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Aquifer Analogues to Assist Modeling of Groundwater Flow: the Pleistocene Aquifer Complex of the Agri Valley (Basilicata)

Modellazione del flusso idrico sotterraneo assistita da analoghi di acquifero: il complesso acquifero pleistocenico della Val d'Agri (Basilicata)

BERSEZIO R. (*), FELLETTI F. (*), GIUDICI M. (*),
MICELI A. (*), ZEMBO I. (*)

Abstract - The Agri Valley is a Quaternary intramontane basin which developed after strike-slip and extensional deformation of the Neogene thrust belt of the Lucanian Apennine. The syn- post-tectonic basin infill is represented by the Agri Valley Complex, a group of clastic units of Mid-Upper Pleistocene age, which were deposited in scree, alluvial fan, braid-plain, fan delta and lacustrine environments. The subsurface part of this succession represents a huge aquifer complex which hosts a significant groundwater resource. Due to the poor knowledge of the subsurface stratigraphy of the Pleistocene succession, hydrogeological modelling can be usefully assisted by the help of the study of the "aquifer analogues", which are represented by the outcropping portion of the Agri Valley Complex. Our study is an attempt to investigate the efficiency of this approach in view of the computation of a simple and traditional groundwater model of the North-western Agri Valley Aquifer Complex.

The study was based on 1) reconstruction of stratigraphy of the exposed Pleistocene succession and conversion into an analogue hydrostratigraphic scheme, 2) characterization of aquifer analogues (facies and compositional analyses, estimate of hydraulic conductivity of the different lithofacies), 3) correlation with the subsurface geophysical and borehole data to define a hydrostratigraphic model of the aquifer complex, 4) development of a preliminary and standard groundwater flow model, to evaluate the effectiveness of the hydrostratigraphic model.

The basin fill of the Agri Valley includes coarse breccia bodies of possible Early Pleistocene age which prograded into a lacustrine succession, alluvial fans of Middle Pleistocene age which interfinger with lacustrine and alluvial sediments (Middle-Late Pleistocene) and are covered by the most recent fan deposits (Late Pleistocene-Holocene). This stratigraphy has been translated into an analogue hydrostratigraphic framework including: 1) lowermost aquitard with small aquifer lenses (lacustrine with fan delta deposits); 2) intermediate multilayer aquifer (alluvial fans and axial braid plain deposits; Middle Pleistocene); 3) upper discontinuous aquitards (palaeosoils and fine grained palustrine to flood plain sediments); 4) unconfined uppermost aquifer (alluvial fan sediments).

The correlation with the subsurface reconstruction obtained by geoelectrical tomography and water well stratigraphic logs, confirmed that the outcropping hydrostratigraphic architecture of the northern side of the basin represents a good analogue for the study of the buried aquifer units. Therefore a standard groundwater flow model has been implemented on a GMS® platform. It incorporates the hydrostratigraphic model, assumes flow stationarity (average annual conditions) and includes source terms and boundary conditions (no flow on boundaries). Calibration was obtained by the use of piezometric data and maps drawn from 132 shallow water wells with 1 to 10 years seasonal measurements. Several alternative simulations have been run. At the northern side of the basin they predict the radial shape of flow lines of the phreatic aquifer and the drainage effect by the Agri River. The simulations show also the emergence of the water table in three areas. In one case this is in agreement with the presence of springs which originate minor streams; in the other two cases this fact could be justified by reclamation of the area, but some inefficiency of the simulation is also likely. A more efficient calibration of the model would require additional well data, which are evidently not sufficient at present; nevertheless the approach based on analogue hydrostratigraphy allowed to obtain realistic results which encourage for future development of more reliable models.

(*) Dipartimento Scienze della Terra, Università di Milano, Via Mangiagalli 34, 20133 Milano. Corresponding Author: riccardo.bersezio@unimi.it

KEY WORDS: Agri Valley, Alluvial Sediments, Aquifer Analogues, Groundwater, Hydrostratigraphy, Pleistocene.

RIASSUNTO - L'alta Val d'Agri è un bacino intermontano quaternario, sviluppatosi in conseguenza della tettonica transpressiva e distensiva che interessò la catena a pieghe e sovrascorrimenti dell'Appennino Lucano, a partire dal Pliocene superiore. Il riempimento del bacino è costituito da sedimenti continentali, tra i quali la porzione attribuita al Pleistocene medio – superiore affiora nel settore sud-orientale del bacino stesso. In quest'area affiora il Complesso Val d'Agri, un gruppo di unità clastiche depositate in ambiente di conoide detritica, conoide alluvionale, piana alluvionale a canali intrecciati, delta-conoide e lago. Nel settore vallivo privo di affioramenti, i sedimenti correlabili al Complesso Val d'Agri ospitano una risorsa acquifera plausibilmente considerevole. Per queste caratteristiche, l'alta Val d'Agri si presta utilmente allo studio della caratterizzazione degli acquiferi sepolti, basata sul confronto tra questi e le successioni affioranti, che possono venire considerate come "analoghi di acquifero". Questo studio si focalizza sulla valutazione dell'efficienza di questo approccio, comune nella geologia del petrolio ma meno frequentemente utilizzato in idrogeologia. Lo studio ha seguito i seguenti passi: 1) ricostruzione della stratigrafia della successione pleistocenica affiorante e traduzione in uno schema di "analogo idrostratigrafico", 2) caratterizzazione degli analoghi di acquifero (analisi di facies e composizione dei sedimenti, stima della conduttività idraulica delle singole facies), 3) correlazione tra i dati di superficie ed i dati di sottosuolo disponibili nell'area priva di affioramenti (indagini geofisiche, dati di pozzo) e definizione di uno schema idrostratigrafico valido per quest'ultima, 4) allestimento di un modello idrogeologico semplificato e tradizionale per valutare l'efficienza della ricostruzione idrostratigrafica.

Nel settore affiorante ("area degli affioramenti"), il riempimento del bacino dell'Alta Val d'Agri comprende brecce basali grossolane (Pleistocene inferiore?) interdigitate con sedimenti fini lacustri, conoidi alluvionali progradanti entro argille e sabbie lacustri per mezzo di limitati apparati di delta-conoide ed interdigitate con ghiaie e sabbie alluvionali di piana braided (Pleistocene medio - superiore), conoidi alluvionali del Pleistocene sommitale - Olocene e sedimenti alluvionali terrazzati olocenico - recenti. Questa stratigrafia corrisponde ad una classificazione idrostratigrafica che prevede la presenza di un acquitardo basale (sedimenti fini lacustri con lenti ghiaioso-sabbiose), sormontato da un acquifero intermedio, semiconfinato e suddiviso da acquitardi minori di limitata estensione ed efficienza. L'acquitardo superiore, rappresentato da paleosuoli associati a minori orizzonti fini di piana di esondazione, delimita discontinuamente a tetto questo acquifero ed è a sua volta ricoperto dall'acquifero sommitale, costituito da ghiaie e sabbie di conoide alluvionale associate a limitati depositi fluviali terrazzati. La correlazione tra questa successione e le unità di sottosuolo, che caratterizzano l'area nord-orientale del bacino non intaccata dall'erosione tardo pleistocenico-olocenica e priva di affioramenti ("area del modello"), ha dato risultati soddisfacenti alla scala delle unità idrostratigrafiche e deposizionali di ordine gerarchico elevato. In questo modo è stato possibile allestire un modello idrogeologico semplificato, per mezzo del software GMS®, basato sulla ricostruzione geologica eseguita nell'area degli affioramenti. Il modello assume inoltre flusso stazionario (condizioni medie annue), condizioni di flusso nullo al contatto con il substrato e limiti di carico costante a contatto con il reticolo idrografico superficiale, includendo i termini di ricarica superficiale sulle aree di conoide e di piana alluvionale. I risultati di differenti simulazioni alternative, per le quali sono stati scelti diversi parametri di ricarica e permeabilità allo scopo di valutarne l'influenza sui risultati, riproducono la forma radiale delle linee di flusso e prevedono l'effetto drenante del Fiume Agri. Le simulazioni presentano inoltre almeno tre aree di emergenza della tavola d'acqua. Questo risultato è evidentemente non realistico, sebbene occorra tenere conto del fatto che negli stessi settori sono localizzate diverse sorgenti da cui traggono origine corsi d'acqua minori, e che ampie porzioni degli stessi sono state soggette a bonifica alcuni decenni addietro. L'eccessiva semplificazione dell'idrostratigrafia utilizzata nella realizzazione del modello giustifica sotto diversi aspetti la sua parziale inefficienza, e nel contempo indica che l'approccio basato sull'utilizzo degli analoghi affioranti è utile e promettente; il miglioramento dei risultati dipende dalla disponibilità di una migliore ricostruzione stratigrafica dell'area da modellare.

PAROLE CHIAVE: Acque sotterranee, Analoghi di acquifero, Idrostratigrafia, Pleistocene, Sedimenti alluvionali, Val d'Agri.

1. - INTRODUCTION

During 1999-2002 the AGRIFLUID project was set up and developed by a team led by Albina Colella (Basilicata University). The project aimed to describe and quantify the groundwater resources of the north-western sector of the Agri Valley, a prominent intramontane basin of the Lucanian Apennines. The results have been collected in a special volume printed by Regione Basilicata, which covered different topics, from the water reservoirs hosted into the Apenninic substratum to the porous alluvial aquifers of the Quaternary Agri Valley fill (COLELLA Ed., 2003).

Our contribution to this project consisted in the study of the outcropping part of the Quaternary basin fill, to describe hydrostratigraphy and to provide aquifer characterization in view of groundwater flow modelling of the subsurface aquifer complexes. One of our purposes was the attempt to apply the methods for characterization of exposed analogues of hydrostratigraphic units to the study of their buried counterparts. This was intended to provide a support for the computation of traditional groundwater models, evaluating the efficiency of this approach both in the specific case of the Agri Valley and concerning the more general topic of the use of "*aquifer analogues*" in hydrogeology. In fact the use of "analogues" is current in petroleum geology since forty years, and is getting more and more habitual also in hydrogeology (ALEXANDER, 1993; WHITTAKER & TEUTSCH, 1996; HUGGENBERGER & AIGNER, 1999).

In the present paper we describe the results of the hydrostratigraphic reconstruction of the Agri Valley Aquifer Complex, which was obtained with the help of the sedimentological analysis of the outcropping analogues which are present in the same area. The study allowed us to evaluate the bearings of this approach on the development of a simple groundwater flow model, which was computed for a limited part of the Agri basin, at its north-western termination. In the following sections we shall refer to the two different sectors which were considered in this study, with the terms of "*outcrop area*", where the analogue of hydrostratigraphy was studied, and "*model area*", where groundwater modelling was applied to the buried stratigraphy.

In the first section of the paper we present the methodology used in this study, then the geological and stratigraphic setting of the Quaternary Agri Basin is briefly outlined from literature and original data; in the fourth section the hydrostratigraphic scheme of the Quaternary succession is defined, based on outcrop analysis. The comparison between outcrops and the geophysical image of the subsurface is presented in the fifth section, which is followed by the description of the set-up and of the outcomes of the application of a simple and traditional 3D-groundwater model to the groundwater reservoir. The final discussion highlights the advantages and the problems that we encountered when applying the aquifer analogue approach to the study of the subsurface.

2. - METHODS

The study was developed in the following steps:

1) study of the "*outcrop area*", by geological mapping of the highest rank unconformity surfaces and depositional units, assisted by photo-interpretation and GIS treatment of the data-base;

2) stratigraphy and facies analysis of outcrop cross-sections;

3) compositional analysis of gravel-size units and palaeocurrent analysis, to assist the stratigraphic correlations and the geological reconstruction;

4) estimate of porosity and permeability of the different lithofacies, by grain-size analysis and application of empirical formulas, to characterize aquifer analogue units;

5) elaboration of a hydrostratigraphic scheme of the outcrop area, which is the analogue of the real aquifer complex of the subsurface;

6) correlation with the subsurface picture of the "*model area*", which was obtained by geoelectrical tomography and borehole-well stratigraphic logs (LA PENNA & RIZZO, 2003; COLELLA *et alii*, 2003a, 2003b);

7) delimitation of the model area; implementation of a standard, quasi-3D hydrogeological model on a GMS® platform. It incorporates the hydrostratigraphic model on a discretization grid with rectangular cells of variable size (large grid model: 224 x 563 m; fine grid model: 110 x 280 m), assumes stationary flow (average annual conditions), includes the estimate of the parameters of recharge, and the boundary conditions;

8) calibration of the model, that was obtained by the use of piezometric data and maps drawn from 132 shallow water wells with 1 to 10 years seasonal measurements (data from SPILOTRO *et alii*, 2003);

9) sensitivity analysis, to assess the influence of the input parameters, with specific attention to the recharge parameters and to aquifer data which were derived from the outcrop analogue.

3. - THE QUATERNARY AGRI BASIN

The Agri Valley is a Quaternary intermontane basin which developed after strike-slip and extensional deformation that affected the Neogene thrust belt of the Lucanian Apennine, since Early Quaternary (CELLO & MAZZOLI, 1999, with references therein; fig. 1). The basin configuration derives from extension and left strike-slip that occurred during Pleistocene along the N120 trending Val d'Agri Fault System (CELLO, 2000; CELLO *et alii*, 2000). The genesis of the Agri basin is polihistory; a first stage is represented by Lower(?) – Middle Pleistocene, left-lateral strike-slip along the N120 master faults, in association with transpression and local uplift, originated by restraining bends of the master faults (GIANO *et alii*, 1997; SCHIATTARELLA, 1998). During a second stage (Middle – Late Pleistocene) extensional reactivation of the master faults occurred, together with faulting of the continental syntectonic basin fill (GIANO *et alii*, 2000). Active extensional faulting lasted up to the latest Pleistocene (GIANO *et alii*, 2000) and determined the south-westwards tilting of the basin floor. Images of the shape of the basin bottom have been obtained by MORANDI & CERAGIOLI (2002) by seismic tomography and resistivity surveys. Their NW-SE striking cross-sections show: 1) the basin asymmetry, with the deepest depocentres close to the northern basin margin; this could be related to the first stage of deposition during and after the first tectonic stage described by GIANO *et alii* (1997) and SCHIATTARELLA (1998), 2) the steep profile of the northern faulted basin margin, 3) the late shift of active extensional faulting at the southern basin margin, with the consequent south-eastward displacement of the depocentres and of the recent hydrography (Agri River); this can be interpreted as a result of extensional reactivation of the oldest fault systems, 4) the presence of several superimposed alluvial cycles; the youngest three are represented by a more than 250 m thick succession, which presumably corresponds to the Agri Valley Aquifer Complex.

Based on electrical tomography and borehole data, LA PENNA & RIZZO (2003) and COLELLA *et alii*, (2003b) obtained a map of the basin floor topography, which shows the existence of three separate depocenters, with a WNW – ESE elongation, parallel to the faults which bound the basin.

The basin fill crops out in the south-eastern sector of the Agri Valley (*outcrop area*, fig. 1), where about 100 m of thickness are exposed; the unconformable boundary with the tectonic substratum crops out only at places, close to the basin margins, in the regions of minimum thickness of the clastic succession. The exposed part of the syntectonic basin infill is represented by Lower – Middle Pleistocene slope breccia bodies ("Brecce di Galaino", GIANO *et alii*, 1997) and the "Complesso Val d'Agri" (DI NIRO *et alii*, 1992; DI NIRO & GIANO, 1995), a group of clastic units of Mid-Upper Pleistocene age, which were deposited in scree, alluvial fan, braid-plain, fan delta and lacustrine environments. This sedimentary succession has been divided by DI NIRO & GIANO (1995) in three informal lower rank units: A, middle Pleistocene, lacustrine clays, silts and sands; B, middle-upper Pleistocene, gravel, sand and silt lenses with tabular conglomerates, of alluvial fan and braided stream environments; C, upper Pleistocene, alluvial fan coarse gravels and conglomerates. The uppermost Pleistocene and Holocene sediments are represented by terraced recent alluvial fan and fluviatile gravels and sands (Unit "tf", or fluviatile terraces, of CARBONE *et alii*, 1991).

The buried succession is still poorly known in details. The most recent reconstruction by COLELLA *et alii* (2003a) is based on a few borehole stratigraphic and compositional data and on some geo-electrical tomographies (LA PENNA & RIZZO, 2003). The Authors' interpretation shows that a lower breccia unit is present close to the northern basin margin; it is faulted and interfingers within a mostly fine-grained unit (clays and silts) that contains gravel-sand lenses, interpreted as lacustrine deposits. An upper unit of sandy gravels and conglomerates is interpreted as the result of south-westward progradation of alluvial fans which are heteropic with the gravelly sands of an axial unit, that the Authors suggest to be deposited by an axial Agri alluvial system. The total thickness of these sediments does not exceed 200 m, but the tectonic basement was never reached by boreholes in the depocentral areas. This reconstruction seems to match the geophysical interpretation of MORANDI & CERAGIOLI (2002), concerning their uppermost three "alluvial cycles".

4. - ANALOGUE HYDROSTRATIGRAPHY OF THE AGRI VALLEY AQUIFER COMPLEX

The study of the exposed Agri Valley Complex in the outcrop area allowed to elaborate a hydrostratigraphic scheme which represents an *analogue* of hydrostratigraphy of the buried aquifer complex. Such a specification is necessary because the studied sediments are located some kilometres east of the model area; moreover the exposed units, which crop out on the flanks of deeply incised N-S streams, are mostly in the non-saturated zone at present, therefore no true "hydrostratigraphic unit" (in the sense of MAXEY, 1964) can be defined in outcrops. The Agri Valley Complex is exposed at present both in the area to the North of Lake Pertusillo (Villa d'Agri - Viggiano - Montemurro - Tramutola - Grumento Nova, fig. 1) and in the region South of the lake (Grumento Nova - Moliterno - Spinoso Sarconi, fig. 1). The stratigraphic architecture of the Agri Valley Complex in the southern area differs from that of the northern sector (BERSEZIO *et alii,* 2003) and therefore it has not been considered for the purposes of this work. The hydrostratigraphic analogue succession of the northern side of the basin, which is of interest, will be presented with the help of two N-S cross-sections, which are labelled respectively T1 (Montemurro - Scazzera Valley -Lake Pertusillo) and T2 (Aspro Valley; fig. 1, 2, 3).

The available exposures allowed to investigate a maximum total cumulative thickness of some 120 m within the Agri Valley Complex; this complex pinches-out towards the northern basin slopes, where the Tertiary rocks crop out. The tectonic substratum to the Quaternary succession of the outcrop area is represented by siliciclastic formations of Miocene age, namely the Ligurian Albidona Flysch covered by the Gorgoglione Flysch. This points to some difference with the model area, in which the substratum of the Agri Valley Complex is represented by the complex stack of Panormid nappes (Mesozoic carbonates) and Tertiary Flysch formations (CARBONE *et alii*, 1991). In the outcrop area, the unconformable boundary with the bedrock can be mapped and/or interpreted only in the neighbourhoods of the present-day slopes (fig. 2, 3).

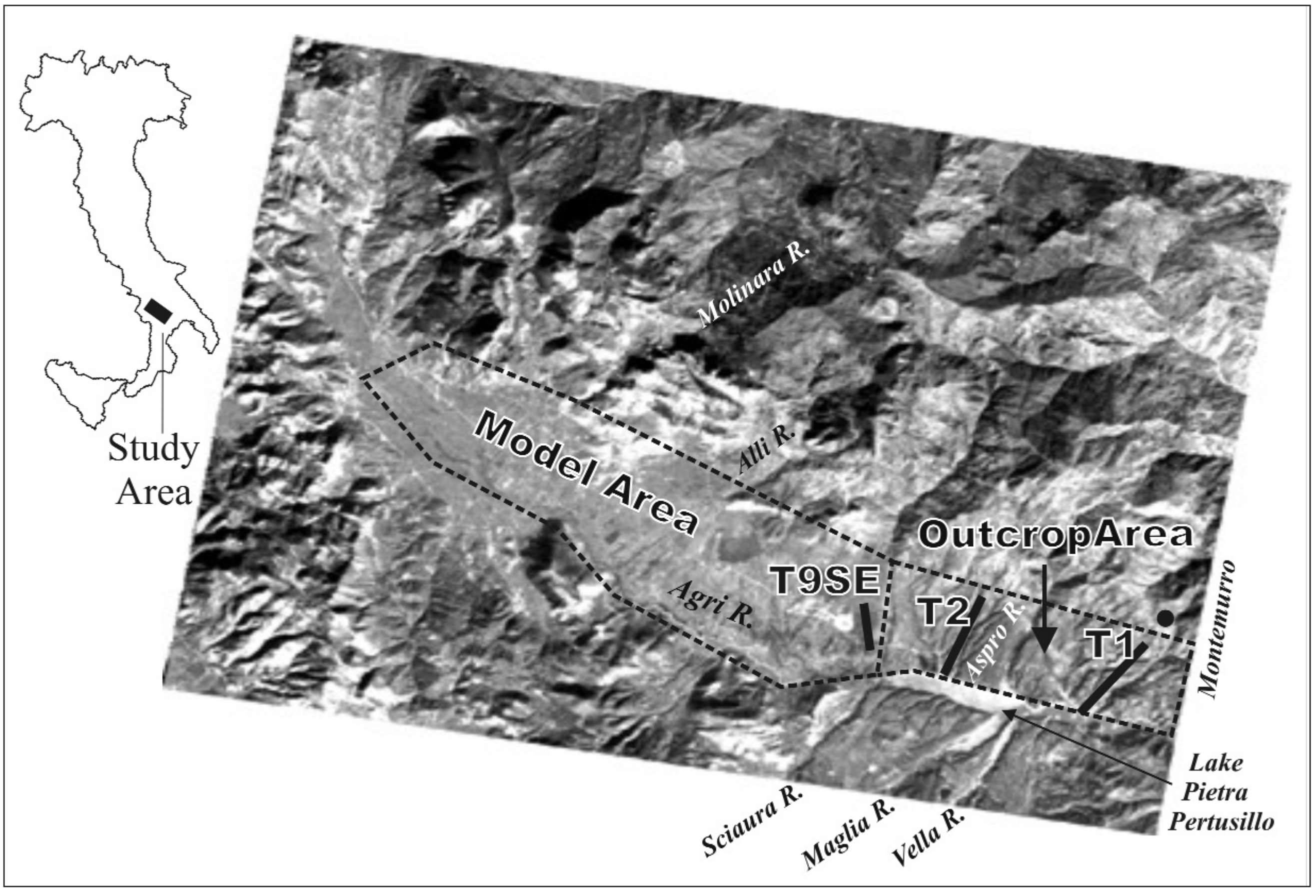

Fig. 1 - Location map of the Agri Valley. The "outcrop area" and the "model area" are framed. T1 and T2 are the cross-sections presented in fig. 2 and 3; T9SE is the geoelectrical tomography, after LA PENNA & RIZZO (2003).
- Ubicazione della Valle dell'Agri. L'area in affioramento e l'area del modello sono riquadrate. T1 e T2 sono le tracce delle sezioni stratigrafiche presentate nelle fig. 2 e 3. T9SE è la tomografia geoelettrica di LA PENNA & RIZZO (2003).

4.1. - STRATIGRAPHIC ARCHITECTURE

The stratigraphic reconstruction was based on a hierarchic criterium, which led us to recognize depositional units (DU) and bounding surfaces (S) of different rank. The highest rank boundaries are 6th order surfaces (ranking after MIALL, 1996) which are labelled by arabic numbers in fig. 2, 3; they bound the highest rank depositional units, which are labelled by roman numbers in fig. 2, 3; these units have the scale of depositional systems. The 5th order surfaces bound units of the rank of depositional elements. The lowest rank surfaces and units cover the hierarchy between architectural elements (MIALL, 1985) and facies and the relative boundaries. Following this method, we recognized four depositional units of 6th order in the outcrop area. They are described in ascending stratigraphic order in the next section.

Depositional Unit I. This is the lowermost unit which can be studied in the outcrop area, and corresponds to the lowermost part of the "lower interval" of the Agri Valley Complex (DI NIRO *et alii*, 1992). It is exposed close to the northern shore of Lake Pertusillo and can be traced for some tens of metres towards the northern basin slope (fig. 2, 3). Its lower boundary (S1) is a 6th order surface which is exposed only in a narrow peninsula within the lake, to he south of Montemurro (fig. 1). DU I consists of grey to brown silty-clays and clays, with gravel, sand and pebbly mudstone lenses (fig. 4). The fine grained sediments are plane-parallel laminated or massive, with recurrent organic-rich layers. The gravel lenses which are embedded within fine sediments lay above concave and sometimes steep erosion surfaces; they show sigmoidal to trough–cross lamination and crude normal grading. The sand facies are generally massive and fine grained, forming tabular or lenticular units. They occur in the upper part of DU I. Some pebbly mudstones, with pebbles and boulders mixed with a silty-clay matrix, occur within the same unit outside the studied outcrop area, close to the southern shore of Lake Pertusillo (Maglia River, fig. 1). The well known palaeontological findings described by De Lorenzo (1898), were collected in this area, into the lowermost fine grained sediments of DU I (diatom-rich layers, molluscs and mammal vertebrate fossils).

The facies assemblage of DU1 has been interpreted as typical of a lacustrine depositional system since the early work by De Lorenzo. Small fan-delta bodies prograded from some river mouths, both from the north-western and from the southern basin margins, forming gravelly distributary channel units and sand-sheet bars. As a consequence of the progradation-aggradation dynamics, the deposition of fine-grained sediments shifted progressively to the south-east, resulting in filling of the ancient lacustrine area. Based on this interpretation we presume that the fine-grained intervals within Unit I should be interfingered northwards and westwards with the coarse-grained units, reaching the bedrock of the basin marginal slope, which dips south, below the Agri Valley Complex. The total thickness of Depositional Unit I in the outcrop area is unknown at present; a minimum of 20 m can be figured out by the available exposures (fig. 3). The palaeontological data by De Lorenzo (1898), and morpho-structural considerations, (Di Niro *et alii* 1992), and Di Niro & Giano (1995), date the

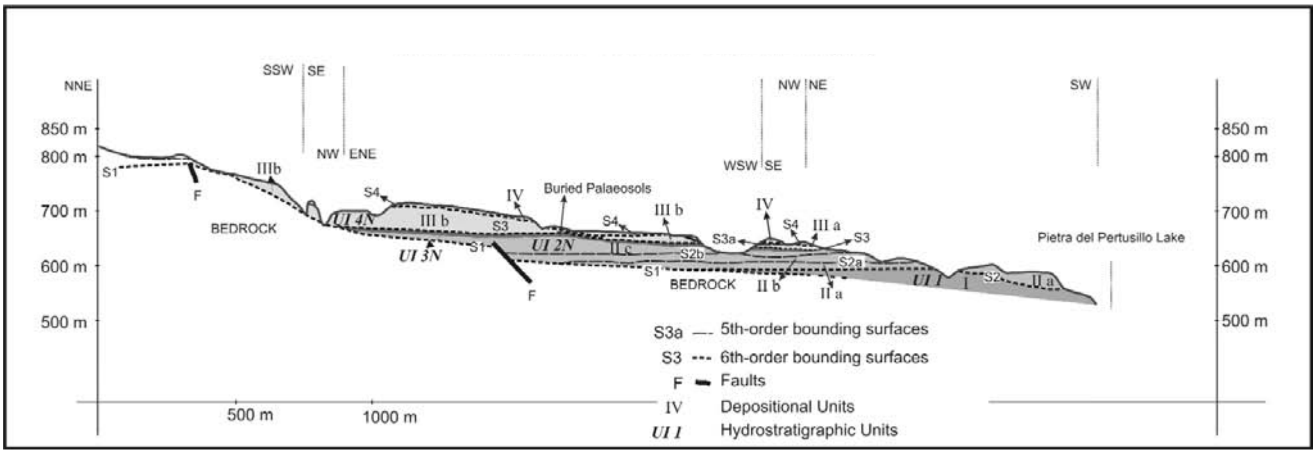

Fig. 2 - Stratigraphic cross-section of the Montemurro area (T1, location in fig.1).
- *Sezione stratigrafica della zona di Montemurro (transetto T1, ubicato in fig.1).*

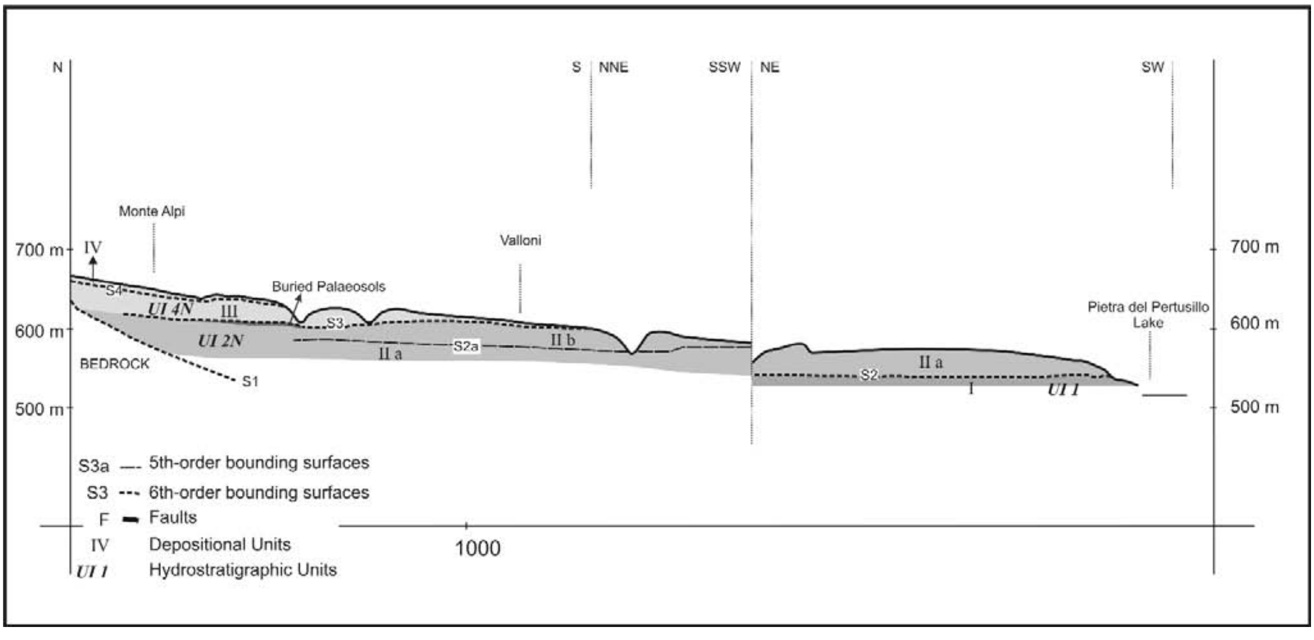

Fig. 3 - Stratigraphic cross-section of the Aspro River (T2, location in fig.1).
- *Sezione stratigrafica della zona del T. Aspro (transetto T2, ubicato in fig.1).*

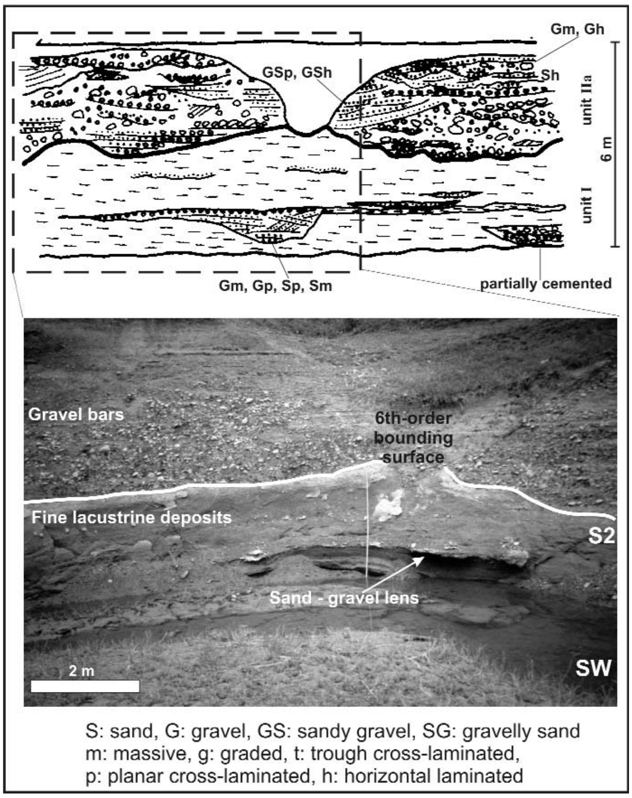

Fig. 4 - Example of facies association of Depositional Unit I and lowermost Depositional Unit II (southern margin of T2, Aspro River, close to Lake Pietra del Pertusillo).
- Esempio dell'associazione di facies dell'Unità Deposizionale I e della parte inferiore dell'Unità Deposizionale II (estremo meridionale del Transetto T2, Valle dell'Aspro, presso il Lago di Pietra del Pertusillo).

sediments corresponding to our DU I to the Middle Pleistocene.

Bounding Surface S2 separates DU I from DU II and has been ranked as 6th order because of its important geological significance (boundary between different depositional systems) combined with its basinwide distribution. In the northernmost outcrops it is an almost flat surface, gently dipping SE (between the present-day elevation of 520 and 600 m above sea level), above which the sands and gravels of DU II suddenly cover the finer sediments of DU I. Towards the SE, S2 assumes the features of an erosion surface, scoured into the lacustrine deposits (fig. 2).

Depositional Unit II is a composite sedimentary body, up to 70 m thick, formed by three minor units which are framed by 5th order boundaries (respectively IIa, IIb and IIc, S2a and S2b in fig. 2 and 3). The almost tabular external geometry of DU II results from compensation of the wedge-shaped mentioned minor units. DU II terminates abruptly northwards, onto the bedrock (Tertiary Flysch formations in the study area). In the Montemurro area it onlaps and seals a normal fault, which was probably active during (or post) deposition of DU I (Middle Pleistocene). Other field evidences of this normal faulting event have been reported by DI NIRO *et alii* (1992), in the Montemurro area (fig. 1). Differently in the model area, the Lower Pleistocene, faulted slope-breccia bodies (Brecce di Marsico Vetere, DI NIRO *et alii*, 1992; Brecce di Galaino, GIANO *et alii*, 1997) represent the bedrock of the lacustrine and alluvial sediments at the northern basin slope. The age of DU II is not well constrained; the intermediate part of the Agri Valley Complex, which partly corresponds to this unit, has been attributed to Middle – Late Pleistocene, based on morpho – structural considerations (DI NIRO & GIANO, 1995).

As a whole DU II is formed by two sandy gravel intervals (IIa and IIc) which are separated by a succession which is rich of fine-grained sediments (IIb). The lowermost interval IIa consists of stacked fining upwards sequences of laminated to massive sandy gravels and cross-laminated sands (fig. 5). The wide array of paleaeocurrent directions and the polygenetic composition points to deposition into braided, coarse-bedload channels, presumably representing an ancient axial alluvial system (i.e. parallel to the major axis of the basin). At the top of these sediments, above S2a surface, very fine sand, silt and clay facies become more and more abundant; they are characterized by the presence of organic-rich clays and recurrent development of hydromorphic soils. Coarsening upwards sequences of trough cross-laminated sands, gravelly sands and massive gravels are interbedded more and more frequently upwards into these fine grained facies. Very fine grained, light coloured, sheet sands begin to occur close to the top of interval IIb; very typical lenses of massive gravels, rarely crudely stratified or graded, sometimes with huge boulders, are cut and filled into these sands. These coarse grained units have a monogenetic composition, derived from erosion of the Tertiary Flysch formations, which are at present exposed at the northern basin slope. Above S2b, the facies association of the IIc interval is characterized by laminated gravelly sands and poorly organized to massive gravels, which form coarsening upwards bodies, resting on concave-up minor erosion surfaces. These bodies alternate with huge beds of disorganized and poorly sorted gravelly sands, fine-grained and tabular massive sands and lens-shaped gravels, with monogenetic composition. In the Montemurro area (east), the uppermost meters of DU II show a well developed weathering profile, with the local preservation, below surface S3, of a 1 – 3 m thick red palaeosoil. Westwards (i.e. towards the model area) the preserved weathering profile and palaeosoil becomes more and more thin. In the Aspro Valley (fig. 3), the soil at the top of DU II is present in a very limited area, close to the northern basin slope.

The architecture of DU II can be interpreted as the result of deposition by an axial braided river, which built its alluvial and flood plain above the former lacustrine sediments. Alluvial fans started to prograde southwards, since the time of deposition of interval IIb, and their deposits replaced the axial system before the end of the history of DU II. The development of the weathering profile and palaeosoil testifies to the morphological and depositional stabilization of the top surface of DU II, which was correlative to the local base-level (at present its elevation is at about 600 m above sea level).

Bounding Surface S3 is a composite surface, which develops between 600 and 660 m above sea level (fig. 2, 3). The southern part of this boundary is an erosion surface, which truncates the weathering profile at the top of DU II; northwards it is correlative to a flat deposition surface, without evidences of truncation.

Depositional Unit III. This unit is confined in the northern part of the outcrop area. Its southern termination corresponds to a sudden reduction of dip of the surface morphology. DI NIRO *et alii* (1992), interpret this morphological step as the southern end of coalescent alluvial fans. We suggest that the morphology step could have been enhanced by erosion, that led to the origin of the bounding surface S4. The external shape of DU III is that of a wedge, with an abrupt northward termination above the bedrock and a southward gentle thinning; this suggests a mostly aggradational style of deposition, before the subsequent erosion. Thickness of this unit ranges between 0 and 30 m. DU III covers the bedrock, which is mostly represented by the Tertiary Flysch units in the outcrop area. Differently, in the model area, DU III covers the Pleistocene Marsico Vetere and Galaino breccias, and interfingers with corse-grained slope deposits, which accumulated at the base of calcareous relieves. The age is poorly constrained by stratigraphic position and cross-cut relations between the bounding surfaces. Actually the top of DU III predates the entrenching of the drainage network, which occurred as a consequence of breakthrough of the basin threshold, presumably during the latest Pleistocene (DI NIRO & GIANO, 1995).

The facies assemblage is characterized by the repetitive association of massive and poorly sorted

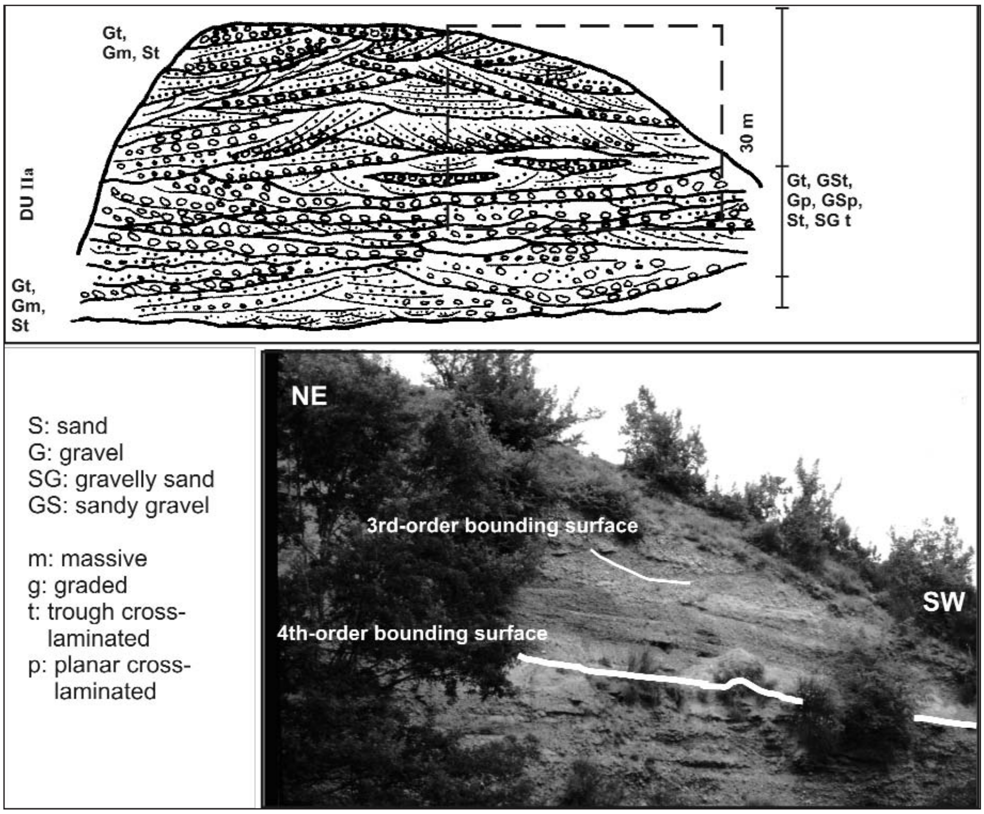

Fig. 5 - Example of facies association of Depositional Unit II (upper part corresponding to Depositional Unit IIa) in the Aspro River cross section (T2).
- *Esempio dell'associazione di facies dell'Unità Deposizionale I (parte superiore corrispondente alla sotto-unità deposizionale IIa) nel Transetto T2, Valle dell'Aspro.*

sandy gravels, crudely bedded gravels, sometimes normal graded and imbricated, sheeted massive sands (fine to very fine grained and well sorted) with lenses of very coarse gravels and boulders (fig. 6). The monogenetic composition of gravels points to northern sources (Tertiary Flysch) as it was observed in the alluvial fan deposits of DU II. In the southeastern sector only (Montemurro, fig. 3), the lowermost interval of DU III (i.e. IIIa in fig. 3) shows different facies and composition. This thin and poorly preserved interval is formed by polygenetic gravels and sands, with trough cross lamination and/or horizontal lamination, suggesting a different source and depositional style in comparison to the overlaying sediments. These features allow to interpret the sediments of interval IIIa as the last evidence of the ancient axial system, covered by aggrading and prograding alluvial fans, fed from the northern tributaries to the Agri basin, which drain a catchment sculptured into the Tertiary Flysch units.

Bounding Surface S4. This is a composite erosion surface which contributes to shape the morphology of the top boundary of DU III. It is formed by different almost flat surfaces, which get more and more steep towards the marginal slopes. S4 locally joins the present-day erosion surface, which started to form during the fast entrenchment of the present-day drainage network leading to the present-day shape of the terraced part of the Agri Valley. In the cases in which the sediments of DU IV are absent, it is quite difficult to separate S4 from the present-day erosion surface.

Depositional Unit IV. It is represented by a thin veneer of gravelly sands and sands which form different terraces, on top of the Agri Valley Complex. DU IV corresponds to the "alluvioni terrazzate" *(tf)* (CARBONE *et alii*, 1991). This unit does never exceed the thickness of 5 - 10 m and consists of crudely laminated sandy gravels and sands. The top of this units preserves an alluvial soil profile, 1 - 3 m thick. It can be interpreted as the result of the first stage of development of alluvial terraces, presumably latest Pleistocene in age, which marked the beginning of erosion through the Agri Valley Complex, in the area between the ancient threshold (which could have been located east of the present-day position of the Pertusillo dam) and the Monticello di Tramutola bedrock spur (fig. 1).

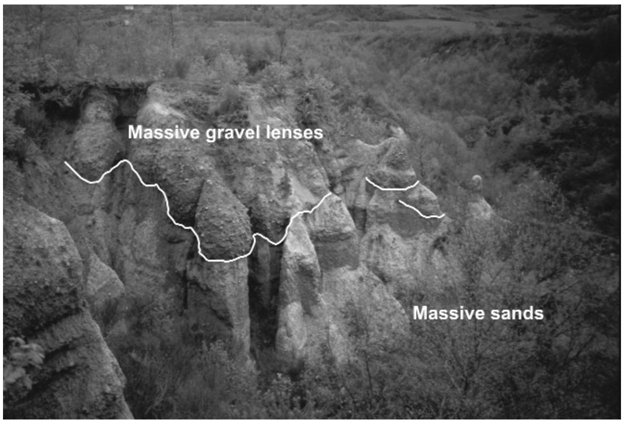

Fig. 6 - Example of facies association of Depositional Unit III in the northern portion of the Aspro River cross section, (T2).
- *Esempio dell'associazione di facies dell'Unità Deposizionale III nel Transetto T2, settore settentrionale, Valle dell'Aspro.*

Recent sediments, Holocene to present in age, are represented by terraced alluvial sediments, which are telescoped into the deeply entrenched drainage network. They interfinger with slope, scree and colluvial deposits, both at the base of the terrace walls and at the base of the bedrock slopes. After building of the Pertusillo dam, all the Holocene Valleys north of the artificial lake became oversupplied, with cycles of deposition/erosion of sands and gravels, modulated by the artificial lake level.

4.2. - ANALOGUE HYDROSTRATIGRAPHY IN THE OUTCROP AREA

The stratigraphic architecture of the Agri Valley Complex can be translated into an analogue hydrostratigraphy which incorporates also the results of laboratory textural analyses (42 samples collected into the fine gravel, sand and silt/clay facies), and the estimates of permeability, obtained by the application of different empirical formulas (tab. 1). The analogue hydrostratigraphic scheme includes 4 units: two semipervious units (aquitards) which frame two aquifer units. More specifically, the lowermost aquitard analogue (UI 1 in fig. 2, 3) coincides with DU I (fine grained lacustrine sediments with lenses of gravels and sands of fan delta environment). It is characterized by very low permeable ($10^{-9} < K < 10^{-7}$ m/sec; tab. 1), thick and laterally continuous layers. The permeable lenses within this unit are not well connected and should not provide pathways for groundwater exchanges with the underlying units (aquifers hosted both in the carbonate bedrock and/or in ancient alluvial cycles, whose presence in the model area can be inferred by the seismic interpretation provided by MORANDI & CERAGIOLI (2002) as it has been discussed in Chapter 3). The major intermediate aquifer analogue (UI2N in fig. 2, 3) is represented by DU II (sub-units a, b and the poorly weathered lower part of c). Its lower part (DU IIa) is the most permeable (estimates of K vary between 10-

Tab. 1 - *Estimates of hydraulic conductivity, based on grain size analyses of 42 samples and empirical formulas (Bear, 1979).*
- Stima delle conduttività idrauliche, basata sull'analisi granulometrica di 42 campioni e sull'uso di formule empiriche (Bear, 1979).

Facies	K (m/sec)	Krumbein & Monk	Harleman	Hazen
GRAVELS	Max	2,13 10^{-2}	2,26 10^{-2}	3,20 10^{-2}
	Min	>1,00 10^{-9}	>1,00 10^{-9}	>1,00 10^{-9}
	Medium	2,99 10^{-6}	3,16 10^{-6}	4,49 10^{-6}
	-Log K_{modium}	5,52	5,50	5,34
	σ (standard deviation –Log K)	1,63	1,63	1,63
SANDS	Max	5,32 10^{-3}	5,64 10^{-3}	8,00 10^{-3}
	Min	>1,00 10^{-9}	>1,00 10^{-9}	>1,00 10^{-9}
	Medium	3,25 10^{-7}	3,44 10^{-7}	4,88 10^{-7}
	-Log K_{medium}	6,48	6,46	6,31
	σ (standard deviation –Log K)	1,72	1,72	1,72

^{2} and 10^{-5} m/sec). The intermediate part (DU IIb) is characterized by the presence of relatively abundant semi-pervious layers ($10^{-9} < K < 10^{-7}$ m/sec) but their thickness and lateral continuity is poor; moreover they are interbedded with permeable gravel/sand units. Therefore the sediments belonging to DU IIb are here interpreted as a very low-efficient and local confining layer. The upper part of the intermediate aquifer analogue is represented by DU IIc, which shows K values ranging between 10^{-2} and 10^{-7} m/sec, because of the alternation of gravel lenses and sheets with very fine grained sands. The weathering profile at the top of unit DU IIc reaches a thickness of about 10 m, with a soil profile up to 3 m thick. The very low permeability of the palaeosoil (10^{-9} m/sec) and its lateral persistence suggest that this horizon could represent a relatively poorly efficient confining layer, that we called upper aquitard analogue. It gets progressively truncated towards the NW (fig. 3), by the erosion surface S3 and therefore its presence and efficiency in the model area are highly uncertain. The uppermost aquifer analogue includes the thick and coarse-grained DU III and the thin, coarse grained sediments of DU IV. Somewhere, the recent terraced sediments of the Agri River and tributaries lay above or are juxtaposed to this unit; in these cases they are enclosed into the uppermost aquifer analogue. This unit is mostly present in the northern sector of the basin; its southern boundary is roughly coincident with the surface morphological boundary between the northern alluvial fans and the southern terraces. Its sediments are in contact with the topographic surface by means of several different soil profiles, which developed either at the top of DUIII (poorly preserved after erosion) or at the top of DUIV. Some recent soil profiles are also present, mostly in the least steep zones. As a consequence, the uppermost aquifer analogue is poorly confined and protected at its top in the outcrop area. Ciaponi *et alii* (2002) and Spilotro *et alii* (2003) infer a good protection of deep aquifers in the area corresponding to our model area, due to the interpreted presence of thick fine grained deposits both at the top of the alluvial fans area and in the terraced area to the south.

5. - THE MODEL AREA-COMPARISON WITH THE ANALOGUE HYDROSTRATIGRAPHY OF THE OUTCROP AREA

The model area is adjacent to the outcrop area, at its north-western termination (fig. 1); its shape and extent are shown in figure 7. It encompasses the entire sector of the Agri Valley which was not affected by the latest Pleistocene – Holocene erosion stage, just north of the present-day course of the Agri stream. Due to its present position, close to the southern valley slopes, the model area includes more than 80% of the Agri Valley, to the north-west of Viggiano (fig. 1, 7).

Constraints to aquifer architecture of this area can be obtained by 1) surface geology, at the border between the marginal slopes and the alluvial sedimentary fill, 2) subsurface data from water wells, some oil wells and geophysical experiments (seismic and electrical tomography) and geomorphology.

The outstanding geological features in the model area are the following:

1) The border between the alluvial aquifers and the bedrock can be observed at the exposed marginal slopes. The substratum consists of Ligurian nappes (low permeable), Tertiary Flysch units (low permeable) and Panormid nappe carbonates, the latter representing the most important water reservoir in the upper Agri Valley area (Civita *et alii*, 2003). Carbonate slope breccias of plausible Early Pleistocene age (Brecce di Galaino, Brecce di Marsico Vetere, Di Niro *et alii*, 1992; Giano *et alii*, 1997) cover the pre-Quaternary substratum, dipping below the alluvial succession equivalent to the Agri Valley Complex. WNW – ESE normal faults affect the pre-Quaternary bedrock and the breccia bodies, with systematic down-throw of the southern limbs.

2) Two major, composite alluvial fan complexes interfinger from the north with the fluvial sediments of the axial Agri River (WNW – ESE striking). A morphological step between two areas with different steepness can be mapped by field and photo-geological work (fig. 7). The fans are portrayed in the geological map by CARBONE *et alii* (1991) with the label of "dt" (slope deposits).

3) Unfortunately very few stratigraphic logs from water wells are available; moreover the oil well data are based only on widely spaced cutting samples, an therefore the stratigraphic image of the subsurface is very poorly constrained. For this interpretation we refer to COLELLA *et alii* (2003a). The Authors interpret (their fig. 2, 7) the presence of a lowermost aquitard unit, probably equivalent to the lacustrine deposits of our DU I (lowermost aquitard of the outcrop area), above which a multilayer aquifer occurs. This consists of interbedded gravels, sands and clay-silt units, which form most of the upper 150 m of the buried alluvial succession in our model area. These sediments interfinger northwards with alluvial fan sediments. An uppermost local aquitard unit, probably poorly efficient, is reported at the top of the multilayer aquifer, in the alluvial plain, south of the southern reach of the northern fans. This reconstruction shows a good agreement with the less detailed interpretation of the subsurface provided by MORANDI & CERAGIOLI (2002).

4) Very good geophysical data are available. The seismic image by MORANDI & CERAGIOLI (2002) has been already discussed. Geo-electrical tomographies by LA PENNA & RIZZO (2003), calibrated with the few available well data, allow for the most precise comparison between the outcrop area and the model area. As an example of this comparison we present in fig. 8 the match between the Authors' easternmost tomography (T9SE) and our westernmost cross-section (T2 – Aspro Valley). The correlation between electro-stratigraphic unit B and DU I, as well as the good match between electro-stratigraphic unit A and DU II - III is enough convincing, taking into account also the stratigraphic reconstruction of COLELLA *et alii* (2003a) and the seismic data.

In synthesis, a comparison between the aquifer architecture of the outcrop area and the model area seems to be possible. Obviously, the poor detail of the subsurface stratigraphy and of the geophysical image do not allow for correlation at the scale of the outcrops' observations, therefore we decided to assume the very simplified model of figure 8 as the reference for the set-up of the preliminary groundwater model. It includes: 1) a basal aquitard/aquiclude; 2) a thick aquifer unit above it, formed by river and alluvial fan deposits,

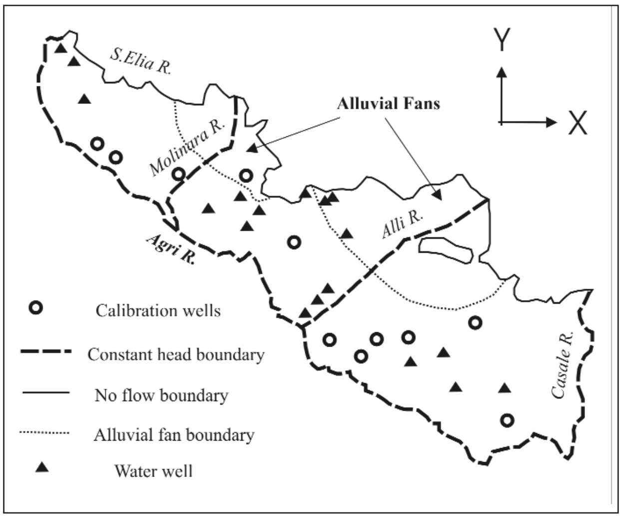

Fig. 7 - Scheme of the "model area"; note the rock spur in the northern sector of the Alli River Alluvial fan.
- Schema dell'area del modello. Si noti lo sperone di substrato nel settore settentrionale della conoide alluvionale del T. Alli.

for which we assumed the permeability estimates obtained from the outcrop analogue and some water well data; 3) no water exchange with the bedrock-hosted aquifers. The latter assumption is mostly based on the outcomes of hydrogeological balance computed by CIVITA *et alii* (2003), who suggested minor or no exchange between the bedrock and alluvial aquifers.

6. - SET-UP AND OUTCOMES OF THE SIMPLIFIED HYDROGEOLOGICAL MODEL

Based on the conceptual model obtained from integration of the outcrop analogue with the stratigraphic and geophysical data in the model area, we set-up a very simple, traditional hydrogeological model in order to test the reliability of the hydrostratigraphic reconstruction. It has been implemented on the popular Mod Flow© module of GMS® software. The model area is shown in figure 1 and figure 7. The set-up of the simulation is based on the following data and parameters:

- surface topography, obtained from the IGM 1:25.000 DTM of the Agri Valley;
- aquifer geometry and architecture, based on the conceptual model that has been presented above. The local shape of the aquifer bottom has been obtained by interpolation of about 250 control points (Inverse Distance Weighted method), based on the data by LA PENNA & RIZZO (2003) and COLELLA *et alii* (2003a);
- permeability estimates: an average value

was used for the entire aquifer, above the lowermost aquitard; it was derived from the K estimates in outcrops (tab. 1, 2) and the values figured out by SPILOTRO *et alii* (2003) from well tests in the adjacent areas;

- recharge: two different values were used for the alluvial fan and the alluvial plain areas (fig. 7; tab. 2). The parameters were obtained after computation of the hydrologic balance presented by GIUDICI *et alii* (2003);
- boundary conditions: based on the previous discussion we assumed that the bedrock/aquifer contact represents a no flow boundary. Moreover we assumed the water heads of the surface river network as constant head boundaries (fig. 7);
- flow regime: we assumed stationary flow (average annual conditions)
- calibration: we used 11 calibration wells, as reported in figure 7;
- grid: the simulation grid consisted of 560 rectangular cells (224 m x 563 m), with the major side parallel to the average valley axis (N120 in strike).

To evaluate the influence of the estimates of recharge and permeability, we run several computations, assigning different combinations of arbitrary values (some of which unrealistic) to these two parameters (tab. 2).

As an example of the model's outcomes, the result of Simulation 1, which has been worked out assigning the original and more realistic input parameters, (tab. 2) is presented in figure 9. Some considerations can be drawn:

1) the oversimplification and the poor hydrogeological constraint to the model are evident; this is due to poor information about the subsurface architecture and hydrogeology of the model area;

2) the model correctly forecasts the radial shape of the flow lines related to the simulated piezometric surface and the draining effect of the Agri River. This outcome is in good agreement with the piezometric maps we could draw using the complete data-set of the 132 available water wells for the 2000 – 2002 time span. Comparable piezometric maps had been presented by CIAPONI *et alii* (2002) and SPILOTRO *et alii* (2003) for the same area;

3) the large amount of flooded cells, which are located in three areas (fig. 9) indicates some inefficiency of the model. Only minor changes of this configuration have been obtained with alternative simulations, which have been run assigning arbitrary values of permeability and recharge; therefore the inefficiency is due to the oversimplification of the aquifer architecture and properties. Nevertheless, based on field observations, it must be noted that this picture is not totally unrealistic. Actually some springs are present in the northern parts of the Alli alluvial fan, which is one of the areas with flooded cells in the simulation. Moreover the water table is very shallow in two of the southernmost sectors corresponding to flooded cells; this is testified by the well data and by the farmers' practice of digging very shallow trenches (0.5 m) for irrigation. The same areas have been the sites of land reclamation in the second half of the 20th century. These observations are obviously insufficient to validate the outcomes of this simplified simulation, but help to appreciate its actual degree of inefficiency.

7. - DISCUSSION AND CONCLUSION

Petroleum geologists usually compare outcropping analogues with the subsurface reservoirs, in order to obtain input data for modelling heterogeneity. The analogues are looked for in the exposed portions of the sedimentary basin fills, as counterparts of the formations to be studied in the subsurface. The intramontane Agri basin provides a useful case to apply a similar procedure to aquifer geology and characterization, which is less habitual to hydrogeologists. Our attempt to use the outcrop analogue data as a proxy of the buried Agri Aquifer Complex is far to be completed and satisfactory, but the first results of integration of the exposed analogue hydrostratigraphy with the available knowledge of the subsurface, encourage to go in depth with this approach, allowing to draw some conclusions on this specific case history and some more general considerations.

1) The exposed Agri Valley Complex, represents the analogue of a quite heterogeneous and anisotropic aquifer complex. At present most of the outcrops show sediments which belong to the non-saturated zone or contain minor perched aquifers. The knowledge of geometry, facies architecture and permeability distribution through these units provides a tool to forecast the distribution of these features in the subsurface, at a smaller scale and with less detail. For instance, the description and the reconstruction of the geological evolution of the sediments forming the *lowermost aquitard analogue* (DU I) allows to formulate a strong working hypothesis on the existence and configuration of correlative units in the buried part of the basin. This is based on the "soft" data provided by the geological reconstruction, which suggest progradation of non-connected gravel lenses (fan delta deposits)

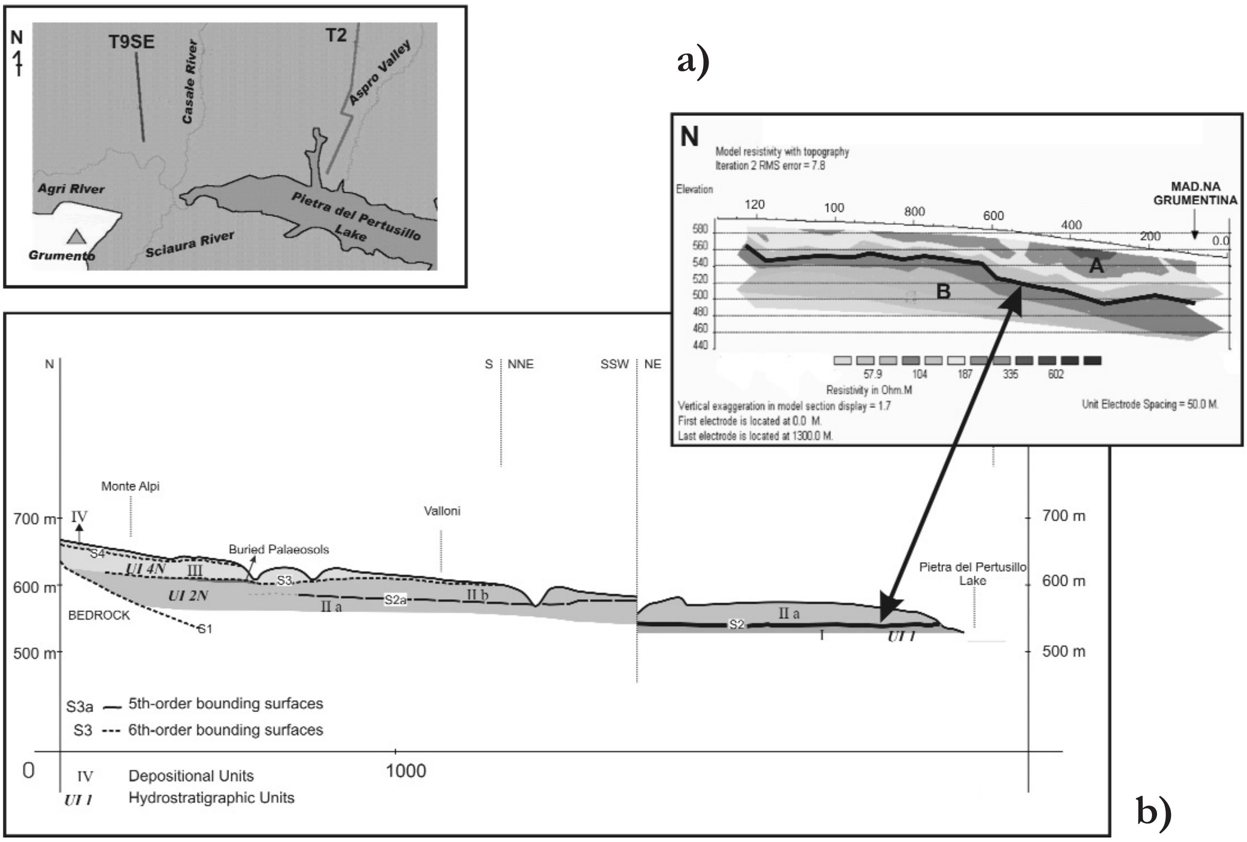

Fig. 8 - Comparison between the geoelectical tomography T9SE, a) (La Penna & Rizzo, 2003) and the Aspro Valley cross-section T2, b).
- *Confronto tra la tomografia geoelettrica T9SE,* a) *(*La Penna *&* Rizzo*, 2003) e la sezione stratigrafica T2,* b)*(Valle dell'Aspro).*

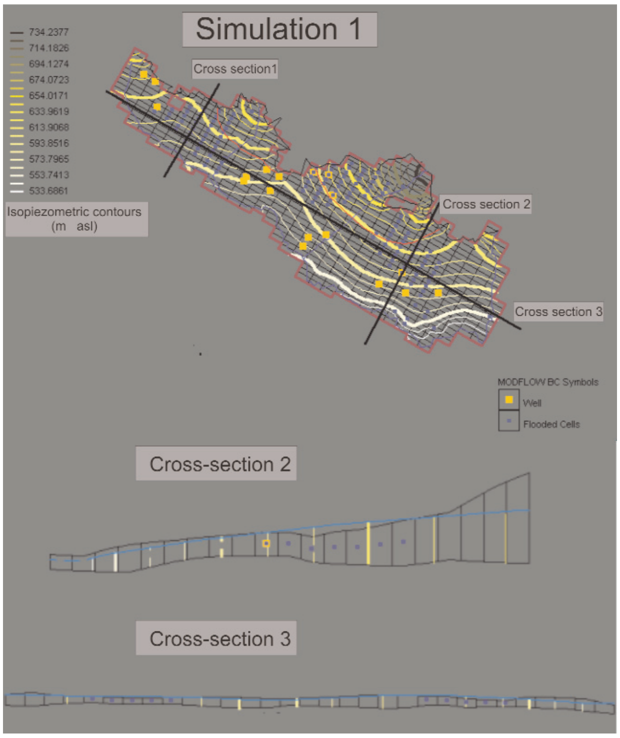

Fig. 9 - Plan view and cross-sections of Simulation 1. See discussion in the text.
- *Visualizzazione in pianta e sezioni verticali attraverso la Simulazione 1. La discussione è nel testo.*

into a fine-grained dominated succession of lacustrine environment. Progradation from both the northern marginal slope and the longitudinal "axial" direction, suggests that a comparable architecture should be looked for in the buried sector (our "model area") which is located up-current with respect to the "outcrop area". The same consideration holds also for the overlaying *intermediate aquifer analogue* (DU II), the *upper aquitard analogue* (DU IIc) and the *uppermost aquifer analogue* (DU III and DU IV). More specifically, the vertical and horizontal distribution of strong and/or weak confining layers can be forecasted taking into account that they are formed by two kinds of units: a) lacustrine and flood plain fines, whose presence and position is strongly related with the facies changes of the alluvial sediments; b) buried palaeosoils, which developed in wide and stable areas and were preserved only in the basin sectors (and during times) dominated by an aggradational style of deposition. In the outcrop area this situation has been shown to occur mostly at the south-eastern basin termination and during the Middle Pleistocene, being the Late Pleistocene the time for structural reactivation and subsequent erosion of the basin fill.

Tab. 2 - *Set of alternative parameters used for 5 different simulations. The parameters relative to simulation 1 are those estimated by real data; the other Simulations have been run with the indicated arbitrary values in order to estimate sensitivity of the model.*
- Insiemi di parametri alternativi utilizzati per 5 simulazioni differenti. I parametri relativi alla Simulazione 1 sono quelli stimati per mezzo dei dati reali; le altre simulazioni sono state calcolate con i valori arbitrari riportati in tabella, allo scopo di valutare la sensitività del modello.

SIMULATION	**RECHARGE (mm/year)**		**K (m/year)**
I	Alluvial fans	160	6.300
	Alluvial plain	229	
II	Alluvial fans	160	63.000
	Alluvial plain.	318	
III	Alluvial fans	160	6.300
	Alluvial plain	318	
IV	Alluvial fans	318	330.000
	Alluvial plain	160	
V	Alluvial fans	229	6.300
	Alluvial plain	229	

2) The comparison between outcrop and model area can be considered satisfactory at the scale of the high rank hydrostratigraphic units, allowing to identify the basal aquitard and the overlaying unconfined aquifer complex in the latter region. On the contrary, the characterization of the analogues could not be used neither to interpret the architecture of buried hydrostratigraphy, nor to constrain the exercise of hydrogeological modelling. It is trivial to assess that more stratigraphic data should have been necessary to obtain a better calibration of the very good geophysical images of the model area (Morandi & Ceragioli, 2002, La Penna & Rizzo, 2003). The permeability estimates obtained from outcrops have been integrated with well data to compute an average K estimate, which is one input parameter for the simplified hydrogeological model. This procedure is unsatisfactory, because of the loss of any image of K variations in the subsurface. The availability of at least one stratigraphic well (with core recovery) in the model area would have helped to introduce some more incisive characterization of the aquifer properties.

3) The very simple ground water flow model was developed mostly as an exercise, to estimate the reliability of the match between analogue and real aquifers, at the high rank scale of aquifer groups/depositional systems. The outcomes of simulations show some adherence to the real behaviour of the aquifer (radial shape of the flow, drainage by the Agri River, location of some springs). This suggests that, at the scale we could operate, the architecture of the aquifer complex has been portrayed in a realistic way. Most of the shortcomings of the model's results are evidently to be attributed to oversimplifications (aquifer internal architecture, permeability estimates and distribution, relations with the bedrock-hosted aquifers). Sensitivity analysis suggests that the uncertainty on the estimate of the recharge has been probably the least important factor in biasing the results of this kind of very simple model, in the specific case of the Agri Valley.

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