

The alluvial aquifer of the river Roja in Ventimiglia Numerical flow modelling in temporary regime and instructions concerning transportation

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Abstract: The aquifer modelled in this study is approximately 3 km long and 450-600 m wide and is hosted in Quaternary alluvial and detrital sediments that crop out to the north of Ventimiglia (Liguria, Italy), covering about 2 km² at the confluence of the Roia river and the Bevera torrent. The aquifer is of strategic regional and cross-border importance, providing drinking water to part of Liguria and the French coast. Starting from a conceptual model of the aquifer, numerical transient regime flow and solute transport models were developed. The two watercourses, and especially the Roia, were found to play a key role in this aquifer system. Analysis of the overall water budget and those of the various sectors showed that exchange of water between the watercourses and the aquifer compensated the volumes pumped from the wells.

Introduction

The aquifer modelled in this study (Fig. 1) is approximately 3 km long and 450-600 m wide and is hosted in Quaternary alluvial and detrital sediments cropping out north of Ventimiglia (Liguria, Italy), covering about 2 km² at the confluence of the rivers Roia and Bevera. The aquifer of the Roia River is a transboundary aquifer of strategic relevance for drinking water supply in the Liguria region and in the French coast.

The aim of this study was to implement qualitative and quantitative data by flow and transport modelling to enable correct management and planning for protection and sustainable exploitation of water resources.

Keywords: aquifer, model, balance.

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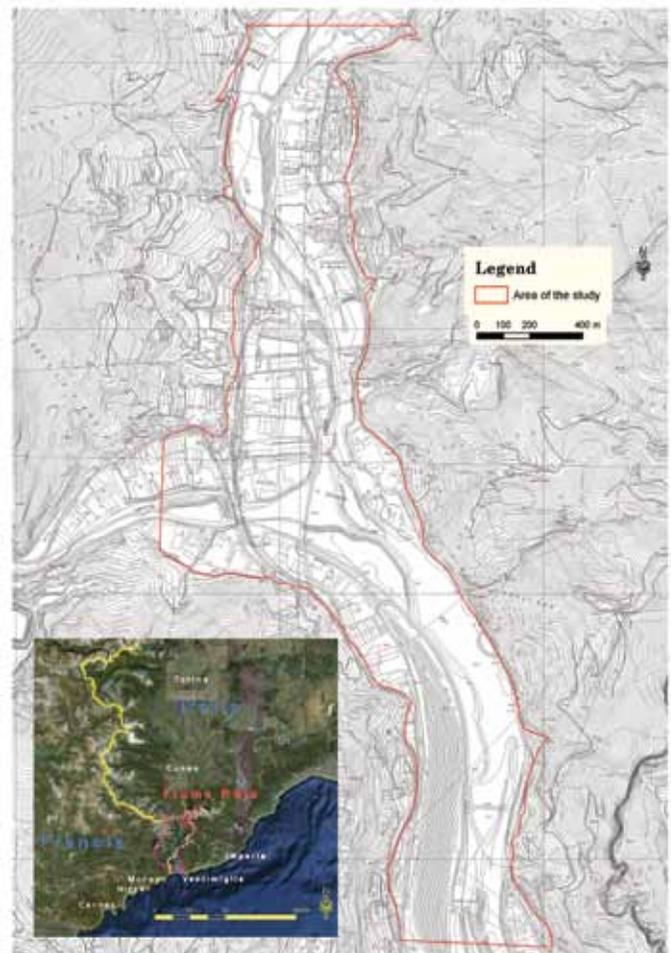


Fig. 1: Geographical setting.

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Geological setting

The reconstruction of the subsurface geology was made on the basis of lithostratigraphic data from geognostic surveys and geophysical prospecting performed in the framework of the European Community projects Eurobassin (AA.VV., 2006) and Risknat (AA.VV., 2012) (Fig. 2):

- 14 geognostic surveys
- 8 electric tomographies
- 7 seismic tomographies
- 4 refractor microtremor ReMi surveys
- 3 vertical electric soundings
- 24 Lefranc permeability tests
- 2 tracer tests
- 4 stream gauging tests.

These investigations had the primary aim of defining the thickness of the alluvial formations, in some points up to 60 m. The data indicated variations in the thickness of the alluvial sediments constituting the aquifer, in direct relation to substrate topography. The main consequence of this irregularity is the thickness variation in saturated with substrate depth (Fig. 3).

In the sections, the substrate (consisting almost completely of Ventimiglia flysch and only in a few areas of clayey-silty deposits) is represented by a single symbol, without distinguishing geological types. However, inside the aquifer four different grain sizes were identified and represented in different colours (gravel with pebbles and silty sand, gravel with silty sand, clayey sandy silt and detrital cover, consisting of coarse reworked alluvial material).

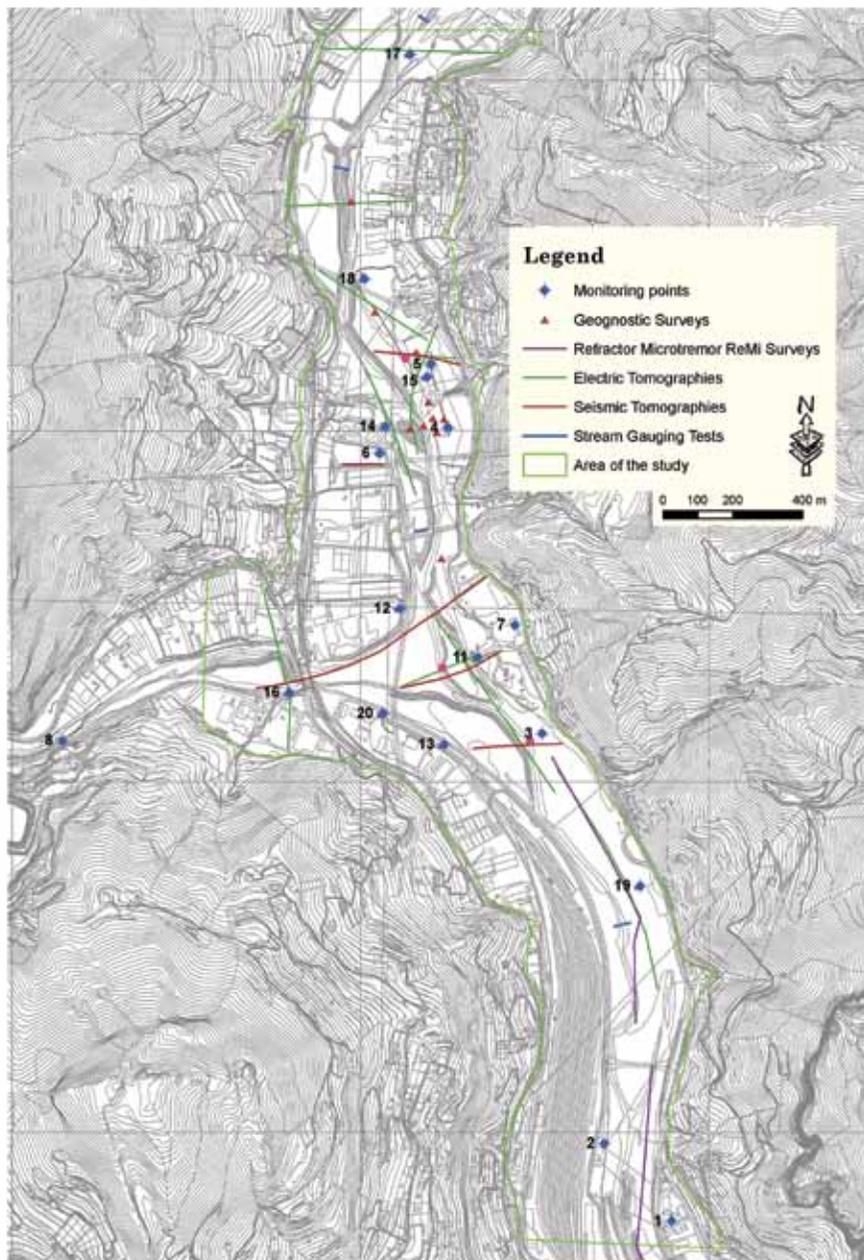


Fig. 2: Study site and geological survey.



Fig. 3: Example of lithostratigraphic section.

Using all available data, the surface area of the impermeable substrate was obtained by measuring the depth of the base of the gravely alluvial mattress (aquifer) in contact with the flysch (substrate). Analysis of the base of the aquifer showed a structural high in the area immediately north of the confluence of the Roia and Bevera and a depression in the area of confluence. The mean altitude of the bedrock was about -6 m asl.

We then generated an isopach map of the alluvial formations of the aquifer (Fig. 4).

The whole alluvial mattress proved to have a mean thickness of about 32.5 m, with a maximum of about 64 m in the central part coinciding with the palaeobed.

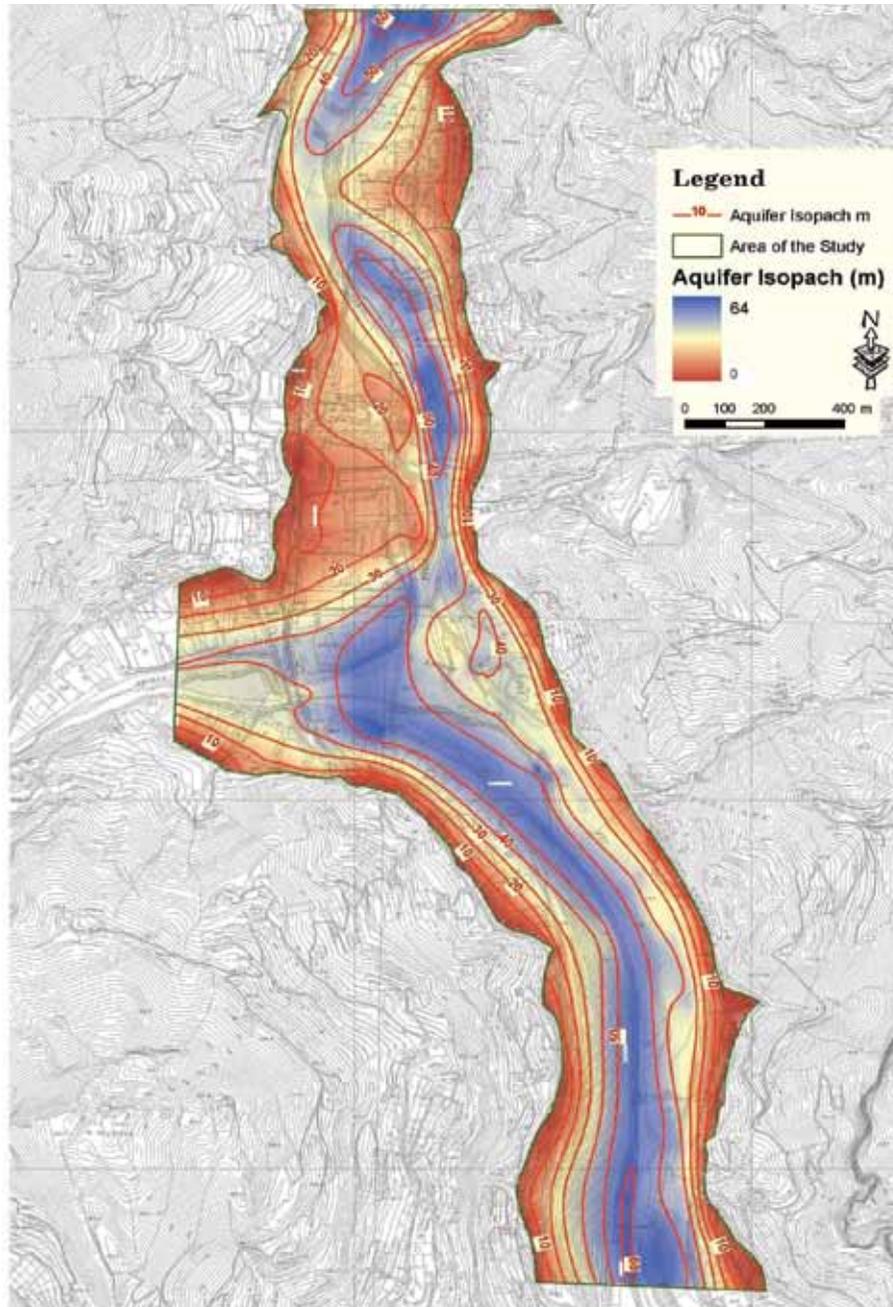


Fig. 4: Isopach map of the alluvial formations of the aquifer.

Hydrogeology

The hydrodynamic characteristics of the aquifer were determined by piezometric survey at 21 points (wells and piezometers) showed in Figure 2.

The first survey began in June 2010, proceeding monthly until February 2012. Using piezometric levels as reference, the mean aquifer resource was estimated during the monitoring period. The mean saturated thickness of the aquifer proved to be about 30.5 m and the saturated area was 1.7 km².

From this data it was possible to calculate the mean volume of water in storage. For an aquifer consisting prevalently of gravel, pebbles and sand with a silty fraction, the literature indicates an effective porosity of 15-20%. The value used here was $P_e = 17\%$.

$$V_{H_2O} = 30.5 * 1.7 * 10^6 \text{ m}^3 * (17/100) \approx 8.8 * 10^6 \text{ m}^3$$

Since the quantity of water in the aquifer is essentially due to the contribution of the Roia river, this estimate can be considered indicative because current consumption is much higher than the “calculated resource”. Actually the resource is determined with reference to the flow rates of the Roia and not the water stored in the aquifer (reserve) or the range of levels (Fig. 5).

Conceptual hydrogeological model

The first phase of the study was the development of a conceptual model of the aquifer (Fig. 5), necessary for numerical modelling. The model included inputs and outputs of the unconfined portion of the aquifer to be studied. This portion has a mean saturated thickness of about 30.5 m and a saturated surface area of 1.7 Km². The aquifer has a main direction of flow from NW to SE, with a variable hydraulic gradient ranging from 1% in the northern part and 0.7% in the central and southern parts.

Collection, organisation and interpretation of data indicated that recharge of the system was prevalently from the river (about 236.5*10⁶ m³/year from the Roia R. and about 28.4*10⁶ m³/year from the aquifer). Artificial aquifer outputs are mainly due to exploitation for drinking water (AIGA/GDU and AAMAIE wells) and only to a minor extent for industrial and private use. These quantities were estimated at about 63*10⁶ m³/year from direct measurements and data provided by the Province of Imperia.

The two water courses play an important role in this aquifer system. The Roia and Bevera recharge, and where the aquifer supplies the river for morphological reasons, partly drain the water table, as

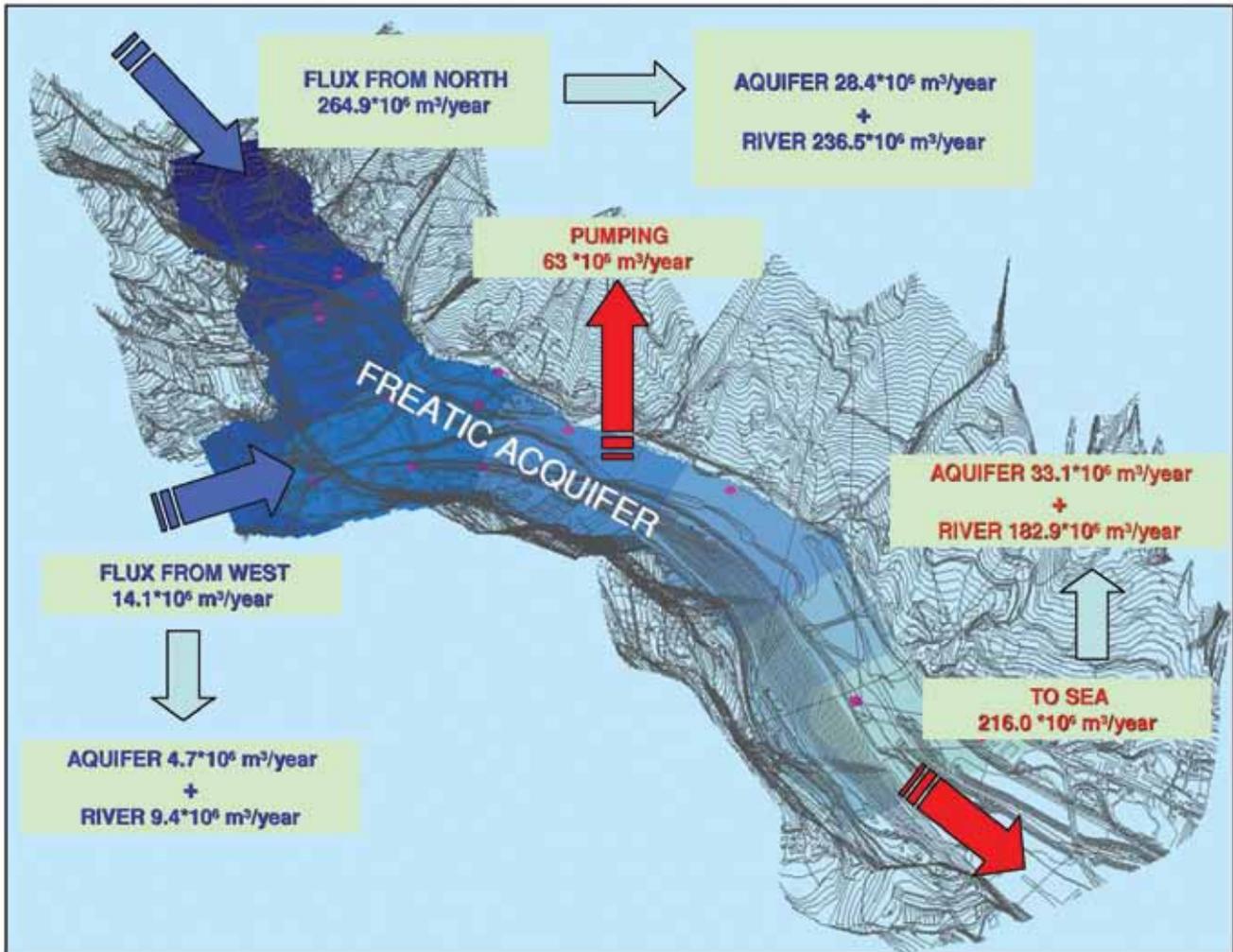


Fig. 5: Aquifer conceptual model.

shown by analysis of the piezometric surface of the aquifer. The estimated output from the study area to the south and the sea was about $33.1 \cdot 10^6 \text{ m}^3/\text{year}$ from the aquifer and about $182.9 \cdot 10^6 \text{ m}^3/\text{year}$ from the rivers. The conceptual model did not include recharge by infiltration because the volume was negligible with respect to system input and output. As shown in Figure 5, the overall budget was positive, because input was greater than output.

Numerical modelling

As mentioned above, recharge is almost entirely from the Roia and its main affluent the Bevera, and negligibly from infiltration of precipitation in the study area. This is demonstrated by the estimation of infiltration performed by assessing water excess and the potential infiltration coefficient of the aquifer terrains. Natural output is diffuse and towards the sea, whereas artificial output consists of withdrawal of water from wells.

The aquifer system was represented by a three-dimensional finite element numerical model. The numerical simulation of the aquifer was developed with FEFLOW code ver. Finite Element subsurface FLOW system; Diersch, 1998 a,b. We used reconstruction of the conceptual model of the Roia alluvial aquifer to develop a scheme of the actual aquifer to study dynamic effects occurring in the system.

This hydrogeological model was developed in four steps:

1. definition of the model domain.
2. development of a two-dimensional grid (Fig. 6). In this case, the algorithm Triangle was chosen to generate a grid composed of a series of triangles that render the model discrete. This method makes it possible to define local variations in grid density in an intuitive manner. Indeed, we defined dense areas along the Roia and Bevera, as well as at pumping points and possible contamination sources. At wells and contamination sources we entered fixed points that constrained the grid in a node. Higher density was chosen here to obtain more precise evaluations. Grid construction with triangular elements is the basis of finite element analysis, since it is at nodes that calculations of the mathematical model are made. The grid thus obtained had 8275 nodes/slice and 16118 elements per layer.
3. development and verification of a three-dimensional grid (Fig. 6). The choice of multiple layers depended on the fact that the first layer is 12 m below ground level at a permeability transition detected by permeability tests, such as that of Le Franc, and on the fact that the second limit between the second and third layers is a calculation limit enabling homogeneous vertical discretisation in order to improve the results processed by the software.
4. Definition of numerical model settings

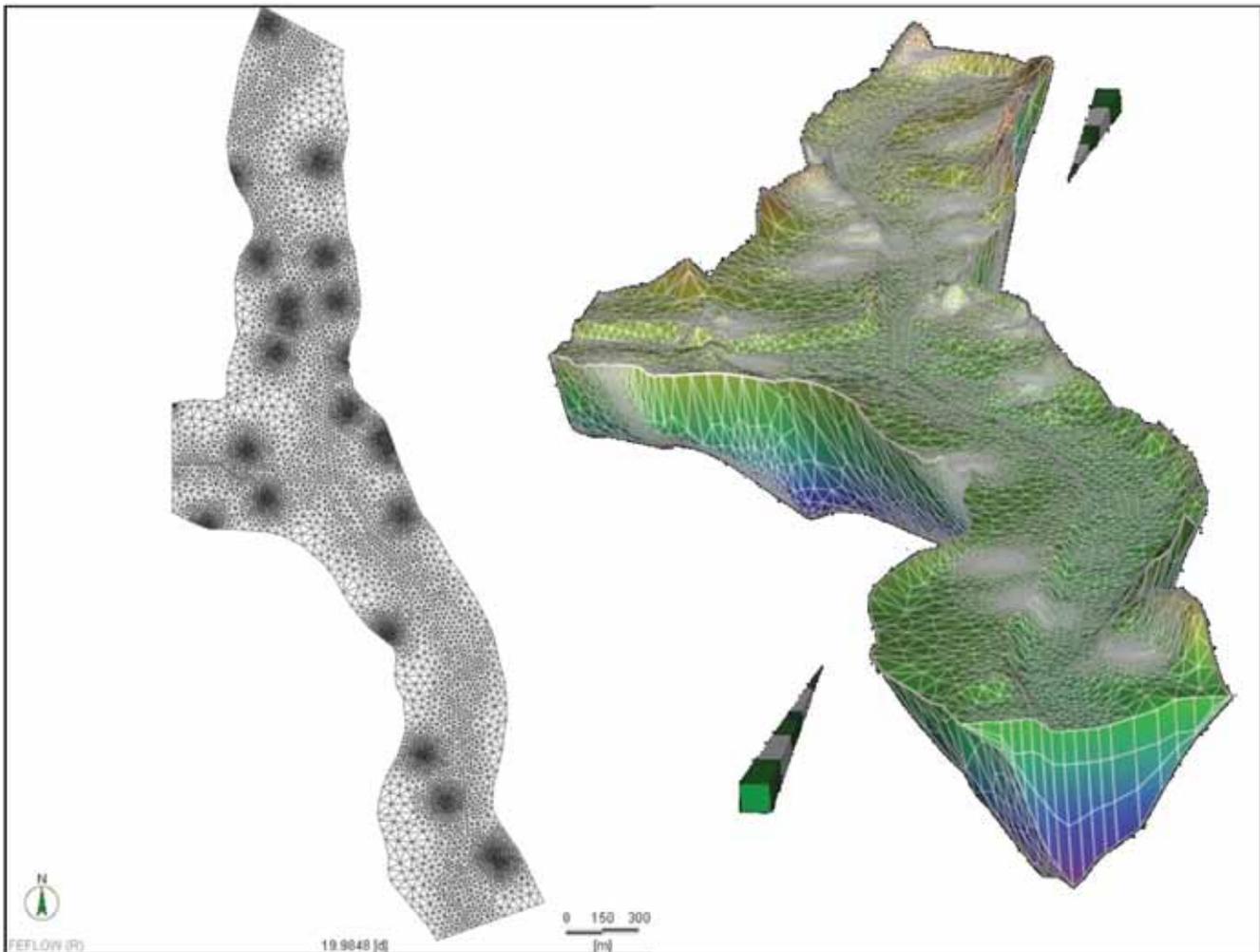


Fig. 6: Two and three dimensional grid viewed.

After defining aquifer geometry, the next step was to set the conditions and parameters necessary to define the numerical model so that it matched the conceptual model. We first entered the steady-state parameters of June 2010, which also marked the start of the transient period of the simulations ending in June 2011. FEFLOW makes it possible to set the following:

Boundary conditions

Three boundary conditions (BC) and one constraint were imposed on the Roia aquifer.

Condition of the first type (Hydraulic head BC)

The limit in terms of potential was that water at the system extremes has a known and/or estimated hydraulic head. In our case this was imposed at the northern, western and southern limits of the study area (Tab.1).

Tab. 1: Values assigned of the hydraulic head (m).

NORTH		SOUTH		WEST	
Time (days)	Hydraulic head	Time (days)	Hydraulic head	Time (days)	Hydraulic head
0	32.3	0	9.52	0	22.43
30	32.27	30	9.41	30	22.14
60	32.02	60	9.23	60	21.78
90	31.95	90	8.58	90	21.44
120	32.15	120	9.17	120	21.91
150	32.4	150	9.32	150	22.54
180	32.35	180	9.41	180	22.14
210	32.11	210	9.59	210	22.09
240	31.8	240	9.21	240	21.73
270	31.94	270	9.46	270	22.31
300	32.25	300	9.3	300	22.05
330	32.2	330	9.03	330	21.83
365	31.87	365	8.93	365	21.68

Tab. 2: Values in meters assigned of the fluid transfer and constraint (bottom).

NORTH AREA			SOUTH AREA			WEST AREA		
Time (days)	Hydraulic head	Bottom	Time (days)	Hydraulic head	Bottom	Time (days)	Hydraulic head	Bottom
0	30.08	29	0	20.2	19	0	11.36	10.8
30	30.05	29	30	20.07	19	30	11.25	10.8
60	29.9	29	60	19.87	19	60	11.07	10.8
90	29.84	29	90	19.76	19	90	10.92	10.8
120	29.93	29	120	20.02	19	120	11.01	10.8
150	30.18	29	150	20.33	19	150	11.16	10.8
180	30.13	29	180	20.03	19	180	11.25	10.8
210	29.89	29	210	20.01	19	210	11.43	10.8
240	29.73	29	240	19.75	19	240	11.05	10.8
270	29.82	29	270	19.97	19	270	11.3	10.8
300	30.03	29	300	19.92	19	300	11.14	10.8
330	29.98	29	330	19.83	19	330	11.07	10.8
365	29.78	29	365	19.78	19	365	10.97	10.8

Condition of the third type (Fluid transfer BC)

This type of condition defines a reference hydraulic head and was used to model the river, in combination with a drainage parameter (see transfer rate under Material Properties) i.e. water exchange between river and aquifer and vice versa. This boundary condition was applied to the whole river Roia and to a small part of the Bevera in slice 1 of the model. A constraint of minimum hydraulic head was also applied (Tab.2, at the end of the page).

Condition of the fourth type (Well BC)

This type of condition describes injection or extraction of water from a single node of the model. In our case, as illustrated, pumping from public and private wells was entered. The pumping values (Tab.3) refer to the plants present, as declared during field work and reported in the well chart of the Risknat project, as well as to water licences granted by Imperia Province and the results of calibration of the numerical model to fit the piezometric values measured in the field to those calculated by the model.

Tab. 3: Values of the pumping wells.

Pumping Well		Pumping value
X	Y	m ³ /s
1386386.1	4853266.6	0.007
1386463.1	4852956.8	0.347
1385996.9	4853755.3	0.002
1386144.5	4854009.7	0.417
1386194.1	4853828.4	0.289
1386641.0	4851788.0	0.532
1386835.5	4851567.6	0.440

Material properties

The material properties assigned included:

- conductivity (Kxx; Kyy; Kzz)
- drain/fillable porosity
- in/outflow at top/bottom
- transfer rate (in/out).

Conductivity, Tab.4, (Kxx and Kyy) of the first layer was assigned on the basis of the results of two tracer tests (5 and $4 \cdot 10^{-2}$ m/s) and then calibrated to obtain the best fit between piezometric and calculated data.

Tab. 4: Conductivity assigned to the model.

LAYER	Kx (m/sec)	Ky (m/sec)	Kz (m/sec)
1	3.3×10^{-2}	3.3×10^{-2}	3.3×10^{-3}
2	0.75×10^{-2}	0.75×10^{-2}	0.75×10^{-3}
3	0.75×10^{-2}	0.75×10^{-2}	0.75×10^{-3}

For layers 2 and 3, we assigned a conductivity of about one quarter, based on the results of Lefranc-type permeability tests (Tab.5) conducted during the soundings. A Kzz one order of magnitude lower than Kxx and Kyy was assigned as customary in the absence of direct data.

Tab. 5: Results of Lefranc-type permeability tests.

N° Survey	N° test	Permeability K (cm/s)	Permeability K (m/s)	Deep
1	1	$6.75 \cdot 10^{-2}$	$6.75 \cdot 10^{-4}$	4.5 - 5.0
1	2	$1.17 \cdot 10^{-2}$	$1.17 \cdot 10^{-4}$	10.0 - 10.5
1	3	$2.64 \cdot 10^{-3}$	$2.64 \cdot 10^{-5}$	19.0 - 19.5
2	1	$1.56 \cdot 10^{-1}$	$1.56 \cdot 10^{-3}$	2.5 - 3.0
2	2	$1.33 \cdot 10^{-2}$	$1.33 \cdot 10^{-4}$	10.0 - 10.5
2	3	$7.75 \cdot 10^{-3}$	$7.75 \cdot 10^{-5}$	20.0 - 20.5
3	1	$8.89 \cdot 10^{-2}$	$8.89 \cdot 10^{-4}$	4.5 - 5.0
3	2	$2.33 \cdot 10^{-3}$	$2.33 \cdot 10^{-5}$	12.5 - 13.0
3	3	$1.03 \cdot 10^{-3}$	$1.03 \cdot 10^{-5}$	21.0 - 21.5
4	1	$1.15 \cdot 10^{-1}$	$1.15 \cdot 10^{-3}$	2.0 - 2.5
4	2	$2.53 \cdot 10^{-3}$	$2.53 \cdot 10^{-5}$	9.0 - 9.5
4	3	$1.32 \cdot 10^{-3}$	$1.32 \cdot 10^{-5}$	18.0 - 18.5
5	1	$1.15 \cdot 10^{-1}$	$1.15 \cdot 10^{-3}$	1.0 - 1.5
5	2	$4.42 \cdot 10^{-3}$	$4.42 \cdot 10^{-5}$	7.0 - 7.5
5	3	$2.59 \cdot 10^{-3}$	$2.59 \cdot 10^{-5}$	15.0 - 15.5
6	1	$9.99 \cdot 10^{-2}$	$9.99 \cdot 10^{-4}$	1.0 - 1.5
6	2	$1.16 \cdot 10^{-2}$	$1.16 \cdot 10^{-4}$	8.0 - 8.5
6	3	$5.89 \cdot 10^{-3}$	$5.89 \cdot 10^{-5}$	16.0 - 16.5
7	1	$1.59 \cdot 10^{-3}$	$1.59 \cdot 10^{-5}$	4.0 - 4.5
7	2	$4.15 \cdot 10^{-3}$	$4.15 \cdot 10^{-5}$	11.5 - 12.0
7	3	$1.14 \cdot 10^{-3}$	$1.14 \cdot 10^{-5}$	18.0 - 18.5
8	1	$1.93 \cdot 10^{-1}$	$1.93 \cdot 10^{-3}$	1.5 - 2.0
8	2	$7.32 \cdot 10^{-3}$	$7.32 \cdot 10^{-5}$	19.0 - 19.5
8	3	$8.13 \cdot 10^{-4}$	$8.13 \cdot 10^{-6}$	27.0 - 27.5

The natural recharge of the aquifer (from rain) was assigned on the basis of terrain infiltration (Barazzuoli et al., 2011). Recharge values due to infiltration are negligible, being around 0.3 million mc/year as indicated by Barazzuoli et al. (2011) and by the mass balance. Compared to the volumes involved, this is negligible and was only included in the model for the sake of completeness. A time series (June 2010 – June 2011) of infiltration was obtained in the study area.

Effective porosity of 18% was assigned for layer 1 and 15% for layers 2 and 3 (Celico, 1988). Since this is an unconfined aquifer, these values also match the storage coefficient.

With regard to the third boundary condition, the material property transfer rate in/out, which defines water exchange between river and aquifer, was assigned different values for the terrains of the river-aquifer interface, dividing the study area into fluvial domains: Roia and Roia + Bevera (Tab.6).

Tab. 6: Values of transfer rate.

	NORTH AREA	CENTER AREA	SOUTH AREA
Transfer Rate In (1/s)	0,009	0,003	0,009
Transfer Rate Out (1/s)	0,009	0,003	0,009

After assigning boundary conditions and parameters, calibration is the longest phase of the modelling process. The least known parameters must be adjusted so that measured values fit those simulated. Because of the variability over the whole domain of hydrodynamic parameters (conductivity, porosity, etc.) and the simplifications inherent to the modelling process, calibration is never perfect. Indeed, there are always differences between simulated results and real observations, albeit minimized at the end of calibration (Figure 7).

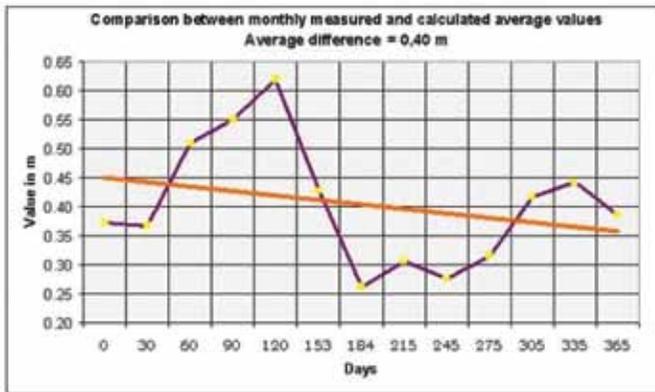


Fig. 7: Comparison of model-simulated and field-measured values.

The figure shows the mean monthly error/difference between calculated and simulated piezometric values, as described in the caption, which the programme has unfortunately not labelled in the figure itself. The calibration was conducted at each control point using the permeability values and transfer rate as calibration parameters, until a mean error/difference of about 40 cm was reached, as a good compromise. What we endeavoured to simulate was the general trend of the system, focusing in particular on having the piezometry as close as possible to actual values, since it is the starting point for transport simulations.

Figure 8 (next page) shows an example of the results of transient flow regime simulations obtained with reference time steps such as December and September 2010, which marked the piezometric maximum and minimum of the year, respectively. In particular, the piezometric maps show the substantial stability of the hydraulic head, which for maximum values varied by about 30 cm, whereas minimum values oscillated by up to about 80 cm.

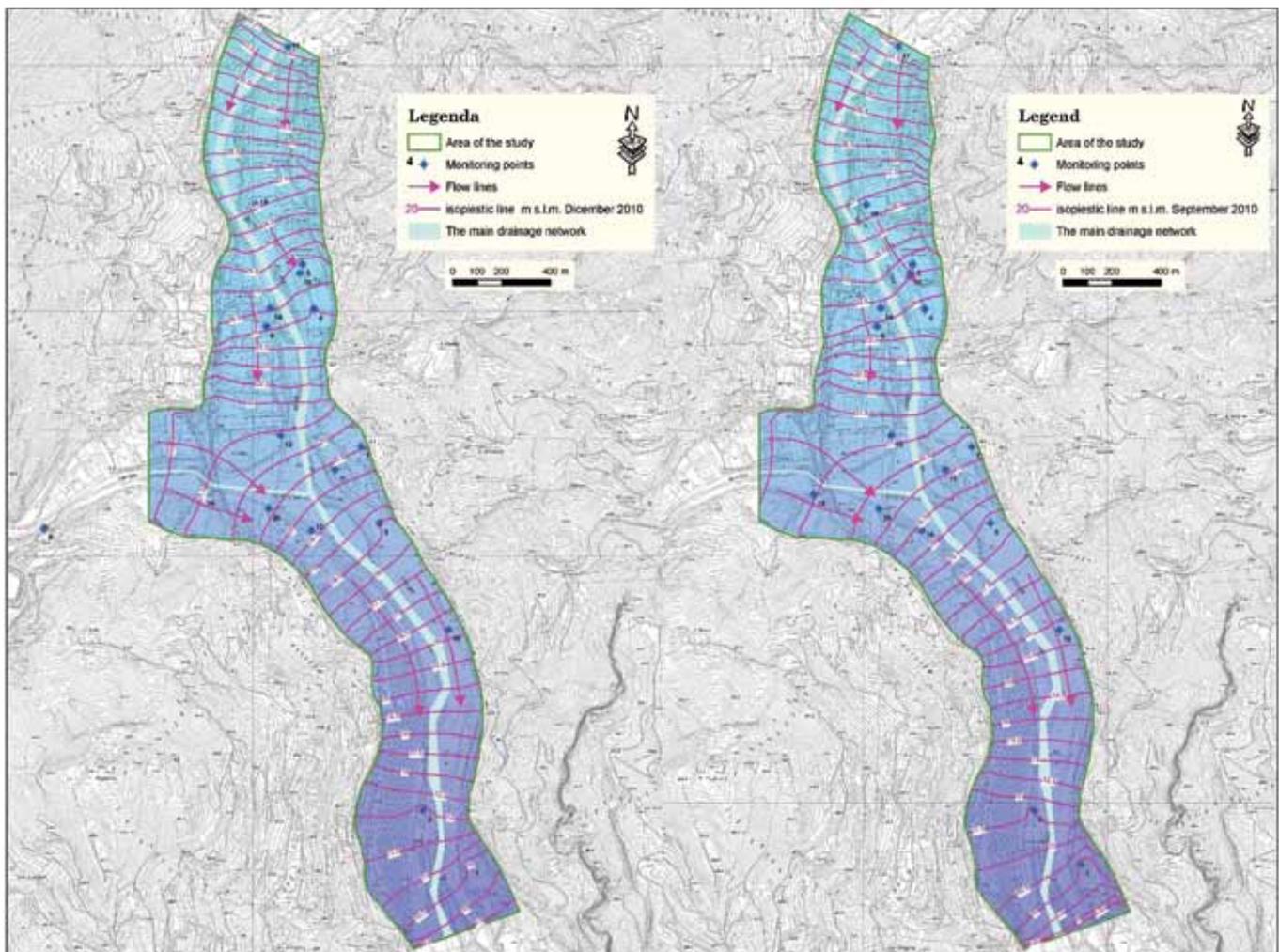


Fig. 8: Piezometric maxima and minima of the period.

Analysis of results

Analysing annual mass balance (Tab.7), the following deductions can be made:

1. good agreement between numerical and conceptual model;
2. annual input volumes were $42 * 10^6 \text{ m}^3$ (Roia + Bevera and recharge) and output volumes were about $45 * 10^6 \text{ m}^3$ (Roia), which are quite similar (circa $\pm 1.3 \text{ m}^3/\text{s}$);
3. water exchange between river and aquifer in the study area was about $105 * 10^6 \text{ m}^3$ (river to aquifer) and $38 * 10^6 \text{ m}^3$ (aquifer to river) with a difference of about $67 * 10^6 \text{ m}^3$, which is practically equal to the volume pumped from wells in the study area;
4. the volume of water stored in the aquifer (about $9 * 10^6 \text{ m}^3$) is small with respect to the volumes exchanged between river and aquifer and the volumes pumped.

In particular, the volumes (Tab.7) show the importance and fundamental role of the river Roia and the quantity of water exchanged with the aquifer that balances and maintains the system in equilibrium, despite pumping of about $64 * 10^6 \text{ m}^3$ per year (about $2 \text{ m}^3/\text{s}$), almost all for drinking purposes. Further confirmation of this comes from river flow figures, which indicate input (Roia + Bevera) of about $239.6 * 10^6 \text{ m}^3/\text{year}$ ($7.6 \text{ m}^3/\text{s}$) and output (Roia) of about $176.6 * 10^6 \text{ m}^3/\text{year}$ ($5.6 \text{ m}^3/\text{s}$).

Tab. 7: Overall aquifer budget simulated for 365 days (June 2010 - June 2011).

WATER VOLUMES – NUMERICAL MODELLING IN TEMPORARY REGIME (1+2+3)		
BOUNDARY CONDITIONS AND INFILTRATION	INFLOWS ($10^6 \text{ m}^3/\text{y}$)	OUTFLOWS ($10^6 \text{ m}^3/\text{y}$)
1 st Type (Hydraulic Head)	42.28	44.97
3 rd Type (Fluid Transfer)	133.00	33.94
4 th Type (Pumping/ Injection)	-	97.02
INFILTRATION	0.35	-
TOTAL	175.63	175.93
BALANCE	-0.30	

We then looked for critical aspects of the system, dividing the model into northern, central and southern sectors (Fig. 9) and calculating the respective budgets (Tab.8).

No particularly critical situations were found, but the southern sector proved to be subject to greater stress, as shown by the high volumes exchanged between river and aquifer (about $57 * 10^6 \text{ m}^3$ per year), largely due to greater pumping than in the other sectors. The budgets of the other two sectors showed that the central sector was exploited less than the others and is therefore the best candidate for increasing the existing drinking water supply.

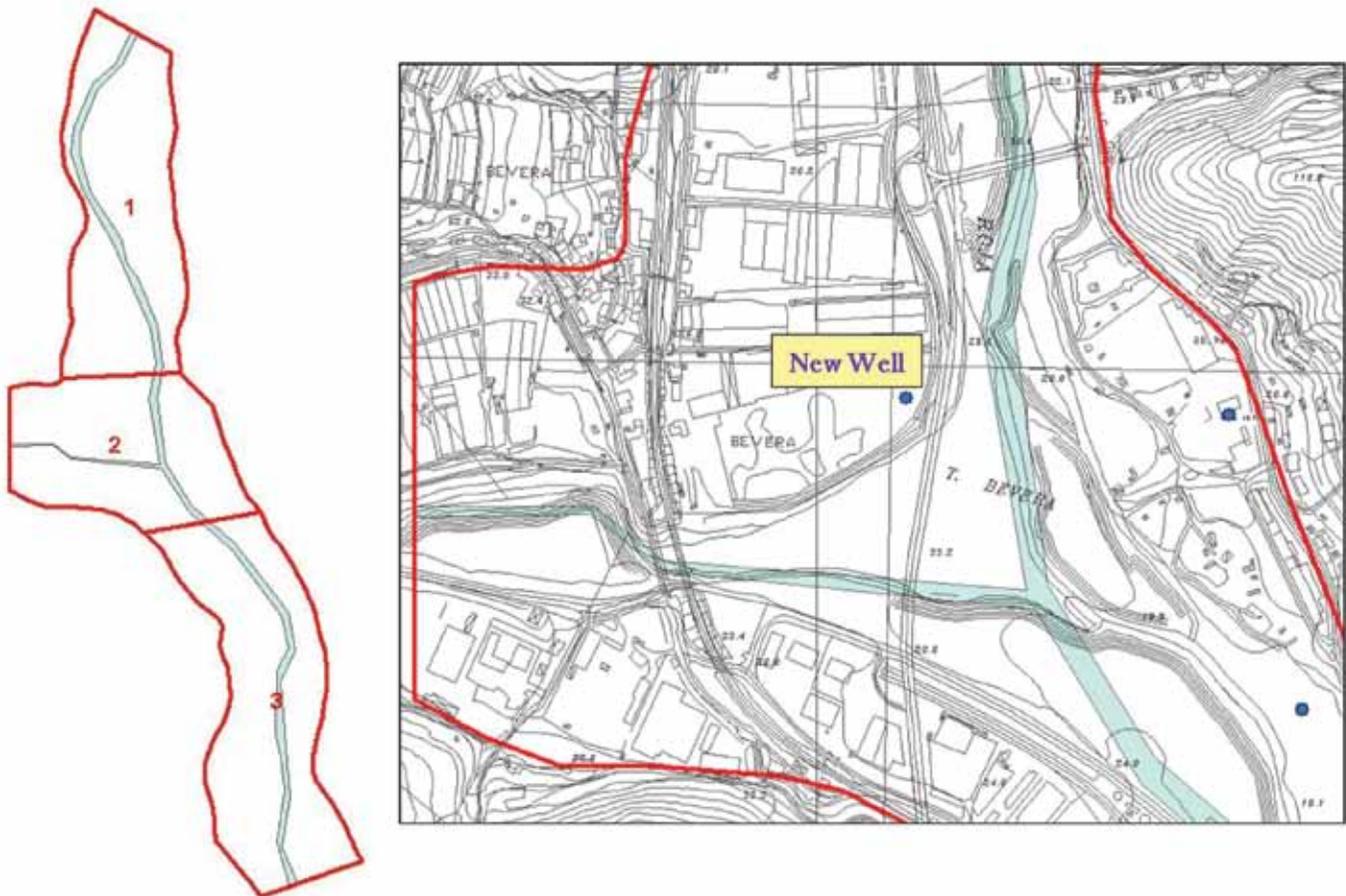


Fig. 9: Division of model area into three sectors and position of new well.

Tab. 8: Overall aquifer budget divided into north 1, central 2 and southern 3 sectors, simulated for 365 days (June 2010 - June 2011).

WATER VOLUMES – NUMERICAL MODELLING IN TEMPORARY REGIME - NORTH SECTOR (1)		
BOUNDARY CONDITIONS AND INFILTRATION	INFLOWS (10 ⁶ m ³ /y)	OUTFLOWS (10 ⁶ m ³ /y)
1 st Type (Hydraulic Head)	32.32	-
3 rd Type (Fluid Transfer)	49.34	17.69
4 th Type (Pumping/ Injection)	-	38.76
INFILTRATION	0.13	-
TOTAL	81.79	56.45
BALANCE	-0.30	
WATER VOLUMES – NUMERICAL MODELLING IN TEMPORARY REGIME - CENTRAL SECTOR (2)		
BOUNDARY CONDITIONS AND INFILTRATION	INFLOWS (10 ⁶ m ³ /y)	OUTFLOWS (10 ⁶ m ³ /y)
1 st Type (Hydraulic Head)	9.95	-
3 rd Type (Fluid Transfer)	17.30	5.51
4 th Type (Pumping/ Injection)	-	19.38
INFILTRATION	0.10	-
TOTAL	27.35	24.89
BALANCE	2.46	
WATER VOLUMES – NUMERICAL MODELLING IN TEMPORARY REGIME - SOUTH SECTOR (3)		
BOUNDARY CONDITIONS AND INFILTRATION	INFLOWS (10 ⁶ m ³ /y)	OUTFLOWS (10 ⁶ m ³ /y)
1 st Type (Hydraulic Head)	-	44.95
3 rd Type (Fluid Transfer)	68.77	10.74
4 th Type (Pumping/ Injection)	-	38.87
INFILTRATION	0.12	-
TOTAL	68.89	94.56
BALANCE	-25.67	

Prediction simulations

After calibration, two possible scenarios created by continued pumping for drinking water were hypothesized:

1. Addition of another well in the central sector of the study area near the Roia-Bevera confluence (Fig.9).
2. The water withdrawn from the new well would be 1 m³/s (+ 50% of current pumping) in a less exploited sector of the aquifer having better hydrogeological characteristics for exploitation. The results showed an increase in water exchange from river to aquifer in the central sector quantified in about 23 * 10⁶ m³ p.a., making a total of 37 * 10⁶ m³ p.a. However, this sector can sustain such an increase without becoming critical, whereas the southern sector is currently the most stressed.
3. Distribution of withdrawal of 1 m³/s from existing wells. This scenario involved an increase in exchange between river and aquifer to compensate increased pumping. The situation was not very different from the current one, although it increased the critical aspect of the most exploited southern sector.

The two scenarios both indicate that the aquifer can withstand a 50% increase in current pumping without any particular problems. The first scenario is probably preferable because it tends to balance and distribute pumping in the three sectors.

Numerical transport modelling

In the framework of assessments of potential sources of contamination in the study area identified by Regional Agency for Environmental Protection and Prevention of the Liguria (ARPAL) and the Province of Imperia, we chose three situations in which to apply the numerical transport model to create risk scenarios.

The transport boundary conditions considered were:

- flow conditions or mass flux (Neumann or second type)
- injection boundary conditions or mass nodal sink/source (fourth type).

Regarding the material properties, we set the linear partition coefficient (sorption coefficient, Henry isotherm) and longitudinal and transverse dispersion largely on the basis of hydraulic conductivity and the scale effect, namely the distance along the flow line between source and “target” of the transport simulation. We entered the following values of longitudinal dispersion:

- a. aL = 50 m for contaminants with medium-low affinity for the solid phase, i.e. quite mobile (pesticides);
- b. aL = 100 m for high mobility contaminants only involving the fluid phase (specifically nitrates and caustic soda).

1. Road tanker accident involving loss of 50,000 l of 30% caustic soda (NaOH) at 400 l/min at Airole (a site north of the modelled area where water from the Roia enters a hydroelectric power station that returns it into the modelled area).

The site was chosen to involve the whole modelled area of the river Roia. Water contaminated with caustic soda at 200 mg/l would transit for two hours, based on a boundary condition of the fourth type (mass nodal sink source BC) and on a reference transient flow of September 2010, which was the minimum in the study year, also reflecting the minimum flow regime of the Roia river.

River flow at the time of the accident was set at the worst scenario (minimum flow), namely 4 m³/sec from the accident site and 1 m³/sec from the Roia. The river water would reach the study area two hours after all the contaminated water entered the water course (Fig. 10). The simulation was conducted in three phases:

- 0 – 2 h;
- 2 – 4 h;
- 4 h – 120 days.

Since the pollution involved the whole river and since a flow condition was set, the caustic soda diffused through most of the aquifer as shown in Figure 11.

2. Percolation of sodium nitrate (NaNO₃) from a farm. The farm was a source of nitrate percolation due to continuous leaching by rain and irrigation. The area (1000 m²) was in the north –west of the area study. Nitrates (300 g/day/m²) were assumed to be leached 24 h a day for 40 days, which is the mean duration of treatment. The most suitable boundary condition to apply to this case is the second type, namely mass flux (g/m²/day).

The simulation covered 150 days and the different phases of evolution and concentrations in the nitrate plume are shown in Figure 12.

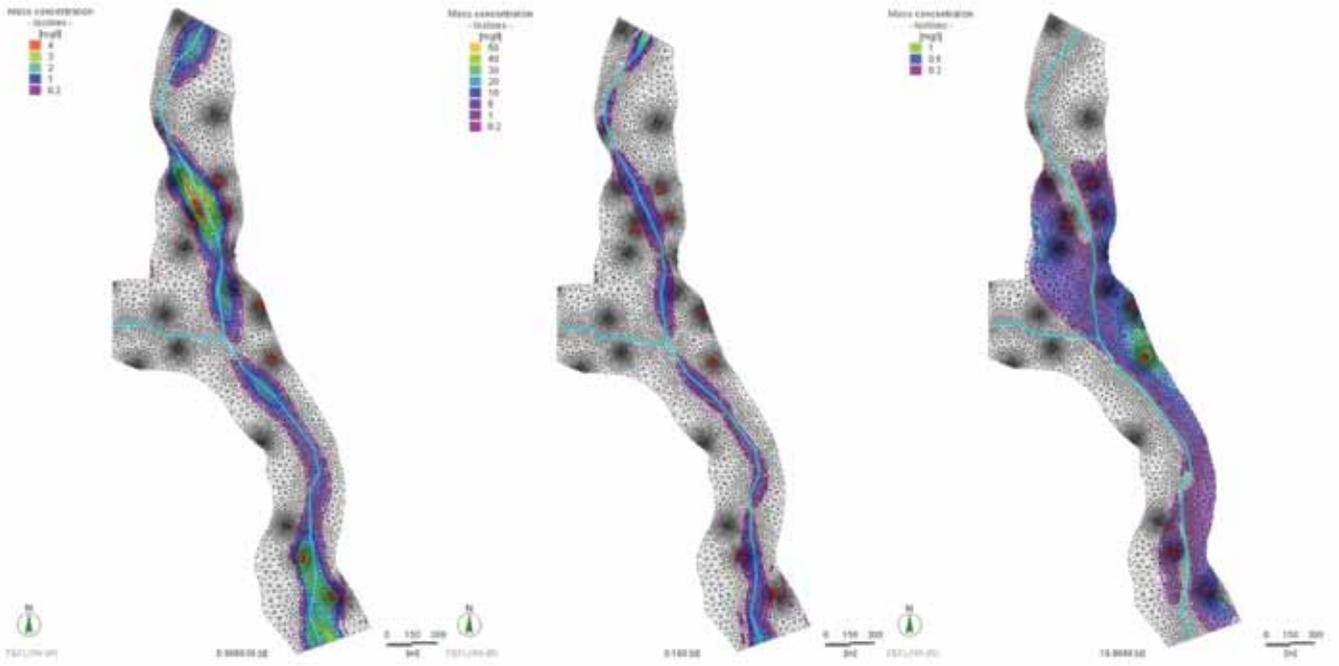


Fig. 10: Area of NaOH input from 0-2 h (in red the positive-flow nodes between river and aquifer).

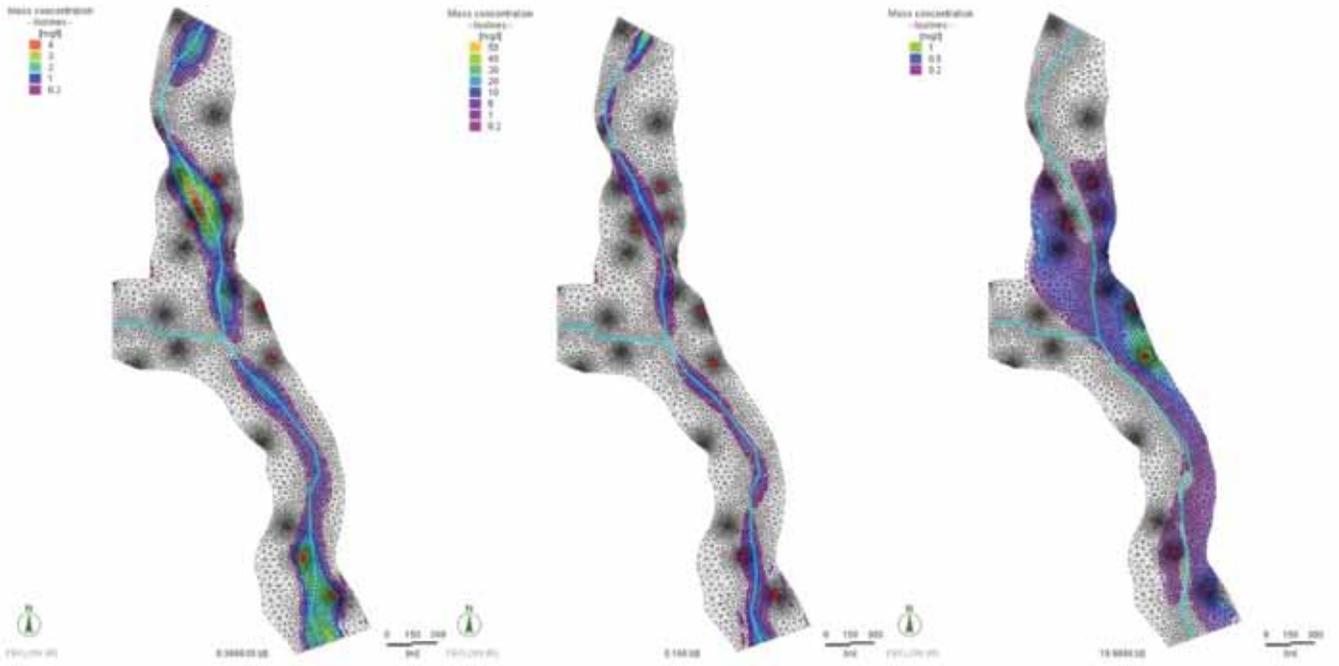


Fig. 11: Diffusion of NaOH plume after 4 h, 1 day and 20 days.

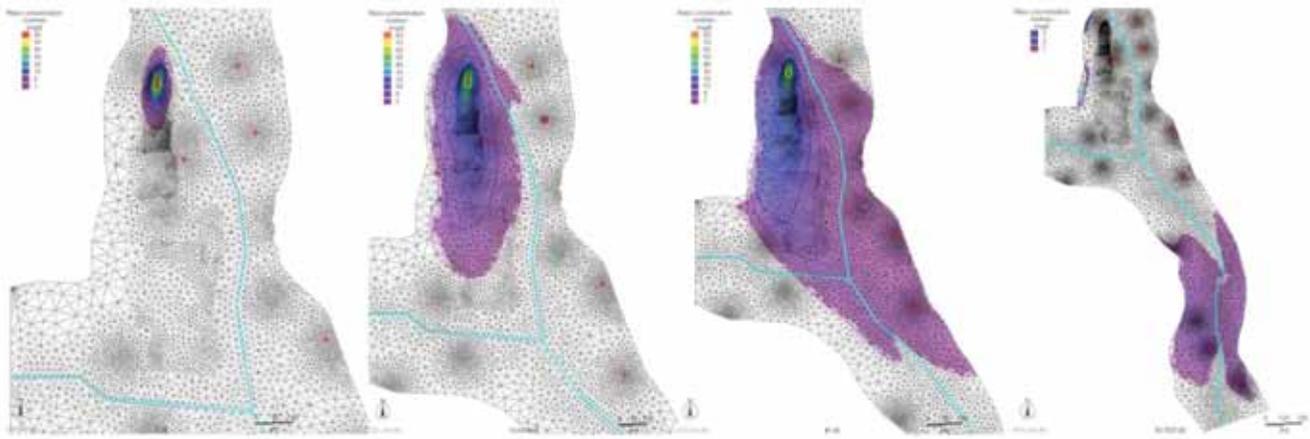


Fig. 12: Evolution of nitrate plume at various times (1, 10, 41 and 93 days).

3. Percolation of generic pesticides from a farm. The same farm was a source of generic pesticide percolation due to continuous leaching by rain and irrigation. The area (1000 m²) was the same as for the nitrate scenario. A mean flow of 3 g/day of active principle for 40 days, which is the mean period of treatment, was considered. The most suitable boundary condition to apply to this case is the

second type, namely mass flux (g/m²/day). Interaction with the substrate (sorption model) delayed transport of the plume. Mass did not vary but transport velocity decreased with increasing concentration due to a decrease in the plume area. The simulation was conducted over 1461 days (4 years). Figure 13 shows temporal evolution and concentrations in the pesticide plume.

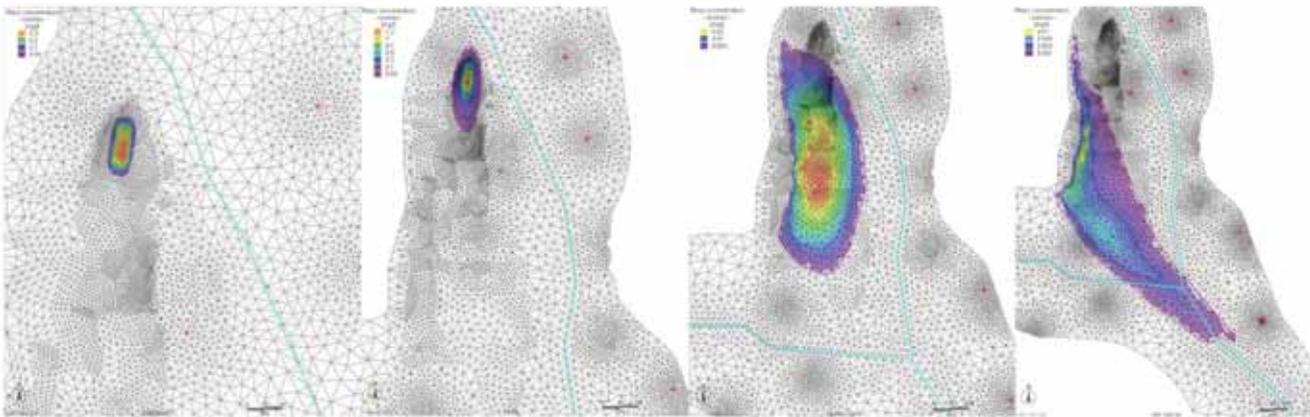


Fig. 13: Evolution of pesticide plume at various times (1, 41, 360 and 991 days).

Conclusions

Study of the phreatic aquifer of the Roia river enabled numerical modelling of flow in permanent (fundamental to obtain an idea of the volumes involved and to set the initial flow in June 2010) and transient regimes and transport modelling on the basis of a conceptual model of the aquifer.

It proved possible to quantify inputs and outputs of the system in detail, as well as water exchange and diffusion of contaminants.

The two water courses and especially the Roia river play a fundamental role in this groundwater system. As shown by analysis of the overall water budget and those of the various sectors, exchanges of water between water courses and the aquifer compensate the volumes pumped from wells.

The study effectively simulated flows of the aquifer in sediment of the Roia alluvial plane, providing insights into the way in which

this system works, its dynamics and potential new areas for wells. It enabled us to define a quantitative balance of water volumes exchanged between the aquifer and the river and to optimise current and future exploitation of existing water resources. The numerical transport model can be used to track the diffusion of contaminant plumes, as illustrated in the risk scenarios reported.

The study provided new information on the geometric structure and hydrodynamics of the Roia aquifer and a versatile model for the management and evaluation of any well-defined flow or transport scenario. The scenarios illustrated here are only preliminary examples of its possible applications.

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