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Conceptualization, modelling and management of alluvial aquifers: case studies of Sangro and Vomano plains (central Italy)

Concettualizzazione, modellazione e gestione di acquiferi alluvionali: i casi di studio delle piane del Sangro e del Vomano (Italia centrale)

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ABSTRACT - The analysis of complex hydrogeological problems related to alluvial aquifers through conceptualization and numerical modelling is of great relevance particularly for defence and management of groundwater and surface water systems. Assessment of conceptual models and uncertainties related to system geometries, parameter distributions, boundary and internal conditions are essential in application of density-dependent flow and transport numerical modelling.

Investigations and numerical analysis have been carried out on Sangro and Vomano rivers alluvial plains (Central Italy), supported by specific hydrogeological and hydrochemical geodatabases within ESRI ArcGIS platform and developed using finite-difference MODFLOW and density-dependent finite-element FEFLOW numerical codes.

These studies highlight the role of aquifer geometry, recharge conditions and hydrodynamic processes related to main hydrological features and applied stresses. The management of well fields exploitation for drinking and irrigation purposes has also been assessed, considering hydraulic connections with surface water bodies and groundwater hydrochemistry. The alluvial plains waters are characterized by facies of both Apennine origin and up flow from deep underlying mineralized systems; there is also evidence of marine intrusion phenomena along coastal areas. The found chemical-physical layering of groundwater proves to be important to environmental characterization and monitoring.

By focusing on the key-role of rivers as recharge and drainage bodies and hydrogeological properties of major palaeo-rivers, numerical modelling supported an overall analysis of the underground hydrology, including analysis of fundamental components of local hydrogeological balance, flow pathlines and velocity fields, as well as possible problems related to contaminants migration. After calibration processes, models have been used to investigate some major issues, concerning optimisation of well fields pumping regimes as well as establishment of wellhead protection areas.

The salt water intrusion dynamics, which often play a major role along the eastern Italian coastline, are amplified by localized groundwater exploitations as proved by physical-chemical evidence. Simulated scenarios confirm risks of marine intrusion due to groundwater over-exploitations related to civil uses and irrigation; mobilisation of salt waters normally requires some years to take place but is a persistent phenomenon once established.

Long-term environmental monitoring, system conceptual refinement, numerical models uptuning are of fundamental importance for confidence building on simulation results for comprehension of relevant hydrological processes and adequate decision-making in socio-economic changing times.

KEY WORDS: alluvial aquifers, Central Italy, conceptualization, density-dependent conditions, groundwater modelling.

RIASSUNTO - L'analisi di problematiche idrogeologiche complesse di acquiferi alluvionali tramite un approccio integrato basato su concettualizzazione e modellistica numerica è fondamentale per la difesa e la gestione dei sistemi idrici superficiali e sotterranei. La definizione dei modelli concettuali, in relazione alla variabilità delle geometrie dei sistemi, dell'entità e distribuzione dei parametri, delle condizioni interne ed al contorno, è presupposto essenziale per l'analisi modellistica di flusso e trasporto in condizioni densità-dipendenti.

Indagini ed analisi modellistiche hanno riguardato gli acquiferi delle piane alluvionali dei fiumi Sangro e Vomano (Italia centrale), sviluppate con il supporto di specifici geodatabase idrogeologici ed idrochimici, implementati in ambiente ESRI ArcGIS, e tramite i codici numerici alle differenze finite, MODFLOW, ed agli elementi finiti, FEFLOW. Gli studi condotti evidenziano il ruolo della geometria degli acquiferi, delle condizioni di ricarica e dei processi idrodinamici in relazione ai principali elementi di rilevanza idrogeologica e degli emungimenti operati. La gestione degli emungimenti, in particolare da campi pozzi per uso idropotabile ed irriguo, è stata valutata in relazione alle condizioni di ricarica, riconducibili prevalentemente ai corpi idrici superficiali, ed alle caratteristiche idrochimiche delle

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falde idriche di subalveo. Le acque sotterranee presentano facies di origine appenninica e di risalita da sistemi mineralizzati profondi attraverso fasce tettonizzate; nelle zone costiere sono evidenti salinizzazioni delle acque sotterranee riconducibili sia a fenomeni localizzati di *upconing* che di ingressione del cuneo salino. La zonalità chimico-fisica verticale rilevata risulta di fondamentale importanza per la caratterizzazione ed il monitoraggio ambientale. Le analisi modellistiche, condotte in condizioni 3-D densità-dipendenti, evidenziando il ruolo dei corpi idrici superficiali come principali elementi di ricarica e drenaggio e delle proprietà idrogeologiche dei principali paleoalvei, hanno permesso di ricostruire la circolazione idrica sotterranea, incluso le componenti fondamentali del bilancio idrogeologico locale, tracciare le linee di flusso e definire i campi di velocità, oltre che di valutare problemi relativi alla migrazione di contaminanti. I modelli numerici implementati, a seguito di calibrazione ed analisi di sensitività parametrica, sono stati impiegati per l'analisi di problematiche relative all'ottimizzazione dei regimi di emungimento dei campi pozzi esistenti ed alla definizione delle aree di salvaguardia delle captazioni.

Le dinamiche di intrusione salina, rilevanti nelle zone costiere adriatiche, sono accentuate da emungimenti idrici concentrati, come evidenziato dalle evidenze chimico-fisiche. Gli scenari simulati confermano il rischio di fenomeni di intrusione salina riconducibili a sovraemungimenti; i tempi di mobilizzazione delle acque salate sono generalmente lunghi, nell'ordine di anni, ma tali fenomeni sono estremamente persistenti qualora si manifestino.

Il monitoraggio ambientale di lungo periodo e l'affinamento continuo dei modelli concettuali e numerici dei sistemi idrogeologici sono di fondamentale importanza nel processo di sviluppo confidenziale nei risultati degli scenari simulati sia per la comprensione dei processi idrogeologici ed idrochimici rilevanti che per gli aspetti decisionali in un contesto socio-economico ed ambientale recentemente in rapida e talora drammatica evoluzione.

PAROLE CHIAVE: acquiferi alluvionali, concettualizzazione, condizioni densità-dipendenti, Italia centrale, modellistica numerica.

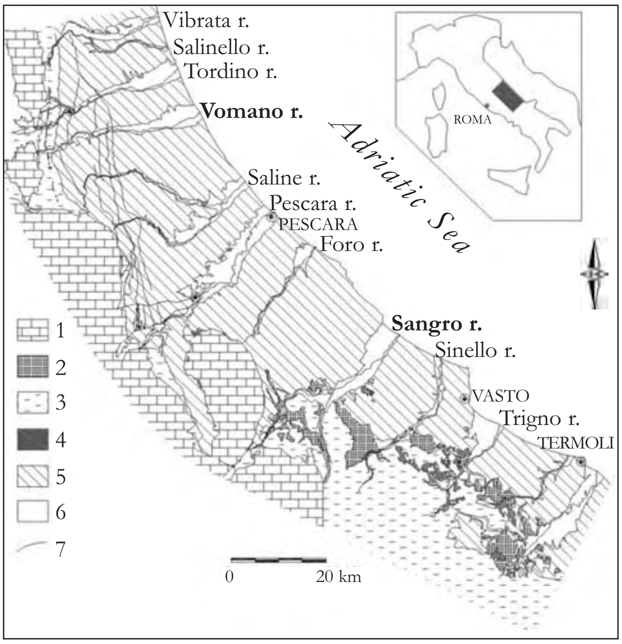

Fig. 1 – Location of the case studies and geolithological scheme. 1) Carbonate sequence (Upper Triassic-Miocene). 2) Varicoloured Clays (Upper Cretaceous-Oligocene). 3) Turbiditic deposits (Laga formation and Molise nappe, Miocene). 4) Evaporitic deposits (Upper Miocene). 5) Pelitic deposits of Abruzzo and Molise foredeep (Plio-Pleistocene). 6) Alluvial deposits (Holocene). 7) Main faults and thrusts in the Mesozoic-Cenozoic and Miocene deposits.
- Ubicazione dei casi di studio e schema geolitologico. 1) Successione carbonatica (Triassico superiore–Miocene). 2) Argille Varicolori (Cretaceo superiore-Oligocene). 3) Depositi torbiditici (Formazione della Laga e coltre molisana, Miocene). 4) Depositi evaporitici (Miocene superiore). 5) Depositi pelitici dell'avanfossa abruzzese – molisana (Plio-Pleistocene). 6) Depositi alluvionali (Olocene). 7) Principali faglie e sovrascorrimenti nei depositi meso-cenozoici e miocenici.

1. - INTRODUCTION

The conceptual models, based on hydrogeological setting and principal hydrodynamic and hydrochemical aquifer characteristics are fundamental for numerical modelling applications finalized to water resources analysis and management; investigations and numerical analysis have been developed for Sangro and Vomano river plains (Central Italy) and presented (fig. 1), in current paper, as representative case studies for characterization, modelling and management of alluvial aquifers.

Depositional environments and aquifer geometry have been defined with the aid of geological, geomorphological, photogeological, geognostic and geophysical investigations (over 170 boreholes in Sangro plain and over 120 VES and 20 boreholes in Vomano plain).

The hydrological balance was evaluated using data from pluviometric and thermometric stations within hydrologic basins; the aquifer hydrodynamics was investigated considering seasonal piezometric measurements in monitoring wells and water springs, and pumping tests, with contemporary acquisition of physical-chemical groundwater parameters; chemical analysis of groundwater samples were used to define hydrochemical facies. Specific salinization processes, such as sea-water intrusion in coastal area and upward migration of deep waters along alluvial plain borders, were analysed by multiparametric profiles and chemical analysis.

Data and information management, analysis and visualisation were undertaken through development of hydrogeological geodatabases in ArcGIS environment (ESRI, 2009), inspired by ArcHydro (MAIDMENT, 2002) and Groundwater Data Model (STRASSBERG & MAIDMENT, 2004) and useful for data exchange with the finite-difference MODFLOW (MCDONALD & HARBAUGH, 1984; MCDONALD *et alii*, 2000) and finite-element FEFLOW (DHI-WASY, 2009) numerical codes; geostatistical and statistical analysis was undertaken within external software environments like GeoDa (ANSELIN, 2004).

A regional numerical model, relative to lower

Sangro alluvial valley (DESIDERIO *et alii*, 2007) was developed to estimate groundwater resources and river-aquifer exchanges, while a local scale numerical model was also developed for saline intrusion phenomena analysis in coastal area, both applied for interpretation purposes (ANDERSON & WOESSNER, 1992) and simulation of different exploitation scenarios.

The Vomano valley aquifer, playing a key-role on water supply at both local and regional scale, has been previously analysed for definition of hydrogeological settings and groundwater dynamics (recharge, geometry, parameter distribution, surface water body interactions and fresh-salt water interface) by DESIDERIO *et alii* (2003), DESIDERIO & RUSI (2003), RUSI *et alii* (2004).

The optimisation of well fields pumping regimes and protection of water resource quality represent some major hot issues for a sustainable development; the application of groundwater modelling techniques has improved the knowledge of hydrogeological framework, useful for problems analysis related to concentrated groundwater exploitations, as sea water intrusion, and impacts of anthropic activities.

2. – THE SANGRO ALLUVIAL VALLEY

2.1. – GEOLOGICAL SETTING

The lower Sangro valley (fig. 2) is located between the terrigenous alloctonous units of the molisan facies (SELLI, 1962; CATENACCI, 1974; PATACCA *et alii*, 1992) and plio-pleistocenic marine deposits of the Abruzzo-Molise foredeep (MOSTARDINI & MERLINI, 1986; GHISETTI & VEZZANI, 1996-97); these units, mainly clayey deposits, constitute the basement of the alluvial deposits (fig. 3) superimposed on top of the Aventino-Sangro gravity flow deposits (ENI-AGIP, 1972), upstream of the confluence with Aventino river, while overlay marine plio-pleistocenic deposits downstream (CRESCENTI, 1971; CRESCENTI *et alii*, 1980). The plio-pleistocenic basement is mainly constituted by clays, sandy clays and marly clays, while arenaceous conglomerates are predominant near the coastal areas; sometimes the arenaceous conglomerates vary to sandy silts and clayey silts that have typical facies of marine-coastal to fluvio-deltaic environments.

The I, II and III order alluvial terraces are con-

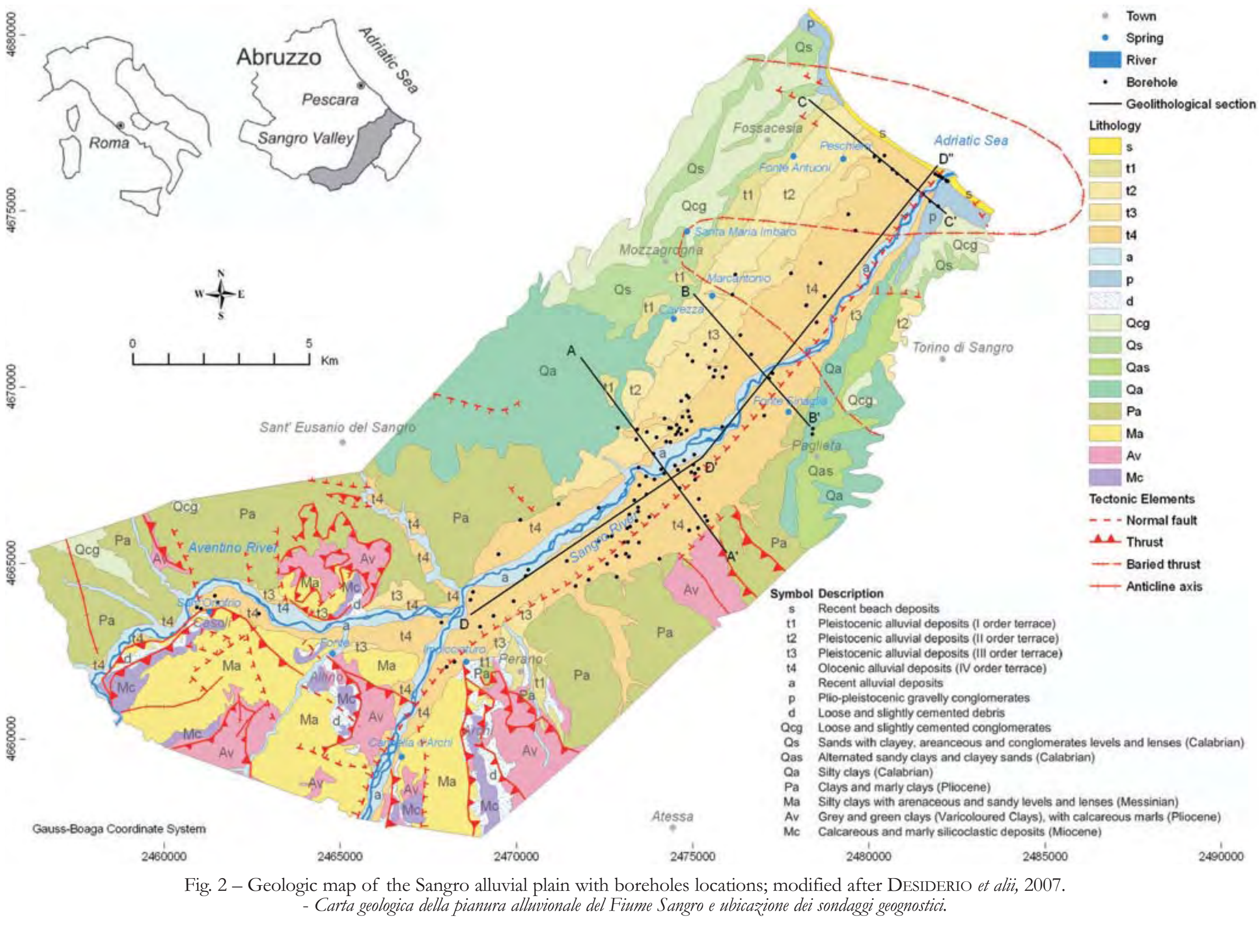

Fig. 2 – Geologic map of the Sangro alluvial plain with boreholes locations; modified after DESIDERIO *et alii,* 2007.
- Carta geologica della pianura alluvionale del Fiume Sangro e ubicazione dei sondaggi geognostici.

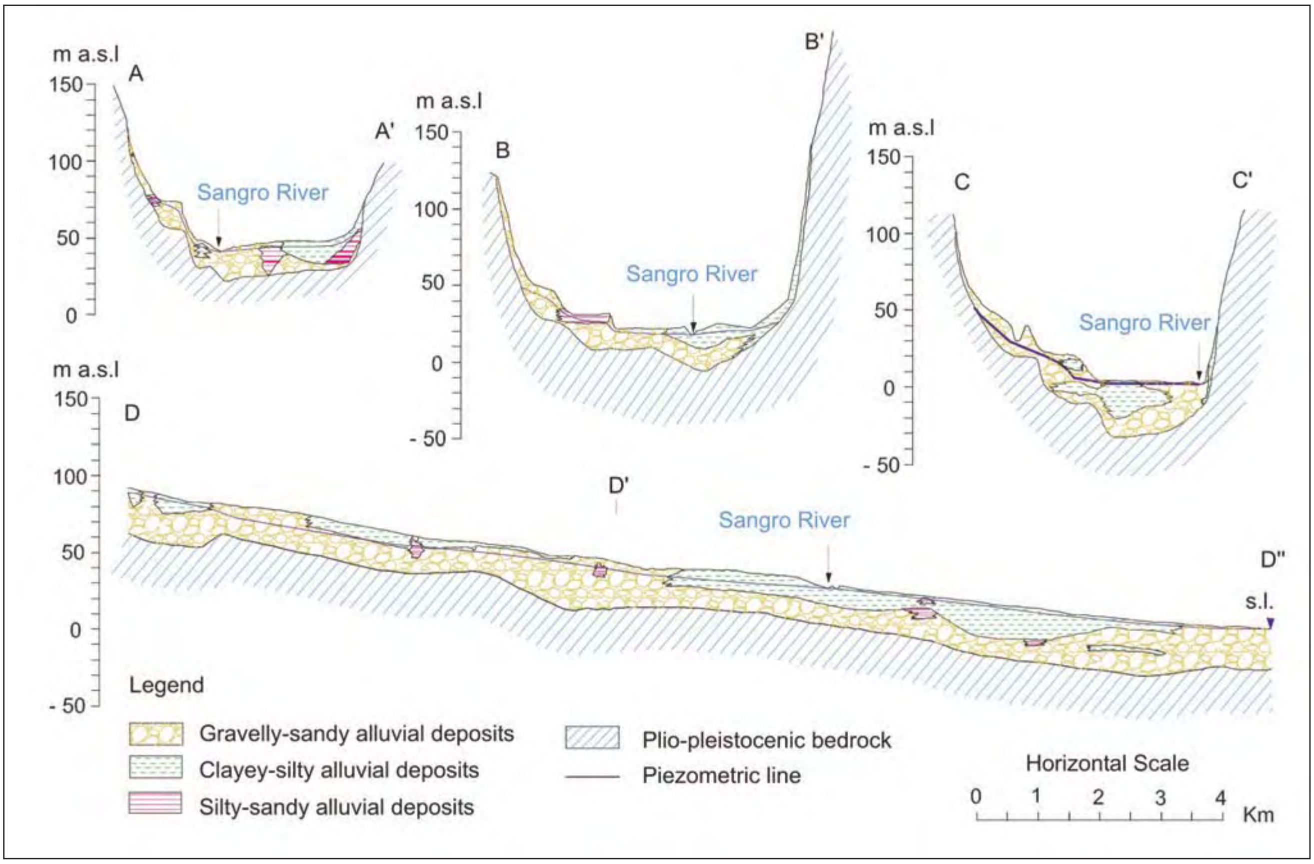

Fig. 3 - Schematic geolithological sections of the Sangro alluvial plain; modified after DESIDERIO *et alii*, 2007.
- *Sezioni geolitologiche schematiche della piana alluvionale del Sangro.*

stituted by gravelly sand deposits, sometimes slightly cemented, with silty-sandy-clayey lens and occasional brown-blackish paleosoils. The sandy matrix shows ferritazation signs more evident in relation to the deposits age. Sandy and gravelly deposits with silty-sands and clayey lens constitute the IV order alluvial terrace, which has been cut by Sangro river. Thalweg alluvial deposits are mainly formed of gravels and sands.

The alluvial deposits are located in corrispondence of a complicated mainly strike-slip faults system related to Volturno-Sangro tectonic lineament (DEMANGEOT, 1965; CASNEDI *et alii*, 1981; GHISETTI & VEZZANI, 1983).

The coastal areas are dominated by gravelly and sandy beach deposits and sandy fluvial deposits related to the latest flandrian marine ingression; huge debris deposits, related to weathering of plio-pleistocenic hills, lay on Sangro river right side.

2.2. - HYDROLOGY AND ANTHROPIC SETTING

The hydrological balance was evaluated considering data from 34 pluviometric and thermometric stations (SERVIZIO IDROGRAFICO E MAREOGRAFICO, 1955-1995) of the whole Sangro-Aventino hydrologic basin, considering a 40 years observation period; the network has been integrated also by 8 fictitious pluviometric stations.

Applying TURC (1961) and THORNTHWAITE & MATHER (1957) methodologies, the mean precipitation is about 1060÷1080 mm/year while the global surface runoff of about 560÷670 mm/year, with high spatial variations due to orography, distance from sea and provenience of humid currents. The pluviometric regime underlines an Apennine sublittoral climate, with marine influences in coastal area; the minimum precipitation values occur in summer time and along coastal area, while the maximum ones occur in winter and spring months, especially in mountainous zones, when the temperature is also lower.

The Sangro alluvial plains is characterized by an enormous social and economic development that require a huge hydroelectric, irrigation, industrial and civil exploitation of superficial and groundwater resources; the Sangro river flow regime is influenced by dams of Bomba, Casoli, Serranella and Sant'Angelo of Altino hydroelectric stations, with an average discharge to sea of about 30 m^3/s.

2.3. - HYDROGEOLOGY

Sangro aquifer geometry has been defined by surface geological and geomorphological surveys, photogeological multitemporal and multiscale analysis and bibliographical geognostic and geophysical investigations (fig. 2). The aquifer is constituted by recent and ancient alluvial deposits characterized by high variable grain-size.

The thickness of the I, II and III order terraces are between 2÷3 m up to 30 m, while the recent alluvial deposits thickness ranges from a few meters in the upstream and lateral plain areas up to 35÷40 m near the coastline (fig. 3). The upstream area is dominated by sandy-gravelly deposits, with only local thin silty-sandy and silty-clayey deposits, while the central and downstream areas of the valley are dominated by gravelly-sandy deposits with clayey-silty lens on Sangro river left side, and silty-sandy and silty-clayey deposits, on the right side. The silty-clayey deposits on the alluvial succession top are relatively thick in the central valley, about 15 m, and near coastline, up to 20 m; topsoil, mainly constituted by organic silty clays, is about 1÷2 m thick. The aquifer is unconfined even if the silty-clayey lens often tend to configure as aquitards near coastline and on Sangro river right side (DE RISO *et alii*, 1994), a typical condition of many Abruzzo and Marche alluvial plains (NANNI, 1985; DESIDERIO *et alii*, 1999), and only locally is multilayer.

2.4. - HYDRODYNAMICS

The Sangro valley piezometry and its temporal oscillations have been evaluated by seasonal surveys on over 160 wells.

Groundwater flow is mainly influenced by paleo-rivers (fig. 4), from alluvial plain borders towards the main water body. Piezometry is dependent on basement morphology, amounts of seasonal recharge and withdrawals, thus the hydraulic aquifer-river exchanges tend to vary. The main drainage axis lays on Sangro river right side in central-upper alluvial plain, then moves to left side due to the presence of a groundwater divide, and converges again towards the river in coastal area. Large depression cones are related to heavy with-

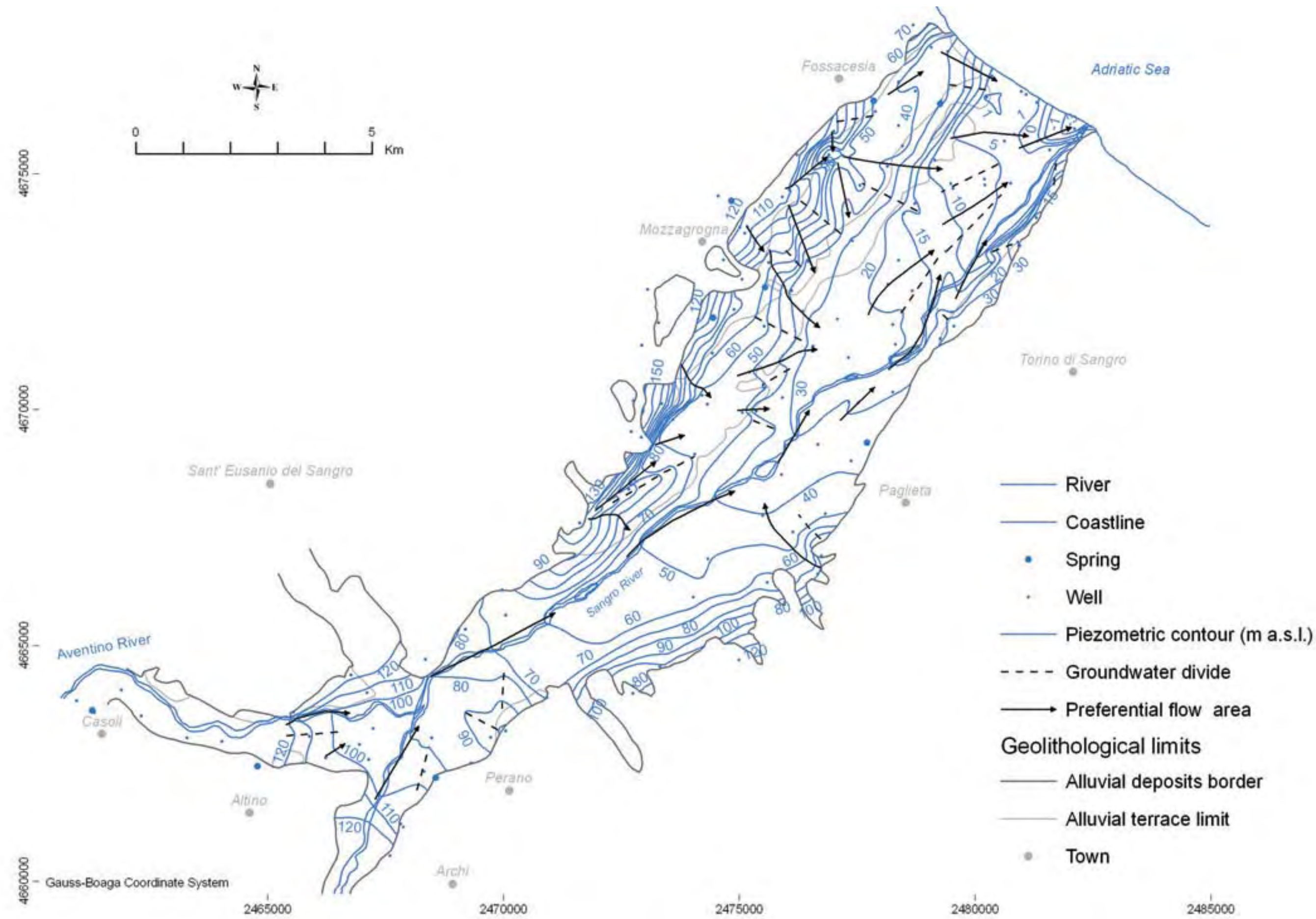

Fig. 4 – Piezometric heads with preferential flow areas and groundwater devides (April 2000), on the basis of more than 160 wells and 10 springs; modified after DESIDERIO *et alii*, 2007.
- *Piezometria con le principali aree di deflusso preferenziali e spartiacque sotterranei (Aprile 2000), ricostruita sulla base di oltre 160 pozzi e 10 sorgenti.*

drawals for irrigation purposes. Upper alluvial terraces contribute to recharge of the preferential drainage axis in relation to surface and basement morphology, hydraulic conductivities, geometry and Plio-Pleistocene system contributions.

Hydraulic gradient is about 4÷5‰ near the recent and IV order terrace deposits and 20÷50‰ in other areas; it is locally higher due to aquifer thinning, hydraulic conductivity variations and local recharge conditions. Groundwater exchange occurs from alluvial terraces towards recent deposits due to sandy-silty overlying layers assuring hydraulic communication; hydraulic gradient increase in coastal area is related to silty-clayey deposits.

Piezometric oscillations are related to amount and distribution of effective recharge related to precipitations, hydrodynamic characteristics of alluvial and overlying deposits, infiltration from surface streams, irrigation and withdrawals. Annual water table oscillations vary from 0.3 up to 1.3 m, with maximum levels recorded in March-April and minimum ones in July-August; variations, after rainfall events, occur within 1÷2 months, due to medium and high hydraulic conductivities. The discharge period varies from 4 up to 5÷6 months, while recharge period varies from 4 up to 8 months.

Aquifer hydrodynamic properties (SCANDELLARI, 1970; CELICO, 1983; DE RISO *et alii*, 1994; DESIDERIO *et alii*, 2007) depend on silt, silty-sandy and silty-clayey deposits distribution with an average hydraulic conductivity value less than 4×10^{-4} m/s. The gravelly-sandy deposits have hydraulic conductivity values varying from 1.8×10^{-4} m/s up to 4.4×10^{-4} m/s. Paleo-river conductivities are about 2×10^{-3} m/s. The Sangro river has strong water exchange, variable through time, with its underlying aquifer. Locally relevant water quantities flow also from secondary valleys. Sangro aquifer water flux towards Adriatic sea is estimated of about 0.2÷0.3 m^3/s (DESIDERIO *et alii*, 2007).

Some springs, monitored between October 2000 and November 2001, are located at the contact between terraced alluvial deposits and low conductivity gravity flow and Plio-Pleistocene deposits. Spring discharges, generally modest and concentrated during winter, are normally less than 1 l/s with short time responses of 1÷2 months or even lower, days, to rainfall events; discharge regimes are extremely variable, Rv > 100% (MEINZER, 1923), related to limited recharge zones and high hydraulic conductivities.

The wells are used mostly for irrigation, sometimes for civil uses; pumping rates, varying from 1÷5 l/s up to 10÷15 l/s, are discontinuous in time and applied principally during dry seasons.

2.5. – HYDROCHEMISTRY

Specific electrical conductivities highlight spatial and temporal changes in Sangro plain varying from about 400 to more than 2000 μS/cm. The lower values are found in the medium to higher valley in correspondence of preferential flow axis and I, II and III alluvial terraces. Dilution effects cause lowering of specific conductivity values in periods of higher aquifer recharge; in the lower valley there are locally opposite trends due to dissolution of substances in unsaturated zone.

Values higher than 2000 μS/cm, also more than 7000 μS/cm, are detected in coastal area due to sea water intrusion related to localized withdrawals; values between 3000 and 11400 μS/cm were detected in the medium-lower valley, all the way to the river outlet; these anomalies are related to upward migration of deep mineralized waters (DESIDERIO & RUSI, 2004). Groundwater temperatures are influenced by atmospheric variations in lower valley due to a shallow water table. Temperature ranges from 12 up to 18 °C in winter and 15 up to 28 °C in summer. Groundwater temperatures along preferential drainage axis are lower than those of the next recharge areas due to different circulation times.

Spring waters monitoring has shown average specific conductivity values from 695 up to 1624 μS/cm. Average temperatures, from 13.9 up to 16.6°C, are essentially related to atmospheric temperature varations.

The dominant hydrochemical facies within Sangro aquifer is bicarbonate-calcium facies (fig. 5). Some waters have bicarbonate-alkaline and sulphate-chloride-earthy alkaline facies; the later is related to mixing with deep and marine mineral-

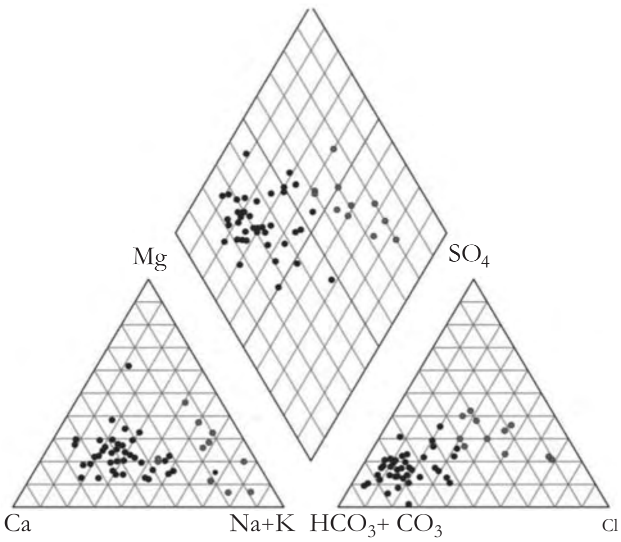

Fig. 5 – Piper's diagram of the Sangro plain groundwaters.
– *Diagramma di Piper relativo alle acque della piana del Sangro.*

ized waters. Bicarbonate-calcium waters are mainly distributed in the higher valley and along river thalweg, where appennine origin waters prevail.

2.5.1. - *Deep flow mineralization*

Mineralised waters, typical of areas with high specific electrical conductivity, normally have sulphate-chlorine-alkaline-earthy alkaline facies, as chloride-sodium and sulphate-sodium. These anomalies are related to saline intrusions (DESIDERIO & RUSI, 2003), due to upward migration of deep mineralized waters from Abruzzo-Molise foredeep, and dissolution of evaporitic deposits within the depositional sequence (DESIDERIO & RUSI, 2004).

Mineralization phenomena are proved on the basis of the ^{18}O - ^{2}H isotopic ratio and rSO_4^{2-}/rCl^- and rMg^{2-}/rCa^{2-} characteristic ion ratios; other typical ion ratios like rK^+/rNa^+, rSr^{2+}/rBr^-, rBr^-/rCl^- and rLi^+/rSr^{2+} are also evidence of these phenomena. Mineralized waters along tectonic lineaments on Sangro right side have higher rSO_4^{2-}/rCl^- and rMg^{2-}/rCa^{2-} ion ratios, while water, affected by saline intrusions have lower values than average aquifer deposits.

The unconfined aquifer is recharged mainly by fluvial waters from calcium-bicarbonate facies of Apennine origin, as confirmed by electrical conductivity and groundwater temperature values. River recharge is further testified by groundwater chemistry; close to riverbed the waters present calcium-bicarbonate facies with low saline content. Waters of this type are also found along paleo-river draining Vomano river and its primary tributaries. The high terraces, on the other hand, are recharged mostly by rainwater. Deep flow mineralization is due to Pliocene or Messinian origin waters (NANNI & VIVALDA, 1998, 1999 and 1999a; DESIDERIO & RUSI, 2004, DESIDERIO *et alii*, 2007b), rising along fault-associated fracture zones in plio-pleistocenic basement deposits up to overlaying unconfined aquifer. The mixing of sodium-chloride and calcium-sulfate facies Pliocene and Messinian mineralised waters with the calcium-bicarbonate waters of the aquifer lead to different hydrochemical facies in emerging zones. Recharge by the Messinian and Pliocene waters is very slight and mainly influences the groundwater chemistry, causing enrichment in Cl^-, Na^+, Mg^{++} and SO_4^{--} of calcium-bicarbonate waters originating from fluvial recharge (fig. 5).

2.5.2. – *Sea-water intrusion*

Piezometric levels show minimum values, sometimes negative, on Sangro river left side near coastline, related to withdrawals for irrigation purposes during summer (10÷15 l/s). Local drainage from river occurs where gravelly and sandy alluvial deposits related to paleo-rivers are present. There is a vast recharge area to the western side, which partially compensates summer withdrawals.

The multiparametric profiles conducted on monitoring wells located in the lower valley (fig. 6) show a three dimensional variability of groundwater chemical-physical (T, χ, Eh) parameters (fig. 7).

Temperature measurements ranged from 14.4 up to 26.8 °C in July 2005. Vertical temperature changes are generally modest; negative trends were recorded within upper aquifer related to influence of surface temperatures and subsurface hydrodynamics.

Electrical conductivity values change more than 8000 µS/cm along the vertical. This parameter often increases at just 1÷2 m below the surface in coastal areas. In other wells, even though water exploitations occur (discontinuous and variable, between 1 and 5 l/s), chemical-physical parameters tend to be constant along the vertical, due to greater hydraulic conductivities. Specific electrical conductivity values exceed 2000 µS/cm near the left side river outlet, where a negative piezometry of more than -1 m a.s.l. exists. These irrigation wells tend to mobilise higher salinity waters. Values larger than 5000 µS/cm in vertical direction were recorded in wells located at about 1 km from the coastline where no exploitations occur, due to upward migration of deep water from the plio-pleistocenic deposits (DESIDERIO & RUSI, 2004).

The Eh parameter tends to decrease with depth, from 2÷3 m from the water table, then stabilizes on negative values. The reducing conditions are related to circulation within deposits with a silt-clay fraction, sometimes peaty, characterized by low hydraulic conductivities. A possible influence is related with mobilization of deep waters with negative Eh values.

2.6. - MODEL DESIGN, CALIBRATION AND SENSITIVITY ANALYSIS

Scope of Sangro valley groundwater numerical modelling, carried out by the finite-element FEFLOW code (DHI-WASY, 2009), was the quantitative assessment of underground water fluxes and saline intrusion phenomena. The conceptual model is supported by soft ideas (NYKRAVESH *et alii*, 2003; AMINZADEH, 2004). This method enhances peculiar aquifer characteristics. Integrated use of both hard data and soft ideas are fundamental for defining aquifer geometries,

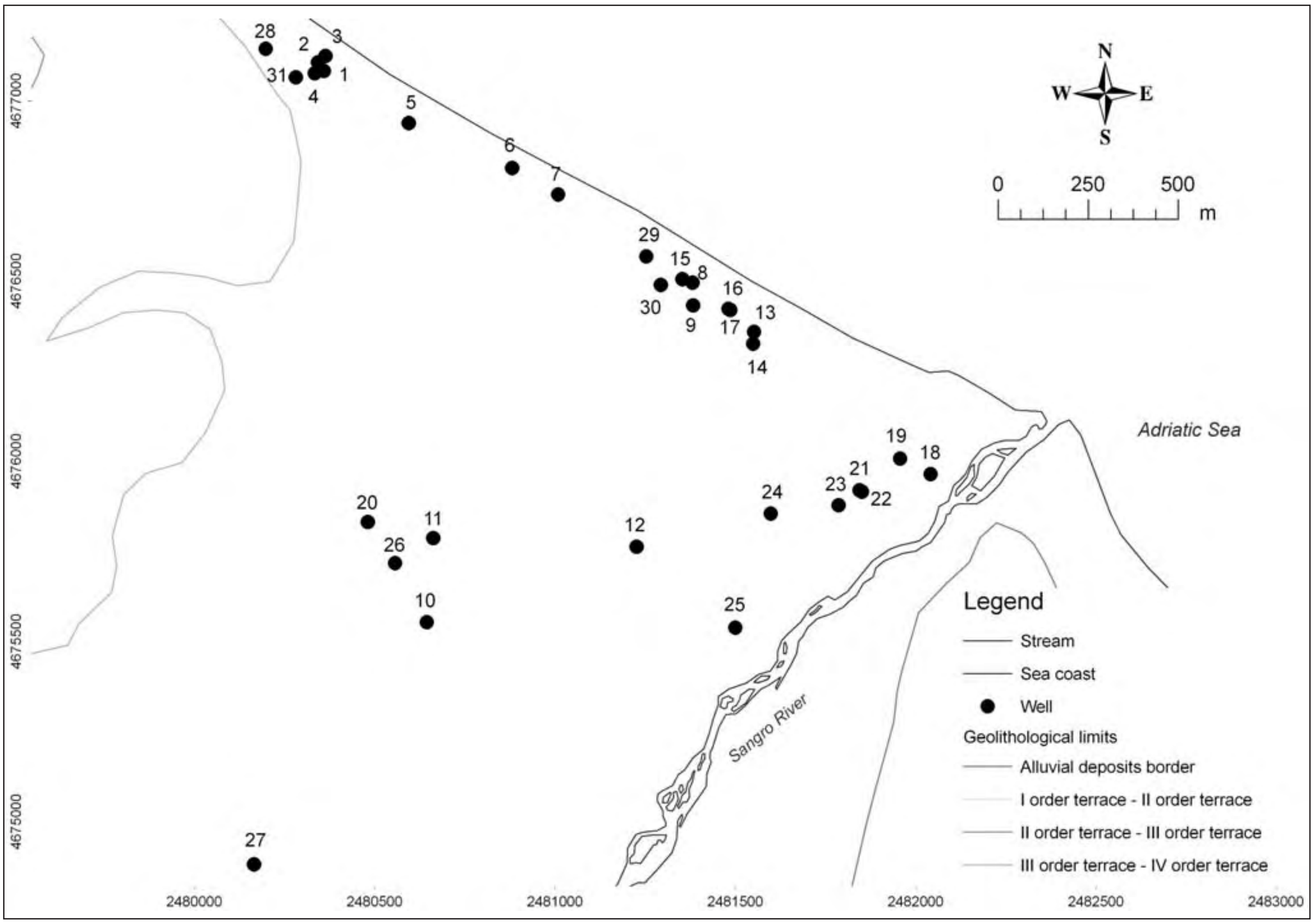

Fig. 6 - Wells used for multiparametric logs.
- Pozzi nei quali sono stati eseguiti i profili multiparametrici.

hydrodynamic parameters, effective recharge and issues related with salt water intrusion phenomena. Variability of hydrogeological and hydrogeochemical parameters and boundary conditions was analysed respect to simulation of conservative scenarios.

A regional numerical model was built to assess groundwater resources, river-aquifer water exchange, the influence of palaeo-rivers and fluxes from alluvial terraces; a local model was so used to estimate groundwater fluxes to sea and saline intrusion phenomena, with higher resolution details in coastal area.

The regional 3D mesh (fig. 8), developed over an area of about 82.67×10^6 m^2, has 118380 elements and 76360 nodes over 5 vertical layers. The dimensions of the triangular-based prismatic elements gradually vary from 120÷130 to 25÷30 m near wells. Steady-state conditions were used during simulations with free and movable conditions (DIERSCH & MICHELS, 1996; DIERSCH, 1998). Geometry settings was defined on the basis of 55 geolithological sections, while hydrogeological parameters were assigned on the basis of available hydrodynamic data.

The hydraulic conductivities and the recharges were distributed on a zone basis (ANDERSON & WOESSNER, 1992; PINDER, 2002; RUSHTON, 2005). Hydraulic conductivities of 8×10^{-4} m/s were considered reasonable for the IV order terraces and recent deposits. Hydraulic gradients and borehole logs justify hydraulic conductivity values of about 2.5×10^{-3} m/s in areas of preferential flow, with analogies to other Abruzzo coastal alluvial valleys (CELICO 1983; DESIDERIO *et alii*, 2007a). Silty-sandy drift deposits have an hydraulic conductivity of 4×10^{-4} m/s (SCANDELLARI, 1970). The regional model is not very reliable in relation to the I, II and III order terraces due to scarce availability of data. Hydraulic conductivities however vary from 7×10^{-4} up to 2×10^{-3} m/s. The hydrodynamic parameters, evaluated through numerical modelling, produce plausible piezometric configurations.

Effective recharge was differentiated respect to estimated rainfall recharge and surface lithologies; locally recharge components are also related to irrigation, especially during dry seasons. Sensitivity analysis proves that modest parameter

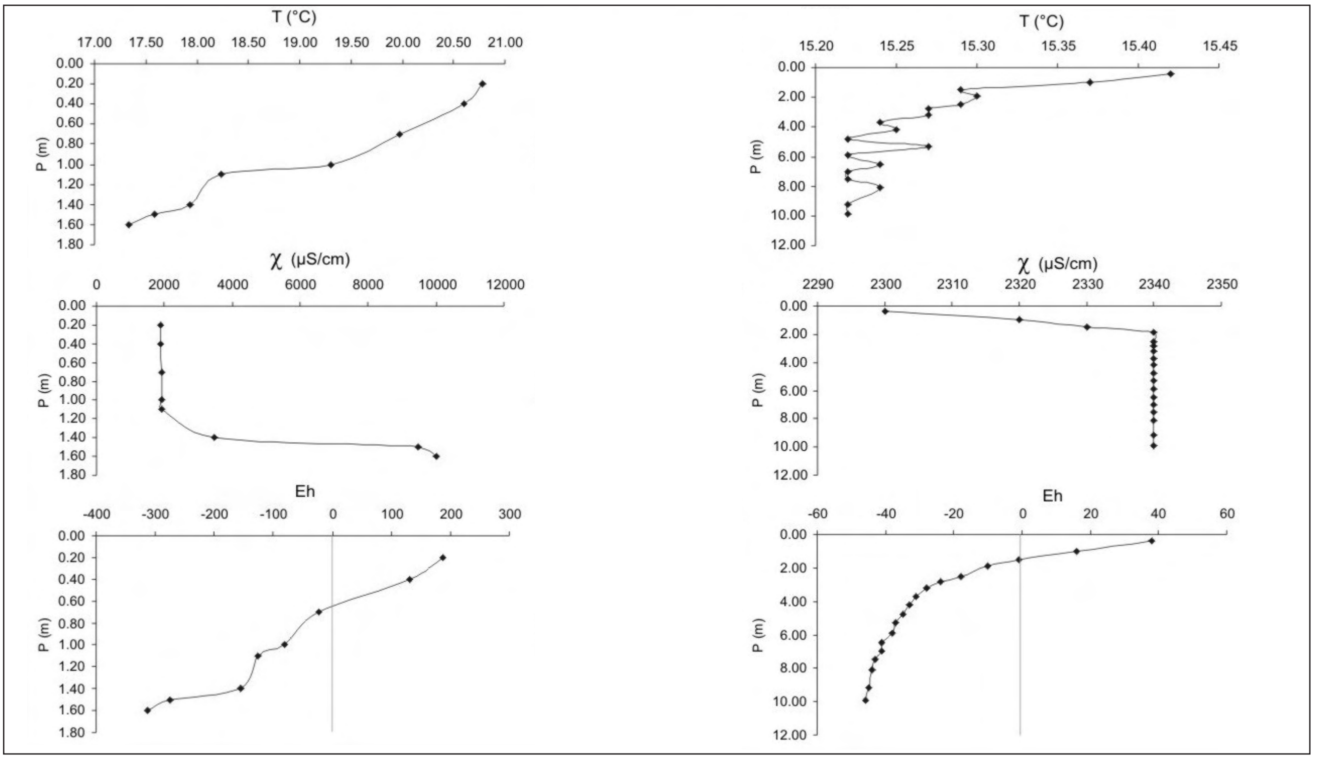

Fig. 7 – Multiparametric logs of a coastal well (at left, n. 7 in figure 6) and a well with mineralized waters (at right, n. 12 in figure 6).
– Profili multiparametrici di un pozzo costiero (a sinistra, n. 7 in figura 6) e di un pozzo con acque mineralizzate (a destra, n. 12 in figura 6).

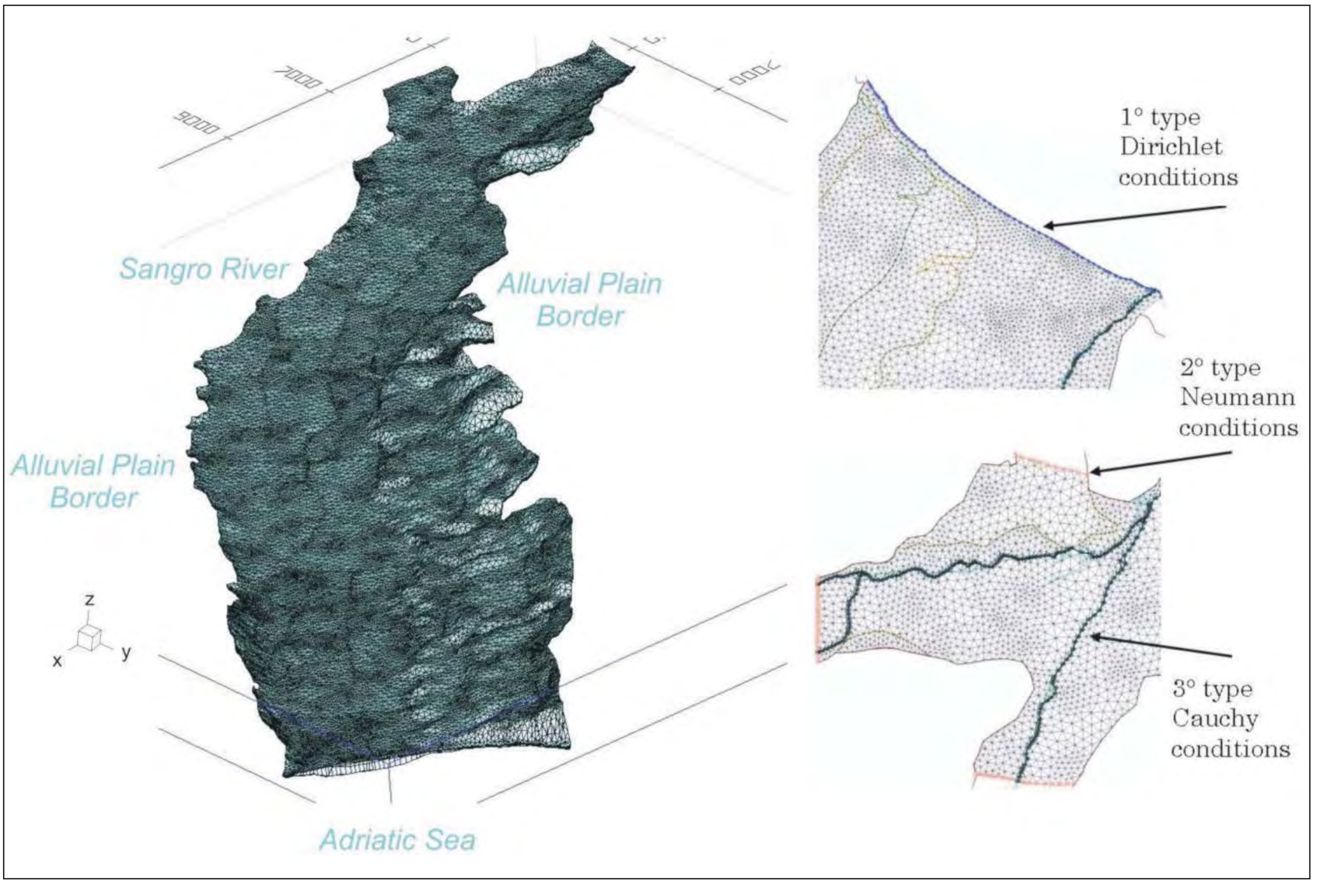

Fig. 8 - 3D mesh and boundary conditions of the Sangro plain regional numerical model (exaggeration factor 10:1); mod. from DESIDERIO *et alii*, 2007.
- Mesh 3D e condizioni al contorno del modello numerico, a scala regionale, della piana del Sangro (esagerazione verticale 10:1).

changes have a great influence in hydraulic heads distribution.

Boundary conditions were assigned considering hydrogeological characteristics and model domain extends up to Plio-Pleistocene hills, while the basement is considered impermeable. In the higher alluvial plain border and in correspondence of secondary valleys, fixed flux conditions were applied on the basis of estimated groundwater discharge. Transfer type conditions (DIERSCH, 2002) were applied along Sangro river and constant hydraulic heads, 0 m a.s.l., were applied along coastline.

Averages of piezometric heads, from monitoring program, were used for different observation points during calibration phase; the dominance of positive residual values is justified by the simulation of conditions without exploitations (fig. 9).

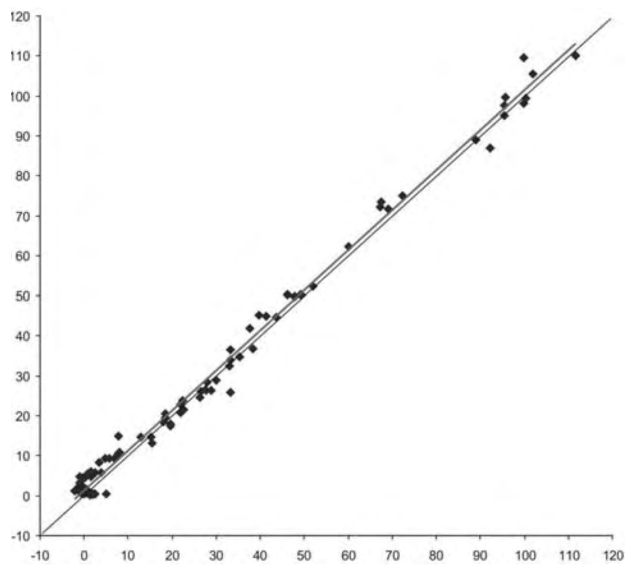

Fig. 9 - Measured vs. simulated value of hydraulic head in the calibration graph of the regional numerical model of Sangro alluvial plain.
- *Confronto tra valori misurati e valori simulati di carico idraulico nel grafico di calibrazione relativo al modello numerico regionale della piana del Sangro.*

2.6.1. - *Simulation of sea-water intrusion*

Conceptual and numerical analysis of Sangro valley aquifers highlights typical problems in groundwater withdrawals and management in coastal areas due to sea-water intrusion and salinization process.

The local numerical models simulates density-dependent flow and transport conditions in the aquifer thus taking into account differences of saline concentrations. The mesh of Sangro local model, which extends over an area of about 5.93 $\times$ 10^6 m^2, is constituted by 211680 cells and 116130 nodes over 14 layers. Triangular-based prismatic elements have orthogonal projections that vary in dimensions from 70 m in the western coastal area to 30 m in areas near the coast and finally 10÷15 m in the proximity of the exploitation wells.

The topmost 7 layers identify the silty-sandy superficial deposits in the western area, and the sandy gravels and silty-clayey lenses in the coastal areas. All remaining layers represent the sandy-gravelly deposits. The distribution of the hydrogeological properties and the effective recharge is derived from the regional model. Constant fluxes in the western area and equivalent hydraulic heads (DIERSCH & KOLDITZ, 1998; DIERSCH, 2002), assuming a sea water density of 1025 g/l for an average salt concentration of 35 g/l, were assumed as boundary conditions. Constraints were applied on the concentrations of incoming and outgoing water fluxes.

The local model was used to simulate scenarios, starting from undisturbed conditions, using different exploitation schemes. The scenario simulating undisturbed conditions was obtained from transient conditions over a long period of 100000 years. The other simulations with ongoing exploitations were run with variable periods going from 30 up to 100 years. Distribution of hydraulic heads and concentrations were calculated at both the end of the time interval and during transient conditions so as to simulate saline intrusion phenomena.

The first scenario considered typical summer exploitations related to irrigation purposes (fig. 10). Variable exploitation rates vary from 0.1 up to 0.2 m^3/s through several irrigation wells, up to 15÷20 l/s per well. In some stations the exploitation is lower of about 2÷5 l/s and occurs over a short period of few hours. Saline intrusion phenomena occur in these conditions mainly in the areas on the left side of the river near coast. Strong saline intrusion evidences occur in some wells located at short distances from the coast line. These wells are sometimes located on low hydraulic conductivity alluvial deposits. This scenario maximizes the stress conditions of the system due to the fact that the exploitations are not constant on time and superficial recharge is present due to irrigation.

A second scenario with a limited exploitation of only 1 l/s per well, produces reduced saline intrusion phenomena near those wells that are very close to the coast-line where only local high concentrations are recorded.

Other scenarios have been simulated with exploitation rates varying between 0.12 and 0.3 m^3/s on wells located 2÷4 km from the coast-line and others with wells that are in proximity of the

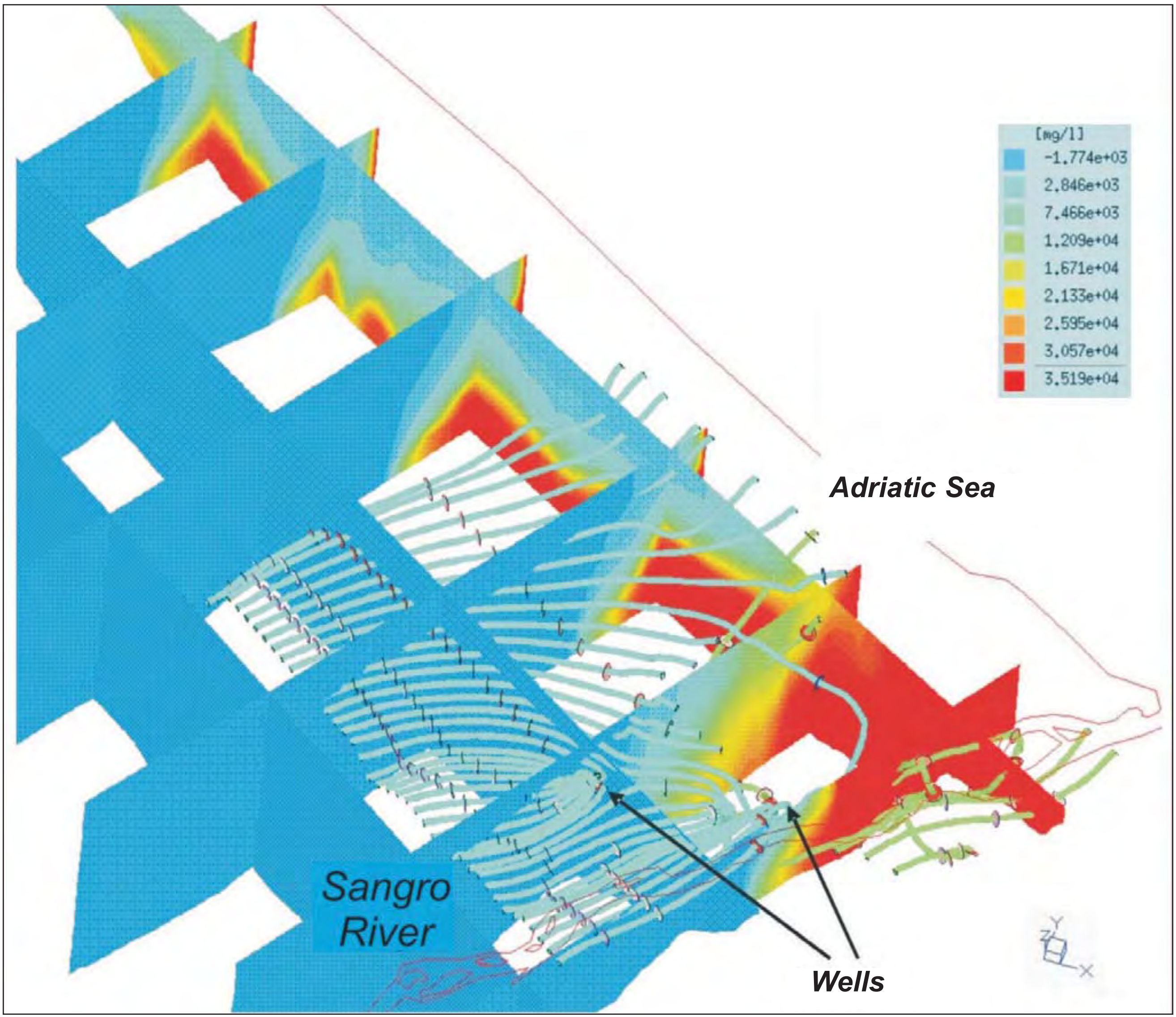

Fig. 10 - Salt water intrusion phenomena near the coastal area and flow lines, typical summer exploitations scenario (total salinity in mg/l; exaggeration factor 10:1); after DESIDERIO *et alii*, 2007.
- *Fenomeni di intrusione salina nella zona costiera e linee di flusso, relativamente allo scenario tipico estivo (salinità totale in mg/l; esagerazione verticale 10:1); da* DESIDERIO et alii*, 2007.*

river outlet. Intense agricultural schemes are in place in these areas and the absence or reduced presence of superficial irrigation systems increases the need for groundwater exploitations for irrigation. The pumping rates often accelerate the saline intrusion phenomena.

Hydraulic heads tend to reach equilibrium usually within 2÷3 years, while concentrations tend to have significant variability for periods that range from 15 to 25 years.

The different scenarios confirm saline intrusion phenomena due to exploitation in areas near to the river outlet, especially when these are constant through time. Critical conditions of variable concentrations due to strong decrease of piezometric levels are present even after long periods thus proving the persistence of salt water intrusions.

3. – THE VOMANO ALLUVIAL VALLEY

3.1. – GEOLOGICAL SETTING

The ancient and recent alluvial deposits of the Vomano river plain (fig. 11) consist of gravel, sandy-gravel and gravelly-sand bodies. Above these, in the middle-low part of the plain, clayey-muddy-sandy and muddy-sandy-clayey deposits are present, varying in thickness from few metres up to 20 m near the coastal belt. Sandy-gravelly deposits crop out in the upper part of the river valley. The substrate beneath the alluvial deposits mainly comprises lithotypes such as the marly clays and clayey marls of the Cellino Formations and Argille Grigio Azzurre (CRESCENTI, 1971; CRESCENTI *et alii*, 1980; CASNEDI *et alii*, 1981;

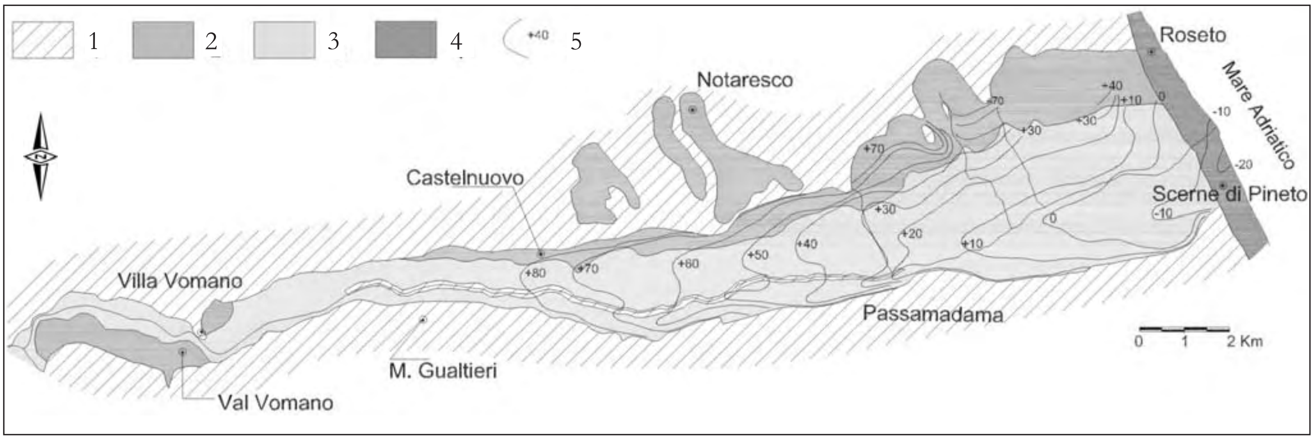

Fig. 11 – Schematic geologic map of the Vomano alluvial plain. 1) Pelitic-arenaceous deposits (Pliocene-Pleistocene). 2) Alluvial terrace (I and II order). 3) Alluvial terrace (III and IV order). 4) Coastal deposits. 5) Substratum morphology (contour lines in m a.s.l.); modified after DESIDERIO *et alii*, 2003.
– *Schema geologico della piana alluvionale del Vomano. 1) Depositi pelitico-arenacei (Pliocene-Pleistocene). 2) Alluvioni terrazzate (I e II ordine). 3) Alluvioni terrazzate (III e IV ordine). 4) Depositi costieri. 5) Morfologia del substrato (isolinee in m s.l.m.).*

VEZZANI & GHISETTI, 1998). In the upper part of the plain, however, the substrate is made up of more permeable lithotypes: these are arenaceous and marly deposits originating from the Laga Formation and the Messinian deposits. The clay basement elevation contours were interpolated after 9 geoelectric prospecting profiles, in the well fields area, including more than 120 Vertical Electrical Soundings (CASSA PER IL MEZZOGIORNO, 1971; CELICO, 1983) and 18 borehole logs (fig. 12).

The top of the substrate of the alluvial deposits is characterised by the presence of a palaeo-thalweg, shifted some hundreds of metres north or south in relation to the present-day riverbed.

3.2. - HYDROLOGY AND WELL FIELDS

The hydrological balance was evaluated using data from pluviometric and thermometric stations (SERVIZIO IDROGRAFICO E MAREOGRAFICO, 1955-1995). An average infiltration rate of about 110 mm/yr was estimated by THORNTHWAITE & MATHER (1957) and TURC (1961) methodologies, considering a 30 years observation period (1965-1995). The pluviometric regime underlines an Apennine sublittoral climate, with marine influences; the minimum precipitation values are registered in summer time, while the maximum ones occur in winter and spring months, while the temperature has an opposite trend. The water balance was calculated using more than 30 pluvio-termometric stations to evaluate the global surface runoff; the superficial hydrographic network is very limited due to high hydraulic conductivity of shallow alluvial deposits and soils so that most of meteoric waters recharges the aquifer, after satisfaction of the soil deficit.

In the eastern part of the Vomano valley, two well fields, Saf 1 and Saf 2 of ACA S.p.A. (a local water agency) are located, not far away from the coastline. The two well fields are located on a highly conductive palaeo-river, as resulted from geophysical prospecting and boreholes. Current overall withdrawal is in the range of 200÷470 l/s, depending upon season, with the average of about 270 l/s. The pumping regimes consist in about 150÷250 l/s for Saf 1 and, when the water request is higher or in emergency conditions as in drought periods, in about 100 l/s for Saf 2, with hydraulic heads up to 3÷4 m below mean sea level in Saf 1 area located near to coastline.

3.3. - HYDROGEOLOGY

As emerging from previous hydrogeological studies (CASSA PER IL MEZZOGIORNO, 1971; CELICO, 1983; DESIDERIO *et alii*, 2003), the Vomano valley is characterized by a single phreatic aquifer system, with minor semi-confined layers, overlying an impermeable clay basement (fig. 13). Major hydrogeological features include Vomano river and some, possibly highly conductive, paleo-rivers related to geomorphological and tectonic history of most alluvial valleys of Abruzzo and Marche regions.

The alluvial deposits overlay an impermeable clay basement, with thickness varying from few meters in the proximity of its outcrops, up to about 28 m along the main paleo-river.

The alluvial deposits constitute the III and IV order terraces of Vomano plain; the aquifer system consists mostly of gravel, sandy-gravel and gravelly-sand bodies. In the middle-low plain, clayey-muddy-sandy and muddy-sandy-clayey deposits with much lower hydraulic conductivity

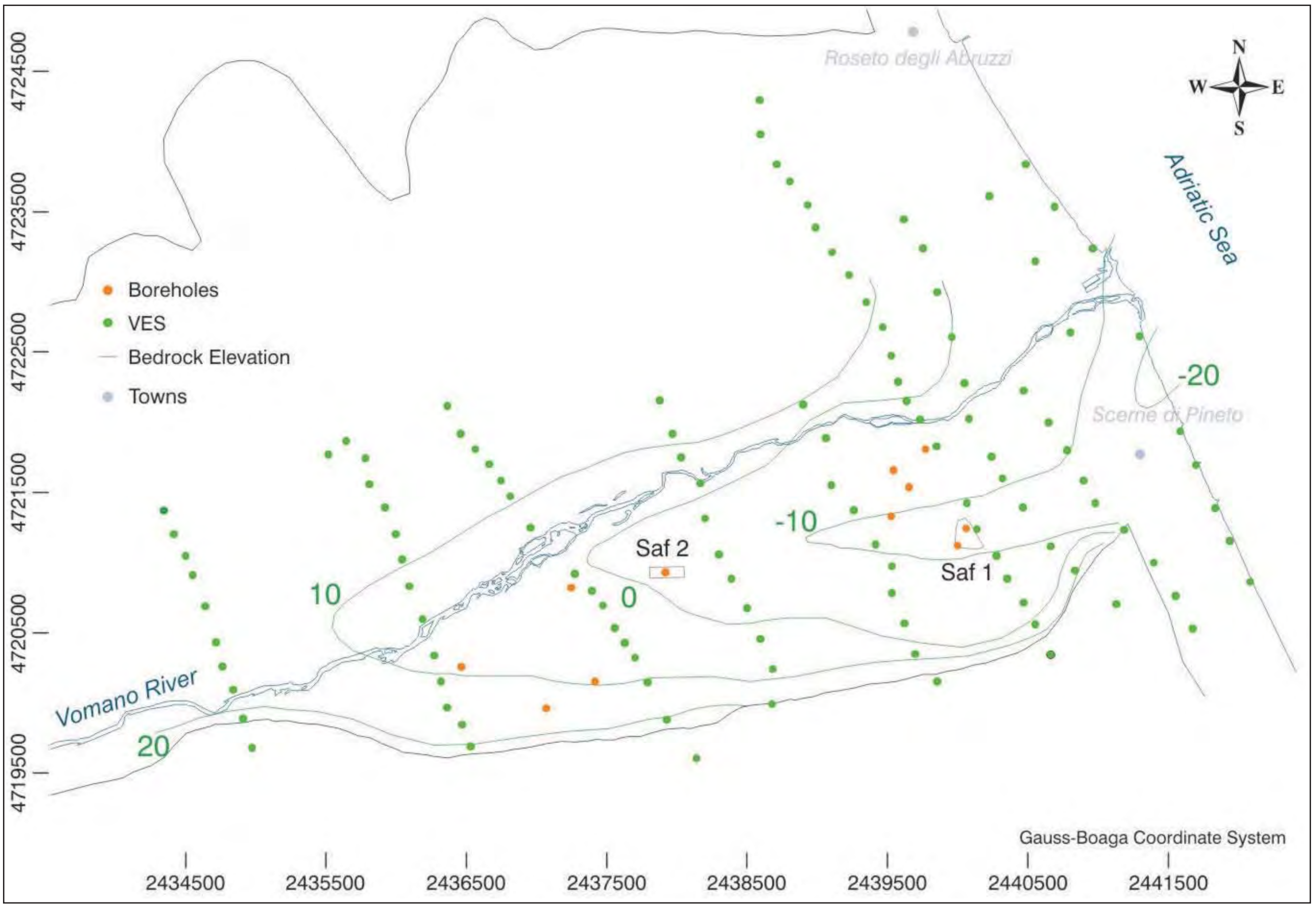

Fig. 12 - Bedrock elevation map with location of VES and boreholes in the lower Vomano alluvial plain.
- Carta del substrato con ubicazione dei SEV e dei sondaggi geognostici nella piana alluvionale del Vomano.

values, are responsible for local semi-confined conditions. The silty and clayey soil, is 1÷2 m thick.

The palaeo-river, with a northern deviation close to the coastline, is made by gravelly and sandy deposits, while in the adjacent zones silty matrix gravelly-sands are present; at the valley border sandy silts are prevalent.

The Vomano river thalweg, in the study area, is made by recent alluvial gravelly and locally sandy deposits; hydraulic continuity with aquifers occurs with a prevalent surface water contribution respect to direct precipitation recharge.

3.4. – Hydrochemistry

The unconfined aquifer is recharged mainly by fluvial waters from calcium-bicarbonate facies of Apennine origin, as confirmed by the values of electrical conductivity and groundwater temperature (Desiderio *et alii*, 2003. River recharge is further testified by the chemistry of the groundwater: close to the river bed the waters present calcium-bicarbonate facies with low saline content. Waters of this type are also found near the main drainage axes, which drain the waters of the Vomano river and its primary tributaries through palaeo-thalwegs.

The aquifer is also recharged by deep waters of Pliocene or Messinian origin (Desiderio *et alii*, 2003, 2004). These waters, rising along fault-associated fracture zones in the Plio-Pleistocene substrate deposits, are carried to the base of the unconfined aquifer. The mixing of sodium-chloride and calcium-sulfate facies Pliocene and Messinian mineralised waters with the calcium-bicarbonate waters of the aquifer lead to different hydrochemical facies in the aquifer areas close to the zones where the mineralised waters emerge.

Recharge by the Messinian and Pliocene waters is very slight and mainly influences the chemistry of underground waters, causing enrichment in Cl^-, Na^+, Mg^{++} and SO_4^{--} of the calcium-bicarbonate waters originating from fluvial recharge (fig. 14).

3.5. - Hydrodynamics

Vomano valley groundwater circulation is closely dependent on palaeo-rivers.

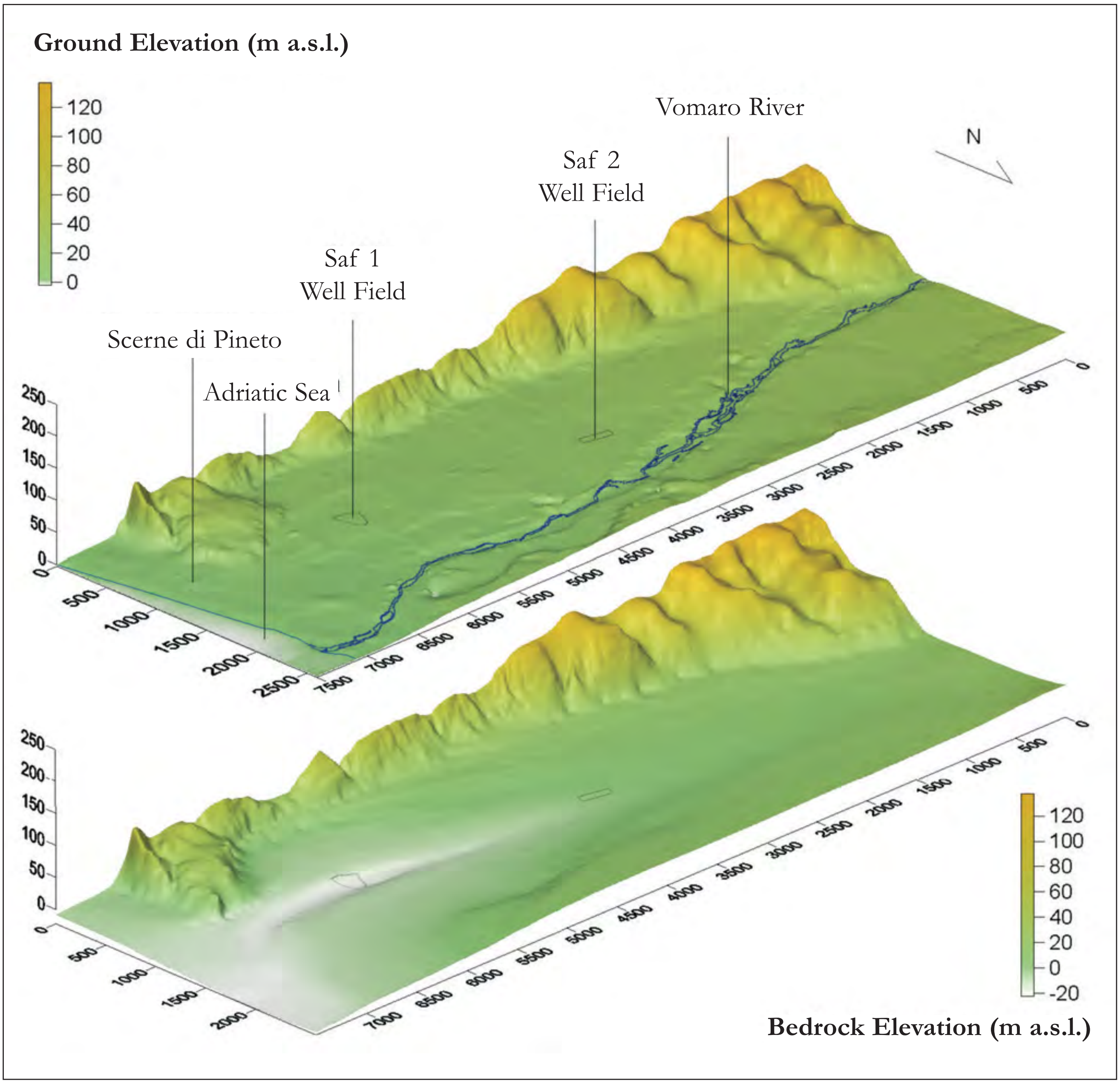

Fig. 13 - A 3D overview of the ground above) and bedrock (below) surfaces (exaggeration factor, 5:1); after RUSI *et alii* 2004.
- *Vista 3D della superficie topografica (in alto) e del basamento impermeabile (in basso; esagerazione verticale, 5:1).*

Piezometry, based on seasonal monitoring of 150 wells during 2000, highlights (fig. 15): - groundwater heads generally interesting gravels and gravelly sands under overlaying low conductivity silt deposits; - a water circulation depending on basement morphology related to palaeo-rivers; - left side river drainage in medium and lower valley for riverbed gravels and sands; - aquifer drainage into river where flowing directly on basement deposits; - groundwater flow to recent III and IV order terraces from ancient I and II order terraces aquifers, with a prevalent recharge by precipitations.

Aquifer recharge is related to direct precipitation and Apennine contributions in the higher valley; differently in the lower valley it is influenced by river inflows especially along palaeo-rivers, direct precipitations, superficial runoff on hillsides and, during dry seasons, irrigation components.

Several pumping tests of different duration and operative plan were executed in Saf 1 and Saf 2 well fields to evaluate hydrodynamic parameters. The pumping tests were executed with constant flow rates considering the installed pumps typology and aqueduct system (RUSI *et alii*, 2004).

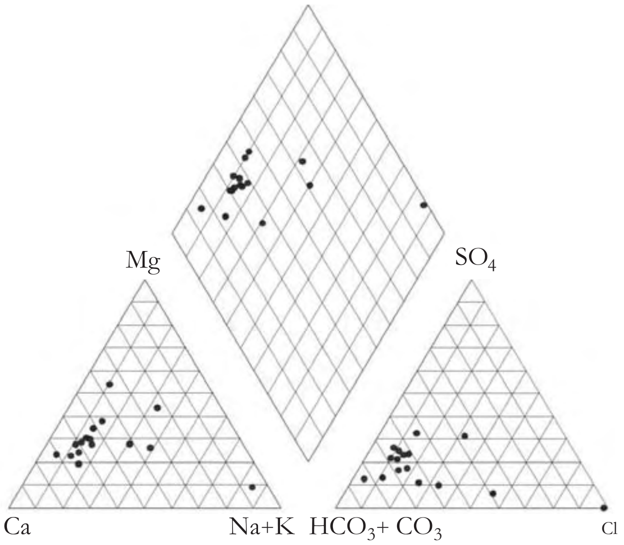

Fig. 14 - Piper's diagram of the Vomano plain groundwaters.
- Diagramma di Piper relativo alle acque della piana del Vomano.

Some pumping tests were executed on single wells in transient and steady-state conditions for short and long periods (from 3 up to 76 h), monitoring drawdowns in surrounding wells (fig. 16).

Equilibrium was reached in Saf 1 well field about 2 h after the beginning of pumping at the highest possible flow rate allowed by the installed pump (60 l/s). The high aquifer transmissivity involves not only piezometric surface stabilization but even water levels rising in testing and surrounding monitoring wells; these pumping tests were so worked out only considering the steady-state condition (DUPUIT, 1863).

Hydraulic conductivity values range from 2.0×10^{-3} m/s to 3.1×10^{-3} m/s, and average transmissivity is 4.1×10^{-2} m^2/s, considering an aquifer thickness of 18 m.

It was possible for Saf 2 well field pumping tests also the transient condition (THEIS, 1935) because the transmissivity is limited due to a smaller aquifer thickness; hydraulic conductivity values range from 1.5×10^{-3} m/s up to 2.7×10^{-3} m/s, with an average transmissivity of about 2×10^{-2} m^2/s, considering an aquifer thickness of 9.5 m.

Other pumping tests were executed in maximum stress condition allowed by pumping stations (approximately 50 l/s for each well), for about 24 h, to evaluate the hydrodynamic response under overexploitation. The influence of the well fields, in these conditions, was limited in the surrounding areas already at distances of a few hundreds of meters; definitely the influence is limited on short period (one or two days); in any case it is very influential on long periods (some days). Hydraulic conductivity values, based on long time pumping tests and geophysical evidence, are generally in order of 2×10^{-4} m/s up to about 2.5×10^{-3} m/s in correspondence of the palaeo-river.

3.6. - MODEL DESIGN AND NUMERICAL ANALYSIS

A finite-difference groundwater flow model was developed for lower Vomano aquifer by using MODFLOW 2000 numerical code, in steady-state and transient conditions for optimization of well fields pumping regime.

The domain was discretised using a regularly spaced grid with 48750 cells, with cell size of 20 m; applying Telescopic Mesh Refinement (TMR) approach (WARD *et alii*, 1987), two site models were implemented around Saf 1 and Saf 2 well fields, with irregularly spaced grids, characterized by a denser refinement near pumping wells (fig. 17).

A constant head boundary of 0 m a.s.l. was used for the coastal zone; no-flow boundaries were specified near southern impermeable hills where the water recharge looks like to be very

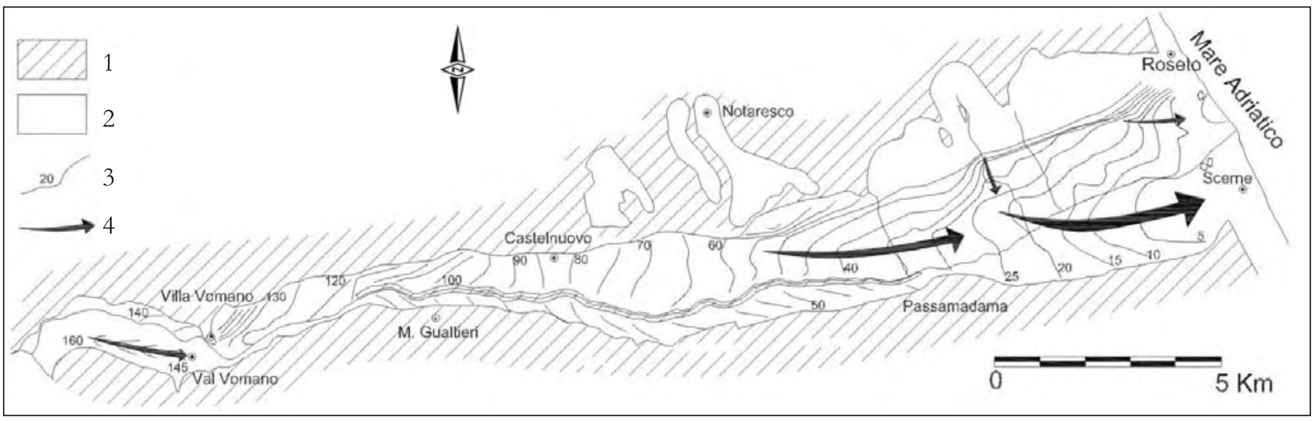

Fig. 15 - Piezometric map of the Vomano alluvial plain. 1) Pelitic-arenaceous bedrock. 2) Alluvial terrace (I - IV order). 3) Piezometric contour (m a.s.l.). 4) Preferenzial flow area; modified after DESIDERIO *et alii*, 2003.
- Carta piezometrica della piana alluvionale del Vomano. 1) Substrato pelitico-arenaceo. 2) Alluvioni terrazzate (I - IV ordine). 3) Isopiezometriche (m s.l.m.). 4) Zone e direzioni di drenaggio sotteraneo.

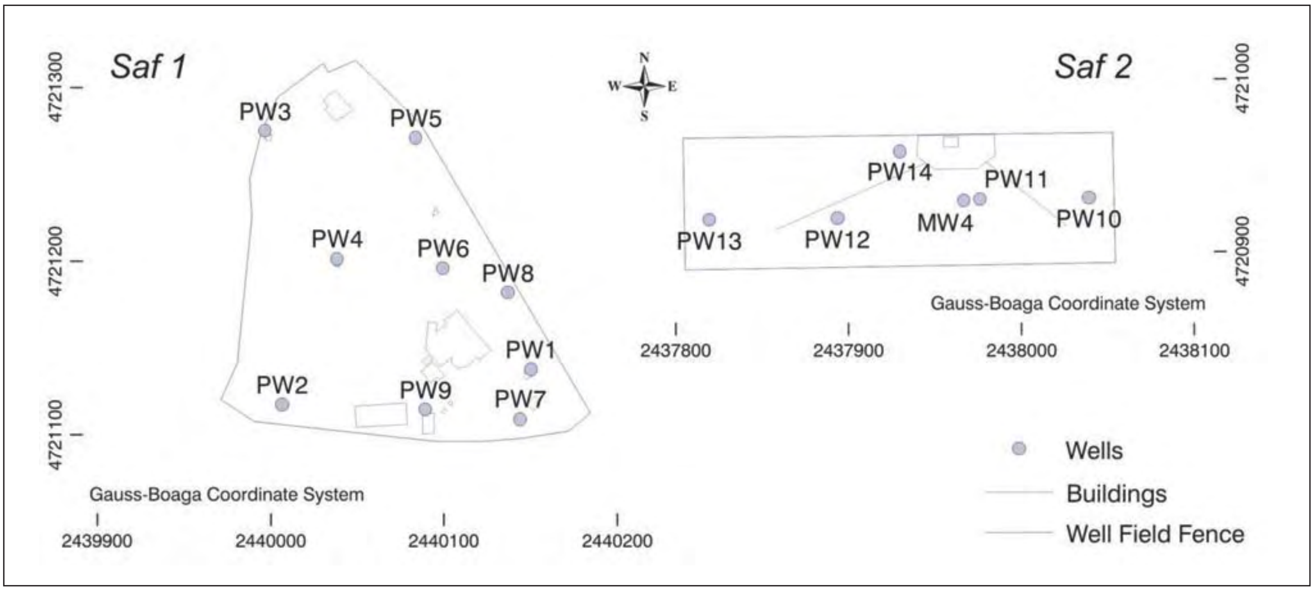

Fig. 16 - Location of Saf 1 and Saf 2 wells used for pumping test.
- Ubicazione dei pozzi nei campi Saf 1 e Saf 2 sottoposti a prove di emungimento.

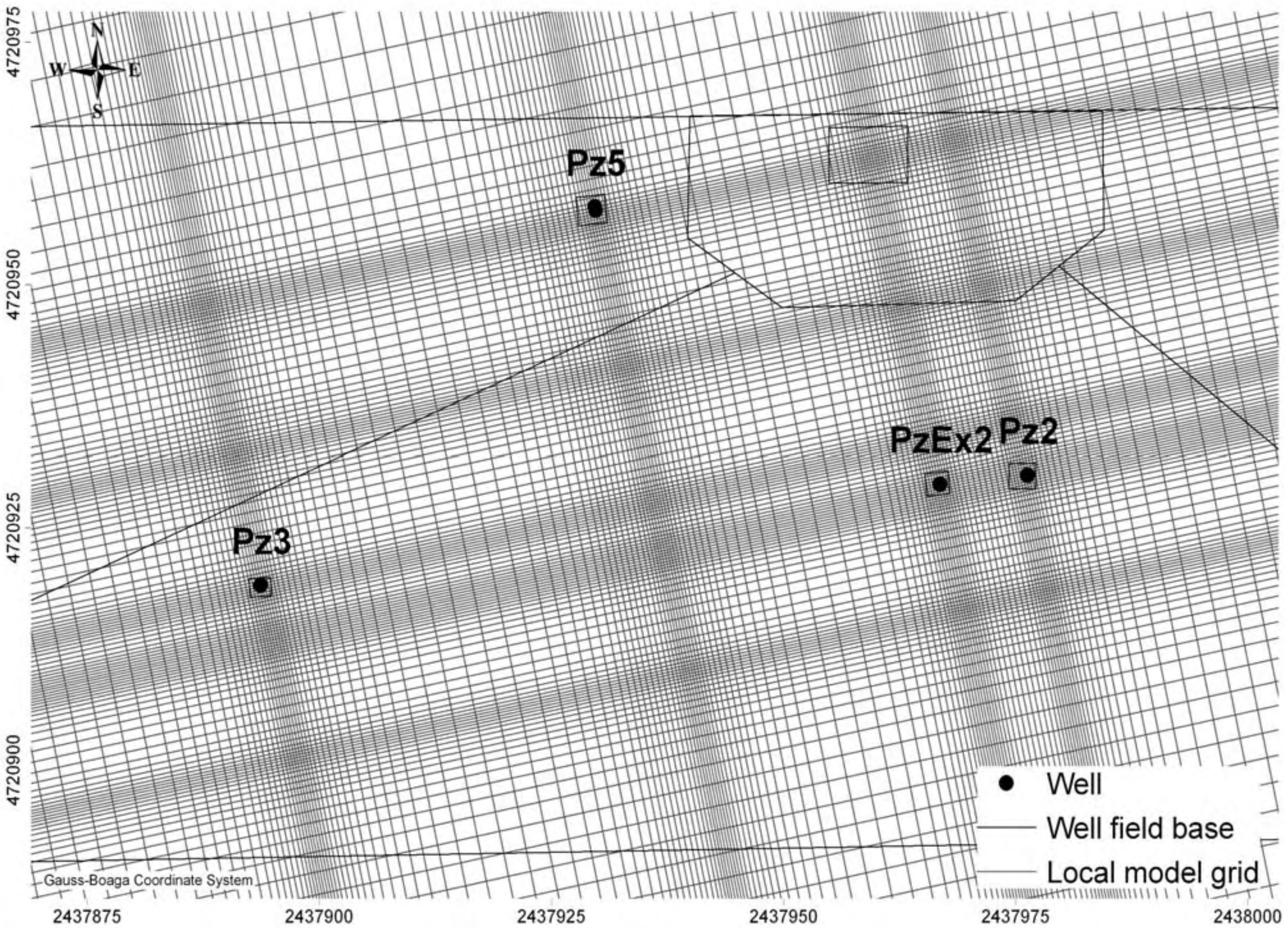

Fig. 17 - Detail of the irregularly spaced grid of the Saf 2 well field local model of the Vomano plain.
- Dettaglio della griglia a spaziatura irregolare del modello numerico del Campo Pozzi Saf 2 della piana del Vomano.

small due to the presence of a very thin and low permeable aquifer and lack of a relevant superficial hydrographic network; Vomano river was simulated using variable flow boundaries (Cauchy conditions), and infiltration was assumed constant in time. Different pumping rates were considered, both for steady-state and transient calibrations and simulations.

The model domain was divided in zones with different hydrogeological properties based on the interpretation of well fields pumping tests (fig. 18), geophysical prospecting outcomes and borehole logs. The specific focus was to capture the hydrogeological characteristics of the depositional environment. The reference values, obtained by calibration with the best fitting between the calculated and observed drawdown curves, are the most reasonable because they are in accordance with the hydrogeological parameters values evaluated through the pumping tests with DUPUIT (1863) and THEIS (1935) methods and the literature reference values (CASSA PER IL MEZZOGIORNO, 1971; RUSI *et alii*, 2004).

The seasonal measurements of the piezometric heads were executed in 150 wells on the whole Vomano plain to observe the piezometric oscillations. The highest oscillations, some meters, were observed in the study area due to water exploitation for drinking, irrigation and industrial purposes, while in other parts of the valley the oscillations were smaller, lower than 1 m. Initially the model was calibrated in steady-state conditions using the mean observed water levels and considering the average wells exploitation in the area.

Afterwards the model was calibrated using the drawdown curves both in the case of the single well tests and the overexploitation conditions. The model calculates an adequate piezometric heads distribution for the different stress conditions, even if there are some differences between the computed and observed heads mainly due to uncertainty in parameter values distribution, particularly in the areas located at a certain distance from the well fields, where no pumping tests were available, and in the initial heads distribution. The residuals are minimum at the end of pumping tests for both well fields.

3.6.1. - *Well fields management*

Definitely the calibrated flow model is reasonable to investigate some major issues, concerning the optimisation of the existing well fields pumping regimes as well as the establishment of the wellhead protection zones.

The model supported an overall analysis of the hydrogeological system, highlighting the key-role of the major palaeo-river in controlling aquifer behaviour, as emerging from fundamental

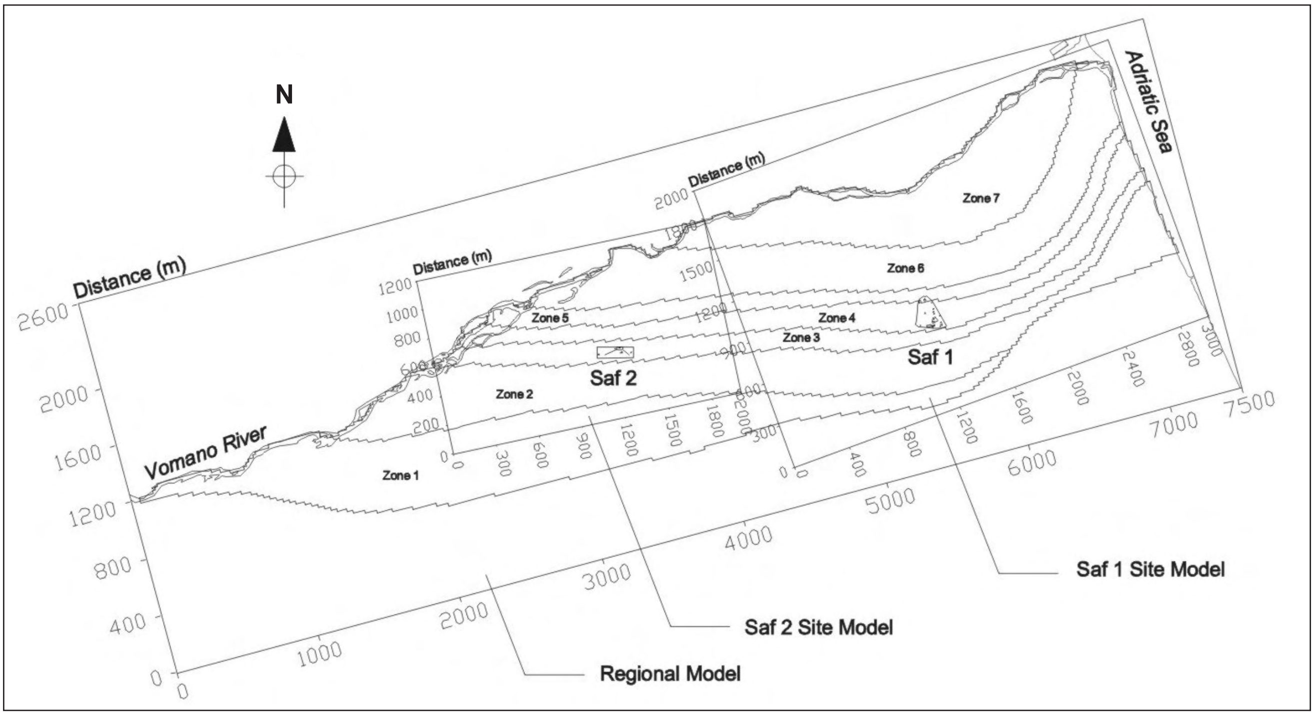

Fig. 18 - The location of the hydrogeological zones with the numerical model domains; from RUSI *et alii*, 2004.
- *Localizzazione delle differenti zone idrogeologiche con individuazione dei domini dei modelli numerici implementati.*

components in the local hydrogeological balance, flow paths and velocity fields. The attention was also focused on Vomano river recharging role. At first, the piezometric heads distribution in steady-state conditions and without exploitations was computed (fig. 19), considering the reference parameter values. In this condition the aquifer drains the Vomano river superficial waters in the western area near the Saf 2 well field, while the river drains the aquifer waters along the north area near the Saf 1 well field. The water circulation is mainly influenced by high conductivity palaeo-river, impermeable bedrock geometry and alluvial deposits hydraulic properties as demonstrated by the computed velocity field. The water budget results were computed using the ZONEBUDGET code (HARBAUGH, 1990), so it was possible to evaluate the river-aquifer water exchanges in different hydrogeological zones, and to estimate the groundwater flow to the Adriatic Sea.

Afterwards the calibrated model was used to simulate different exploitation scenarios, both in steady-state and transient conditions (fig. 19). The sustainable pumping rates were established considering the steady-state conditions, while the periods of overexploitation were determined in transient conditions, assuming respectively the overall withdrawals of 450 l/s and 250 l/s for Saf 1 and Saf 2 well fields, with a pumping rate of 50 l/s for each well.

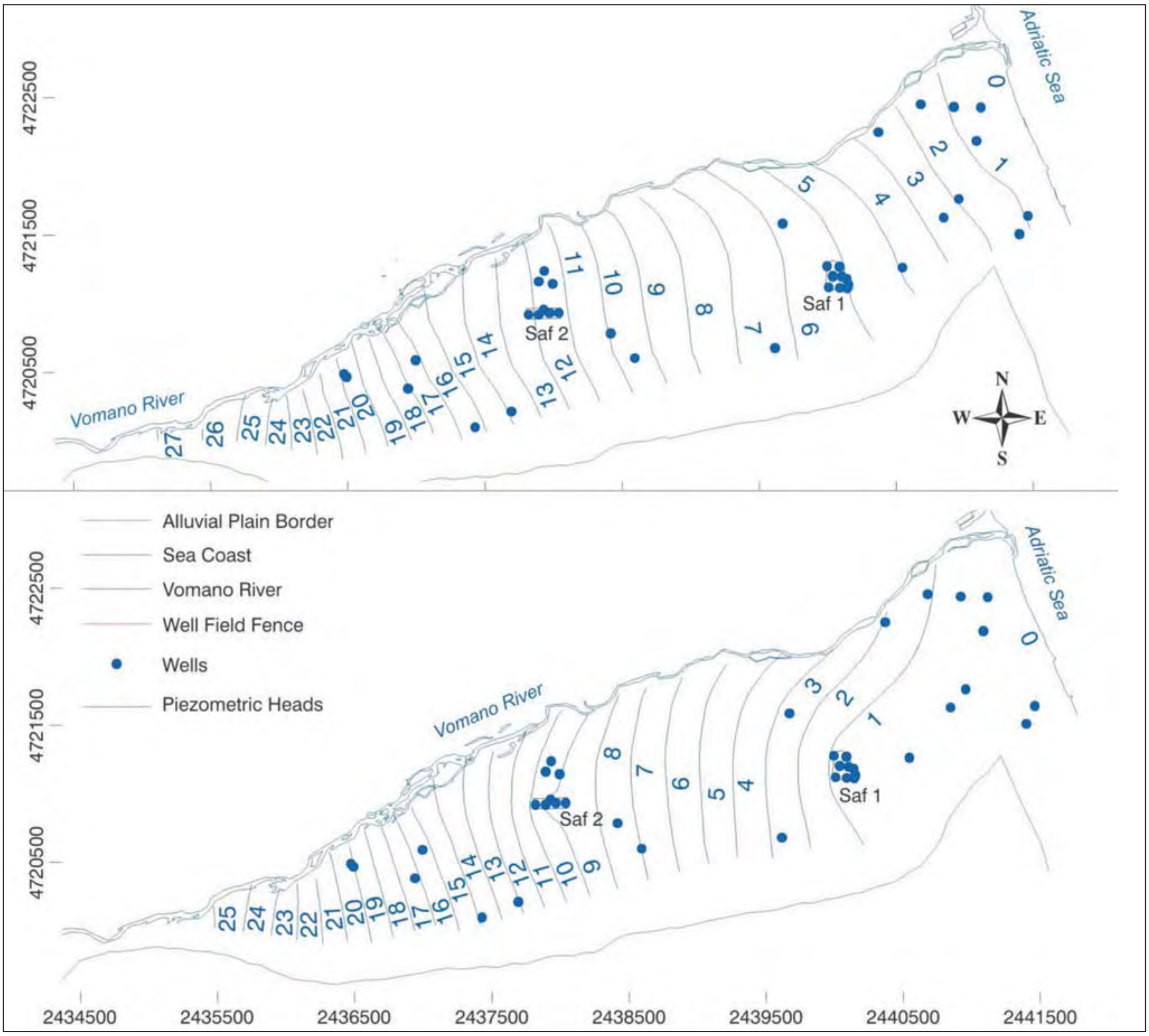

Fig. 19 - Simulated piezometric heads in steady-state condition, without withdrawals (above) and considering the mean withdrawals (below) from the eastern Vomano pumping wells.
- Distribuzione dei carichi piezometrici della zona orientale della Valle del Vomano simulati in condizioni stazionarie, senza emungimenti (in alto) e con emungimenti medi dai pozzi di pompaggio (in basso).

The sustainable pumping regime for the Saf 1 well field is about 150 l/s, due to high aquifer transmissivity (about 4.1×10^{-2} m^2/s), to be applied alternatively to three wells, maintaining a flow rate of about 50 l/s from each well. The overexploitation of 450 l/s can be supported by the aquifer for a time of about 15 days. In any case it is preferable not to apply overexploitation pumping regime because it can cause salt water intrusion.

The Saf 2 well field can support an overall exploitation of about 100 l/s in steady-state condition, while the overexploitation of 250 l/s can be applied only for short periods (about 5 days), afterwards dry conditions occur in wells with high piezometric drawdown in the aquifer system.

The area is characterized by the presence of industrial plants, agriculture and quarry activities. Preliminary estimate of the wellhead protection areas were made applying the MODPATH particle-tracking code (POLLOCK, 1989). The flow pathlines were computed for scenarios in suggested steady-state conditions for Saf 1 (150 l/s) and Saf 2 (100 l/s) well fields and the wellhead protection areas defined in a conservative way, considering the advective component (fig. 20).

The computed heads and flow pathlines clearly show the water contribution from the river.

3.6.2. - *Simulation of sea-water intrusion*

Salinization problems related to sea-water intrusion in Vomano coastal plain, potentially due to Saf 1 and Saf 2 well fields, have been numerically analyzed with finite-element 3D density-dependent FEFLOW code. Model domain is extended from Vomano river up to Plio-Pleistocene very low conductivity hills; the mesh is formed by 251770 elements and 141229 nodes over 10 vertical layers and is refined near well fields, for numerical efficiency and stability, with triangular-based prismatic elements gradually varying from about 50 to less than 1 m near wells. Boundary conditions are defined hydraulic heads along Vomano river and coastline, considering here a water density of 1025 g/l. After a calibration tuning, the density-dependent model (CRESTAZ *et alii*, 2007) confirmed the previous numerical results yet highlighting: - high pumping rates for short periods do not induce sea water intrusion related to limited times and high piezometric heads between well fields and coastline due to Vomano river drainage; - overall withdrawals of about 250 l/s from Saf 1 and Saf 2 for a long period induce groundwater salinization along palaeo-river up to lower and principal well fields in about 8÷10 years (fig. 21).

Conceptual and density-dependent numerical analysis highlights the quantitative and qualitative sustainability of withdrawals on short and long periods, that contribute to avoid environmental and socio-economic damage.

4. - CONCLUSIONS

Groundwater resources of Sangro and Vomano rivers alluvial plain have been analyzed through flow and transport numerical simulations with MODFLOW and FEFLOW codes, in density-dependent conditions. The conceptual model has been based on geological, geomorphological,

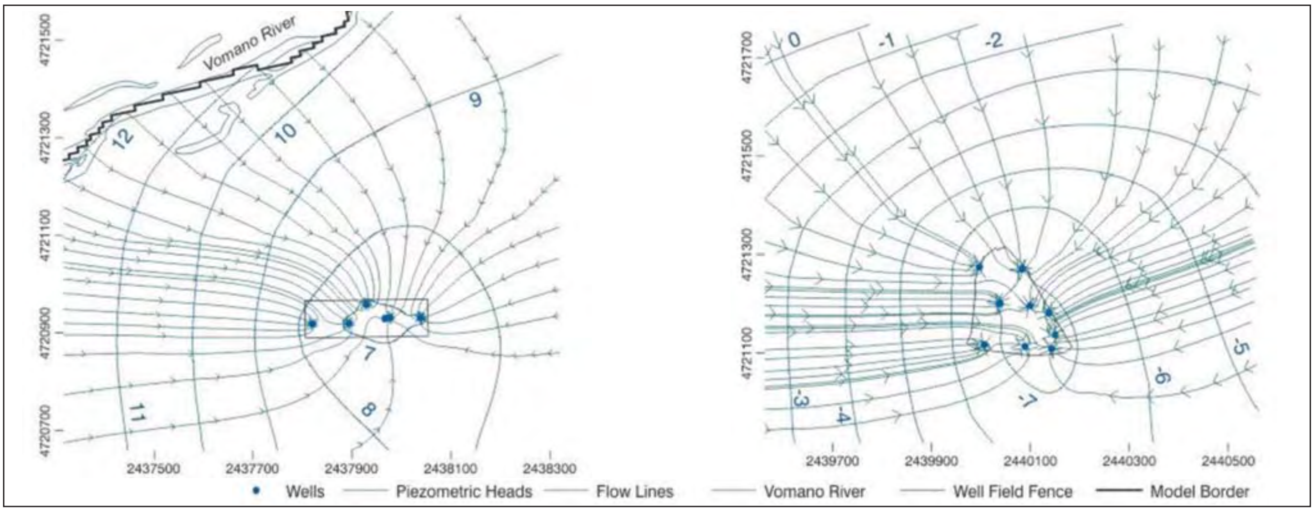

Fig. 20 - Flow pathlines with markers every 30 days. Left: the Saf 2 well field area, considering the simulated steady-state condition with an exploitation of 100 l/s. Right: the Saf 1 well field with an exploitation of 150 l/s.
- *Linee di flusso con markers ogni 30 giorni. A sinistra: campo pozzi Saf 2, scenario in stato stazionario, con un'estrazione idrica complessiva di 100 l/s. A destra: campo pozzi Saf 1 con un'estrazione idrica complessiva di 150 l/s.*

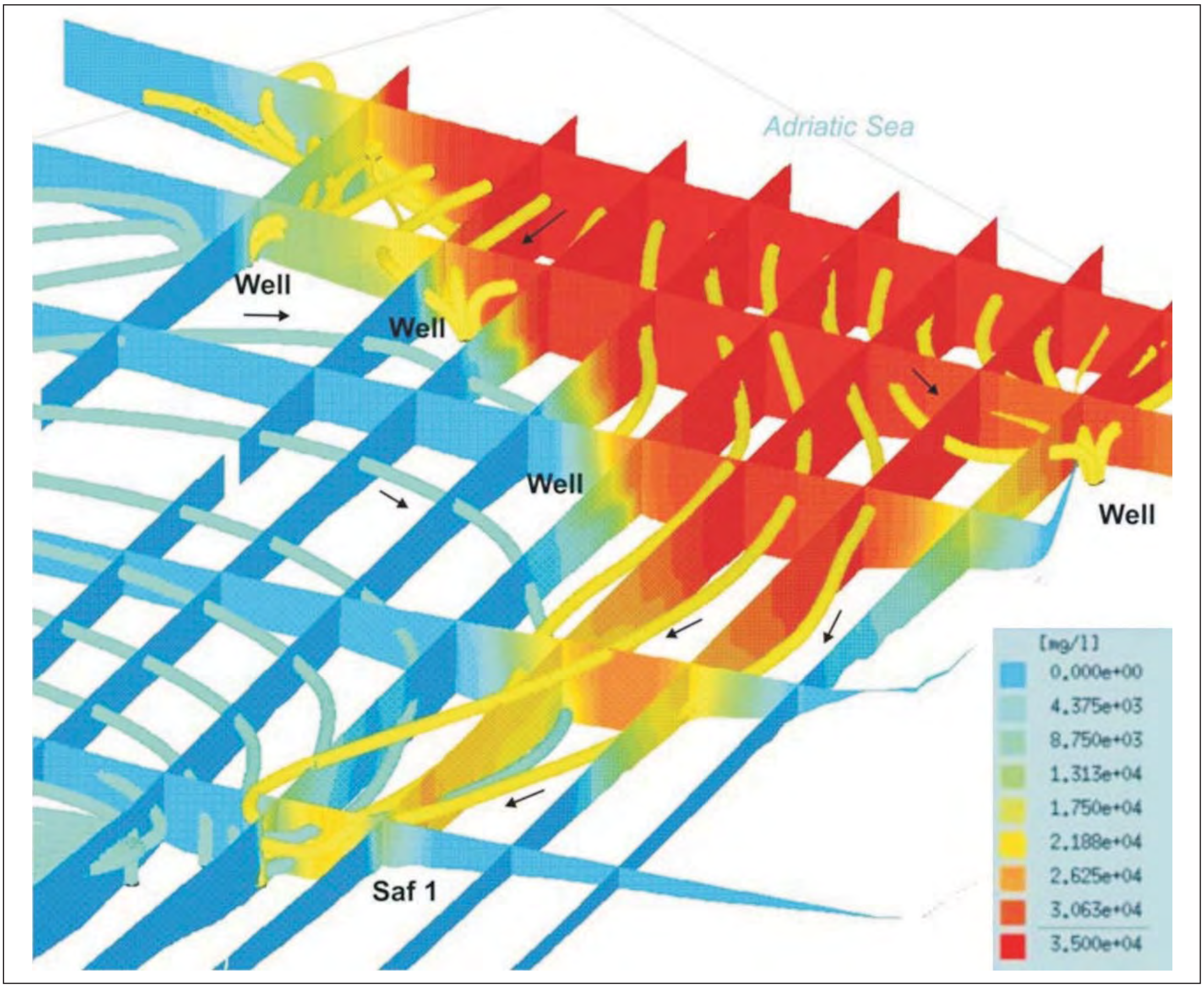

Fig. 21 - Salt water intrusion phenomena near the coastal area and flow lines in the Vomano plain, scenario with withdrawals of about 250 l/s from Saf 1 and Saf 2 well fields for a long period (total salinity in mg/l; exaggeration factor 10:1).
- Fenomeni di intrusione salina nella zona costiera e linee di flusso nella piana del Vomano, relativamente allo scenario con emungimenti di 250 l/s per lungo periodo (salinità totale in mg/l;esagerazione verticale 10:1).

geognostic, geophysical, hydraulic, hydrogeological and chemical data and interpretations.

The alluvial valleys, mainly constituted of both ancient and recent terraced alluvial deposits, are constituted by unconfined aquifers, even if semi-confined conditions are locally reached due to silty-clay lenses. Groundwater flow is strongly influenced by palaeo-rivers, while the influence of higher order terraces is generally modest. The dominant hydrochemical facies is calcium-bicarbonate up to sulphuric-chloride-alkaline to sodium-chloride and sodium-sulphuric facies related to deep up flowing of mineralized waters.

Quantitative assessment of water resources has been possible through numerical modeling in relation to aquifer-river exchanges, influence of palaeo-rivers and water discharges coming from higher order terraces.

Salt-water intrusion phenomena in coastal areas of Sangro aquifer are related to withdrawals for civil and irrigation purposes; vertical chemical trends are evident due to variations in hydrodynamic conditions with depth and mixing with mineralized waters. Simulation results highlight that saline intrusion phenomena can be limited when exploitations are not concentrated during summer and a better spatial configuration of wells is adopted.

The Vomano well field sustainable pumping regimes and wellhead protection areas were defined both in steady-state and transient conditions. The simulated different exploitation scenarios highlight that maximum acceptable exploitation for Saf 1 and Saf 2 well fields is respectively in the order of 150 l/s and 100 l/s, under steady-state conditions, while a pumping regime of 50 l/s for each well can be supported, in transient conditions, by Saf 1 and Saf 2, respectively, for about 15 and 5 days.

The model simulated in an adequate way the aquifer behaviour so it provides a reference hydrogeological framework for evaluation of the aquifer capacities and of the superficial water contributions. It was also useful for water quality protection, through the delineation of flow pathlines in different exploitation conditions.

Numerical analysis highlights the risk of seawater intrusion if concentrated withdrawals occur near coastline, particularly during higher water request and smaller aquifer recharge periods.

Geolithological and hydrogeological data of the unsatured zone and river flow measurements could be useful for calibration refining; moreover this research underlines the necessity of a continuous monitoring network of groundwater withdrawals and hydraulic levels for predictive purposes.

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