Impacts of a Railway Tunnel on the streams baseflow verified by Means of numerical modelling

Leonardo Piccinini, Valentina Vincenzi

Abstract: The high velocity railway line between Bologna and Florence (Italy) mostly develops underground through the Tuscan-Emilian Apennine and the tunnels severely impacted groundwater and surface waters. The 15-km-long Firenzuola tunnel crosses siliciclastic turbidites: during the drilling, water inrushes occurred at fault and fracture zones, and the tunnel still continues to drain the aquifer. The water table dropped below the level of the valleys, and gaining streams transformed into losing streams or ran completely dry, as did many springs. Hydrological observations and two multi-tracer tests have previously characterized the streams-tunnel connections and the impact processes.

In the framework of planning mitigation strategies to minimize impacts on streams baseflow, three-dimensional numerical modelling with MODFLOW (EPM approach) is applied in order to evaluate artificial minimum flow needed to maintain a flow continuity along the stream during the recession phase. The setting up of the two presented models is based on hydrogeological monitoring data and results of flow measurements and tracer tests. Maximum flow rates subtracted to streams baseflow by the tunnel along the connection structures are calculated for the two streams with major impacts.

Keywords: numerical modelling, MODFLOW, tunnel drainage, fractured aquifer, Tuscan-Emilian Apennine

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Riassunto: *La linea ferroviaria ad Alta Velocità Bologna-Firenze (Italia) si sviluppa prevalentemente in sotterraneo attraverso l'Appennino Tosco-Emiliano e le gallerie drenanti hanno impattato gravemente le risorse idriche superficiali e sotterranee.*

La sopra menzionata linea ferroviaria, tra l'anno 1996 e il 2005 venne realizzata con l'escavazione di 9 tunnel attraverso l'Appennino Tosco-Emiliano, per una lunghezza totale di 73 km. Il disegno e il progetto di costruzione è visibile nel lavoro di Lunardi del 1998.

I principali problemi riguardanti il drenaggio si sono verificati in prossimità dello spartiacque topografico, dove la galleria attraversa torbiditi silicoclatiche della Formazione della Marnoso Arenacea (FMA) una unità che viene considerata prevalentemente un non-acquifero.

Nel settore Toscano della linea, a causa di importanti fenomeni di inrush nella galleria, furono necessari cambiamenti e adattamenti del progetto iniziale. A parte le procedure di gestione del rischio durante la perforazione, furono necessari ad esempio progettazioni di nuovi sistemi di rivestimento, rivestimenti di roccia e modifiche nel tracciato della galleria.

Tutto ciò con un aggravio nei costi e nella durata dei lavori

Per quanto riguarda la tutela ambientale fu istituito un programma di monitoraggio di dettaglio delle acque superficiali e sotterranee che ebbe inizio nel 1994 e ancora continua, permettendo di registrare l'impatto degli scavi su 60 sorgenti (usate per l'approvvigionamento idrico pubblico e privato) e 30 pozzi.

Tuuto ciò ha permesso di evidenziare le interferenze tra le oscillazioni della linea di falda in più di 8 bacini idrografici con effetti sulla tavola d'acqua che hanno avuto ripercussioni fino ad una distanza di 4 km dalla linea della galleria

La Galleria Firenzuola, lunga 15 km, attraversa torbiditi silicoclatiche; durante gli scavi ha intercettato venute d'acqua nelle zone di faglia e di fratturazione e il drenaggio è ancora in corso. La tavola d'acqua è scesa sotto il livello delle vallate e i torrenti che prima erano drenanti si sono trasformati in disperdenti o si sono prosciugati, come è successo a molte sorgenti. Misure idrogeologiche e due multi-tracciamenti hanno dimostrato e caratterizzato le connessioni torrenti-galleria e i processi di impatto.

Nell'ambito della progettazione di opere di mitigazione degli impatti sul deflusso dei torrenti, si è applicata la modellazione numerica tridimensionale con MODFLOW (approccio EPM) per la stima dei deflussi artificiali minimi da garantire a monte dei tratti impattati per il mantenimento della continuità di flusso sulle aste torrentizie durante la recessione estiva.

L'implementazione dei due modelli presentati è basata sui dati di monitoraggio idrogeologico e sui risultati dei profili di portata e dei test di tracciamento. Per i due torrenti maggiormente impattati sono state stimate le portate massime sottratte dalla galleria al deflusso di base dei torrenti attraverso le strutture geologiche di connessione.

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Introduction

The drilling of some tunnels of the Bologna-Florence High Velocity railway line (Italy) induced the drainage of huge groundwater volumes. This effect was not anticipated during pre-construction phase and design project planning phase, causing heavy problems both on construction and on works environment.

The above-mentioned line, between 1996 and 2005, was realized with the drilling of 9 tunnels across the Tuscan-Emilian Apennine chain, over a total length of 73 km (Vallino Costassa et alii, 1997; Lunardi, 1998). The design and construction of the tunnels is available in Lunardi (2008). Major drainage problems occurred near to the main topographic divide, where the tunnels cross the siliciclastic turbidites of Marnoso Arenacea Formation (FMA) (Ricci Lucchi, 1975, 1978, 1980, 1981; Mutti, 1985; Mutti & Normark, 1987; Mutti, 1992; Martelli, 2004), a geological unit previously considered as non-aquifer.

In the Tuscan sector of the line, huge inrush phenomena requested changes and adaptations of the project to groundwater in tunnels: aside from risk management procedures during drilling phase, new construction operations were needed, e.g.: new planning of lining systems, rock mass linings and changes in the planned route of the tunnels. All these changes increased costs and durations of works.

Concerning the environmental issues, a detailed monitoring programme on superficial and ground- water, started in 1994 and still going on (Agnelli et alii, 1999), allowed to record the impact on 60 springs (for private use and public water supply) and 30 wells; furthermore, it allowed to evidence the interferences with stream baseflow in more than 8 watersheds (Canuti et alii, 2009), with effects on surface which propagated until a distance of 4 km from the tunnel line. This huge data-base (Canuti et alii, 2009) allowed the definition of a conceptual model of groundwater flow systems in turbidites (Gargini et alii, 2006, 2008), confirmed by further studies (Vincenzi et alii, 2009).

In this paper two case studies are presented, in which numerical modelling is applied in order to simulate Firenzuola tunnel drainage impacts on the streams of two watersheds. The modelling approach is that one of Equivalent Porous Medium (EPM) (Pankow et alii, 1986; Gburek et alii, 1999; Rayne et alii, 2001; Scanlon et alii, 2003; Paradis et alii, 2007) through the finite difference code MODFLOW 2000 (Harbaugh et alii, 2000).

Geological Setting

Firenzuola tunnel is 15,060 m long and crosses the main topographic divide between Santerno River on the northern side and Arno River on the southern side (Fig. 1). Drilling works started in 1997 through 4 shafts (total length of 3,519 m) and finished at the end of 2005.

The Tuscan-Emilian Apennine is a typical thrust-fold belt, where different tectonic units thrusted one over the other, due to compressive strengths resulting from the collision between African and Euro-Asiatic plates. Since Messinian, from the Tuscan coastline to the apenninic divide tectonic movements became mainly vertical due to an extensional tectonic related to the opening of the Tirrenian Sea (Bendkik et alii, 1994; Boccaletti et alii, 1997; Cerrina Feroni et alii, 2002).

Firenzuola tunnel is located at the border between the two different tectonic domains: the first one (north of the main water divide) is mainly characterized by thrusts and low-inclination faults; the second one (farther to the south) is characterized by normal faults related to the opening of the Mugello graben, where fluvio-lacustrine sediments accumulated during Pleistocene (Bernini et alii, 1990; Boccaletti et alii, 1995a, 1995b, 1999).

The tunnel is mostly drilled through siliciclastic turbidite units of the Miocene Marnoso Arenacea Formation (FMA), consisting of arenitic layers (sandstones) and pelitic layers (marls) (Ricci Lucchi, 1986; Zattin et alii, 2000). The FMA can be subdivided into lithostratigraphic members according to the ratio of arenitic to pelitic layers (A/P ratio) (Cibin et alii, 2004; Amy & Talling, 2006). The tunnel crosses, from north to south, the following geological formations and FMA members (Fig. 2): Bassana member (FMA7), $A/P \approx 1$, from northern entrance to km 48+000; Nespoli member (FMA8), $A/P > 1$, from km 48+000 to km 49+450 and from km 49+800 to km 50+300; Argille Varicolori con Calcari (AVC), mainly argillitic unit pertaining to Unità Tettonica Sestola Vidiciatico (Bettelli & Panini, 1991; Bettelliet alii, 2002), from km 49+450 to km 49+800; Collina member (FMA5), A/P = 1/5 or 1/6, from km 50+300 to km 50+450; Galeata member (FMA4), A/P = 1/2 o 1/3, from km 50+450 to km 50+700; Premilcuore member (FMA3), $A/P > 1$, from km 50+700 to km 54+700.

From km 55+600 southward Firenzuola tunnel crosses Tuscan Units (Unità Toscane), thrusted over FMA due to a regional inverse fault out of sequence, (Bendkik et alii, 1994; Cerrina Feroni et alii, 2002; Cibin et alii, 2004; Martelli et alii, in press). More in detail (Fig. 2): sandy-silty member of Torrente Carigiola Formation (TCG), siliciclastic turbidites with $A/P < 1$, from km 54+700 to km 55+600; sandy-silty member of Acquerino Formation (AQR), siliciclastic turbidites with $A/P > 1$, from km 55+600 to km 55+650 and from km 55+900 to km 55+980; Marne Varicolori di Villore Formation (MVV), marls, from km 55+650 to km 56+300; from km 56+300 to the southern entrance, the tunnel crosses the fluvio-lacustrine succession of Mugello graben (Fig. 1), represented by alluvial and lacustrine sediments, made of pebbles, sands and clays.

Hydrogeology

Impacts of the tunnel on groundwater and surface waters

During excavation of Firenzuola tunnel, 14 major water inrushes occurred between 1999 and 2003 into the main tunnel and the access windows. Peak inflows were within a range of 30 to more than 500 L/s. The total drainage during drilling advancement reached instantaneous flow rates of more than 1,000 L/s. Two years after completion of the Firenzuola tunnel, the average drainage outflow becomes 355 L/s with an evident relationship to the annual recharge regime: 210 L/s at the end of the recession period in autumn, but more than 400 L/s during winter (Gargini et alii, 2008).

The main impacts on springs and streams occur in the zones consisting of turbidites with a high A/P ratio: the Nespoli member in the northern side and the Premilcuore member in the southern side. As a consequence, 12 springs and 5 previously perennial streams (Rovigo and Veccione in the north; Bagnone, Bosso and Farfereta in the south) were completely or seasonally dried. The mechanisms of the impact were different in the north and in the south, and were established by studying the space-time array of the inrush-impact relationships as derived by monitoring data collected by the Hydrological Monitoring Programme performed by the constructors during drilling advancement.

In the southern part (FMA3), the main inrushes occurred between km 52+850 and km 54+450, during the northward advancement of the Marzano window and the Firenzuola tunnel in 1999–2003, and are related to extensional fracture zones and faults parallel to the Mugello graben. All main springs aligned along these structures

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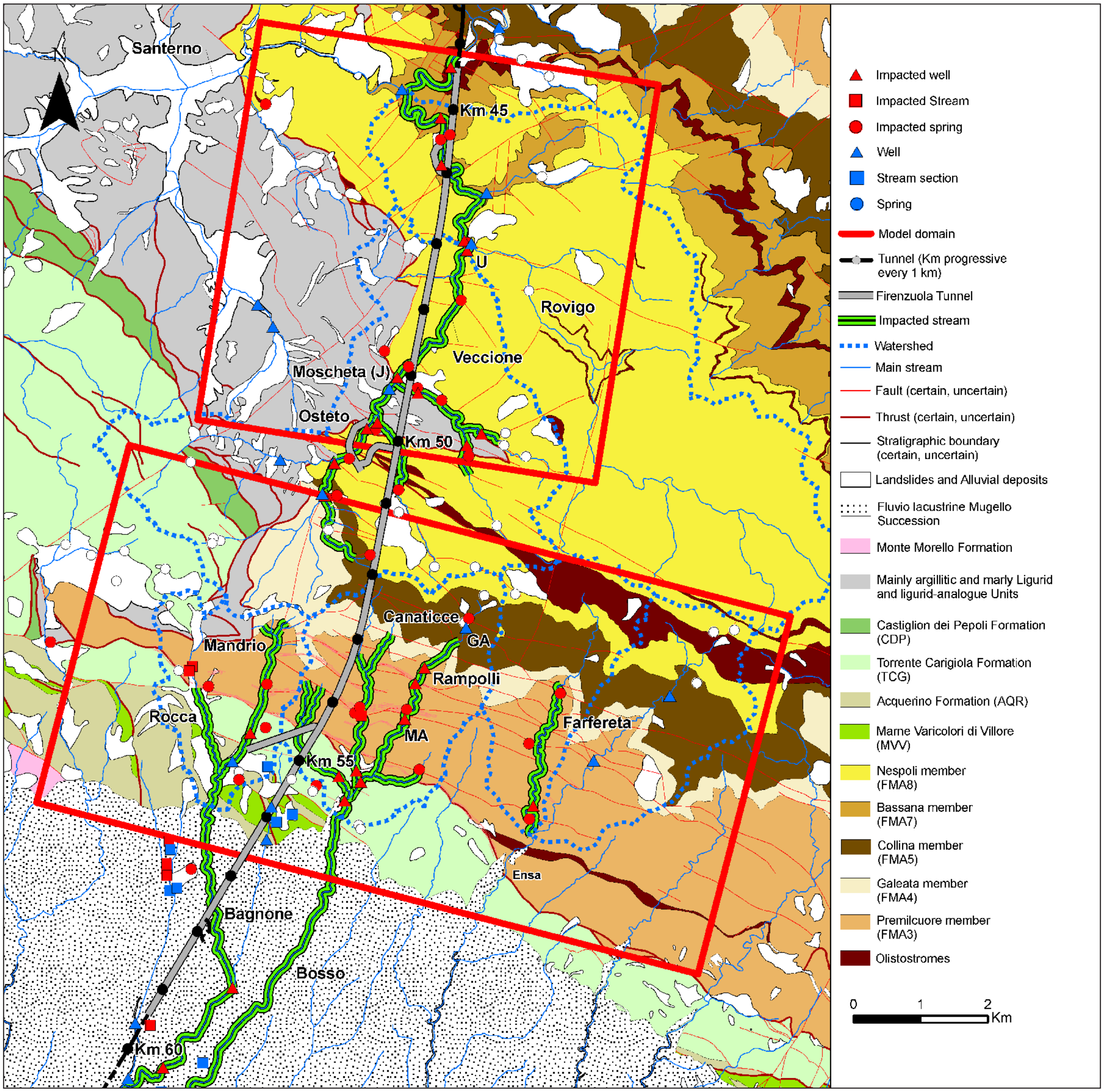

Fig. 1. *Geological and hydrogeological setting of the study area: main geological formations and distribution of impacts on surface; with the red boxes the two model domains are evidenced.*

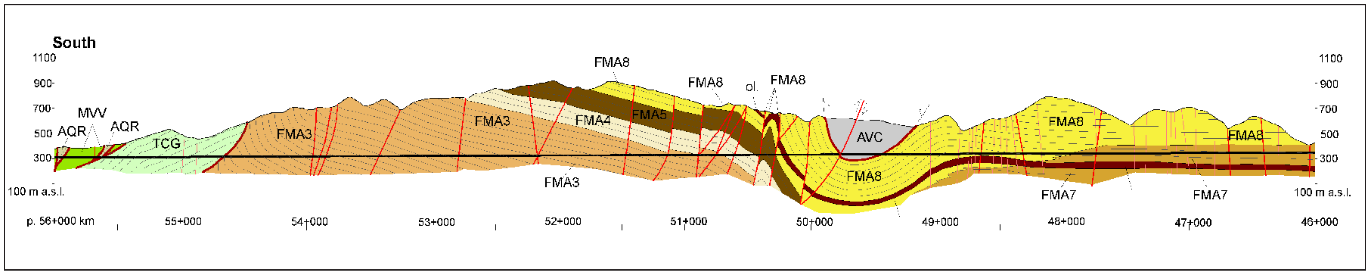

Fig. 2. *Geological section along Firenzuola tunnel (modified from Vincenzi et alii, 2009).*

were completely dried up and the disappearance of summer flow in the five impacted streams is mainly related to water losses in the intersection zones between the streams and the extensional faults.

Analyzing the Hydrological Monitoring Programme data and integrating them through surveys done by the authors in 2000–2002 and 2005–2007, the progressive development of the impact has been inferred. Five main "impact events" can be identified from water inrushes during drilling advancement, increasing drawdown observed in wells, and decreasing spring and stream flows. Most of the impact events are related to tectonic extensional structures crossed by the tunnel, only two of which had been identified from the surface during geologic surveys before drilling (Vincenzi et alii, 2009).

A hydraulic diffusivity was estimated analyzing the time lags between tunnel inrushes and impacts on surface, resulting in a mean value of about 1,000 m/month (Gargini et alii, 2008). Fast and intense impacts were also recorded on streams. However, the stream hydrographs consist of baseflow and direct flow, while the tunnel mainly reduces the baseflow, so the effects are evident mainly during recession periods.

Several watersheds were impacted by the tunnel in the southern side of the Apenninic chain. The most severe impacts can be observed in two tributaries of Bosso Stream. Already during springtime, the western tributary (Canaticce) runs completely dry in its entire lower part, thereby exterminating all active aquatic live in this previously permanent stream. The eastern tributary (Rampolli) also runs dry during summer in its lower part, although the springs in its upper part maintain their flow rates.

In the northern part (Nespoli member), the main inrushes occurred between km 45+900 and km 48+200. Due to the absence of long and continuous extensional fracture zones, these inrushes can be explained as drainage from a decompressed and generally fractured rock mass extending down to 200 m depth. For the same reason, the drainage effect of the tunnel does not propagate for such long distances as in the southern part. Several slope springs and streams (e.g. Rovigo and Veccione) were impacted by the tunnel shortly after the water inrushes occurred.

On the northern side, Veccione Stream is most severely impacted by the tunnel, as well as the lower reaches of Rovigo Stream, which are directly located above the tunnel, and where rock coverage is thin, so that the stream-tunnel connections are obvious.

The tunnel crosses the Veccione watershed over a length of 5.5 km. At two places, the tunnel passes directly under the stream: at km 49+000 (main tunnel) and near km 50+000 (access window). The impacts are not restricted to these zones but the stream flow surveys revealed significant seepage losses along most of the stream.

Moreover, the flow measurement data at the final sections of the catchments allowed the comparison of the mean baseflow of the different streams before (1995–1998) and after (2005–2006) the tunnel excavation, thus providing the baseflow loss estimate. Only stream discharge measurements made after at least 5 days from the last rain have been considered for the calculation of the baseflow values.

The baseflow losses range from 40 to 84%. The highest value corresponds to Bosso Stream; dramatic losses (65%) have also been observed in the Veccione Stream, a tributary of Rovigo Stream.

The slight decrease of total annual rainfall (8% less rainfall in 2005–2006 compared to 1995–1998) is not sufficient to explain this substantial baseflow loss, which can mainly be attributed to drainage into the tunnel. The total baseflow loss is 254 L/s, less than the total outflow of the tunnel (355 L/s in 2005–2006), suggesting that the system is still in a transient state and further impacts have to be expected.

Tracer tests

The monitoring data collected and analyzed allow to identify the impacted stream sections only in a general way. However, in order to localize the most important infiltration zones in the streambeds and to characterize their evolution over the years, repeated and detailed stream surveys were done within the framework of this study and multi-tracer tests with fluorescent dyes. The results of this study, available in Vincenzi et alii (2009), are the main data source for the here presented modelling study and are here briefly summarized.

Applying the salt dilution method (Käss, 1998) flow measurement profiles have been done and repeated during the spring-summer seasons, i.e. flow measurement at different sections of the same stream, from downstream to upstream, in order to identify the losing stream reaches and to compare them with geological structures.

As an example, along Rampolli Stream the two infiltration zones, where the drying up starts in early June, are related with two tectonic structures. In the following weeks, the dry part of the stream migrates progressively upstream, due to additional infiltration zones. During summer, the stream remains dry until intense rainfall and recharge restarts in autumn or winter.

In June 2006, the discharge of Veccione Stream decreased from 60 to 30 L/s in the middle section of the stream (near km 49+000) and from 46 to 25 L/s in the lower section (near km 47+000) within 11 days, demonstrating that the gaining stream had transformed into a losing stream. On 18 July 2006, the stream started to dry up in the lower section, and the dry part slowly propagated upstream. In September, the entire lower and middle section of the stream was dry until the beginning of December due to a particularly dry autumn.

In Vincenzi et alii (2009) two multi-tracer tests, each using uranine and sulforhodamine G, were carried out for the two impacted catchments (Veccione in the N-sector and Bosso in the S-sector) in order to confirm and quantify the stream-aquifer-tunnel interrelations. The results proved connection between losing streams and numerous water inlets in the tunnel, with maximum linear distances of 1.4 km and velocities up to 135 m/d. The tracing experiments allowed to infer the main stream-tunnel connections, i.e. geological structures responsible of the drainage of superficial waters by Firenzuola tunnel. Several of the demonstrated flow paths pass under previous groundwater divides (mountain ridges) in the direction perpendicular to the tunnel, proving that the drainage has completely modified the regional flow system. Significant differences were observed between the northern and the southern sector of the area: the higher velocities and longer distances travelled by the tracers in the southern sector confirm the higher permeability of the turbidites in this zone and also explain the larger tunnel interference radius.

Conceptual model

A conceptual model of groundwater circulation in turbidites was recently proposed on the basis of a large quantity of hydrogeological monitoring data related to tunnel excavations (Gargini et alii, 2008; Vincenzi et alii, 2009). According to this model, three main types of groundwater flow system (GFS) can be identified in turbidite aquifers:

- GFS1: Shallow groundwater circulation in the uppermost 100–200 m, where stress release has caused intense fracturing; regolith, landslide deposits and debris also belong to this zone. A shallow GFS largely follows the topography and discharges into many small springs (often < 1 L/s; 'slope' type spring, S) or streams.

- GFS 2: Along major extensional structures (steep and relatively deep-reaching fracture zones), linear flow systems develop, sometimes across several surface watersheds. These flow systems discharge to few relatively large springs (mean discharge ranging from 1 L/s to > 10 L/s; 'transwatershed' type spring, T) or directly to streams.

- GFS 3: Deep regional circulation systems develop between the central parts of the mountain chain, where high recharge occurs, and the lower-lying areas at their margins. These flow systems often discharge into alluvial sediments or contribute to the baseflow of larger rivers in the deeply incised valleys. Discrete discharge points are rare.

In natural state, before the tunnel excavation, the fractured turbidite aquifer discharged towards small springs (along creeks) and mountain streams, feeding the baseflow. Now, the draining tunnel has modified completely the system equilibrium, lowering the water table below the level of the streams, causing inversion of the natural groundwater-surface water interactions: gaining streams have transformed into perched losing streams and the zones where springs discharge occurred are now the losing reaches, where tracers infiltrated towards the tunnel.

Aim of the work

Even if aquifer restoration is not possible, as long as the tunnel continues to drain the aquifer, the flow disappearing during summer induced the Florence County Government to evaluate and plan several mitigation strategies in order to preserve at least a minimum stream flow downstream to the impact reaches. The strategies contemplate artificial feeding of streams, coupled with local streambed sealing or bypass conduits in zones of preferred infiltration. So a fundamental parameter to know was the stream flow rate drained by the tunnel on the different reaches of streams and the flow rate necessary to maintain the flow continuity along the streams.

The only approach that can take into account all the involved system variables is represented by numerical modelling. The main need is in fact to reproduce both tunnel drainage and the interaction between superficial and ground-water.

As the main Apenninic divide represents a hydrodynamic threshold that avoids the impacts spreading from the northern sector to the southern, two separated modelling domains have been performed: Veccione Stream and Rovigo Stream, in the northern sector, and Rampolli Stream in the southern sector (Fig. 1), which are the streams with major impacts and with tracer results available.

Materials and methods

The used EPM approach consists in considering the rock matrix together with the fractures (the rock mass) and assigning them average hydrodinamic properties, over a rock volume sufficiently wide to be considered statistically representative (representative volume element o REV) (Long et alii, 1982; Kanit et alii, 2003). Inside the REV it is assumed that fracture distribution is casual and uniform and that fracture width does not allow turbulence flow. Geometric and hydrodynamic properties of distinct fractures are not requested, small computational efforts are necessary and good results can be obtained working on wide modelling areas (Mun & Ucrhin, 2004). Different examples are available in literature concerning the use of EPM approach for the simulation of both flow and transport in fractured aquifers, also karst aquifer in some cases (Pankow et alii, 1986; Teutsch, 1993; Gburek et alii, 1999; Rayne et alii, 2001; Paradis et alii, 2007; Worthington, 2009). Most of the authors agree that the EPM approach is particularly suited for flow systems at a regional scale (Scanlon et alii, 2003). At a more detailed scale and with higher heterogeneities the EPM approach can give erroneous results in terms of flow directions or mass balance (e.g. wide karst conduits).

Siliciclastic turbidites of FMA represent a good test site for the EPM, due to the absence of karst phenomena and to a relatively homogeneous fracture pattern, related to the A/P ratio, tectonic events and detensioning (Gargini et alii, 2006).

The choice of REV dimensions suitable to represent FMA is derived from geomechanical surveys in surface (during preliminary investigations) and at drilling faces, during the tunnel boring.

The applied code is MODFLOW 2000, developed by U.S. Geological Survey (Harbaugh et alii, 2000), updated version of the original MODLFOW (Mcdonald & Harbaugh, 1988). It solves the flow equation in the 3 dimensions in saturated media according to the finite difference method.

To simulate surface waters-groundwater interaction the Streamflow-Routing Package (STR1) (Prudic, 1989) is used. It results from a change in the original River Package formulation (Mcdonald & Harbaugh, 1988): STR1 simulates the surface water flow inside streams propagating a flow rate from cell to cell, contemporarily to their interaction with groundwater, controlled by the heads differences between the streams and the aquifer and by the permeability of seepage medium, i.e. the riverbed.

The Drain Package (DRN) (Harbaugh et alii, 2000) is used to simulate the tunnel drainage; it removes groundwater from the corresponding cells as a function of heads differences (between the aquifer and the tunnel elevation) and of the permeability around the tunnel.

MODELS SET UP

Discretization

A model domain of 6000x6000 m has been set up for Veccione catchment, extending from Osteto window to the south to the confluence between Rovigo Stream and Santerno River to the north (Fig. 1).

The domain is oriented parallel to Firenzuola tunnel line, with an inclination of 9° from north direction. On the horizontal plane it is subdivided into cells of 25x25 m, while along the vertical axis 7 variable thickness layers have been represented, starting from the topographic surface derived from DEM Lydar relief of Florence County Government. The model bottom is an almost horizontal plane at elevation of 240 m a.s.l., with a light gradient parallel to the tunnel slope. The total thickness of the model varies between 100 and 900 meters.

The model domain of Fosso Rampolli, on the southern sector, is a 1018x5500 m wide rectangle, that includes the catchments of Bagnone, Bosso, Farfereta and Ensa streams, extending from the main Apenninic divide to the north to fluvio-lacustrine formations of Mugello to the south. The shorter edge is oriented N-S, according to the mean regional flow direction. On the horizontal plane the domain is divided into cells of variable dimensions from 25x25 m along the tunnel to 200x200 m towards western and eastern sides. Topographic surface comes from the same Lydar relief, while the model bottom is parallel to the tunnel plane, with elevations between 270 and 180 m a.s.l. from north to south. Total model thickness is between 100 and 900 m, divided into 7 layers of variable thickness in relation to topographic relief.

Parameters

In the Veccione domain three permeability zones have been distinguished as a function of lithology and fracture density (Fig. 3a and Tab. 1a). The first one represent the FMA rock mass normally fractured; the second zone corresponds to those sectors of FMA where the fracture density is higher, derived from the superposition of geological data, impacts distribution and tracer tests results (Vincenzi et alii, 2009); while the third one represents the argillitic low permeability rock masses pertaining to ligurid units, outcropping in the middle part of Veccione catchment.

In the Fosso Rampolli domain six permeability zones have been distinguished (Fig. 3b and Tab. 1b): FMA turbidites normally fractured; normal faults and high density fracturation zones inside FMA turbidites; argillitic units pertaining to ligurid units; siliciclastic turbidites of TCG normally fractured; AQR turbidites and MVV marls.

Permeability is always assigned as isotropic property, except for the normal faults/fracture zones, where an anisotropy factor of 10 resulted necessary along x and z axis during the calibration process (Tab.1b).

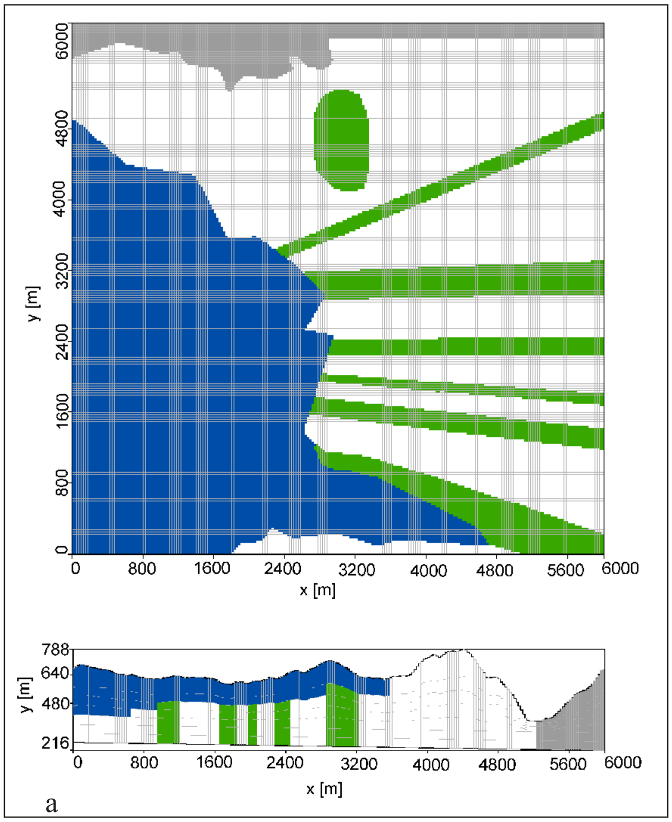

Fig. 3a. *Permeability zones of Veccione model: plan view (above) and N-S section at x=1750 (below); colour legend in Tab. 1a; in gray colour the inactive cells.*

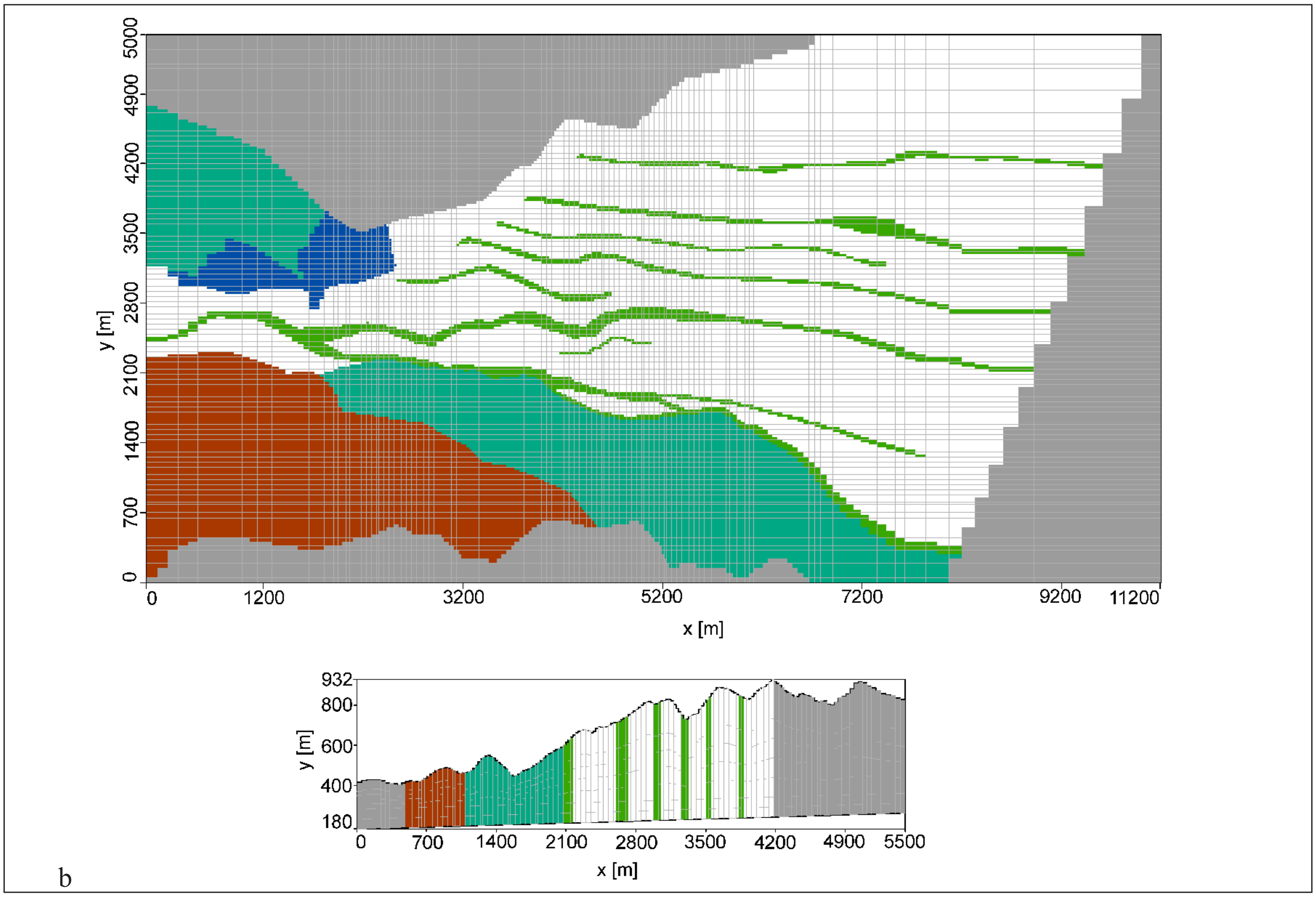

Fig. 3b. *Permeability zones of Fosso Rampolli model: plan view (above) and N-S section at x=4000 (below); colour legend in Tab. 1b; in gray colour the inactive cells.*

Tab. 1. *Permeability values of the different zones: a) Veccione model (see Fig.3a); b) Fosso Rampolli model (see Fig.3b).*

a) Veccione model

Zone		Hydrogeological Unit	K_x (m/s)	K_y (m/s)	K_z (m/s)
1	⬜	Rock mass normally fractured (FMA), aquifer	1.0E-07	1.0E-07	1.0E-07
2	🟦	Ligurian argillitic units, aquiclude	1.0E-09	1.0E-09	1.0E-09
3	🟩	Rock mass with higher fracture density (FMA), aquifer	5.0E-06	5.0E-06	5.0E-06

b) Fosso Rampolli model

Zone		Hydrogeological Unit	K_x (m/s)	K_y (m/s)	K_z (m/s)
1	⬜	Rock mass normally fractured (FMA), aquifer	1.0E-07	1.0E-07	1.0E-07
2	🟦	Ligurian argillitic units, aquiclude	1.0E-09	1.0E-09	1.0E-09
3	🟩	Rock mass with higher fracture density (FMA), aquifer	1.0E-04	1.0E-05	1.0E-04
4	🟩	Rock mass normally fractured (TCG), aquifer	1.0E-07	1.0E-07	1.0E-07
5	🟫	Rock mass normally fractured (AQR+MVV), aquitard	8.0E-08	8.0E-08	8.0E-08

Boundary conditions

In the Veccione model the regional gradient is represented by two 1st type boundary conditions (b.c.) (Constant Head in MODFLOW) on the northern and southern side of the domain. At north head varies from 650 to 450 m a.s.l., depending on the simulated conditions. At south the assigned head corresponds to the Santerno riverbed elevation (359 – 378 m s.l.m.), representing the discharge point of regional flow system. No flow b.c. (Neumann or 2nd type b.c.; Inactive Flow or No specified boundary in MODFLOW) have been used for the southern portion of the domain (under Santerno River) and for western and eastern sector.

Recharge to aquifer is simulated as 2nd type b.c. (Recharge in MODFLOW) applied to all the cells of 1st layer, distinguishing between turbidites (recharge value of 115 mm/year) and argillitic units (2 mm/year).

In the Fosso Rampolli model a 2nd type b.c. is applied to the 1st layer in order to simulate the recharge and 3 zones are distinguished: FMA turbidites, with 200 mm/years; argillitic units with 2 mm/year; TCG, AQR and MVV units with 100 mm/year.

No flow b.c. are applied to western and eastern boundaries of the domain and to all the cells on the other side of the main apenninic divide. The regional groundwater flow and the feeding of fluvio-lacustrine sediments of Mugello are simulated using a 3rd type b.c. along the southern boundary, through the DRN package of MODFLOW.

In both the models the tunnel is simulated by means of the DRN package; the elevation assigned to the drain is that one of the tunnel, while the conductance values (parameter that represents the resistance opposed to flow by the rock mass all around the tunnel; Zaadnoordijk, 2009) are derived from the calibration process and vary from 1 to 3 m^2/day.

The surface water-groundwater interaction is always simulated by means of a 3rd type b.c., the STR1 package of MODFLOW (Prudic, 1989). It is assigned dividing the streams into reaches and segments; every reach corresponds to one cell of the domain, while the segment is a group of connected cells along the surface flow direction. The stream flow rate is propagated starting from the value of the most upstream cell (starting point) and calculated for every cell downstream as the previous flow rate plus or minus the stream feeding or losing flow rate to the aquifer. The in/out flow is calculated multiplying the head difference between the stream and the aquifer with the riverbed conductance. The stream level is calculated on every reach downstream to the first through the Mannings equation for open channels (Ozbilgin & Dickerman, 1984), while the conductance is derived from the riverbed dimensions (width and thickness) and permeability.

More in detail, the parameters used for the STR1 package are: inflow to the first reach of the stream (derived from field measurements); riverbed thickness of 1 m (average value representative of this small mountain streams); river width from field measurements; roughness coefficient of Manning equal to 0.05 (Berti et alii, 2003); riverbed permeability taken as the same of the outcropping lithology.

Lastly, in the Fosso Rampolli model two streams located towards the western boundary are represented with the River Package (RIV), 3rd type b.c., due to the total absence of flow data and the impossibility to apply the STR1 package.

Simulations

In the steady state calibration process of Veccione model two opposite hydrologic conditions are simulated: high flow and low flow of the aquifer system. In the first case a field data set collected in December 2006, before the tracer test, is used. Low flow conditions simulate flow rates and dry sectors in streams as measured in September 2006. In both the cases the surface water flow rate measurements can be considered representative of the only baseflow contribution, because made after periods without rainfall events. The value of the drainage from the corresponding sector of Firenzuola tunnel is available for each field survey. Without head observation data, the calibration process is performed quantitatively on groundwater flow (tunnel drainage) and surface water flow, i.e. stream-aquifer exchange (Fig. 4 and Tab.2).

The Fosso Rampolli model is performed at steady state using hydrologic conditions measured in May 2006, during the tracing test. Besides from groundwater and surface water flow rates, piezometric levels measured at two impacted wells near to Firenzuola tunnel are available. The quantitative calibration reaches a quite good level (Fig.5 and Tab.3a), strengthened by the good comparison between measured and calculated head at the observation points (Tab.3b).

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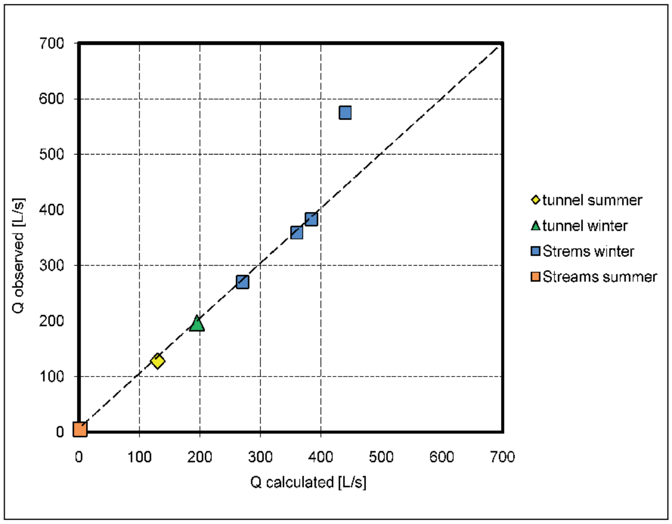

Fig. 4. *Calibration graph of Veccione model: observed vs. calculated flow values.*

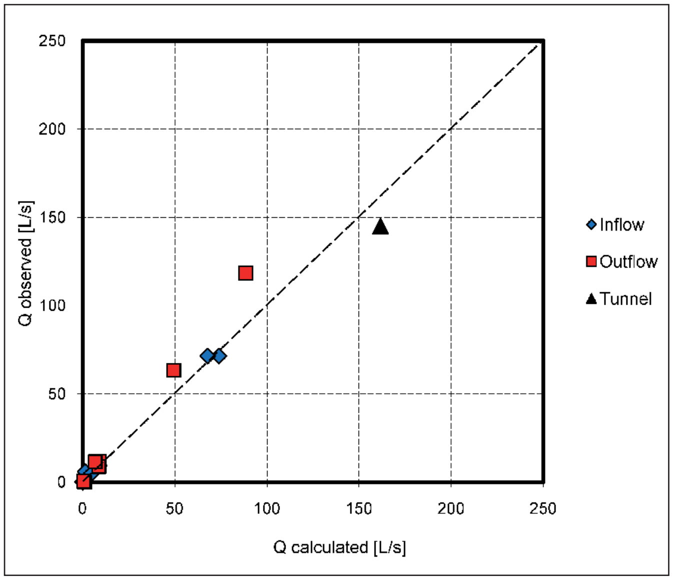

Fig. 5. *Calibration graph of Fosso Rampolli model: observed vs. calculated flow values.*

Results

Concerning Veccione model, starting from the simulation calibrated at low flow conditions, different forecasting simulations are performed in order to assess the minimum artificial flow rate necessary to the upstream reach of the impacted stream (Ponte di Moscheta), in order to maintain the flow continuity along all the stream. A flow rate derived from the average values coming from the hydrological monitoring is assigned to the reaches not impacted by the tunnel: 2 L/s for Fosso dell'Isola and 100 L/s for Rovigo Stream upstream to the confluence with Veccione Stream (Fig. 1).

Tab. 2. *Calibration statistical data of Veccione model.*

Residual Mean (L/s)	22.40
Absolute Residual Mean (L/s)	23.12
Root Mean Squared (L/s)	4.81
Normalized Root Mean Squared (%)	1.09

Tab. 3. *Calibration statistical data of Fosso Rampolli model: a) flow rates data; b) heads data.*

a)	Inflow	Outflow	Total Flow
Residual Mean (L/s)	-0.75	-3.33	-2.18
Absolute Residual Mean (L/s)	1.39	6.95	4.48
Root Mean Squared (L/s)	2.24	11.82	8.94
Normalized Root Mean Squared (%)	3.09	6.57	7.55

b)	Erci Well	Incisa Well
Observed Head (m a.s.l.)	446	448
Calculated head (m a.s.l.)	459	445
Residual Mean (m)	4.60	
Absolute Residual Mean (m)	8.24	
Root Mean Squared (m)	9.44	

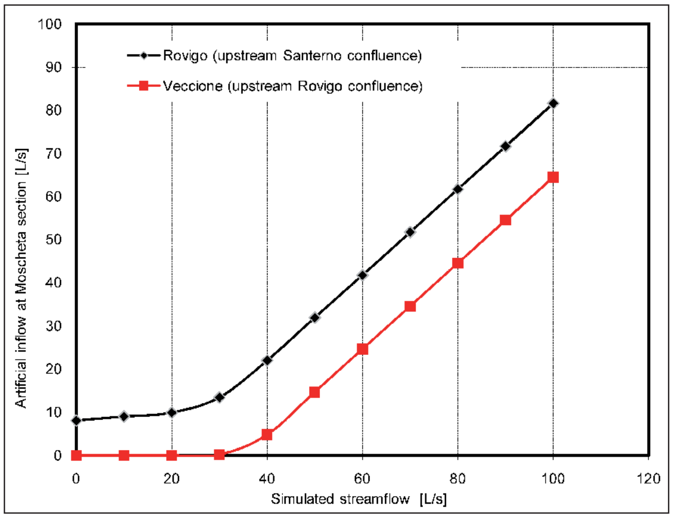

Fig. 6. *Results of Veccione model: graphical comparison between the artificial inflow at the upstream section (y axis) and the residual flow rate at the downstream section of the impacted reach (x axis).*

The minimum artificial flow rate needed at Ponte di Moscheta to maintain flow continuity all along Veccione Stream results between 30 and 40 L/s (Fig. 6); above the 40 L/s the baseflow losses become stationary and are about 35 L/s (Tab. 4). The artificial feeding of Veccione Stream helps also the baseflow of Rovigo Stream, which losses stabilize around 83 L/s (Fig. 6 and Tab. 4).

The comparison with the field measurements at Moscheta section (J) and at the confluence with Rovigo Stream (U) allows the results validation. The flow rate difference between the two sections repre-

Tab. 4. *Results of Veccione model: comparison between the artificial inflow at the upstream section and the residual flow rate at the downstream section of the impacted reach.*

Artificial inflow at Moscheta (L/s)	Veccione outflow upstream Rovigo confluence (L/s)	Loss		Rovigo outflow upstream Santerno confluence (L/s)	Loss	
		(L/s)	(%)		(L/s)	(%)
0	0	-	-	8.07	91.93	85
10	0	10.00	100	8.99	91.01	84
20	0	10.00	100	9.91	90.09	82
30	0.16	29.84	99	13.43	86.73	76
40	4.77	35.23	88	21.99	82.78	68
50	14.70	35.30	71	31.94	82.76	63
60	24.65	35.35	59	41.78	82.87	58
70	34.61	35.39	51	51.74	82.87	55
80	44.56	35.44	44	61.69	82.87	51
90	54.51	35.49	39	71.64	82.87	48
100	64.47	35.53	36	81.6	82.87	46

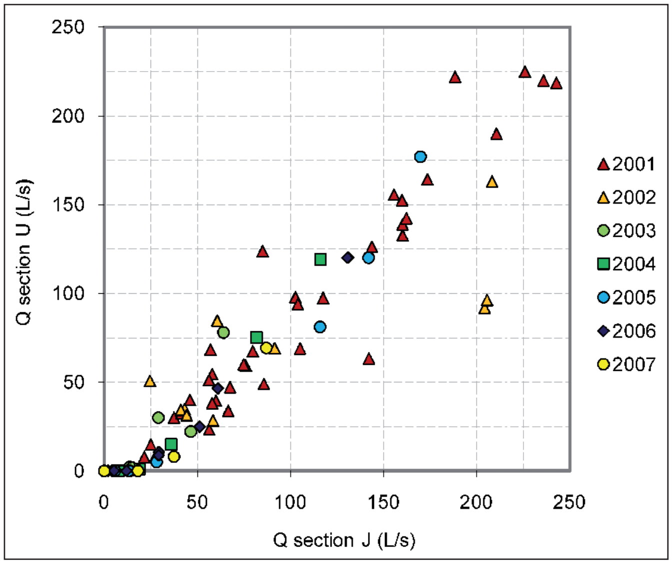

Fig. 7. *Field flow measurements for the years 2001-2007: flow rates (Q) measured at the upstream section (U) vs downstream section (J) of Veccione Stream.*

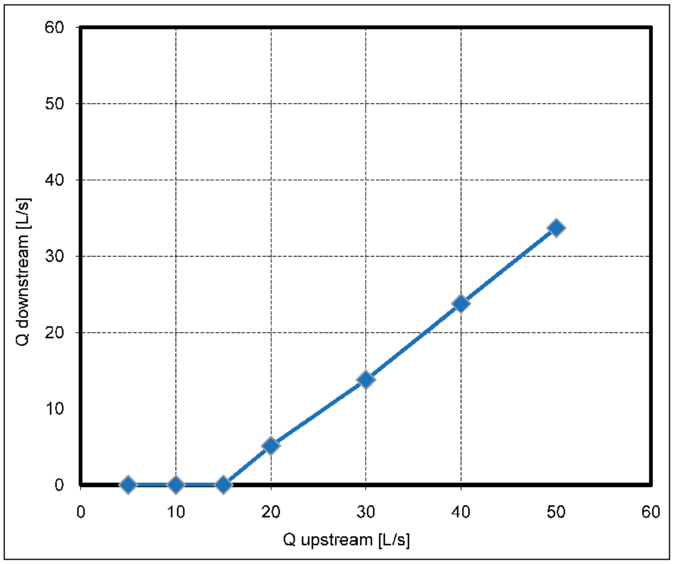

Fig. 8. *Results of Fosso Rampolli model: graphical comparison between the artificial inflow at the upstream section (y axis) and the residual flow rate at the downstream section of the impacted reach (x axis).*

sents in fact the baseflow loss, that depends on the hydrologic conditions at the moment of the field measurement (Fig. 7). The maximum flow rate loss ever detected along Veccione Stream is 66% of the total flow at the upstream section (40 L/s), while the model calculates a value of 88%.

Forecasting simulations of Fosso Rampolli model started from the unique simulation calibrated. Results show that a flow rate of 15 L/s upstream to the impacted reaches is necessary in order to maintain the flow continuity (Fig. 8). Baseflow loss become stable only above the 30 L/s (Tab. 5). Also in this case, field measurements of the environmental monitoring confirm model calculations: the comparison between the section upstream to the impacted reaches (GA) and that one downstream (MA) shows that usually the flow continuity gets lost below the 10 L/s (Fig. 9).

Tab. 5. *Results of Fosso Rampolli model: comparison between the artificial inflow at the upstream section and the residual flow rate at the downstream section of the impacted reach.*

Q upstream (L/s)	Q downstream (L/s)	Loss	
		(L/s)	(%)
5	0	5	100
10	0	10.00	100
15	0	15.00	100
20	5.12	14.88	74
30	13.77	16.23	54
40	23.73	16.27	41
50	33.68	16.32	33

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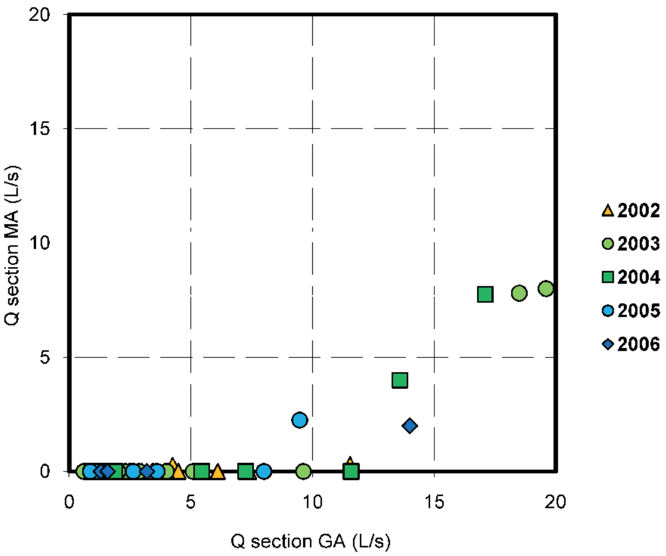

Fig. 9. *Field flow measurements for the years 2002-2006: flow rates (Q) measured at the upstream section (MA) vs downstream section (GA) of Fosso Rampolli.*

Discussion and conclusion

The planning process of mitigation measures on the impacted streams requested a quantitative evaluation of stream-tunnel flow rates in the three catchments with the major impacts.

The evaluation is done using the numerical modelling with the EPM approach. Results put in evidence that this approach is capable to represent groundwater flow in fractured aquifer not only at a regional scale, but also at the catchment scale.

According to modelling results, Firenzuola tunnel at steady state drains respectively 35 L/s, 83 L/s and 30 L/s to the baseflow of Veccione, Rovigo and Fosso Rampolli streams. If artificial water feeding is activated during the dryness season, the minimum flow rates needed are 30 L/s for Veccione Stream and 15 L/s for Fosso Rampolli. This flow rates were previously guaranteed by the upstream springs and particularly by the small springs aligned very closed to the streams riverbeds.

The presented models are a further validation of the hydrogeological conceptual model, because the congruence between the mass balance and the permeability distribution is verified.

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