Development of a TNO-REGIS geo-information system and regional groundwater model of the Friuli-Venezia Giulia coastal plain (NE Italy)

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ABSTRACT A geo-information system TNO-REGIS has been developed for the Friuli-Venezia Giulia (FVG) coastal plain in northern Italy together with a first tentative regional groundwater flow model. These activities are carried out in the framework of the EU-funded CAMI/Life project. The project should be seen as a demonstration project where the consortium partners from different disciplines (universities, scientific institutes, and private companies) provide data and information to achieve a coherent framework of the hydrogeological characteristics in the FVG coastal plain when data sets of deep boreholes are scarce. The TNO-REGIS geo-information system has been used to organise and visualise the data. Local authorities collect data on groundwater and maintain local databases, but without a geo-information system the data remain inaccessible to potential users. TNO-REGIS may fill this gap for the expert users and serves as a demonstration towards an Internet-based system, accessible to the public. A preliminary groundwater model has been constructed using the data from the consortium partners (CAMI/Life project issue) and TNO-REGIS. Again the aim is to demonstrate how groundwater models can be used to understand groundwater flow systems and as a tool for water resource management. The first model results show that groundwater quantity, even with the present rates of abstractions, should not pose immediate problems because of the high rainfall in the area. However, groundwater quality could be an issue as pollution may have infiltrated into the aquifer systems from the industrial centres located in the recharge areas.

1. Introduction

The TNO Geological Survey of the Netherlands has a broad experience in Geosciences as it constitutes the sole institute in the Netherlands responsible for the collection, storage and interpretation of all geological and hydrogeological data in the Netherlands. TNO, as stipulated by government law, is responsible for the maintenance of the DINO database in the Netherlands which is the central repository for all geo-data and is accessible to the public via the World Wide Web. TNO is also involved in numerical modelling activities of the geological and hydrogeological features of the Dutch subsoil.

Based on this expertise and extensive knowledge, TNO is a member of the consortium in the EU-funded CAMI/Life project "Water-bearing characterization with integrated technologies" and is responsible for the following activities or tasks:

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1. development and implementation of a Regional Geohydrological Informations System (REGIS);
2. development, calibration and scenario analysis of numerical groundwater flow model of a part of the Friuli-Venezia Giulia (FVG) coastal plain.

In the CAMI project, TNO has the task of combining and integrating the results of the other technical and scientific partners of the consortium. The main objective of the CAMI project from a scientific point of view can be put forward as follows: is it feasible to use results from geophysical prospecting like seismics, geo-electrics, electro-magnetics and air-borne thermography, supplemented with isotopic and chemical data from groundwaters, to construct a coherent hydrogeological layer model of the subsoil and to interpret the regional water-bearing characteristics when boreholes with geological information are sparse as in the FVG plain?

The lack of data of the subsoil, due to the sparse and uneven distribution in the coastal plain of deep boreholes with sound lithological records may be overcome by the application of these non-destructive and cost-efficient integrated methodologies as compared to the high costs of drilling exploration wells. It is the smart combination of these various disciplines and technologies that yield useful information on the hydrogeological characteristics of the subsoil.

This paper does not expect to publish innovative state of the art research. It is a demonstration of known techniques which may prove to be useful when skillfully combined. The intention of this EU-funded CAMI/Life project is not to produce high level science but to promote the cooperation in Earth Sciences of experts from different European countries and to develop techniques which could be useful for society and the sustainable management of natural resources. These techniques could be exploited by the consortium partners commercially, in later stages after successful completion of the project.

Although the project can be characterised as a multi-disciplinary pilot project to be applied mainly in the test area around the well field of the Torrate water supply company (Acque del Basso Livenza S.p.A), the data has been collected by TNO also from areas beyond the test area to construct a regional picture of the hydrogeological layering and its characteristics. In fact, groundwater modelling requires that the model boundaries should coincide with the natural hydrological boundaries and not be limited by the relatively small extent of a well field. The results of the project should likewise be of interest to the regional authorities (provinces, water boards, municipalities, etc.) involved in issues of groundwater management. Therefore, the project must aim at a regional context which was originally underestimated in the project proposals.

Fig. 1 shows the location of the coastal plain area and the area which is included in the REGIS geo-information system and groundwater model.

2. TNO REGIS v4 geo-information system

In the last decade, Geographical Information Systems (GIS) have become very important tools to visualize maps and data on maps. With the tremendous improvements in graphic capabilities like pixel resolution and colour spectrums of the modern PC, maps can now be easily viewed and manipulated on a PC. The computing power and the enormous storage capacities of modern hard disks have allowed us to run a GIS system on stand-alone computers. TNO also utilizes software from the market leader ESRI® for GIS applications. ArcGIS 9.x is the package

Fig. 1 - Location of the Torrate test area and the area as delineated by the yellow line which is included in the groundwater model. The REGIS v4 geo-information system also covers the encircled yellow area.

also used in the CAMI/Life project. ArcGIS 9.x allows the user to extend the graphical user interface (GUI) by adding so-called plug-ins. These plug-ins can be developed by the user himself or commercially by a third party. As ESRI adheres to the Microsoft® platforms, it follows that computer coding development platforms like MS Visual Studio can be used to develop plug-in software. REGIS v4 is a plug-in developed by TNO and provides the ArcGIS user with a toolbox with typical hydrogeological functionalities. TNO uses existing platforms or readily available commercial software packages to develop dedicated software modules or plug-ins.

REGIS already has a long history at TNO. It originated in the late 1980's as an extension of the menu system on UNIX®-based ArcInfo GIS systems (also from ESRI) programmed in the macro language AML. This was version 2 which was developed for the Dutch provinces as a follow-up to the National Groundwater Mapping Project of the Netherlands. As only a limited amount of basic functionalities were available in ArcInfo, it took a long period of development to create REGIS v2. The disadvantages were the high costs of ArcInfo and the UNIX® computers. With the advent of the ESRI's ArcView, at the beginning of the 1990's, for Windows computers

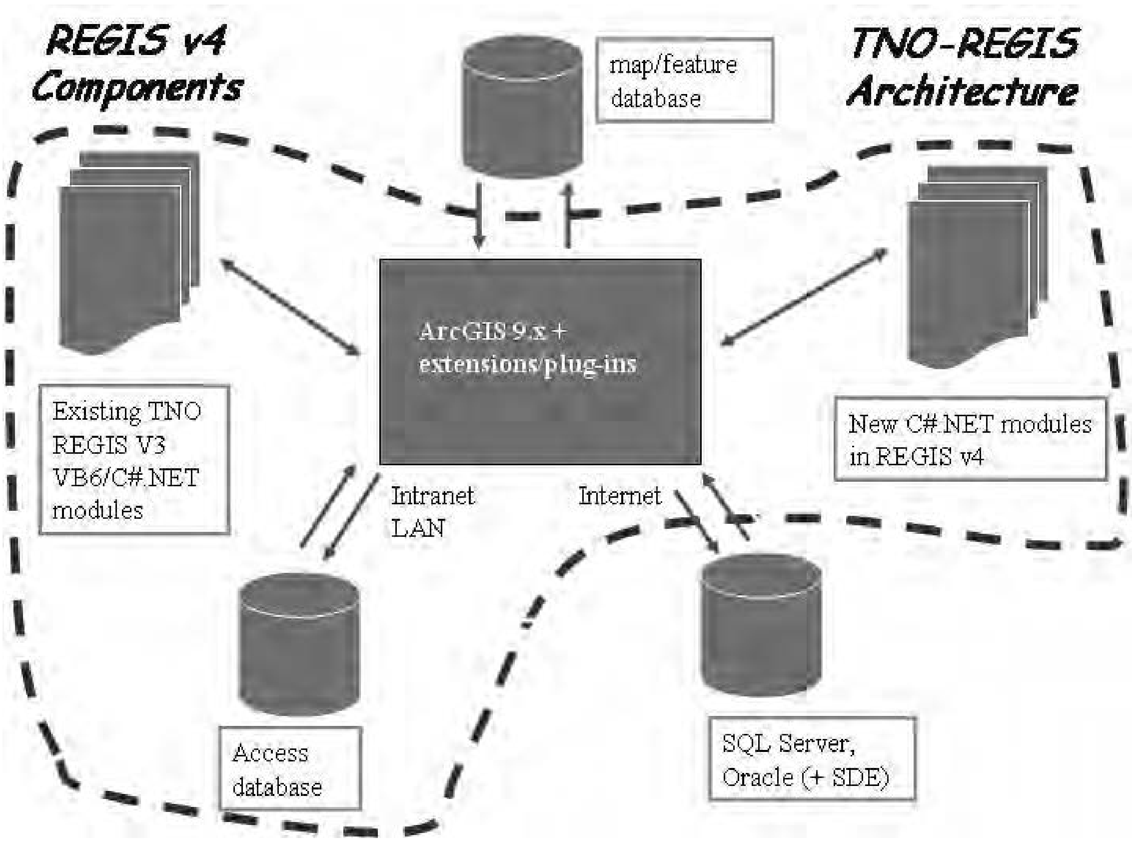

Fig. 2 - General architecture of REGIS v4.

a new development started diverting from the expensive UNIX platforms. Similarly to the Dutch provinces, REGIS v3 was developed using Avenue of ESRI as the programming language. REGIS v3 was also developed at high costs because of the fact that many functionalities had to be programmed. A more advanced version was later developed for South Africa. Major disadvantages were the relatively simple ArcView with rather limited GIS functionalities and the fact that REGIS v3 used Oracle® as the database which requires additional skills to maintain such professional databases. In 1998, TNO adopted a new approach, also because of the fact that a new line of GIS products (ArcGIS 8.x) was introduced by ESRI. This new line was more powerful than the previous ArcView versions and allowed users to link to any database and to add new functionalities by using MS Visual Basic and not be limited to the rather outdated ESRI programming languages. ArcGIS 8.x also featured many standard functionalities which would have to be programmed in the earlier REGIS version 2 and 3. TNO decided to develop comprehensive software modules to be developed in a matter of months only and able suit the user's needs. At first, Visual Basic was used and later the new Microsoft dotNET technology for programming was also used (C#.NET). This resulted in REGIS v4.

Fig. 2 shows the general architecture of REGIS v4 built around ArcGIS 9.x. It consists of

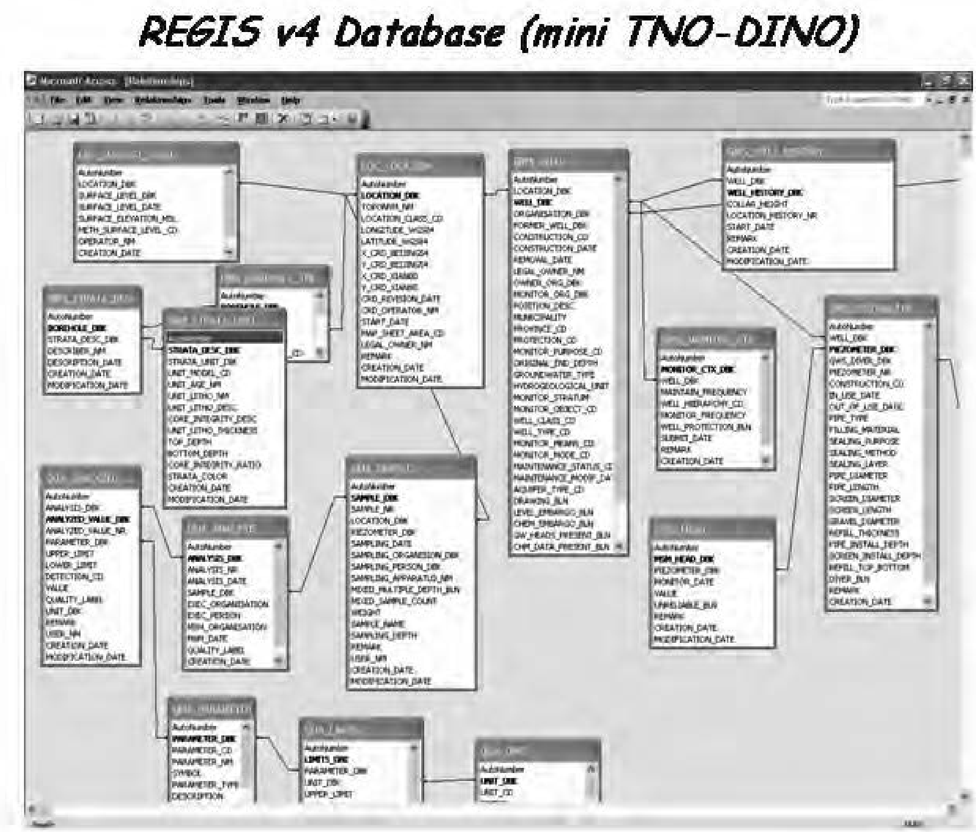

Fig. 3 - Data model of REGIS v4 in MS Access, adopted from the TNO main groundwater database.

modules in C#.NET that can be linked to the GUI of ArcGIS as plug-ins. ArcGIS recognizes the plug-ins once they are registered and loads them automatically. Older modules, from REGIS v3 which were developed in a later stage in Visual Basic 6 can still be used as they are called from the C#.NET modules. In the CAMI project, an Access database is used to store the hydrogeological data, as they are used as stand-alone systems. At a later stage, more professional databases in a network configuration like Oracle or an MS SQL Server could be used.

Fig. 3 shows a diagram of the data model of the Access database. It is, in fact, a subset of tables of the large DINO database in Oracle at TNO which is used for the storage of all geodata in the Netherlands. The data model has proven to be efficient in terms of queries and data hierarchies and is, therefore, adopted as a one-to-one copy of the tables, table structure and relationships.

Fig. 4 shows the chain-like calling sequence of the various modules in C#.NET with XML formatted intermediate files. TNO adheres to the widely accepted XML format for data exchange with other programmes. It also underlines the concept of an “open architecture” in contrast to the previous versions to allow other software developers to easily hook up to the REGIS v4 plug-in.

Fig. 5 shows the REGIS v4 toolbox in the ArcMap graphical user interface. The toolbox is

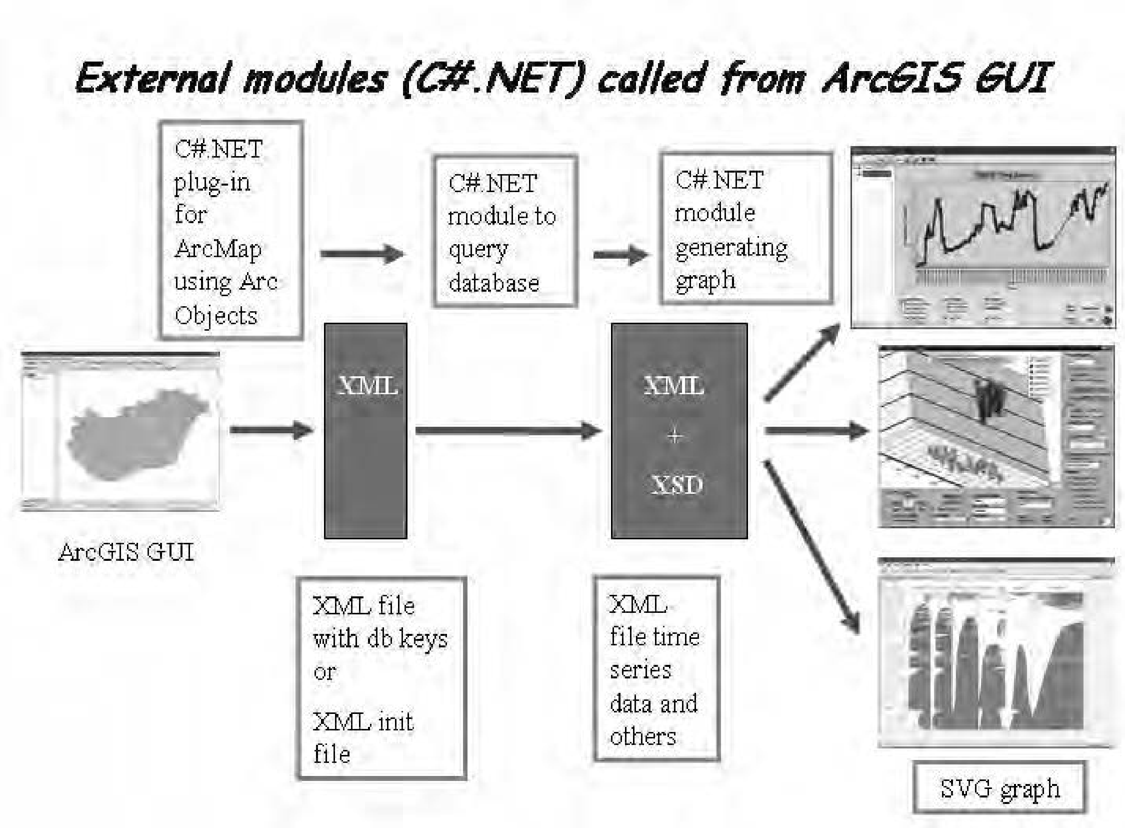

Fig. 4 - Chain-like calling sequence of the various modules in C#.NET starting from a selection in the ArcGIS window, fetching data from the database up to the visualisation in the graphic modules. All intermediate files use standard XML formats to allow exchange of data with to other programmes (open architecture).

designed for maximum flexibility and tools can be added at later stages. Table 1 lists the present operational tools in the toolbox. Any external module can be called from the toolbox and data transfer takes place via XML intermediate files.

Table 1 - Operational tools in the toolbox and the used coding environment.

Tool	Coding platform
Cross-sections of ESRI rasters representing geological interfaces along any line	C#.NET
3D Viewer of solid models, based on ESRI rasters	Java
Groundwater Graphs, time series from data in Access database	C#.NET
Chemistry Suite, typology diagrams, times series, export to MS Excel, etc.	C#.NET
Photo Archive, storage of photos, images, etc. linked to map objects	C#.NET

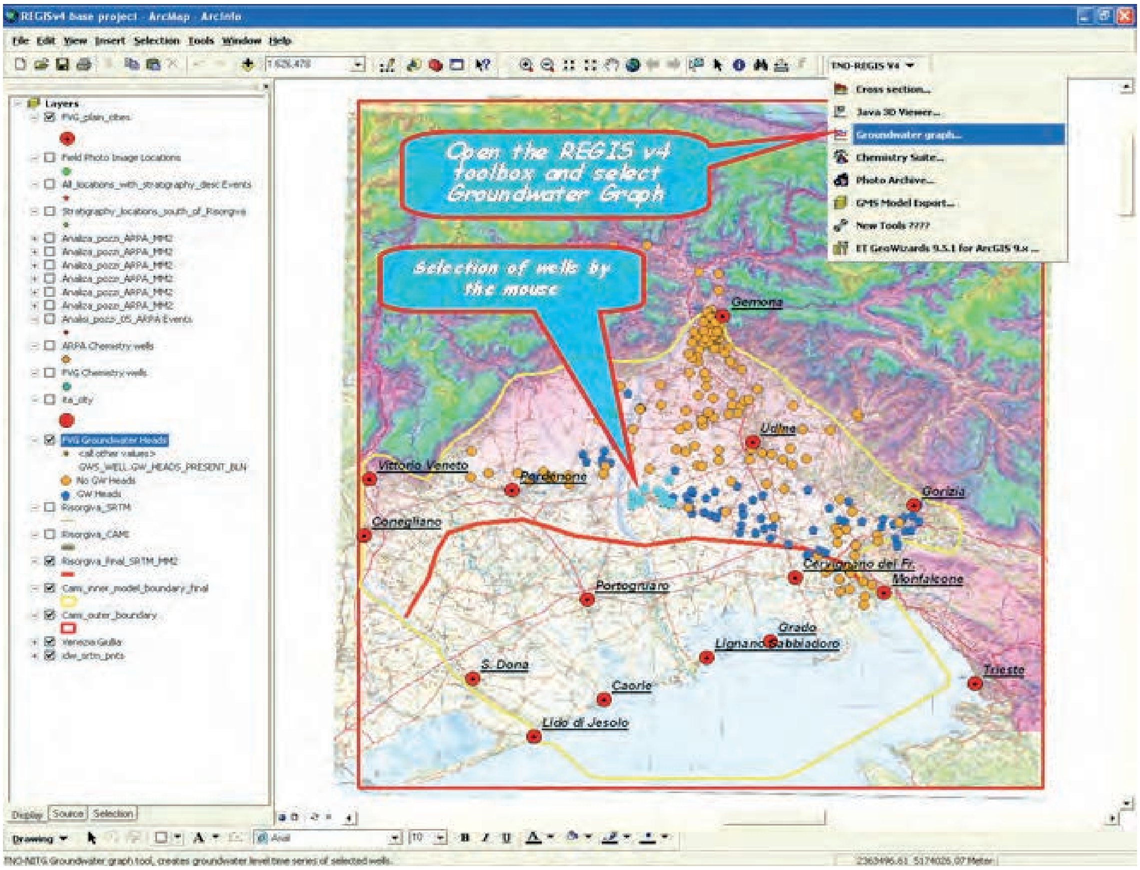

Fig. 5 - The REGIS v4 toolbox as an extension of the ArcGIS menus. More tools will be added and third party tools can be added, by "drag-and-drop" features.

As the CAMI/Life project is mainly conceived as a demonstration project, it follows that the data sets collected and entered in REGIS v4 are far from being exhaustive. Collecting data sets from various organisations involved in water resources always proves to be a difficult task, yet the available sets in REGIS v4 are already sufficient to demonstrate the use of geo-information systems to the local authorities in the FVG plain involved in water resource management. Table 2 shows a snapshot of the collected sets in REGIS v4.

Fig. 7 shows a decline of phreatic groundwater levels in the areas north of the spring line. Only after loading the data into REGIS v4 did this consistent behaviour of declining water tables become apparent.

3. Groundwater flow model development

The other major task for TNO is to develop a preliminary groundwater flow model in the FVG coastal plain using data as stored in the REGIS v4 system and all the information as collected by the other partners of the CAMI project. As argued above, the developed groundwater flow model

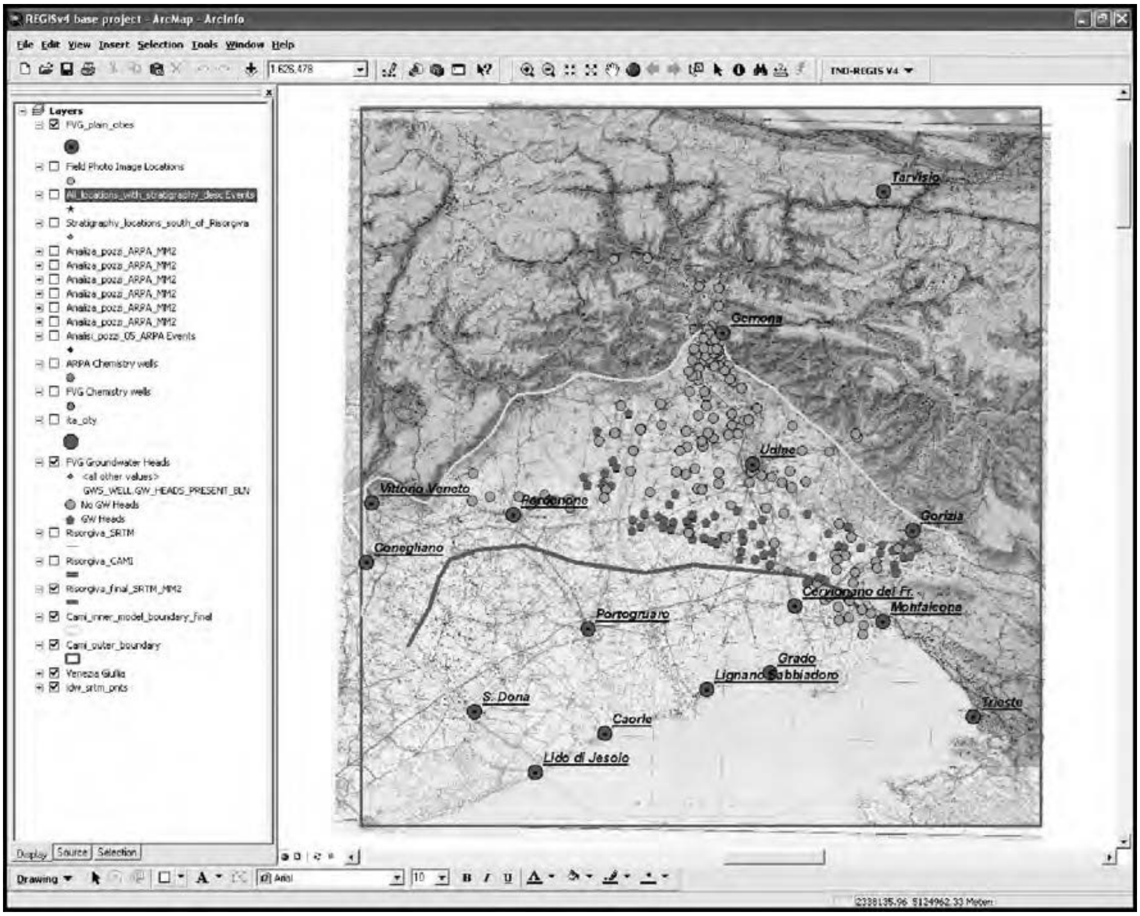

Fig. 6 - Example of a dataset in REGIS v4: phreatic monioring well. Blue coloured wells have groundwater level records. The red line is the "Risorgiva" or sprint line where groundwater seepage takes place.

Table 2 - Loaded data sets in REGIS v4 during the CAMI/Life project.

Type data set	Number of objects, records, etc.
Wells with hydrochemistry	393
Wells with phreatic groundwater levels	74
Chemical analyses	2692
Surface hydrology stations	94
Wells with isotopic sampling	12
Locations with pluviometric data	4
Locations, boreholes with stratigraphical records	1879
Groundwater levels	305644

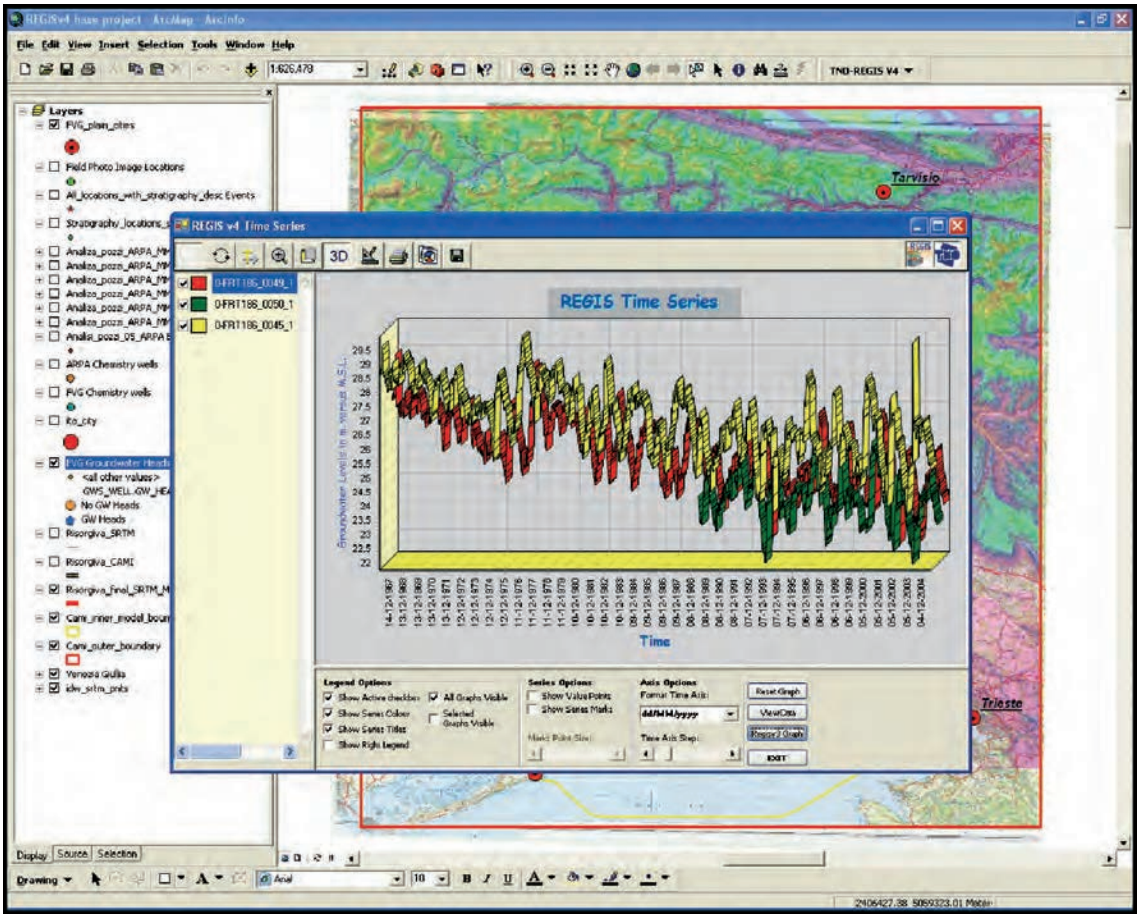

Fig. 7 - Example of a dataset in REGIS v4: times series of groundwater levels showing structural declines of some 3 to 5 meters from the late 1960's onwards.

serves as a demonstration only, and should form a starting point for further modelling activities, in the future, in the FVG plain. The developed model has a considerable regional extension which is much larger than the Torrate test area selected in the CAMI project. Fig. 8 shows the model extent.

GMS 6.0 is used in the CAMI project as the groundwater modelling software package because of its capability to convert complex geological solid models into a 3D grid for MODFLOW. MODFLOW is the computer code developed by the U.S. Geological Survey for the numerical modelling of groundwater flow and is already used worldwide. As many other commercial packages, GMS 6.0 is a user-friendly shell around MODFLOW to enter model data and analyse the modelling results. Model building in GMS 6.0 starts with the construction of the geological solid model from the basic borehole information. Once a solid model is generated and the hydraulic parameters for each hydrological unit are set as attributes, GMS converts the solid model to a 3D grid for MODFLOW. For the study area, the final MODFLOW 3D grid is composed of 1 x 1 km rectangular grid cells which are stacked upon each other as a pile of ten

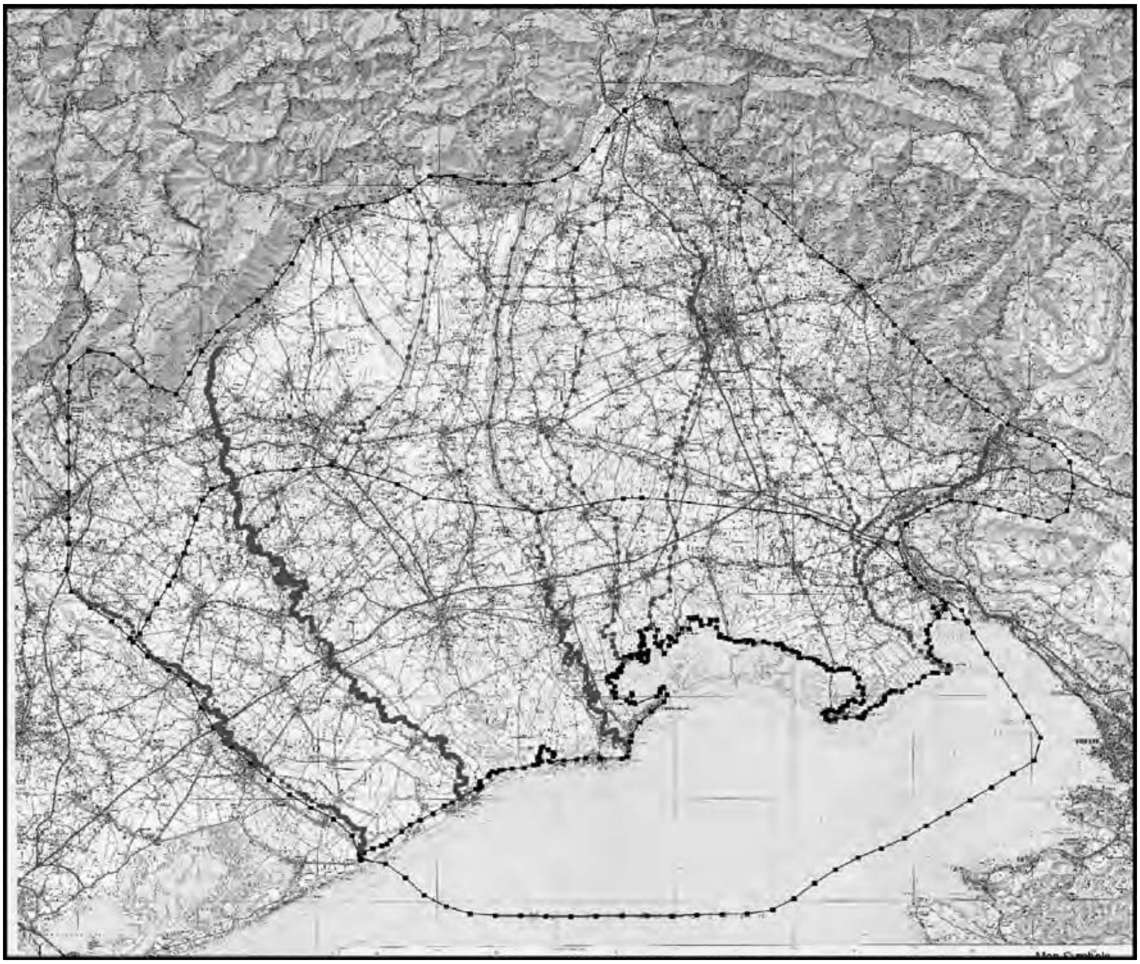

Fig. 8 - Extent of modelled area indicated by the black dotted line (area = 6800 km^2). The major rivers in the model are also indicated. As the deeper aquifers in the FVG coastal plain extend far offshore, the southern model boundary is situated in the Adriatic Sea.

cells towards the depth. The selection of the cell size is based on the available data and accuracy, the model extent and computing performance.

The model is used, initially, in steady-state conditions, to simulate the original reference situation without any abstraction of groundwater by wells. As a second step, the model is applied in transient conditions to reconstruct the history of the groundwater levels starting from the reference situation up to the present situation and using the groundwater abstraction as the forcing factor (Anderson and Woessner, 1992).

Fig. 9 shows the set of boreholes with detailed geological layering data used to construct the geological solid model with GMS 6.0. The geophysical data, as collected by the other consortium partners like 2D/3D seismics, geo-electrical methods, etc. proved to be very useful in refining the solid model by adjusting the cross-sections and forcing GMS to generate a solid model in line with the geophysical data (Nicolich *et al.*, 2004). The final geological solid model is shown in

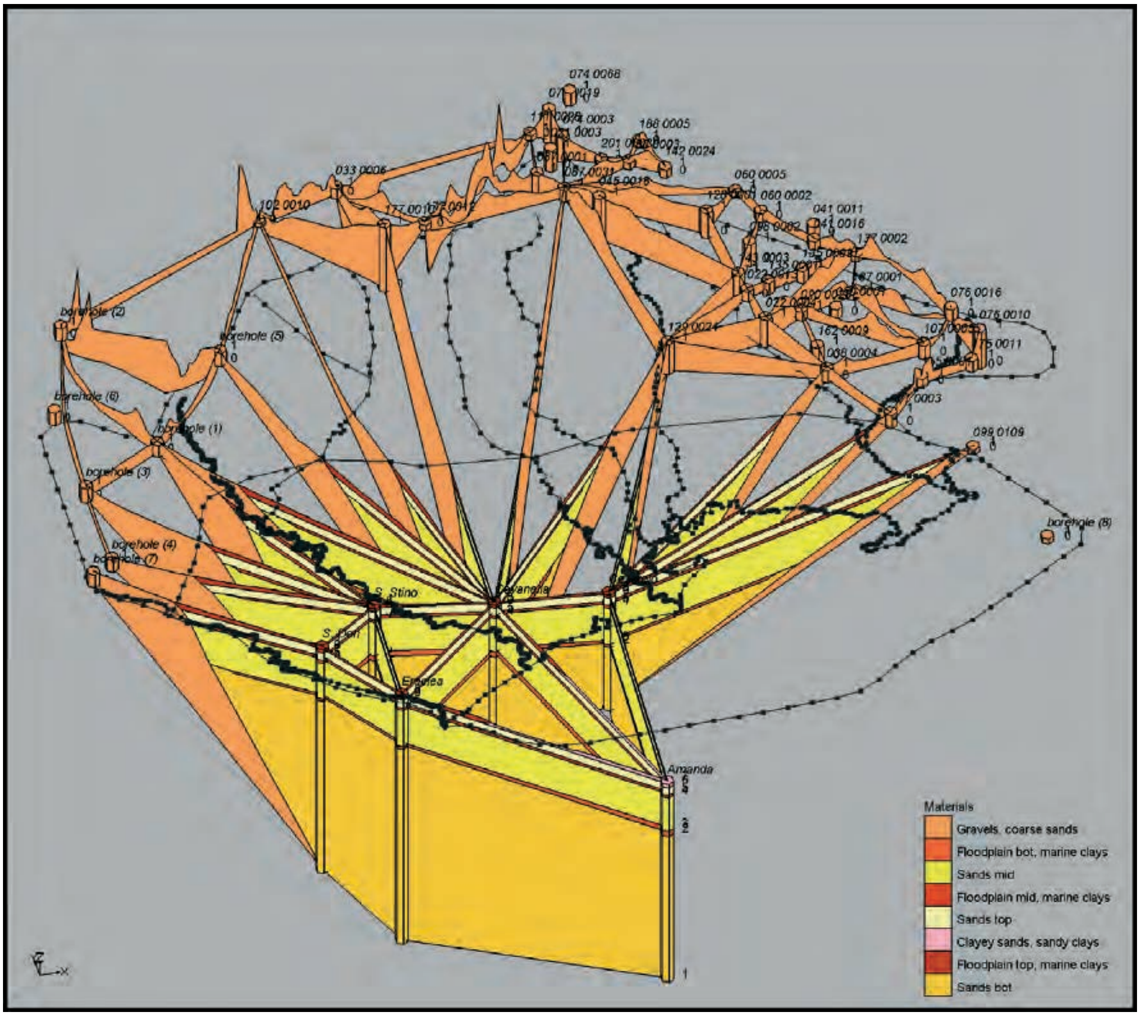

Fig. 9 - Fence diagram showing the set of boreholes used to create a geological solid model. The deep wells are derived from AGIP oil company.

Fig. 10. It features 8 geological units of post-Tertiary age. It is assumed that practically all regional groundwater flows in the FVG plain occupy this pile of sedimentary rocks.

The top of the groundwater model shown as a triangular network in Fig. 10 is derived from the Space Shuttle Radar Topography Mission (Jarvis *et al.*, 20[illegible]).

Most of the data sets used in the model set up have to be estimated. The hydraulic parameters of the hydrogeological units have been derived from data from the Torrate water supply company and data from various Internet sources. The pumping rates for drinking water and industrial uses have been estimated from urban concentrations and obtained from Internet sources. The same applies to the groundwater recharge by precipitation and loss by evapo-transpiration.

Considering the uncertainty of the input data sets, the gaps in data sets, and the lack of regional groundwater level monitoring network other than the incomplete network established in

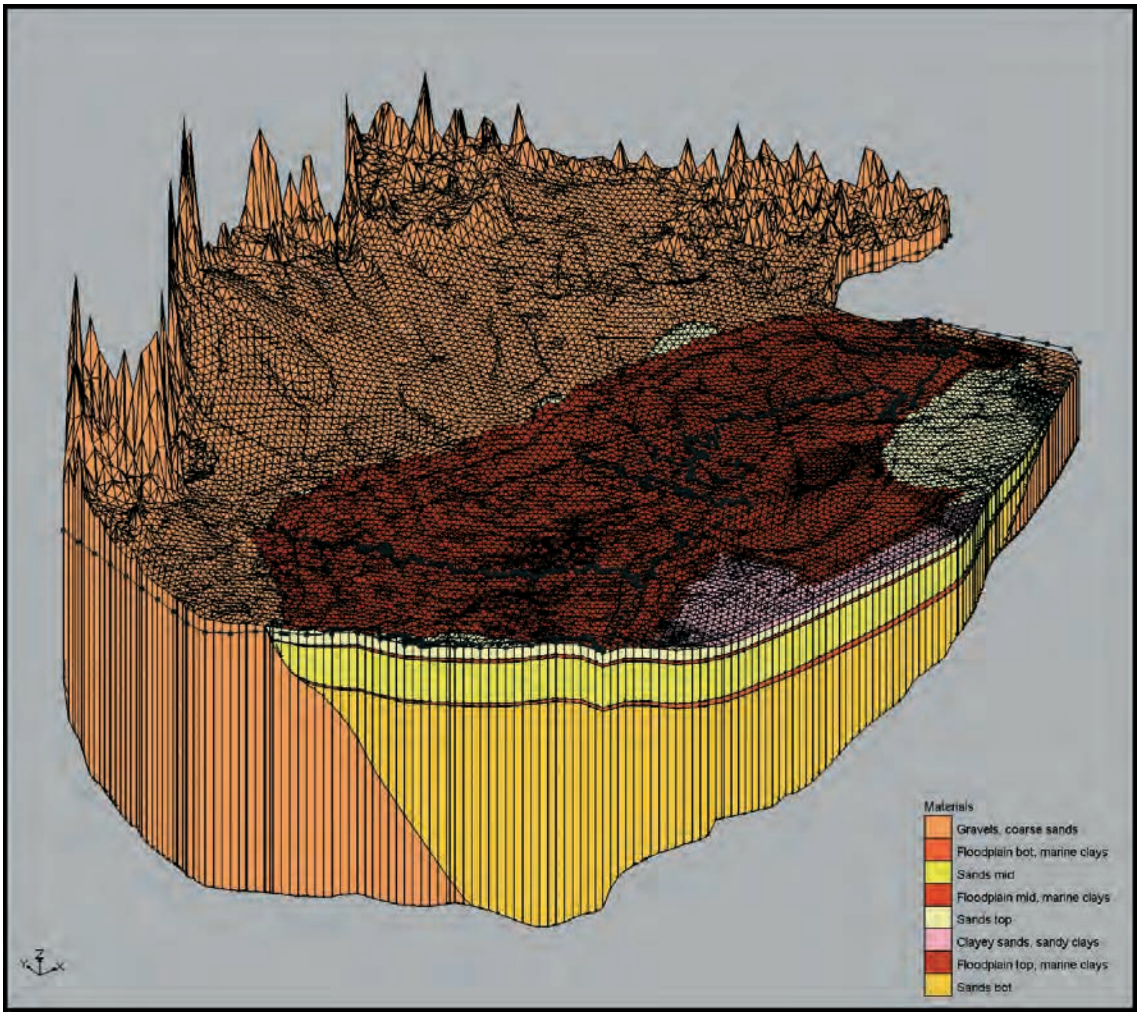

Fig. 10 - The solid model of the FVG coastal plain featuring 8 geological units of post-Tertiary age.

the area north of the Risorgiva (see Fig. 6), only a very rough and preliminary calibration has been carried out. Nevertheless, attempts have been made to match the calculated piezometric heads, in a steady-state condition model, to the present phreatic monitoring data. The major drawback in the process of model calibration is the lack of deep groundwater heads in the areas south of the Risorgiva.

Fig. 1 shows bundles of calculated flow lines in the model, in the reference situation (original situation without any wells). The yellow points, along the surface of the model, indicate the entrance points (water infiltration points). As expected, the area north of the Risorgiva acts as an infiltration area. From the qualitative point of view, the majority of the flow lines, infiltrating in the areas north of the Risorgiva, end up in the floodplain. Also in the floodplain, areas can be found apart from the rivers where groundwater infiltrates. The rivers flowing between the levees in the floodplain area are situated above the surrounding floodplain and can be characterised as

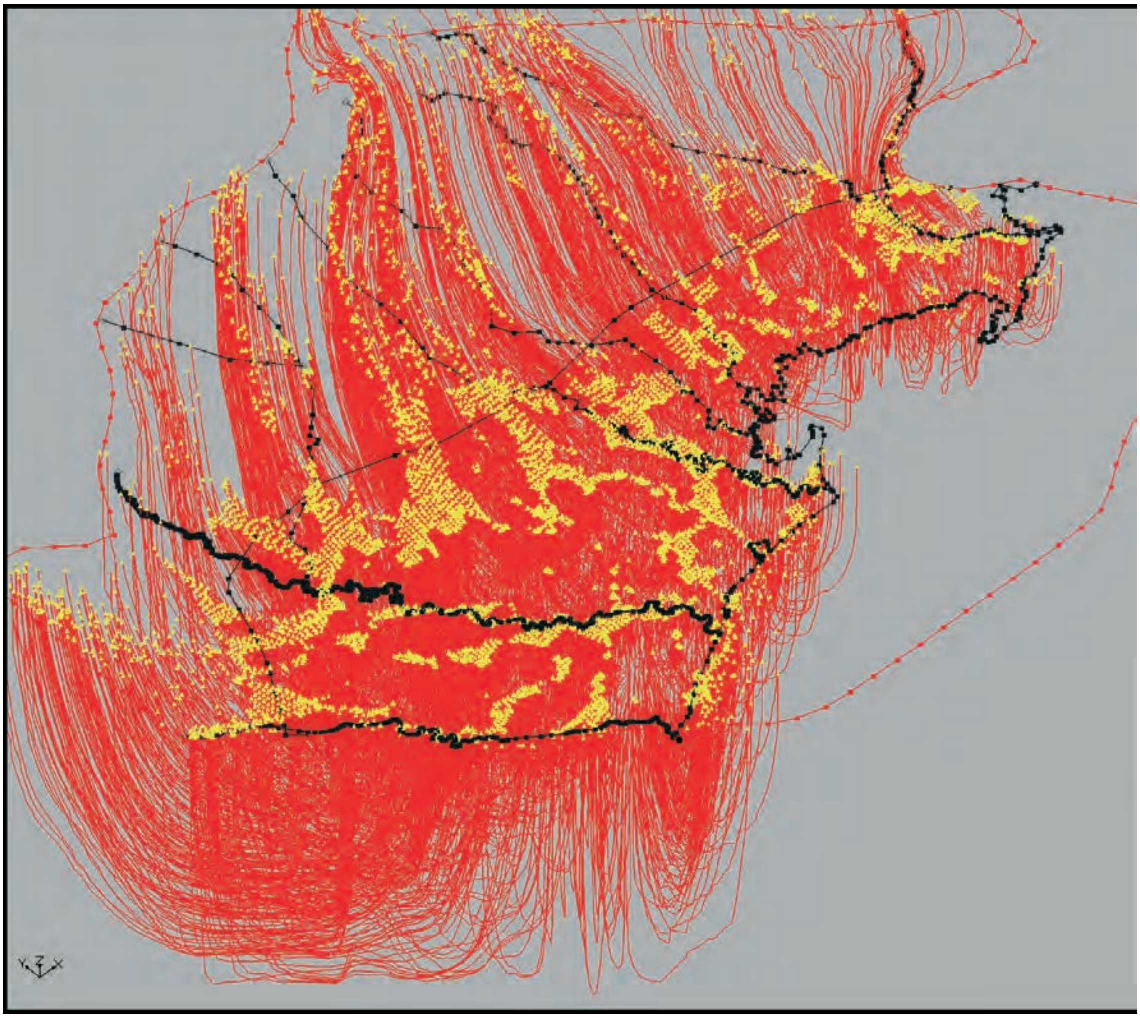

Fig. 11 - Bundles of regional flow lines, as calculated with the model for the reference steady-state situation (no wells).

influent as they lose water by infiltration into the shallow aquifers. Flow lines from these influent rivers end up nearby, in the floodplain. As the coastal plain comprises low-lying parts, it follows that groundwater flows from the seabed (salt water) towards the coastal plain to the areas where the ground level is below sea level. Fig. 1 clearly shows these bundles of flow lines with starting points in the sea. Even the groundwater divide can be discerned between bundles from the north and from the sea.

Fig. 12 shows the flow lines when starting from the Tagliamento River bed. Apparently, none of the flow lines seem to reach the sea, but all end up in the floodplain with its dense network of canals, ditches and drains.

The two pie diagrams of Fig. 13 show preliminary water balances for the entire model area. The recharge (see IN components) comes mainly from rainfall with a minor amount due to infiltration from the rivers in the areas north of the Risorgiva.

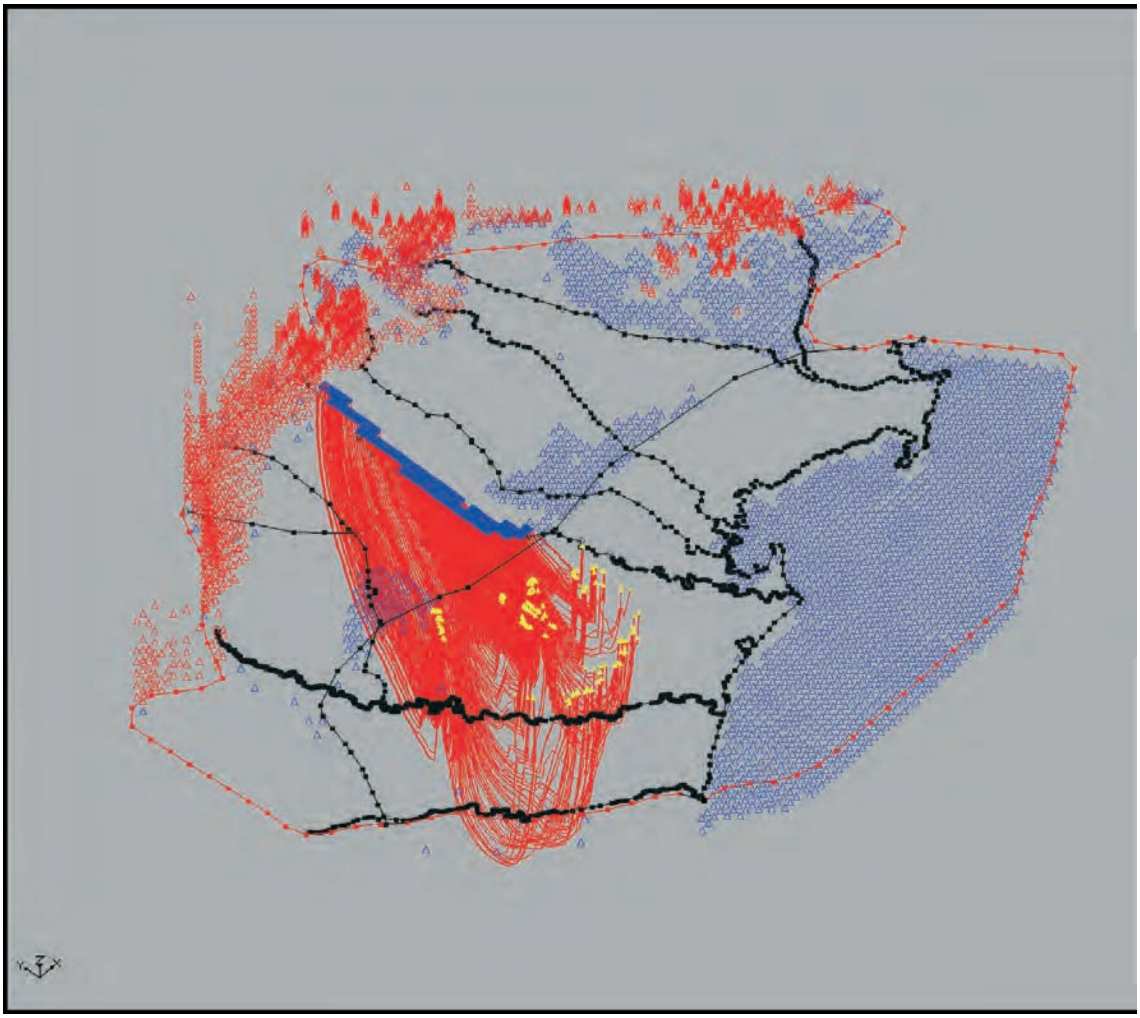

Fig. 12 - Bundles of regional flow lines as calculated from the bed of the Tagliamento River (in the reference situation) where the river is influent. Blue squares = infiltration, yellow triangles = end points.

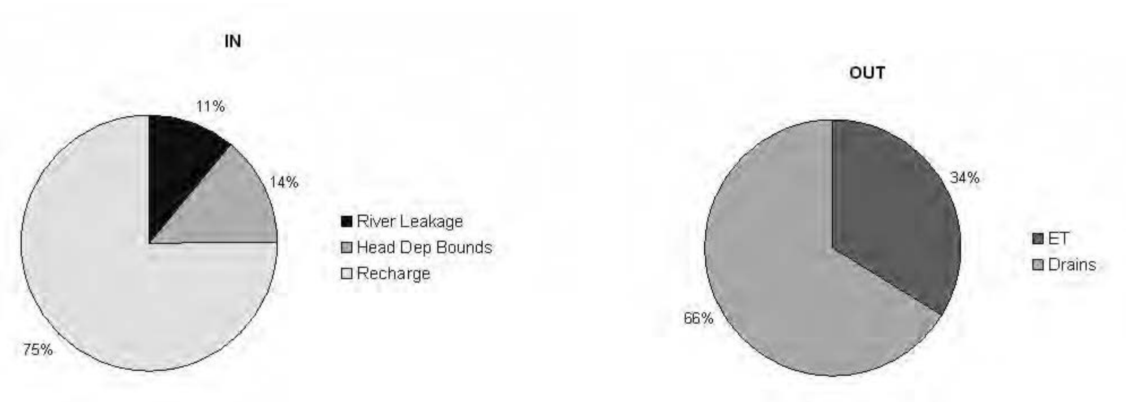

Fig. 13 - Pie diagrams of the water balance components for the steady-state model without wells, representing the original reference condition.

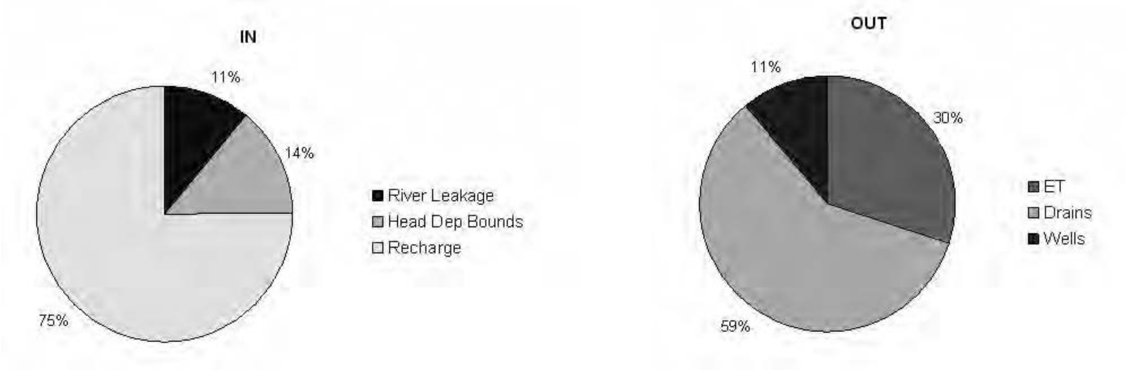

Fig. 14 - Pie diagrams of the water balance components for the steady-state model, with all present-day wells.

Water leaves the model (OUT components) through evapo-transpiration and the largest part through seepage in the floodplain areas south of the Risorgiva. When all the pumping rates are entered into the model, the water balance obviously changes in the OUT components (Fig. 14). The outflow through the drainage system is reduced approximately by some 7% and the evapo-transpiration term by 3%. Yet, the total amount of pumped groundwater is in magnitude still small as compared to the outflow through the drains and ditches in the floodplain. The natural water balance is only slightly disturbed and the pumped amounts are small compared to the recharge by precipitation. The whole water infiltration from the rivers is more or less of the same magnitude as the pumped amount by wells.

4. Conclusions and findings

Systematic collection of data on groundwater resources and central storage and processing is strongly needed for the FVG plain. Data collection and storage is fragmented over various governmental institutions and not easily accessible to potential users or experts. One of the first priorities is to upgrade and extend the present monitoring network for both groundwater quantity and quality. A modern monitoring network must become one of the components of a groundwater monitoring infrastructure, with the data collection, control, storage, processing, and dissemination of results preferably by Internet. An organisation is required to study the monitoring data, perform analyses and advise local governments or water resource managers on the proper and sustainable use of groundwater resources. REGIS v4 in this CAMI/LIFE project only demonstrates in what way hydrogeological data can be stored, processed and visualised. REGIS v4 is designed for the highly technical trained (GIS) user. It is practically inaccessible for the average manager.

In the future, the best solution for the FVG plain would be to introduce a web-based geo-information system featuring a centralised storage (central professional database) of data including an organisation responsible for the collection, control and storage including the information technology infrastructure. Users at any level, even the public, should be able to approach the data simply by web browser through the Internet. REGIS v4 is then a technical tool or component to be connected to the central database via Internet to be used by the technical GIS users.

There is no immediate problem of groundwater quantity in the FVG plain. The first results obtained by the preliminary groundwater model developed in the CAMI project suggest that the water amount pumped by wells practically equals the amount which infiltrates through the river beds. A major problem is maintaining the proper quality of groundwater in the FVG plain. Pollution plumes infiltrated in the coarse sediments from the industrial centres north of the Risorgiva are likely to be expected to travel to the floodplain areas south of the Risorgiva. These plumes should be monitored to determine whether they may reach the groundwater wells for drinking water.

When only a few boreholes with geological descriptions are available, then 2D-3D seismic methods, as applied by OGS, may effectively fill gaps in knowledge (CAMI project issue). Data on hydrogeology, as collected by the various CAMI partners, is very useful for the model construction (CAMI project issue). The regional authorities in the FVG plain should make (more) use of groundwater models to manage the water resources. Scenario evaluations should be carried like the "what happens if" questions for the coming decade(s). For each well field of the water supply companies in the area, the infiltration areas should be determined with a groundwater model to assess the vulnerabilities to possible pollution plumes and other surface sources of pollution. The awareness of (ground)water resources management should be increased. The local authorities should realize that groundwater modelling is absolutely necessary in proper groundwater resource management. It should also be realized that groundwater modelling is an ongoing activity to be improved and refined. It should be a self-propelling activity where gaps in knowledge or data are identified and where the model is subsequently refined.

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