi alluvionali e costieri (Figura 2).

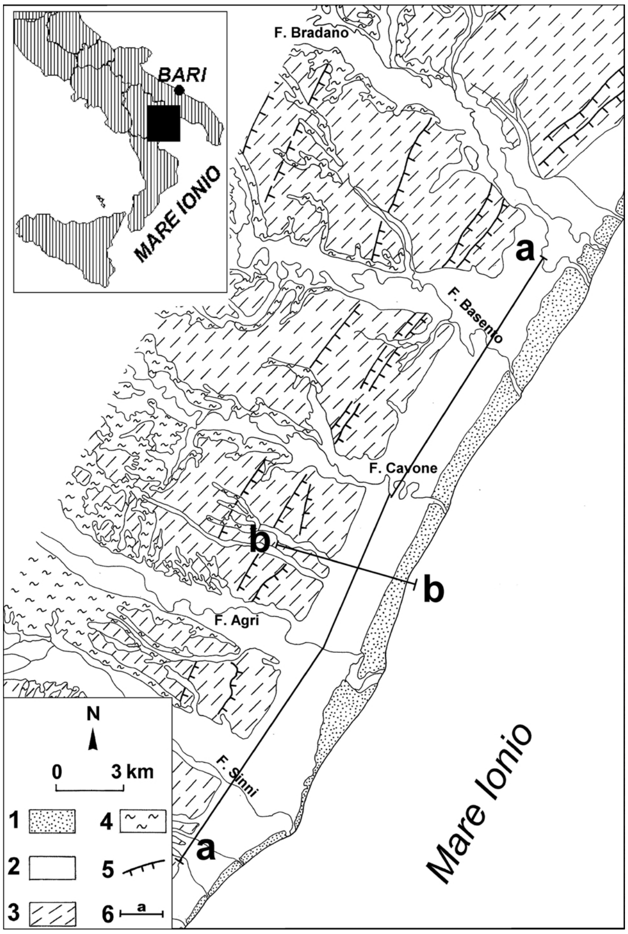

Figura 2: Carta geologica schematica: 1) dune e spiaggia; 2) depositi alluvionali marini e di transizione; 3) depositi marini terrazzati; 4) Argille subappennine; 5) scarpata dei terrazzi marini; 6) traccia di sezione.

Le Argille subappennine sono rappresentate da argille e argille marnose di colore grigio e giallastro, quando sono alterate, passanti verso l'alto ad argille limose e/o sabbiose. A diverse altezze dal piano campagna, sono presenti livelli e lenti sabbioso-limosi, maggiormente frequenti nelle porzioni superiori della successione, e livelli vulcanoclastici di diversa età (Montalbano Ionico: 1.07 Ma-780ka; Pisticci 0.98±0.15 Ma; Capaldi et al., 1979; Ciaranfi et al., 1996). Questa formazione affiora nei settori occidentali dell'area di studio con assetti suborizzontali o debolmente immergenti verso Sud-Est (Figura 2).

I Depositi marini terrazzati affiorano dalle quote di circa 350-400 m fino a circa 12 m s.l.m. (Figura 2). Essi sono costituiti essenzialmente da tre unità litologiche (Bozzano et al., 1991; Bozzano & Scarascia Mugnozza, 1994), variamente combinate nelle successioni verticali e con frequenti passaggi laterali. Esse sono rappresentate da un'unità sabbiosa (sabbie da medie a grossolane, con sottili intervalli limosi, arenacei e ghiaiosi), da un'unità conglomeratica (ghiaia immersa in una matrice sabbioso-limosa, localmente cementata) e, infine, da un'unità sabbioso-ghiaiosa con caratteristiche litologiche intermedie tra le prime due. Sulla base delle caratteristiche morfologiche delle aree di affioramento dei depositi marini terrazzati, sono stati riconosciuti otto ordini di terrazzi (Brückner, 1980; Ciaranfi et al., 1988), con estensione areale diversa ed età variabile da 650.000 anni (VIII ordine) a 80.000 (I ordine). I massimi spessori di affioramento dei terrazzi marini sono stati rilevati nel bacino idrografico del fiume Bradano (circa 30 m) mentre quelli minimi in quello del fiume Sinni (Bozzano & Scarascia Mugnozza, 1994). Le loro superfici sommitali tabulari mostrano una debole inclinazione sia verso NE che verso SE, connessa sia alla genesi di questi depositi che al sollevamento neotettonico differenziale. Infine, la progressiva diminuzione altimetrica osservata per ciascun ordine di terrazzo dall'area del fiume Sinni a quella del Bradano (Bozzano & Scarascia Mugnozza, 1994) evidenzia un basculamento più pronunciato per gli ordini più antichi rispetto a quelli più recenti con differenze di quote comprese tra 150 m (V ordine) e 25 m (I ordine). I depositi alluvionali e costieri affiorano lungo le valli fluviali e nella piana costiera ionica (Figura 2). Nello specifico, i deposti alluvionali terrazzati olocenici, posti a quote variabili tra 300-100 m s.l.m., sono costituiti da ghiaie con lenti sabbioso-limose, quelli recenti sono rappresentati da depositi argilloso-sabbioso-ghiaiosi e quelli attuali da depositi ciottoloso-sabbiosi. Altresì, nella piana costiera i depositi alluvionali recenti si confondono con quelli di origine mista e lagunari, costituiti da sabbie, ghiaie e limi in lenti e livelli, variamente distribuiti nello spazio il cui assetto litostratigrafico è connesso sia all'evoluzione tettonica e alle variazioni glacioeustatiche avvenute nell'area a partire dal Tirreniano che all'evoluzione costiera recente (regime idraulico dei fiumi, apporti solidi, azioni antropiche ecc.).

Infine, i depositi di spiaggia e le dune costiere affiorano lungo la fascia costiera, pressoché continua e larga in media un chilometro (Figura 2). Le dune costiere, costituite da sabbie ocracee poco cementate, sono allineate parallelamente alla costa con altezze di 12-16 m. Le spiagge, ampie da 10 m fino a 100 m, sono essenzialmente sabbiose, con dimensione dei granuli tra 500-300 micron, e progressivamente diventano sabbioso-ghiaiose o sabbiose con lenti di ghiaia procedendo verso il fiume Sinni (Cocco et al., 1975).

ASSETTO LITOLOGICO DELL'AREA DI STUDIO

La ricostruzione litologica dell'area di studio è stata desunta dall'analisi dei dati stratigrafici relativi essenzialmente ai sondaggi eseguiti dall'Ente per lo Sviluppo dell'Irrigazione in Puglia Basilicata ed Irpinia nel periodo 1952÷1956, essendo questi in maggior numero e meglio distribuiti su tutta l'area; ulteriori dati, in particolare stratigrafici e geotecnici, sono stati acquisiti grazie al Comune di Policoro, all'ANAS, alle Ferrovie dello Stato, alla MARINAGRI S.p.A. e alla SO.RI.M. S.p.A. La profondità delle perforazioni censite è in media circa 30 m, raramente si raggiungono gli 80 m di profondità. Alla luce dei dati esaminati, nelle aree di affioramento dei Depositi marini terrazzati, al di sotto del terreno agrario, sono state distinte tre principali unità litologiche: un'unità superiore, ghiaiosa, un'unità intermedia, sabbiosa, ed un'unità inferiore, argillosa (Figura 3).

L'unità superiore, spessa da qualche centimetro a 10 m, è costituita da ghiaia, localmente cementata o dispersa in matrice sabbiosa. L'unità intermedia, spessa al massimo circa 40 m, è composta da sabbia, da fine a media, grigia o giallastra, con livelli o strati argillosi o limoso-argillosi di diverso spessore e lenti di ghiaia. Infine, l'ultima unità è rappresentata da una successione argillosa e argilloso-limosa. Nella piana costiera, al di sotto del terreno agrario (spesso da 1 a 4 m), sono state individuate quattro principali unità litologiche: una argillosa superiore, una sabbiosa intermedia, una argillosa inferiore ed una limoso-sabbiosa inferiore (Figura 3).

L'unità argillosa superiore, costituita da argilla e argilla limosa grigia o gialla, è presente, con andamenti discontinui; in particolare nel settore costiero compreso tra il fiume Cavone e il fiume Sinni, essa raggiunge lo spessore massimo di 10 m. Sottostante al terreno agrario o alla precedente unità argillosa, è presente l'unità sabbiosa intermedia. Essa si rinviene fino a profondità di 45-50 m dal p.c., con spessori medi intorno a 35 m. Il letto di tale unità raggiunge il livello del mare in prossimità della costa nei pressi del fiume Sinni e lontano da essa nell'area dei fiumi Basento e Bradano. E' composta da sabbia, da fine a grossolana, localmente ghiaiosa, con diversi livelli o lenti argillose e limoso-argillose di spessore variabile da alcuni centimetri fino a circa 10 m. L'unità argillosa inferiore è rappresentata da argilla o argilla limosa grigia; nelle sue porzioni superiori sono presenti talora lenti ghiaiose, spesse meno di 6 m e a luoghi cementate.

I sondaggi analizzati terminano generalmente all'interno o a letto di quest'unità, per cui la stima del suo spessore è orientativa e approssimata per difetto. La potenza sembra variare da alcuni metri fino a circa 30 m; i valori massimi sono stati riscontrati nella zona dei fiumi Basento e Bradano. L'unità limoso-sabbiosa inferiore, raggiunta solo in alcune perforazioni, è costituita da limo, localmente argilloso con intervalli sabbiosi.

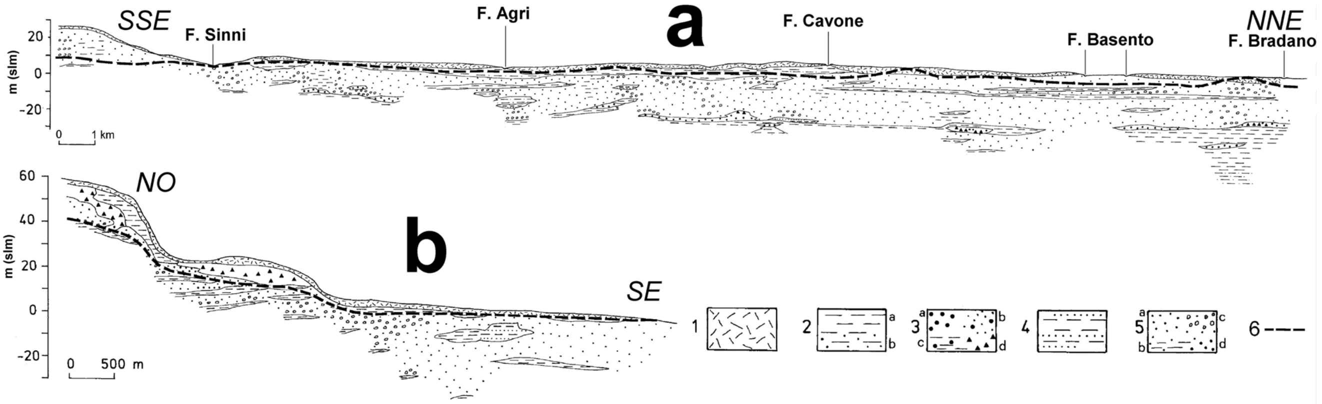

Figura 3: Sezione litologica schematica: 1) suolo; 2) argille o argille limose (a) e localmente argille sabbiose (b); 3) ciottoli (a) in una matrice sabbiosa (b) o argillosa (c) oppure localmente cementati (d); 4) sabbie con livelli argillosi; 5) sabbie o sabbie limose (a), localmente sabbie argillose (b) o con ghiaie (c), localmente arenarie (d); 6) superficie piezometrica (m s.l.m.).

CARATTERI CLIMATICI ED IDROLOGICI

Per delineare le caratteristiche climatiche ed idrologiche dell'area sono stati raccolti i dati mensili pluviometrici, termometrici e idrometrici pubblicati dal Servizio Idrografico e Mareografico Nazionale (SIMN, 1923-2000).

Le stazioni termopluviometriche considerate sono Metaponto, Nova Siri Scalo, Poliporo e S. Basilio, quest'ultima solo pluviometrica.

Il regime pluviometrico è di tipo marittimo, con minimo tra luglio ed agosto e massimo tra ottobre e dicembre (Figura 4). La piovosità media annua è compresa tra 536 e 586 mm, in ogni caso quindi molto bassa. La piovosità annua minima registrata è relativa alla stazione di Metaponto pari a 236 mm, verificatasi nel 1922, la massima è relativa a S. Basilio, pari a 1106 mm, caduti nel 1946.

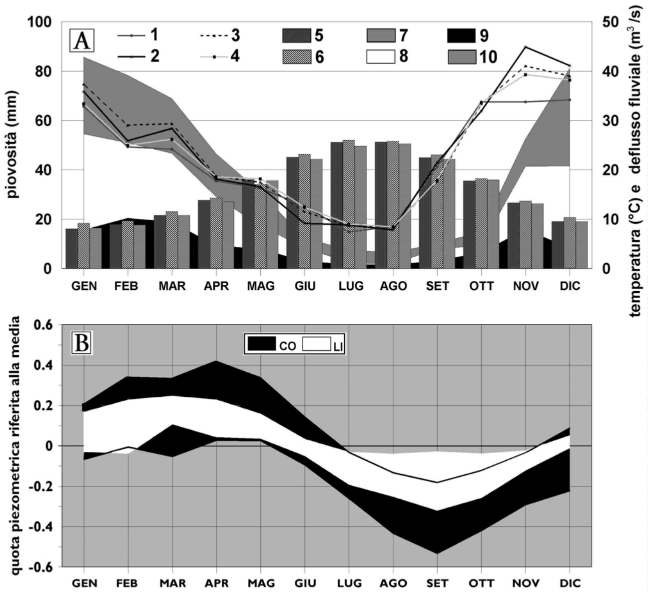

Figura 4: Relazione tra i regimi termopluviometrico, idrometrico e piezometrico. Diagramma A: stazioni pluviometriche di 1) Metaponto, 2) Nova Siri Scalo, 3) Policoro, 4) S. Basilio; stazioni termometriche di 5) Metaponto, 6) Nova Siri Scalo, 7) Policoro; stazioni idrometriche del 8) F. Basento (Menzena), 9) F. Bradano (Tavole Palatine), 10) F. Sinni (Valsinni). Diagramma B: fuso definito dai regimi piezometrici dei pozzi in falda confinata (CO) e libera (LI).

La temperatura atmosferica è stata rilevata in tre stazioni, in periodi diversi, di durata variabile da 26 a 56 anni. Il regime termometrico è moderato, con massimi tra luglio e agosto e minimi a gennaio (Figura 4). La temperatura atmosferica media annua è compresa tra 16,2 e 16,8 °C.

Utilizzando il tradizionale metodo di Thornthwaite e Mather, risulta per la stazione di Metaponto, assunta una capacità di ritenzione di 100 mm, che la piovosità efficace annua è pari a 101 mm, distribuiti da dicembre a marzo. Secondo la classificazione climatica di Thornthwaite il clima è semiarido. Il clima vigente lungo l'arco costiero ionico-lucano non favorisce quindi la disponibilità di risorse idriche.

Le portate fluviali misurate dalle stazioni sui fiumi Basento (a Menzena), Bradano (a Tavole Palatine) e Sinni (a Valsinni) hanno mostrato un regime sostanzialmente regolare, con un minimo ad agosto e un massimo a gennaio o febbraio. Il regime idrometrico relativo al fiume Bradano appare meno regolare e dissimile dai restanti due. Tutti i regimi idrometrici mostrano un andamento stagionale molto simile a quello pluviometrico, denotando una relazione significativa tra piogge e portate fluviali, le cui variazioni seguono con un ritardo variabile da zero a 2 mesi quelle pluviometriche, al passare dalla stagione arida estiva a quella umida invernale (Figura 4).

CARATTERI IDROGEOLOGICI

Nell'area sono presenti 28 sorgenti; la portata media è generalmente bassa, pari a 0,1 l/s. Numerose sorgenti sono alimentate grazie alle perdite dagli alvei fluviali; non sorprende quindi così che si sia osservata la scomparsa di alcune sorgenti determinata dalla costruzione delle dighe.

Il regime piezometrico è stato studiato utilizzando i rilievi eseguiti dal SIMN dal 1927 al 1985 su 60 pozzi. Si è scelto di tracciare il regime piezometrico riferendo per ciascun pozzo l'altezza piezometrica media mensile alla quota piezometrica media del pozzo stesso al fine di eliminare l'effetto della diversa altimetria, generalmente molto accentuato sulla piezometria degli acquiferi superficiali, soprattutto se questi sono caratterizzati da una modesta soggiacenza.

L'analisi delle curve relative a ciascuna stazione ha evidenziato la presenza di due regimi principali: il primo è relativo ai pozzi la cui falda è confinata, il secondo è inerente ai pozzi interessati da flusso idrico sotterraneo freatico. Questi due tipi sono rappresentativi del 90% dei pozzi considerati. I due tipi sono molto simili poiché presentano un unico minimo, principalmente nel mese di settembre e secondariamente ad ottobre, ed un unico massimo, da febbraio ad aprile. In termini di differenze, è possibile osservare che il massimo per i pozzi in pressione sembra arrivare con un ritardo di un mese rispetto a quello dei restanti. Inoltre, come già osservato da Polemio & Ricchetti (1991), il regime piezometrico dei pozzi in pressione è caratterizzato da maggiori escursioni e da andamenti costituiti da spezzate, bruscamente raccordate in prossimità dei valori estremi. Laddove si osservano condizioni freatiche, il regime presenta minori escursioni e un andamento sostanzialmente sinusoidale.

L'escursione piezometrica nell'anno medio è risultata essere compresa tra 0,1 m e 4,8 m. Escludendo quattro dei 60 pozzi considerati, in quanto posti in condizioni idrogeologiche particolari nell'interno rispetto a Nova Siri scalo, il massimo dell'escursione piezometrica diminuisce a 1,0 m. La massima escursione piezometrica mensile, ovvero la differenza tra il massimo e il minimo assoluto mensile di ciascun pozzo, è risultata essere compresa tra 0,5 e 14,7 m, il cui massimo diminuisce a 4,9 m una volta trascurato i quattro pozzi precedentemente citati. Considerando l'andamento planimetrico della massima escursione piezometrica mensile, essa sembra crescere dalla costa verso l'interno e al crescere della distanza dai principali corsi d'acqua. In ogni caso, essa aumenta, anche se lievemente, al crescere del numero di anni di misura considerati.

I caratteri idrogeologici dell'area di studio sono strettamente correlati all'assetto geologico e geomorfologico dell'area stessa. Infatti, le configurazioni litologico-strutturali dell'area determinano l'esistenza di due tipi principali di acquiferi: il primo include gli acquiferi presenti nei depositi marini terrazzati e in quelli alluvionali fluviali, invece il secondo tipo identifica essenzialmente l'acquifero della piana costiera.

Gli acquiferi dei depositi marini terrazzati mostrano una conducibilità idraulica da media ad alta, sono in prevalenza freatici ma anche diffusamente in pressione. La limitata e non omogenea estensione dei livelli a bassa conducibilità idraulica posti al tetto degli stessi acquiferi favorisce l'infiltrazione delle acque pluviali e quindi la loro naturale ricarica (Figura 3). La continuità di questi acquiferi attraverso l'area è regolarmente interrotta dalle valli fluviali.

L'estensione degli acquiferi dei depositi alluvionali è limitata nonché minore di quella degli acquiferi dei depositi marini terrazzati. La conducibilità idraulica di questi acquiferi, variabile da bassa a media, non permette la captazione di rilevanti risorse idriche sotterranee, salvo in corrispondenza delle alluvioni del fiume Sinni. Inoltre, le loro potenzialità per il rinvenimento di risorse idriche sotterranee, rilevanti solo nel caso del fiume Sinni, sono fortemente condizionate sia dalla morfologia e dalla profondità dell'alveo fluviale che dall'entità dei relativi deflussi fluviali.

L'importanza del secondo tipo di acquifero individuato, quello della piana costiera, non deriva dalla sua conducibilità idraulica, essendo essa non particolarmente elevata, bensì è connessa alla continuità, all'estensione (circa 40 km lungo la costa e alcuni chilometri nella direzione trasversale) e alla maggiore potenza dell'acquifero costiero. Inoltre, esso ricade nell'area interessata dal maggiore sviluppo delle attività economiche idroesigenti.

L'acquifero costiero superficiale coincide con l'unità sabbiosa intermedia della piana costiera (Figura 3), caratterizzata da un assortimento granulometrico alquanto variabile: la frazione ghiaiosa varia da 0 al 11%, quella sabbiosa dal 0 fino al 96 %, con valori medi intorno a 48%, la frazione limosa dal 4 al 99%, con valori medi pari al 38% e infine quella argillosa dal 0 al 55%, con valori medi intorno a 14%. Inoltre, la frazione sabbiosa risulta essere maggiore per i campioni prelevati nella zona costiera compresa tra i fiumi Cavone e Basento.

Nell'acquifero costiero, gli strati più permeabili, generalmente sabbiosi, sono confinati all'interno di livelli impermeabili di varia estensione e spessore (Figura 3). Lo spessore totale degli strati permeabili dell'acquifero è maggiore di 10 m e tende ad aumentare generalmente dall'interno verso costa, ad eccezione dell'area compresa fra i fiumi Agri e Cavone.

La quota della letto del suddetto acquifero, coincidente con il tetto dell'unità argillosa inferiore della piana costiera (Figura 3), decresce dall'interno verso la costa, pur se con un andamento alquanto irregolare, caratterizzato anche da locali depressioni del letto, subparallele alla costa. Vicino alla costa il letto dell'acquifero costiero si spinge sotto il livello del mare, permettendo in tal modo, in funzione delle condizioni idrodinamiche, l'intrusione marina. Come evidenziato nel seguito, tale fenomeno sembra accentuarsi da SO verso NE, muovendosi lungo costa poiché il tetto dell'unità argillosa degrada dolcemente dal fiume Sinni al fiume Bradano.

In prossimità della linea di costa e in alcune zone intorno al fiume Basento, l'acquifero è freatico mentre diventa confinato nelle aree ove è delimitato al tetto da un esteso strato impermeabile di argille limose che presenta spessori variabili fra i 3 ed i 10 m (Figura 3).

L'acquifero costiero è limitato a valle (SE) dal Mar Ionio mentre a monte (NO) è in contatto con gli acquiferi dei depositi alluvionali e dei terrazzi marini. Tale limite è generalmente di alimentazione, come si evince dalle Figure 3 e 5. Allo stesso tempo, localmente esso costituisce un limite idrogeologico di emergenza per gli acquiferi dei depositi marini terrazzati, come in prossimità dell'abitato di Policoro, dove si osservano alcune sorgenti al piede della scarpata, dovute al contatto tra conglomerati acquiferi e strati argillosi sottostanti, entrambi appartenenti ai terrazzi marini.

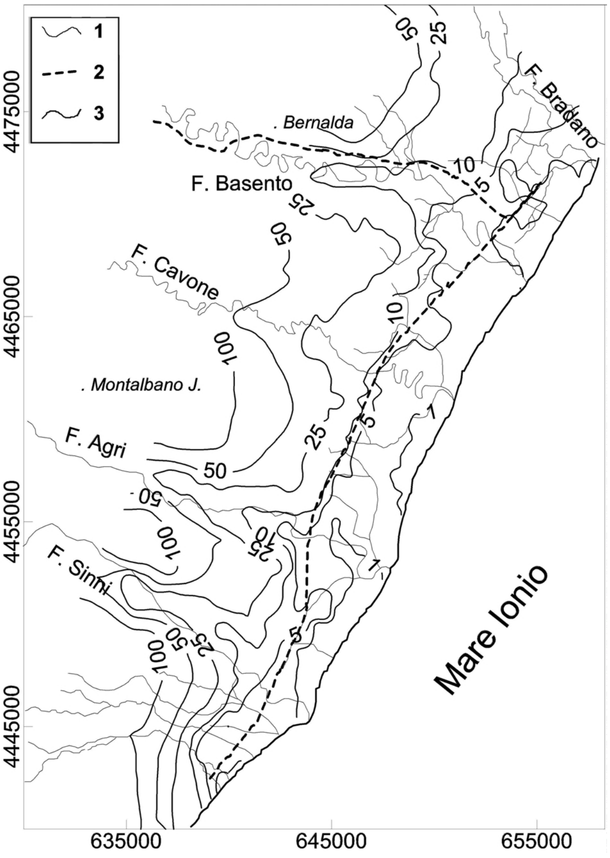

Figura 5: Carta piezometrica dell'area di studio: 1) reticolo idrografico, 2) linea ferroviaria, 3) isopieziche (m s.l.m.).

La ricarica diretta, per infiltrazione di acque piovane, è da ritenersi modesta se non trascurabile per il basso valore della piovosità efficace e per l'effetto del tetto impermeabile. Per questi motivi, la ricarica dell'acquifero costiero è maggiormente garantita dalle acque provenienti dagli acquiferi di monte, in particolare quelli dei terrazzi marini. A tale proposito, si osservi che le isopieziche sono abbastanza rettilinee e alquanto parallele sia alla linea di costa sia al limite idrogeologico tra depositi marini terrazzati e l'acquifero costiero (Figura 5). Tale circostanza permettere di ritenere che le linee principali di flusso idrico sotterraneo, orientate ortogonalmente alla costa, attraversino tale limite senza alcun rilevante effetto, segnalando l'alimentazione a favore dell'acquifero costiero.

L'andamento della superficie piezometrica (Figura 5) indica che i fiumi potrebbero drenare le acque circolanti negli acquiferi delle valli fluviali. Questo effetto sembra particolarmente evidente per i fiumi Basento ed Agri. In ogni caso, come per il fiume Sinni, la concavità verso il basso delle isopieziche non è esattamente sovrapposta all'attuale letto del fiume ma potrebbe essere correlata alla presenza di un alveo sepolto. Inoltre, l'effetto drenante della falda idrica diminuisce gradualmente, termina o si inverte allorquando i fiumi fluiscono lungo la piana costiera. Questo cambiamento è maggiormente evidente in prossimità di alcuni fiumi, quali il Sinni e il Bradano. Altresì, è possibile evidenziare che nella piana costiera gli alvei risultano essere abbastanza incisi, tanto da raggiungere l'acquifero, a scapito del tetto a bassa permeabilità (Figura 3).

Il valore minimo della conducibilità idraulica dell'acquifero costiero (Figura 6), ottenuto dall'analisi delle prove di emungimento, è pari a $3,47\ 10^{-6}$ m/s, dovuto ad una portata di pozzo pari a 0,8 l/s ed ad una depressione di 25,9 m.

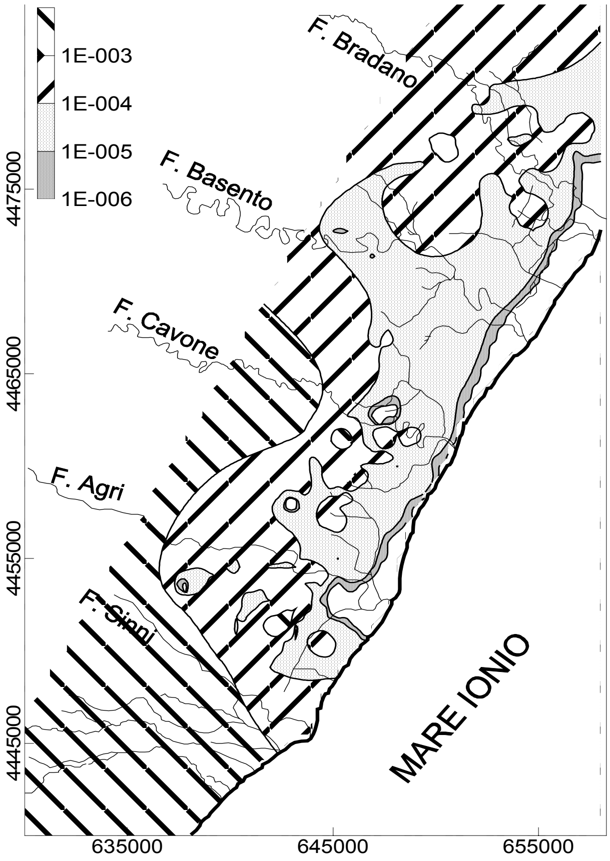

Figura 6: Distribuzione della conducibilità idraulica (m/s).

Il valore medio è pari a $2,28\ 10^{-4}$ m/s e la mediana a $6,53\ 10^{-5}$ m/s. Il valore massimo della conducibilità idraulica è uguale a $5,69\ 10^{-3}$ m/s, dterminato per una portata da pozzo pari a 2,3 l/s e depressione di 0,2 m. Il reticolo idrografico non sembra influenzare l'andamento planimetrico della conducibilità idraulica (Figura 6). La conducibilità idraulica diminuisce muovendosi dall'interno verso la costa e dal Sinni verso il Bradano. La diminuzione di questo parametro vicino alla costa non sembra essere sufficiente a contrastare il pericolo di intrusione marina.

LE CARATTERISTICHE CHIMICO-FISICHE DELLE ACQUE SOTTERRANEE

La caratterizzazione chimico-fisica delle acque sotterranee è scaturita dall'analisi di diversi campioni d'acqua, provenienti da 158 pozzi uniformemente distribuiti su tutta l'area in studio. Un riassunto statistico dei principali parametri chimico-fisici è riportato in Tabella 1.

		T (°C)	pH	TDS a 110°C (mg/l)	CE$^{(*)}$ a 25°C (µS/cm)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Na^{+} (mg/l)	K^{+} (mg/l)	Cl^{-} (mg/l)	SO_4^{2-} (mg/l)	HCO_3^{-} (mg/l)
Depositi marini terrazzati	**minimo**	16,0	6,7	271	348	19	9	27	3	20	1	40
	massimo	22,0	8,6	2310	4000	208	102	549	76	805	372	807
	media	19,3	7,2	868	1333	98	38	142	1	167	127	372
Depositi alluvionali	**minimo**	16,3	6,7	179	211	6	2	14	4	17	2	11
	massimo	22,3	8,8	3410	9031	160	153	2175	38	2645	804	1251
	media	19,3	7,6	940	1786	54	40	180	15	268	123	334
Depositi costieri	**minimo**	19,0	6,8	261	446	12	9	33	49	30	37	124
	massimo	20,2	8,3	1487	15052	192	251	2700	71	3000	163	763
	media	19,5	7,7	805	3190	87	64	510	60	661	101	405

Tabella 1: Valori statistici di alcuni parametri chimici principali in relazione ai litotipi affioranti. (*) Conducibilità elettrica delle acque sotterranee.

Si consideri che i dati utilizzati, determinati da terzi, sono stati attentamente validati dal punto di vista statistico e idrogeochimico. Nonostante la cura prestata in tale fase, non si può valutare quale sia l'accuratezza e la precisione raggiunta con tali determinazioni in quanto generalmente non descritta dalle fonti stesse. Le concentrazioni dei costituenti maggiori sono riportati nel Diagramma di Piper (Figura 7) il quale mostra un'alta dispersione dei punti rappresentativi del chimismo delle acque sotterranee. Tale dispersione non può essere semplicemente giustificata in virtù della diversa natura delle fonti utilizzate, in quanto tale dispersione non si riduce in modo apprezzabile ignorando una o più fonti. Nonostante la dispersione dei dati raccolti, la loro distribuzione permette di riconoscere due principali tipi d'acqua: la bicarbonato-alcalina-terrosa e la solfato-clorurato-alcalina. La prima è tipica delle acque prelevate in corrispondenza dei pozzi eseguiti nei depositi marini terrazzati ed alluvionali, mentre la seconda è ascrivibile ai campioni d'acqua dei pozzi ubicati nei depositi della piana costiera.

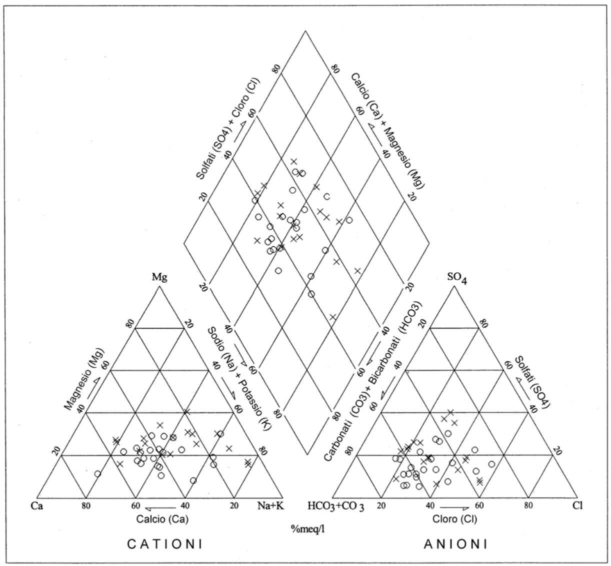

Figura 7: Diagramma di Piper. Campioni di acque sotterranee prelevati ○) dagli acquiferi costituiti dai depositi marini terrazzati e +) dall'acquifero della piana costiera.

Infine, il tipo solfato-clorurato-alcalina-terroso risulta essere molto raro, e caratterizza i campioni d'acqua prelevati in prossimità del fiume Basento, e quindi sembra essere correlabile a fenomeni di inquinamento rivelati in questa zona, descritti nel seguito. Inoltre, è importante ricordare che il bacino imbrifero del fiume Basento è caratterizzato dalle più alte densità abitative e dalla più alta concentrazione di industrie della Basilicata, quindi le stesse acque fluviali sono soggette ad un maggior rischio di inquinamento e, per possibili perdite dal fiume stesso, conseguentemente anche la falda idrica sotterranea ivi presente.

La temperatura delle acque sotterranee, compresa fra i 16°C ed i 22°C, tende ad aumentare verso la costa. Si tratta di un dato da valutare con prudenza in quanto ottenuto con strumentazioni e metodologie varie. In ogni caso, la variabilità della temperatura delle acque sotterranee sembra essere dovuta al progressivo aumento della temperatura dalle aree di alimentazione, poste nell'interno, laddove affiorano i depositi marini terrazzati, che raccolgono le acque di precipitazione meteorica, alle aree di recapito, poste in prossimità delle sorgenti, delle foci fluviali e del mare. Lungo la fascia costiera, dove l'infiltrazione diretta delle acque piovane risulta essere modesta, i tempi di residenza delle acque sotterranee, parametro del quale non si dispone attualmente di dati quantitativi, dovrebbero essere elevati e costituire i massimi assoluti nell'area, se non fosse per l'azione di ricarica svolta dai fiumi. Ciò spiega l'innalzamento progressivo della temperatura per scambio termico fra acque sotterranee e rocce serbatoio. Infine, in prossimità della costa si risente dell'influenza termica del mare.

Il pH varia circa da 6,7 a 9 e tende ad aumentare avvicinandosi alla costa. In prossimità degli alvei fluviali, i valori di questo parametro sembrano essere influenzati dalla presenza delle acque superficiali.

Le maggiori concentrazioni dello ione calcio ed dei bicarbonati sono state misurate nelle zone più interne dell'area in esame mente quelle più basse sono state registrate per i campioni di acqua prelevati in corrispondenza dei pozzi ubicati in prossimità della costa. Anche in questo caso, seppur meno evidente rispetto al pH, si riscontra un effetto del reticolo idrografico sulla concentrazione di questi ioni.

La concentrazione dello ione magnesio aumenta in prossimità della fascia costiera, maggiormente nel tratto di costa compreso fra i fiumi Bradano e Cavone.

Le notevoli ampiezze degli intervalli di concentrazione definiti da ciascuno dei principali ioni non possono essere spiegate semplicemente come l'effetto degli errori associati all'uso di fonti diverse, in quanto tali intervalli non si modificano sostanzialmente al ridursi delle fonti. Altresì, esse non sembrano essere connesse all'inquinamento delle acque sotterranee, essendo inoltre quest'ultimo influenzato da fattori locali. Le ragioni di questa variabilità dovrebbero essere ascrivibili ad altri fattori naturali e antropici.

Primo di tutto, gli ambienti deposizionali delle differenti unità litologiche individuate e i processi litogenetici ad esse associate hanno influenzato i caratteri geochimici dei diversi litotipi, costituenti gli acquiferi, e indirettamente anche il chimismo delle acque sotterranee circolanti in essi. Ad esempio, la presenza di intervalli limoso-argillosi nei depositi marini terrazzati e nella piana costiera possono aver favorito l'instaurarsi di scambi ionici tra questi e le acque sotterranee ivi circolanti.

I suddetti fattori naturali e quelli antropici connessi all'inquinamento delle acque fluviali non possono comunque giustificare la maggiore variabilità delle concentrazioni ioniche stimate per le acque sotterranee circolanti nei depositi alluvionali e costieri rispetto a quelle agenti nei depositi marini terrazzati. Di conseguenza, nel caso dell'acquifero costiero l'elevata variabilità può essere connessa ad altri fattori antropici e all'intrusione marina. Tra i fattori antropici, un rilevante contributo è legato alle diffuse ed irrazionali pratiche irrigue. Queste possono comportare sia un surplus di acqua d'irrigazione, nonché l'utilizzo non oculato di concimi e diserbanti, il quale determina immissioni di sostanze chimiche inquinanti negli acquiferi. Inoltre, essendo l'area in studio caratterizzata da un clima semiarido, con elevato tasso di evapotraspirazione potenziale (860 mm come valore medio annuale e 161% in percentuale della piovosità annuale), l'acqua d'irrigazione diventa un elemento importante per le pratiche agricole dell'area e per la vita delle popolazioni ivi presenti, quindi la variabilità osservata può essere connessa alla composizione chimica delle acque di irrigazione. A partire dagli anni sessanta, queste acque sono fornite dalle dighe, in esercizio nei settori montani dei bacini fluviali principali (eccetto il fiume Cavone). Prima dell'utilizzo delle reti di acquedotto alimentate dalle dighe, invece esse erano fornite dai pozzi, come avviene ancora oggi durante i periodi di siccità. Lo sfruttamento intenso delle acque sotterranee, non associato ad una costante ricarica dell'acquifero, e l'utilizzo di sostanze inquinanti aggiunte al suolo, principalmente fertilizzanti, possono determinare un degrado della qualità delle acque sotterranee e originare una variabilità delle concentrazioni ioniche. Inoltre, un crescente carico di sale e una distribuzione della massa di sale sembrano essere causate dalle pratiche irrigue, quando queste ultime sono alimentate dalle acque dei pozzi, secondo il fenomeno del "ritorno di massa" (Milnes e Renard, 2002).

La sopra menzionata variabilità delle concentrazioni ioniche è relazionata anche alla bassa capacità di drenaggio della piana costiera, che è soggetta a frequenti e vaste inondazioni da parte dei fiumi e, secondariamente, al ruscellamento proveniente dalle alture costituite dai depositi marini terrazzati. L'evaporazione di tali acque è quindi un'altra fonte di sali e di inquinamento, aggiunti al sistema, come già segnalato da Lopez. et al. (1986). Questa situazione è improvvisamente cambiata dagli anni sessanta, quando i lavori di bonifica hanno fortemente ridotto intensità e frequenza degli eventi alluvionali.

EFFETTO DELL'INTRUSIONE MARINA SULLA QUALITÀ DELLE ACQUE SOTTERRANEE E SUL LORO DEGRADO

In base all'andamento del letto dell'acquifero costiero superficiale rispetto al livello medio del mare, è plausibile che il fenomeno dell'intrusione marina possa coinvolgere un tratto costiero maggiormente esteso procedendo da SO verso NE, come descritto in precedenza. Al fine di delineare la zona costiera maggiormente soggetta al rischio di intrusione salina, sono state analizzate la distribuzione spaziale della salinità (TDS), della conducibilità elettrica e dei cloruri delle acque sotterranee, tutti parametri sensibili all'intrusione dell'acqua marina.

Le più alte concentrazioni di TDS, eccedenti 1.000 mg/l, sono state registrate vicino al litorale e lungo i fiumi Bradano, Basento e Cavone, con alcune eccezioni poco significative. Questa tendenza conferma la stretta relazione esistente tra i fiumi e la circolazione idrica sotterranea dell'area in esame. Si noti che in prossimità della costa il letto degli alvei è posto a quote prossime o inferiori a quelle del mare. Di conseguenza, in assenza di deflussi, durante i periodi di bassa pressione, spirando venti del secondo quadrante e comunque in condizioni di alta marea, il reticolo idrografico può divenire un reale veicolo per l'intrusione di acqua di mare vero l'interno. In tal modo è possibile che l'acqua marina risalga gli alvei e quindi si possa infiltrare nell'acquifero. Tale fenomeno potrebbe spiegare gli aumenti della salinità osservati in alcune aree dell'area in esame, in genere altimetricamente depresse, poste non a ridosso della costa. Inoltre, la salinità attualmente misurata potrebbe essersi originata allorquando le morfologie delle foci dei fiumi e la posizione della linea di costa erano diverse da quelle attuali.

La conducibilità elettrica delle acque sotterranee (Figura 8) e la concentrazione dei cloruri tendono ad aumentare irregolarmente procedendo verso l'attuale linea di costa, raggiungendo i massimi valori nell'area intorno al fiume Basento. Quest'ultimo fenomeno presumibilmente è connesso alla maggiore densità di dati a disposizione per la zona del Basento.

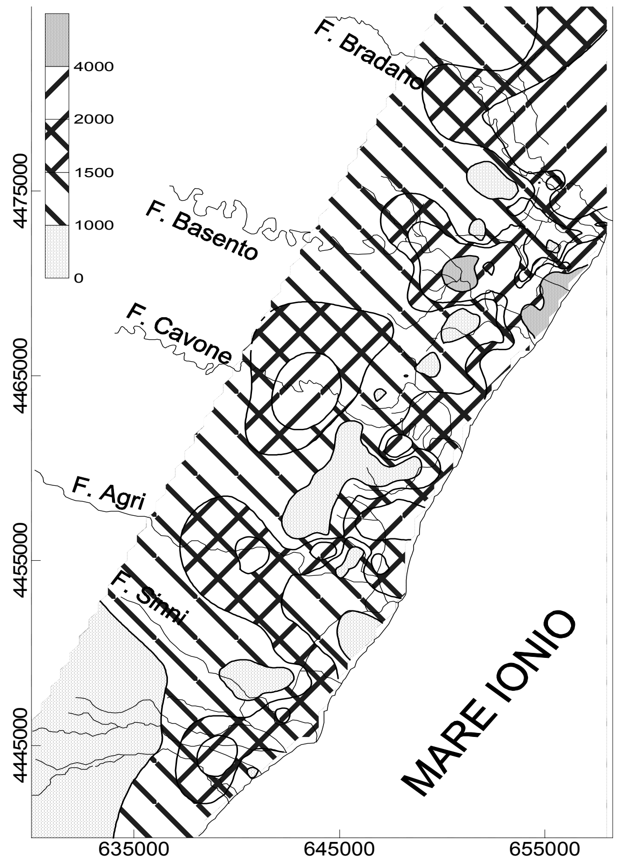

Figura 8: Carta della conducibilità elettrica delle acque sotterranee (µS/cm a 25°C).

L'analisi combinata dei parametri sopra menzionati evidenzia quanto gli effetti dell'intrusione marina si risentano in una porzione del litorale ionico in esame, ampia fino a 2,5 km, con una larghezza media pari a 1-1,5 km. Le zone costiere maggiormente soggette a tale fenomeno sono localizzate fra il Basento e l'Agri.

Il ruolo giocato dall'intrusione dell'acqua di mare e dagli scambi ionici che intercorrono tra le acque fluviali e l'acquifero sotterraneo è stato confermato dai valori calcolati per i rapporti caratteristici più significativi: Na^+/Ca^{2+}, Mg^{2+}/Ca^{2+}, $SO4^{2-}/Cl^-$, Na^+/Cl^-, $(Na^++K^++Cl^-+SO4^{2-})/(Ca^{2+}+Mg^{2+}+HCO3^-)$. In particolare, l'ultimo rapporto caratteristico enunciato, quando eccede l'unità, segnala l'eventualità di contaminazione per intrusione di acqua marina (Cotecchia & Magri, 1966). Tale effetto si osserva lungo una striscia di acquifero, che dalla costa si estende fino ad un massimo di circa 3 km verso l'interno.

Alla luce dei risultati ottenuti dalle elaborazioni eseguite, è possibile confermare che gli effetti dell'intrusione dell'acqua marina siano presenti in prossimità della linea di costa, come già evidenziato da precedenti studi (Radina, 1956; Polemio & Mitolo, 1999). Inoltre, questo fenomeno è risultato essere maggiormente evidente per una porzione dell'acquifero costiero, la cui larghezza tende ad aumentare dal fiume Sinni verso il fiume Bradano. Infatti, la larghezza è pari a circa 1÷1,5 km nella zona costiera fra il Sinni e la sponda destra del fiume Cavone, mentre giunge fino a circa 5 km intorno al fiume Basento e fino alla sponda destra del fiume Bradano.

Una valutazione cartografica quantitativa dell'area a rischio di intrusione marina è stata effettuata con un metodo originale e semplice, basato sulla relazione di Gyben-Herzberg (Davis e De Wiest, 1991). In particolare, applicando metodologie GIS, è stato determinato l'andamento planimetrico della quota dell'interfaccia netta, sulla base del fattore di densità pari a 37 e considerando l'andamento della superficie piezometrica (Figura 9). Tale determinazione è stata effettuata per tutto il territorio, discretizzato con una griglia quadrata larga 400 metri. La quota dell'interfaccia netta è stata confrontata con quella del letto dell'acquifero. Laddove il letto dell'acquifero soggiace all'interfaccia netta, l'area risulta a rischio di intrusione marina e individua l'Area a Rischio di Intrusione marina Attuale (ARIA) riportata in Figura 9. L'ARIA si estende lungo costa con un'ampiezza variabile e coerente con quanto emerso dalla caratterizzazione chimico-fisica delle acque (Figura 9).

Il rischio di inquinamento salino per intrusione marina non è solo potenziale, come mostrato in più modi, ma anche concreto, come confermato per via chimico-fisica.

I danni arrecati alla qualità delle acque sono accentuati dalla consuetudine di realizzare i pozzi fino a raggiungere il letto dell'acquifero, anche al di sotto del livello del mare, senza considerare neanche la posizione teorica dell'interfaccia acque di falda-acque di intrusione.

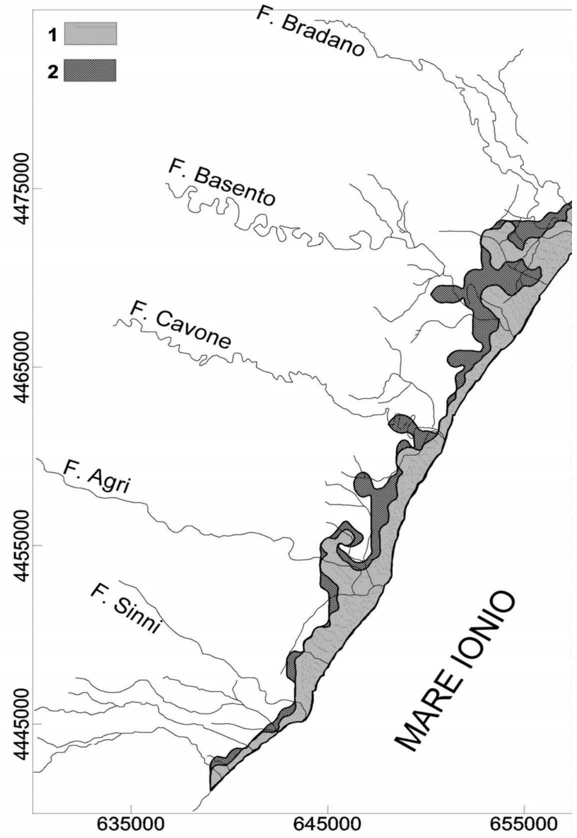

Figura 9: Carta di valutazione del rischio di intrusione marina: 1) Area a Rischio di Intrusione marina Attuale (ARIA), 2) Area a Rischio di Intrusione marina in Estensione (ARIE).

Il rischio aumenta se la differenza fra le quote dell'interfaccia netta e quella del letto dell'acquifero aumenta. Qualora, come nel caso in esame, si temano gli effetti del sovrasfruttamento delle acque sotterranee, la metodologia si presta ad una valutazione preliminare dell'estendersi delle aree a rischio di intrusione marina. Per semplicità, in questo caso è stato ipotizzato un abbassamento omogeneo della superficie piezometrica uguale a 1 m. Si determina così una seconda zona, che si potrebbe definire l'Area a Rischio Intrusione marina per Sovrasfruttamento (ARIS). Sottraendo all'ARIS l'ARIA si ottiene l'Area a Rischio Intrusione marina in Estensione (ARIE), rappresentata in Figura 9. Si noti che per quanto trattasi di una preliminare valutazione del rischio, effettuata con un approccio semplice, la cui originalità non permette confronti critici con altri casi di studio, i risultati, determinati considerando la superficie piezometrica e la superficie del letto dell'acquifero, sembrano essere estremamente coerenti con gli andamenti planimetrici dei parametri fisico-chimici considerati significativi per l'intrusione marina.

Ogni parametro analizzato conferma la natura degli effetti ed il ruolo dell'intrusione marina sulla degradazione della qualità dell'acqua sotterranea del litorale della piana costiera in esame.

INQUINAMENTO E QUALITÀ DELLE ACQUE SOTTERRANEE

L'impatto sull'ambiente delle attività agricole è diventato un problema serio nei paesi industrializzati. L'eutrofizzazione causata da un eccesso di sostanze nutritive nelle acque rappresenta uno dei possibili impatti ambientali dell'agricoltura e della zootecnia. In particolare, l'eccesso di nitrati rappresenta uno delle più importanti cause di degradazione della qualità delle acque e il rilascio degli stessi nelle aree agricole è generalmente maggiore del consumo dell'ecosistema naturale.

Nell'area oggetto di studio, il diretto contributo antropico alla degradazione della qualità delle acque sotterranee è rilevante in termini di concentrazione di nitrati, con valori che talvolta superano i 100 mg/l, ma non solo. Va ricordato che i nitrati, presenti in modo rilevante negli acquiferi dell'area, sono uno dei più mobili e persistenti contaminanti agricoli (Böhkle, 2002).

Dal punto di vista qualitativo, come peraltro ben evidenziato dalla carta dei nitrati (Figura 10) si rileva una diffusa presenza degli stessi sul territorio, fortemente quest'ultimo a vocazione agricola; tale presenza e diffusione è quindi imputabile ad un uso intensivo di sostanze fertilizzanti. Una stretta relazione è stata evidenziata tra le proprietà dei suoli e la distribuzione dei nitrati così come tra la concentrazione dei nitrati e la permeabilità del suolo e del non saturo. Infatti, le aree soggette a una maggiore contaminazione di nitrati (Figura 10) sono caratterizzate dalla presenza di suoli, da sabbioso a sabbioso-limoso, con elevati valori di permeabilità. Inoltre, le concentrazioni dei nitrati sembrano essere relazionate all'uso intenso di fertilizzanti nelle pratiche agricole mentre, solo in aree ridotte, alle attività urbane.

Lo scarso contenuto naturale di azoto presente nel suolo non giustifica l'arricchimento di composti azotati misurati nelle acque sotterranee.

Le maggiori concentrazioni di ammoniaca, superiori a 0,5 mg/l, sono state misurate in due distinte aree.

La prima, caratterizzata anche da elevate concentrazioni di nitrati, ricade fra i fiumi Agri e Sinni, dove sono presenti due importanti centri abitati (Scanzano Jonico e Policoro) mentre la seconda è ubicata vicino Metaponto. Presumibilmente, le elevate concentrazioni di ammoniaca sono ascrivibili alle perdite delle reti di fognatura e comunque all'inquinamento indotto dalle aree urbane ivi presenti.

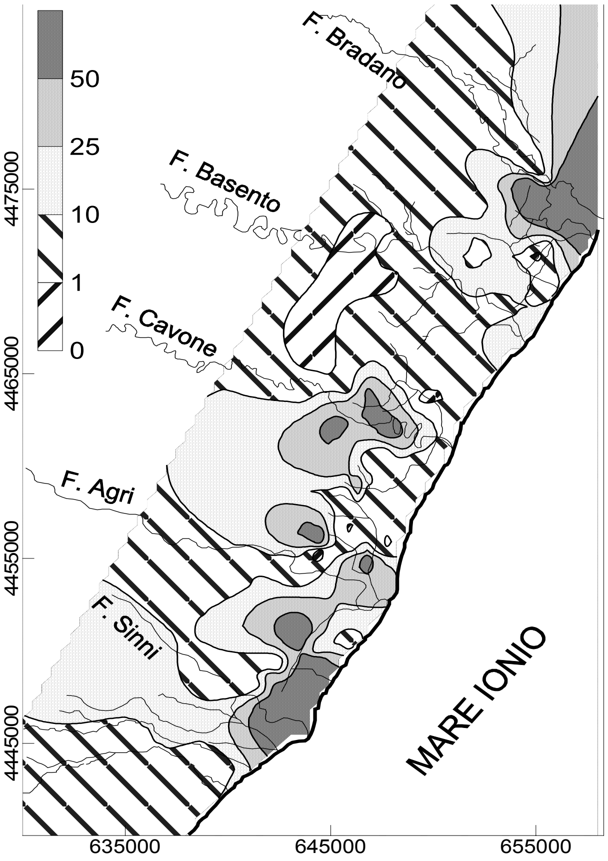

Figura 10: Carta dei nitrati (mg/l).

Lo stesso inquinamento batteriologico e la presenza di alcuni metalli (ad es. Fe^{3+}, Mn^{2+}, Cu^{2+}, As^{3+}, Zn^{2+}) osservati per alcuni campioni di acqua analizzati sono da relazionare essenzialmente a fattori antropici (scarichi urbani, attività zootecniche, inquinanti rilasciati nelle acque dei fiumi ecc.) e solo secondariamente a fattori naturali.

Infine, l'area compresa fra i fiumi Bradano e Basento mostra una situazione alquanto diversificata con una concentrazione di sostanze inquinanti di varia estrazione. Si rileva la presenza di coliformi totali e fecali, in concentrazioni elevate (talvolta superiori ai 15 MPN/100ml), associati ad altri parametri quali gli elementi costituenti il ciclo dell'azoto. Significativa è anche la presenza di elementi cancerogeni quali l'arsenico, lo zinco e il rame. Tale aspetto è sintomo di un malessere generale delle acque circolanti nel sottosuolo dovuto alle attività antropiche ivi presenti. Per quanto tale area sia stata meglio caratterizzata nel tempo, non sorprende che tali risultati si associno ad un fiume a cui si affida il maggiore carico inquinante e che, data la sua configurazione idrogeologica, al tempo stesso è in grado di cedere acque al sottostante acquifero costiero.

CONCLUSIONI

Le caratteristiche idrogeologiche degli acquiferi sono state analizzate per una vasta zona costiera dell'Italia meridionale, soggetta ad un clima semiarido ed afflitta da sempre più frequenti siccità.

Le serie storiche piezometriche considerate hanno mostrato caratteri tendenziali variabili in funzione dei principali interventi antropici capaci di modificare il ciclo idrologico. La piovosità annua in calo significativo, la temperatura annua appena crescente e il deflusso fluviale annuo in forte calo, non forniscono ragioni di ottimismo in relazione alla disponibilità di risorse idriche sotterranee nella Piana di Metaponto. In particolare preoccupa il crescente emungimento in atto in virtù della siccità e la crescente derivazione di acque fluviali altrimenti destinata alla ricarica degli acquiferi.

L'inquadramento geologico e idrogeologico indica che la qualità delle risorse idriche sotterranee dell'area costiera in esame è soggetta ad una progressiva degradazione, connessa essenzialmente a due fenomeni: la contaminazione salina e l'inquinamento chimico-fisico e biologico.

Il fenomeno dell'intrusione marina sta riducendo la disponibilità delle acque sotterranee di buona qualità nelle aree prossime al litorale. Infatti, alla luce dell'analisi dei dati fisico-chimici raccolti, la larghezza della fascia litoranea, sottoposta al maggiore effetto di intrusione dell'acqua di mare, sembra aumentare spostandosi nella direzione NE, per circa 1÷1,5 chilometri, fra il fiume di Sinni e la riva destra del fiume Cavone, fino a circa 5 km, nel settore litoraneo intorno al fiume Basento e in destra del fiume Bradano.

E' stata altresì redatta una preliminare carta dell'andamento delle aree a rischio di intrusione marina, sia in condizioni normali che per sovrasfruttamento delle risorse idriche sotterranee.

Il contributo antropico alla degradazione della qualità delle acque sotterranee è presente specialmente in due aree. La prima è localizzata tra i fiumi Agri e Cavone, la seconda tra i fiumi Basento e Bradano. In entrambe queste aree il suolo nonché il non saturo sono caratterizzati da una maggiore permeabilità, favorendo in tal modo l'infiltrazione degli inquinanti nell'acquifero costiero.

Sono state inoltre rilevate aree contraddistinte da inquinamento batteriologico nonché dalla presenza di metalli, sostanze tossiche e nocive, anche cancerogene.

I risultati, sinora conseguiti, evidenziano la necessità di continuare ed intensificare l'attività di ricerca su questi acquiferi e l'utilità di stabilire criteri per la gestione sostenibile delle risorse idriche sotterranee e generalmente del ciclo dell'acqua.

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SALT WATER INTRUSION IN A GROUNDWATER SYSTEM AT THE BASILICATA REGION, SOUTHERN ITALY

INTRUSIONE MARINA IN UN SISTEMA ACQUIFERO NELLA REGIONE BASILICATA, ITALIA MERIDIONALE

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Abstract. Working package 5 (WP5) of the EU-project CRYSTECHSALIN (fifth framework programme) is considered in this article. CRYSTECHSALIN stands for *CRYStallisation TECHnologies for prevention of SALT water INtrusion*. The project is focused on the development of a new cost efficient and environmental-friendly technology to reduce the permeability of soil formations that are threatened by the intrusion of saline groundwater. WP5 is focused on the creation of a hydrogeological and hydrogeochemical numerical model. The specific field test site of the working package under consideration is located in the coastal plain of the Italian region of Basilicata, Southern Italy, nearby the city of Scanzano Jonico. A regional density dependent groundwater flow model is developed to investigate the regional effects of permeability reductions. The computer code MOCDENS3D (Oude Essink, 1998, 2001) is used for that purpose. This code is a version of MOC3D that has been adapted to simulate transient density-driven groundwater flow and solute transport. It appears that a physical barrier is only effective from a hydraulic point of view when the permeability reduction is relative high.

Keywords: project CRYSTECHSALIN, Basilicata region, seawater intrusion, permeability, numerical modelling, groundwater flow, MOCDENS3D.

Riassunto. In questo articolo si descrive il Work Package 5 (WP5) del progetto dell'Unione Europea denominato CRYSTECHSALIN (V Programma Quadro). L'acronimo CRYSTECHSALIN sta per CRYStallisation TECHnologies for prevention of SALT water INtrusion. Il progetto è focalizzato sullo sviluppo di una nuova tecnologia economicamente efficiente ed ambientalmente compatibile per ridurre la permeabilità dei terreni minacciati dall'intrusione marina. Il WP5 si focalizza sulla progettazione di un modello numerico idrogeologico e idrogeochimico. Il campo prova che è stato considerato nel WP5 è localizzato nella piana costiera della regione Basilicata, nell'Italia meridionale, vicino l'abitato di Scanzano Jonico. Il modello regionale del flusso idrico sotterraneo a densità variabile è sviluppato per caratterizzare gli effetti della riduzione della permeabilità a scala regionale. A tale proposito è stato utilizzato un programma MOCDENS3D (Oude Essink, 1998, 2001). Tale programma è una versione di MOC3D adattata per simulare il flusso idrico sotterraneo a densità variabile in condizioni transitorie, nonché il trasporto solido. Emerge che la barriera fisica è efficace solo dal punto di vista idraulico quando la riduzione della permeabilità è relativamente alta.

Parole chiavi*: progetto CRYSTECHSALIN, regione Basilicata, intrusione marina, permeabilità, modellazione numerica, flusso di acque sotterranee, MOCDENS3D.*

INTRODUCTION

The main task of working package 5 of the EU project CRYSTECHSALIN is to develop a mathematical model that describes the mixing processes in a porous media. The relevant hydrogeological processes are analysed and described mathematically. A numerical concept will be worked out that will describe the flow of calcium carbonate leading to the formation of slightly soluble minerals after in-situ mixing with sea water. The field test site is located in the coastal plain of the Italian region of Basilicata, South Italy, nearby the Torre di Scanzano: viz. Idrovora

4-Torre (Figure 1). Two density dependent groundwater models of the field test site are constructed in order to analyse the existing flow processes in the hydrogeologic system: one coarse model of the whole regional area and one fine model of the field test site. In this article, only the coarse regional model is discussed. The regional large-scale model has been constructed to determine: 1. the natural groundwater flow in seaward direction; 2. the salt water intrusion in the coastal plain; 3. the boundary conditions of the local model; and finally, 4. the regional effect of the hydraulic conductivity reduction. The computer code MOCDENS3D is applied to take into account variable-density flow. The geometry of the hydrogeologic system at the field test site will be modelled in three dimensions, as injection of grouting material in the real field test site is typically a three dimensional problem. Interaction of different grouting materials and in-situ minerals will be considered. Based on the variable-density flow field, multi-species reactive transport in the saturated porous medium will be superimposed, taking into account the relevant geochemical processes in the subsoil: viz. precipitation and dissolution of calcium carbonate which are under influence of an inhibitor. For this purpose, reactive flow and transport of calcium carbonate are coupled with groundwater flow, as changes in porosity and permeability are considered. As such, a reduction in permeability influences the variable-density flow field and the groundwater flow will be recalculated repeatedly to get an up-to-date flow situation. Eventually, an effective methodology to implement a physical barrier will be proposed.

GEOMETRY OF THE TEST SITE

The following hydrogeological parameters of the coastal plain of the Italian region of Basilicata have been considered (derived from the extensive report of Polemio et al , 2002): geometry of the site, depth of the impervious basement, boundary and initial conditions, natural groundwater recharge, groundwater extractions (rate and positions of wells), river fluxes, position, thickness, hydraulic conductivity and porosity of layers, piezometric heads at different levels (corrected for density differences, if applicable), observation wells (position and head of the screen), geochemical data of the observation wells, total dissolved solids in the observation wells and salinity concentration distribution in the system. Two models will be constructed in this working package: a regional model and a local model. The large-scale regional model of the whole coastal plain between the two rivers Cavone and Agri is developed to construct a reliable calibrated model which takes into account all relevent regional physical processe and to check whether the boundary conditions in the fine model are far enough from our field test site to not influence groundwater flow and solute transport. In both cases density dependent groundwater flow and solute transport will be considered.

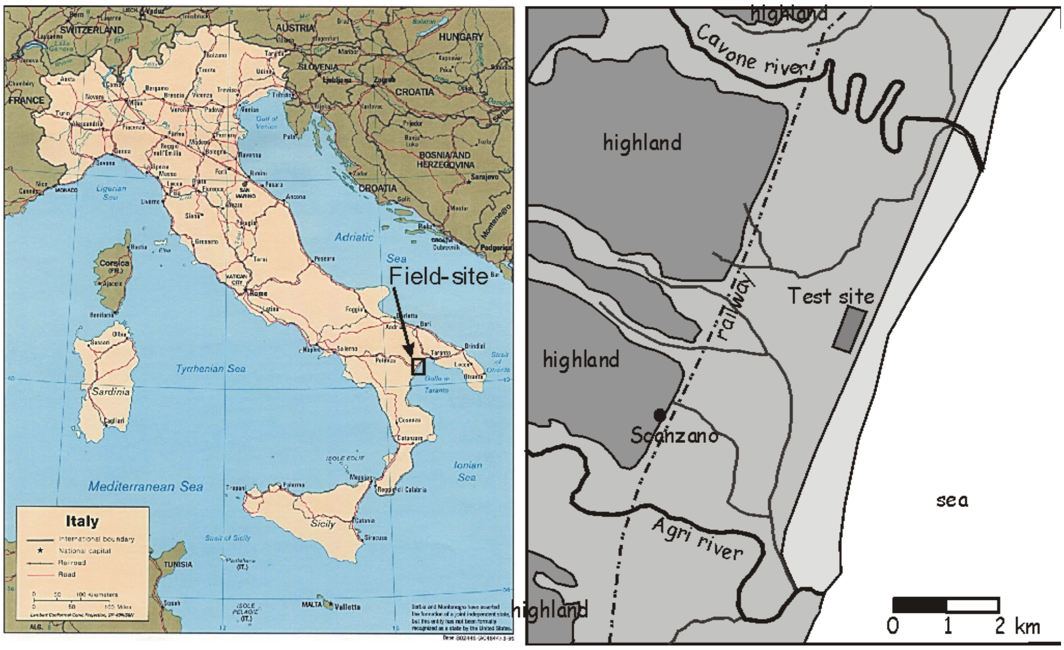

Figure 1: a. Position of the Italian field test site, **b.** Map of the regional model, including the rivers Agri and Cavone

CHARACTERISTICS NUMERICAL CODE

MOCDENS3D (Oude Essink 1998, 2001) is used to simulate the transient groundwater system. It is based on the United States Geological Survey three-dimensional public domain finite difference computer code MOC3D (Konikow et al.,1996). As density differences are considered in the coastal plain, the code has been adapted to simulate variable-density flow in porous media.

Groundwater flow equation

The (adapted) MODFLOW module solves the density driven groundwater flow equation (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). It combines the continuity equation with the equation of motion. Under the given circumstances in the Dutch coastal aquifers, the Oberbeck-Boussinesq approximation is valid as it is suggested that the density variations (due to concentration changes) remain small to moderate in comparison with the reference density ρ throughout the considered hydrogeologic system:

$$\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}=S_s\frac{\partial \phi_f}{\partial t}+W \quad (1)$$

$$q_x=-\frac{\kappa_x}{\mu}\frac{\partial p}{\partial x} \qquad q_y=-\frac{\kappa_y}{\mu}\frac{\partial p}{\partial y}$$

$$q_z=-\frac{\kappa_z}{\mu}\left(\frac{\partial p}{\partial z}+\rho g\right) \quad (2)$$

where q_x, q_y, q_z = Darcian specific discharges in the principal directions [L T^{-1}]; S_s = specific storage of the porous material [L^{-1}]; W = source function, which describes the mass flux of the fluid into (negative sign) or out of (positive sign) the system [T^{-1}]; κ_x, κ_y, κ_z = principal intrinsic permeabilities [L^2]; μ = dynamic viscosity of water [M L^{-1} T^{-1}]; p = pressure [M L^{-1} T^{-2}]; ρ= the density of the groundwater [M L^{-3}]; and g = gravitational acceleration [L T^{-2}]. A so-called freshwater head ϕ_f is introduced to take into account differences in density in the calculation of the head:

$$\phi_f=\frac{p}{\rho_f \mathrm{g}}+z \quad (3)$$

where ϕ_f is the freshwater head [L], ρ_f is the reference density, usually the density of fresh groundwater at reference chloride concentration C_0 [M L^{-3}], p is the pressure [M L^{-1} T^{-2}], and z is the elevation head [L]. Rewriting the Darcian specific discharge in terms of freshwater head gives:

$$q_x=-\frac{\kappa_x\rho_f g}{\mu}\frac{\partial \phi_f}{\partial x} \qquad q_y=-\frac{\kappa_y\rho_f g}{\mu}\frac{\partial \phi_f}{\partial y}$$

$$q_z=-\frac{\kappa_z\rho_f g}{\mu}\left(\frac{\partial \phi_f}{\partial z}+\frac{\rho-\rho_f}{\rho_f}\right) \quad (4)$$

In many cases small viscosity differences can be neglected if density differences are considered in normal hydrogeologic systems (Verruijt, 1980; Bear and Verruijt, 1987).

$$\frac{\kappa_i\rho_f g}{\mu}=k_i \quad (5)$$

$$q_x=-k_x\frac{\partial \phi_f}{\partial x} \qquad q_y=-k_y\frac{\partial \phi_f}{\partial y}$$

$$q_z=-k_z\left(\frac{\partial \phi_f}{\partial z}+\frac{\rho-\rho_f}{\rho}\right) \quad (6)$$

The basic water balance used in MODFLOW is given below (McDonald and Harbaugh, 1988):

$$\sum Q_i=S_s\frac{\Delta\phi_f}{\Delta t}\Delta V \quad (7)$$

where Q_i = total flow rate into the element (L^3 T^{-1}) and ΔV = volume of the element (L^3). The MODFLOW basic equation for density dependent groundwater flow becomes as follows (Oude Essink 1998, 2001):

$$\begin{aligned}
&CV_{i,j,k-1/2}\,\phi_{i,j,k-1}^{t+\Delta t}+CC_{i-1/2,j,k}\,\phi_{i-1,j,k}^{t+\Delta t}+CR_{i,j-1/2,k}\,\phi_{i,j-1,k}^{t+\Delta t}\\
&+(-CV_{i,j,k-1/2}-CC_{i-1/2,j,k}-CR_{i,j-1/2,k}\\
&-CR_{i,j+1/2,k}-CC_{i+1/2,j,k}-CV_{i,j,k+1/2}+HCOF_{i,j,k})\phi_{i,j,k}^{t+\Delta t}\\
&+CR_{i,j+1/2,k}\,\phi_{i,j+1,k}^{t+\Delta t}+CC_{i+1/2,j,k}\,\phi_{i+1,j,k}^{t+\Delta t}+CV_{i,j,k+1/2}\,\phi_{i,j,k+1}^{t+\Delta t}=RHS_{i,j,k}
\end{aligned} \quad (8)$$

$$HCOF_{i,j,k}=P_{i,j,k}-SC1_{i,j,k}/(\Delta t) \quad (9)$$

$$\begin{aligned} RHS_{i,j,k} &= -Q_{i,j,k} - SC1_{i,j,k}\,\phi^{t}_{i,j,k}/(\Delta t) \\ &\quad - CV_{i,j,k-1/2}\Psi_{i,j,k-1/2}(d_{i,j,k-1} + d_{i,j,k})/2 \\ &\quad + CV_{i,j,k+1/2}\Psi_{i,j,k+1/2}(d_{i,j,k} + d_{i,j,k+1})/2 \end{aligned} \qquad (10)$$

$$SC1_{i,j,k} = SS_{i,j,k}\Delta V \qquad (11)$$

$$\begin{aligned} \Psi_{i,j,k-1/2} &= \left(\frac{(\rho_{i,j,k-1} + \rho_{i,j,k})/2 - \rho_f}{\rho_f}\right) \\ \Psi_{i,j,k+1/2} &= \left(\frac{(\rho_{i,j,k} + \rho_{i,j,k+1})/2 - \rho_f}{\rho_f}\right) \end{aligned} \qquad (12)$$

where $CV_{i,j,k}$, $CC_{i,j,k}$, $CR_{i,j,k}$ = the so-called MODFLOW hydraulic conductances between elements in respectively vertical, column and row directions (L^2 T^{-1}) (McDonald and Harbaugh, 1988); $P_{i,j,k}$, $Q_{i,j,k}$ = factors which account for the combined flow of all external sources and stresses into an element (L^2 T^{-1}); $SS_{i,j,k}$ = specific storage of an element (L^{-1}); $d_{i,j,k}$ = thickness of the model layer k (L) and $\psi_{i,j,k-1/2}$, $\psi_{i,j,k+1/2}$ = buoyancy terms (-). The two buoyancy terms $\psi_{i,j,k}$ are subtracted from the so-called right head side term $RHS_{i,j,k}$ to take into account variable density. See Oude Essink (1998, 2001) for a detailed description of the adaptation of MODFLOW to density differences.

The advection-dispersion equation

The MOC module using the method of characteristics solves the advection-dispersion equation, which simulates the solute transport (Konikow and Bredehoeft, 1978; Konikow et al., 1996). Advective transport of solutes is modelled by means of the method of particle tracking and dispersive transport by means of the finite difference method.

$$R_d \frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(CV_i) + \frac{(C-C)'W}{n_e} - R_d\lambda C \qquad (13)$$

The used reference solute is chloride that is expected to be conservative. MOCDENS3D takes into account hydrodynamic dispersion.

The equation of state

A linear equation of state couples groundwater flow and solute transport:

$$\rho_{i,j,k} = \rho_{\mathrm{f}}[1 + \beta_{\mathrm{C}}(C - C_0)] \qquad (14)$$

where $\rho_{i,j,k}$ is the density of groundwater (M L^{-3}), C is the chloride concentration (M L^{-3}), and β_C is the volumetric concentration expansion gradient (L^3 M^{-1}). During the numerical simulation, changes in solutes, transported by advection, dispersion and molecular diffusion, affect the density and thus the groundwater flow. The groundwater flow equation is recalculated regularly to account for changes in density.

MODEL DESIGN

Numerical geometry and model grid

The regional model of the entire regional plain between the two rivers Cavone and Agri consists of a 3D grid of 10.0 km by 12.0 km by 100 m depth. The grid contains about 360000 elements: n_x=100, n_y=120, n_z=50, where n_i denotes the number of elements in the i direction (~60% of the elements is active). Each element is 100 m by 100 m long. In vertical direction the thickness of the elements equals 1 m for the lower 40 layer and 6 m for the upper 10 layers. Even those elements that are situated far into the sea are taken into account. Each element contains eight particles to solve the advection term of the solute transport equation.

As such, some 2.9 million particles are used initially. On the applied time scale, the specific storativity S_s [L^{-1}] can be set to zero, as only a stationary groundwater flow model is generated. Later, a non-steady state model for the solute transport on the local scale will be deduced. The flow time step Δt to recalculate the groundwater flow equation equals one month. The convergence criterion for the groundwater flow equation (freshwater head) is equal to 10^{-3} m. The groundwater flow equation is solved with the preconditioned conjugate gradient procedure.

Boundary conditions

Boundary conditions are implemented at four sides. At the seaside a so-called general head boundary is implemented, as outflow of fresh groundwater from the land to the sea is difficult to implement in the model. The general head boundary (it is in fact a mixed or Cauchy boundary condition) is typically a MODFLOW-feature which models the in or outflow to an element through the difference between the head in the element itself and an external fixed head. A resistance (‘conductance’) attenuates the effect of the external fixed head. In case of implementing the sea, the resistance should be low (or the conductance high). The two rivers Agri and Cavone appear to intersect the groundwater system. As such, these two rivers act as Dirichlet ‘fixed head’ boundaries with interfere with the groundwater flow system through a resistance. The river package of the code MODFLOW is applied to account for this feature, as well as for some other rivers in the area. In addition, the drain package is implementetd at the coastal plain. It takes into account the features of this drained agricultural area. The well package of MODFLOW is used to account for small extractions. At the uphill part, a constant fixed head is inserted in the model. The bottom of the system, at –30 m a.s.l., is considered to be a no-flux boundary. As little is known about hydrodynamic dispersion in the system, a brief sensitivity analysis will be executed to assess the mixing effect on the overall modelling. Initially, the longitudinal dispersivity α_L is set equal to 2 m, while the ratio of transversal to longitudinal dispersivity is 0.1. The phreatic water level in the so-called ‘idrovoras’ is modelled by the drain package of MODFLOW. The constant natural groundwater recharge is in this regional model for the time being set equal to 0 mm/d. In the updated version of the regional model, seasonal fluctuations in the natural groundwater recharge will be considered. At the initial situation (2000 AD), the coastal groundwater system contains some brackish but mostly fresh groundwater (Figure 2 and 3).

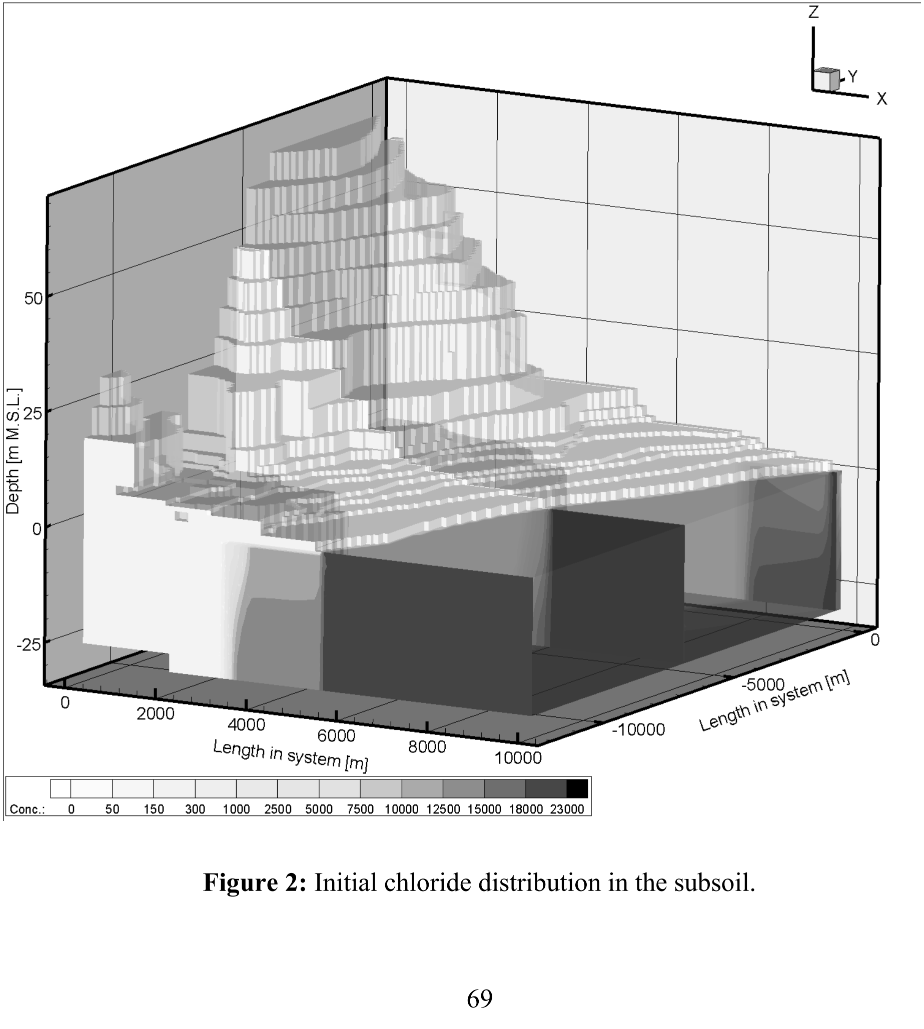

Figure 2: Initial chloride distribution in the subsoil.

On the average, the salinity increases with depth (Polemio et al, 2002). The groundwater system is overall a fresh groundwater system, except near the sea where TDS up to a number of hundreds of mg/l are found. In addition, more inland, some upconing of light brackish water is occurring, which might suggest inflow of brackish water into the aquifer system: salt water intrusion. The volumetric concentration expansion gradient β_C is 1.34 x 10^{-6} l/mg Cl^-. Saline groundwater at the sea does probably not exceed 22000 mg Cl^-/l, as sea water from the Mediterranean has a density somewhat higher than ocean water. The corresponding density of that saline groundwater equals 1029.5 kg/m^3.

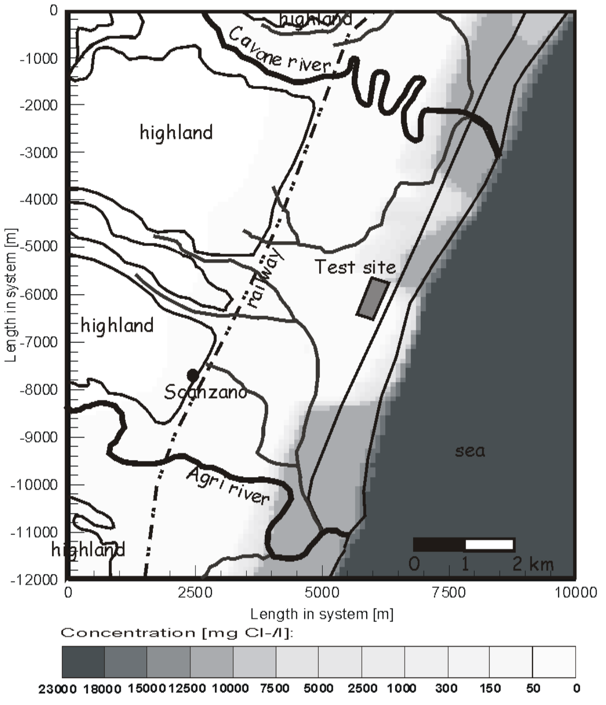

Figure 3: Regional concentration at a horizontal scale, at –5 m a.s.l.

Subsoil parameters

The groundwater system can be subdivided into two regions: the hilly marine terraces and the deposits at the coastal plain (Figure 4 and 5). At ground surface, the system can be divided into three lithological units (Polemio et al., 2002): 1. the coastal deposits, with low hydraulic conductivities (less then 0.2 m/day); 2. the alluvial, transitional and marine deposits; and 3. the marine terraces. Some marine terraced scarps are also present at the highland. At the field test site the top unit consists of soil (less then 2 m thick), followed by grey and/or yellow clays which thickness, viz. 0.5 m, appears to increase landwards. The second unit consists mainly of grey sands, fine-grained to coarse-grained, with a thickness of about 20 m. Hydraulic conductivities k_x varies from 2 to 20 m/day. Pebbly sands and clays intersect this unit. Throughout the large-scale model, the thickness of the second unit varies a lot (Polemio et al., 2002). The third unit is of grey clays.

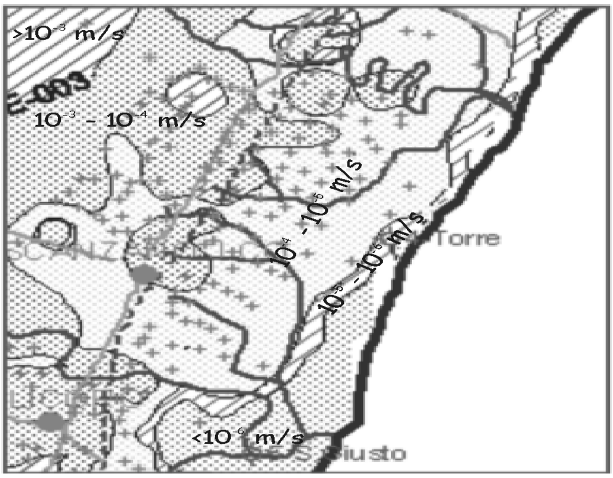

Figure 4: Hydraulic conductivity map (m/s) of the large-scale model area (from Polemio et al, 2002).

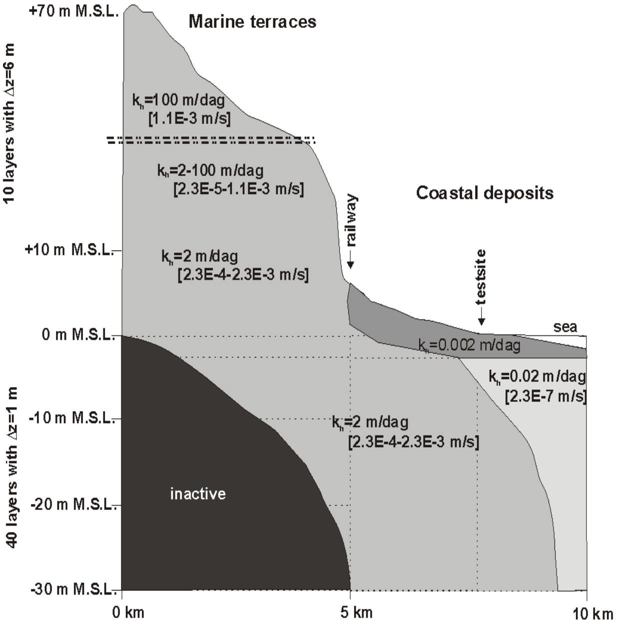

Figure 5: Simplified subsoil composition of the regional model.

The following subsoil parameters are assumed: the anisotropy ratio k_z/k_x equals 0.1 for all layers. The effective porosity n_e is 0.25. The longitudinal dispersivity α_L is set equal to 2 m, while the ratio of transversal to longitudinal dispersivity is 0.1. For a conservative solute as chloride, the molecular diffusion for porous media is taken equal to 10^{-9} m^2/s.

Model parameters

The bottom of the system at –30 m a.s.l. is considered to be no-flux boundaries. At the vertical seaside borders, a so-called general head boundary is implemented with freshwater heads equal to hydrostatic pressure. At the inland hills side, a constant water level (viz. a Dirichlet boundary condition) is inserted. At the top of the system, the ground surface is +70 m a.s.l. The maximum and minimum measured head in the regional model is +54.20 m and -0.40 m a.s.l.

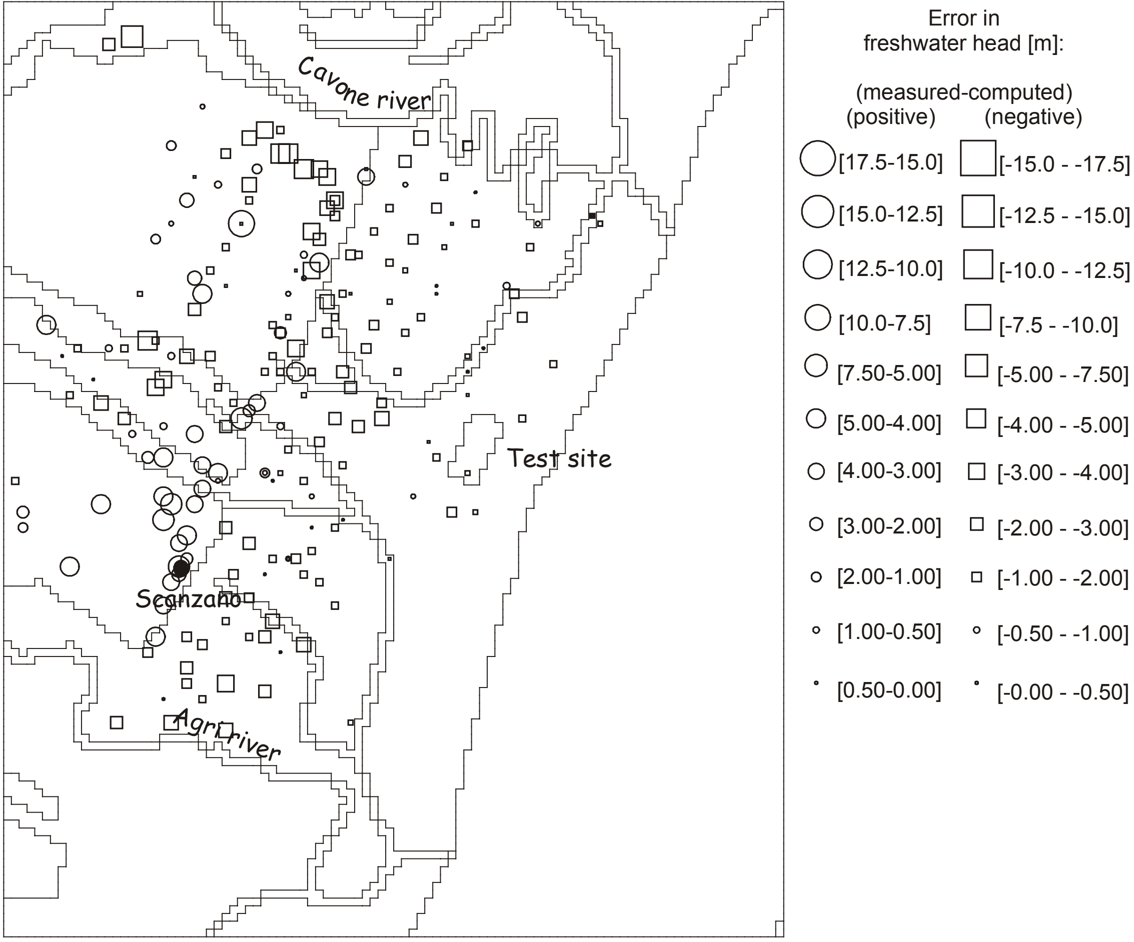

Figure 6: **Spatial distribution of the errors: measured versus computed values at a horizontal scale**

DISCUSSION

Calibration of the model: freshwater head distribution

Calibration of the numerical regional groundwater flow model was focused on the freshwater heads in the hydrogeologic system. There were 327 observation wells present in the Large Scale Area, of which only 208 were useful for the regional model. Freshwater head calibration was executed by comparing those 208 measured and simulated (freshwater) heads, which were corrected for density differences (Figures 6 and 7). The mean error was -0.36 m,the mean absolute error 3.01 m and the standard deviation 4.09 m. Seasonal variations in natural recharge obstruct easy calibration of the density dependent groundwater flow model. In the next phase, seasonal variation will be included. Figure 8 shows the regional freshwater head distribution in the system. Obviously, the hills at the inland side of the hydrogeologic system generate high heads. Groundwater will flow from this upland up towards the coastal plain at a high pace.

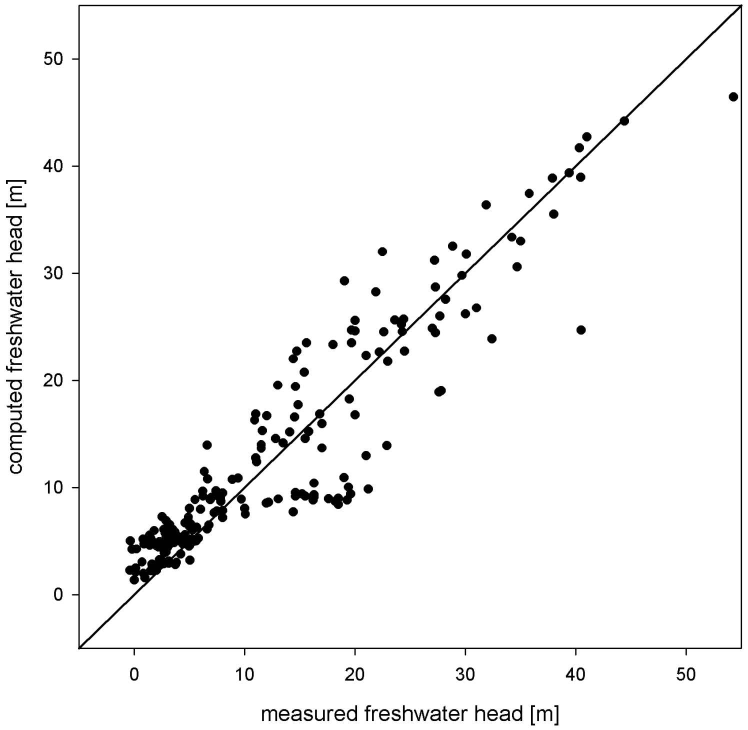

Figure 7: Calibration of the freshwater head: computed versus ‘measured’ freshwater heads.

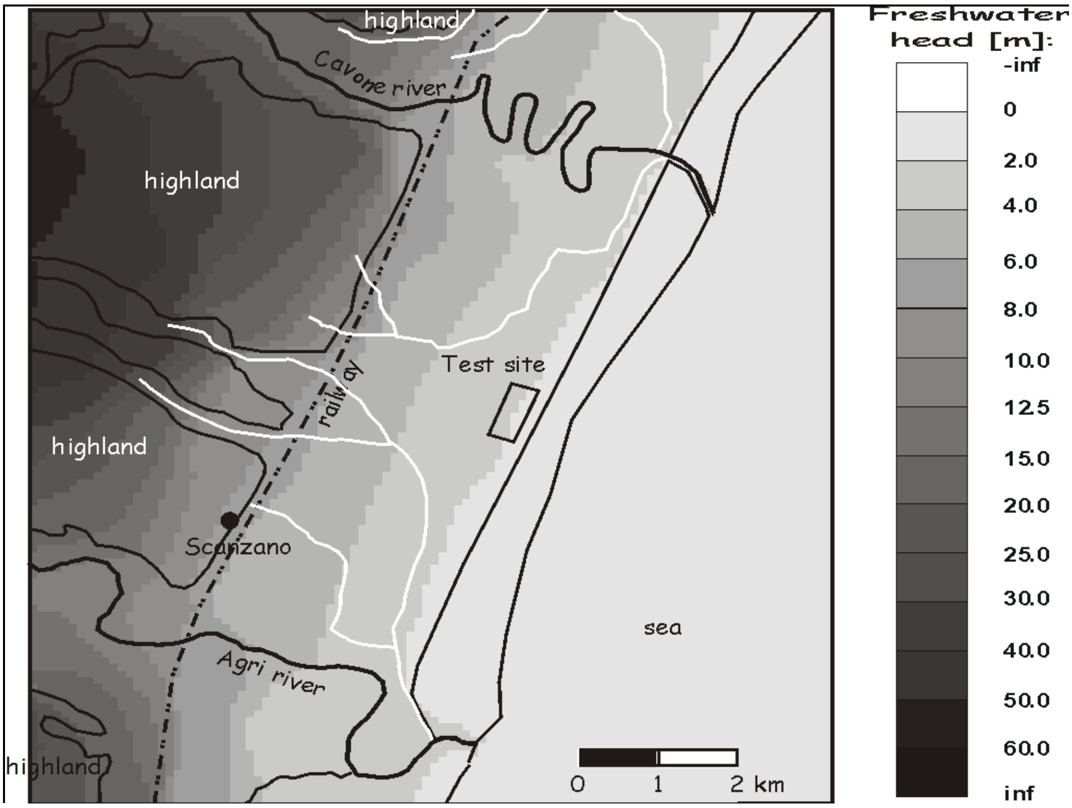

Figure 8: Regional freshwater head at a horizontal scale, at layer 20 (0 -+1 m a.s.l.).

CREATION OF A PHYSICAL BARRIER

The regional model is used to assess the effect of a physical barrier on the groundwater flow regime and the head distribution. Different scenarios of hydraulic conductivity reduction are simulated: 1. a factor 10 reduction; 2. a factor 100; and 3. a factor 1000. The length of the barrier in this numerical experiment is about 1200 m long, and is positioned parallel to the coast, exactly at the field test site. In the regional model, elements have sizes of 100*100*1 m. As such, this barrier geometry implies hydraulic conductivity reductions at blocks with these dimensions. This is not completely realistic for the real field test site situation, where much smaller widths of the barrier will be generated. Nevertheless, this exercise will provide an idea of the possible head changes. Note that in the local model, much smaller elements will be used and a more realistic situation will be computed. Figure 9 shows that the largest drop in head at the landside of the barrier is 1.08 m, for a hydraulic conductivity reduction equal to a factor of 1000. The zone of influence is at least some hundreds of meters.

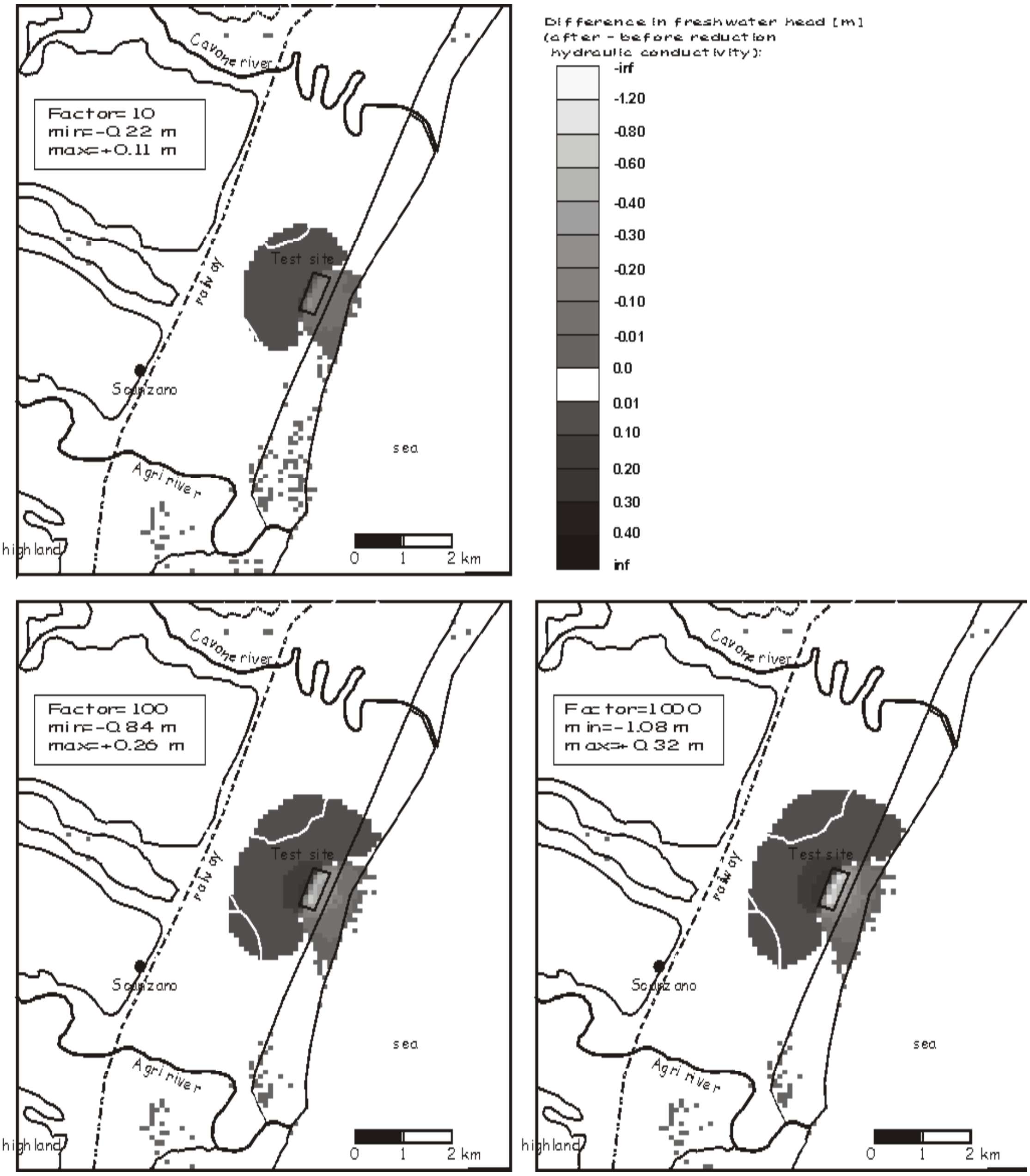

Figure 9: Effect of the reduction of the hydraulic conductivity on the head distribution at layer 20 (0 -+1 m a.s.l.).

CONCLUSIONS

The regional model of density dependent groundwater flow and solute transport in the coastal plain of the Italian region of Basilicata, South Italy, nearby the city of Scanzano, is ready, though seasonal fine-tuning is essential. A change in freshwater heads is only detectable if hydraulic conductivity reduction is large and the length of the barrier is substantial. A local model is necessary to simulate multicomponent solute transport in a variable-density groundwater system at the field test site.

FUTURE RESEARCH

Scenarios of injection/extraction well schemes will be tested numerically to determine the possibility of in-situ mixing of solutions. A local model will be constructed to consider the relevant hydrogeological and geochemical processes in the subsoil: viz. precipitation and dissolution of solutes that is under influence of an inhibitor, which eventually will lead to the formation of slightly soluble minerals. For this purpose, reactive flow and solute transport are coupled with groundwater flow, as also changes in porosity and permeability are considered.

ACKNOWLEDGEMENTS

The author wishes to thank the C.N.R.-I.R.P.I. (ex Ce.Ri.S.T.) Team, viz. Maurizio, Donatella, Pier Paolo and Francesca for assisting and providing the author with all necessary hydrogeological data.

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RINGRAZIAMENTI
ACKNOWLEDGEMENTS

La sperimentazione in territorio italiano del Progetto CRYSTECHASALIN ha tratto notevole giovamento dalla concreta adesione, fin dalla preparazione della proposta progettuale, del Consorzio di Bonifica di Bradano e Metaponto, partner del Progetto, e dalla disponibilità del Comune di Scanzano, del cui Sindaco di seguito si riportano i *Saluti.* Il IV Meeting del Progetto ha beneficiato dell'ospitalità di entrambe le istituzioni alle quali, unitamente al Direttore del Consorzio, Dott. Antonino Ferrara, e al Sindaco, Mario Alterieri, si esprime un vivido ringraziamento.

Si ringraziano inoltre la SE.IN Perforazioni (Ardea, RM) e la Assofruit scarl (Scanzano J., MT) per aver contribuito alla stampa di questo volume.

SALUTI DELLA MUNICIPALITÀ DI SCANZANO JONICO

La complessità e la vastità delle tematiche affrontate, in questo lavoro mettono in chiara evidenza come la mancanza di una visione complessiva e di un disegno programmatico di indirizzo politico e gestionale ha agevolato, quando non direttamente innescato, il progressivo depauperamento dell'ambiente e delle risorse naturali. L'Amministrazione Comunale che dirigo ha favorevolmente accolto l'invito del CNR ad ospitare sul proprio territorio tutta la fase di studio e di sperimentazione della tecnica innovativa basata sulla cristallizzazione controllata, sicuro che utilizzando esperienza e conoscenze scientifiche di tutti gli studiosi che partecipano alle varie fasi del progetto, si giungerà ad efficaci interventi di salvaguardia delle acque sotterranee. Sono certo, pertanto, che l'accoglimento del libro da parte degli interessati sarà pari all'entusiasmo ed all'appassionato impegno che gli Autori hanno dedicato a questo loro lavoro.

Il Sindaco
Mario Altieri