Groundwater flow systems in turbidites of the Northern Apennines (Italy): natural discharge and high speed railway tunnel drainage

Alessandro Gargini · Valentina Vincenzi · Leonardo Piccinini · Gian Maria Zuppi · Paolo Canuti

Abstract Turbidites crop out extensively in the Northern Apennine mountains (Italy). The huge amounts of groundwater drained by tunnels, built for the high speed railway connection between Bologna and Florence, demonstrate the aquifer-like behaviour of these units, up to now considered as aquitards. A conceptual model of groundwater flow systems (GFS) in fractured aquifers of turbidites is proposed, taking into account both system natural state and the perturbation induced by tunnel drainage. Analysis of hydrological data (springs, streams and tunnel discharge), collected over 10 years, was integrated with analysis of hydrochemical and isotopic data and a stream-tunnel tracer test. Hydrologic recession analysis of undisturbed conditions is a key tool in studying turbiditic aquifer hydrogeology, permitting the discrimination of GFS, the estimation of recharge relative to the upstream reach portion and the identification of springs most vulnerable to tunnel drainage impacts. The groundwater budgeting analysis provides evidence that the natural aquifer discharge was stream-focused through GFS, developed downslope or connected to main extensional tectonic lineaments intersecting stream beds; now tunnels drain mainly active recharge groundwater and so cause a relevant stream baseflow deplenishment (approximately two-thirds of the natural value), possibly resulting in adverse effects on local ecosystems.

Keywords Conceptual models · Groundwater/surface-water relations · Turbidites · Northern Apennines · Italy

Received: 11 May 2007 / Accepted: 8 July 2008
Published online: 15 August 2008

Electronic supplementary material The online version of this article (doi:10.1007/s10040-008-0352-8) contains supplementary material, which is available to authorized users.

A preliminary version of the study was presented, as oral communication, at the Second International Workshop “Aquifer Vulnerability and Risk”, held in Colorno (Parma, Italy) on 21–23 September 2005, and organized by Italian CNR (National Research Council) -National Group for the Defense from Hydrogeologic Disasters (Representative: Prof. M.Civita)

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Introduction

Turbiditic deposits dominate the landscape in the Northern Apennines chain, Italy (Fig. 1) with distinct features: rounded peak reliefs with maximum elevations seldom higher than 1,000 metres above sea level (m a.s.l.), alternance of arenitic and pelitic (marls and siltstones) layers over tens of kilometres (Cerrina Feroni et al. 2002; Fig. 2), frequent occurrence of rockslides and debris deposits. These units (commonly called “flysch”) have been the subject of detailed studies concerning the sedimentologic tectonically driven evolution of submarine turbiditic fans (Zuffa 1980; Ricci Lucchi 1986; Bruni et al. 1994; Zattin et al. 2000; Argnani and Ricci Lucchi 2001; Cibin et al. 2004).

These deposits have deserved little attention from a hydrogeological standpoint, being considered as aquitards; the Central and Southern Apennines carbonatic and volcanic aquifers have been the main target for local

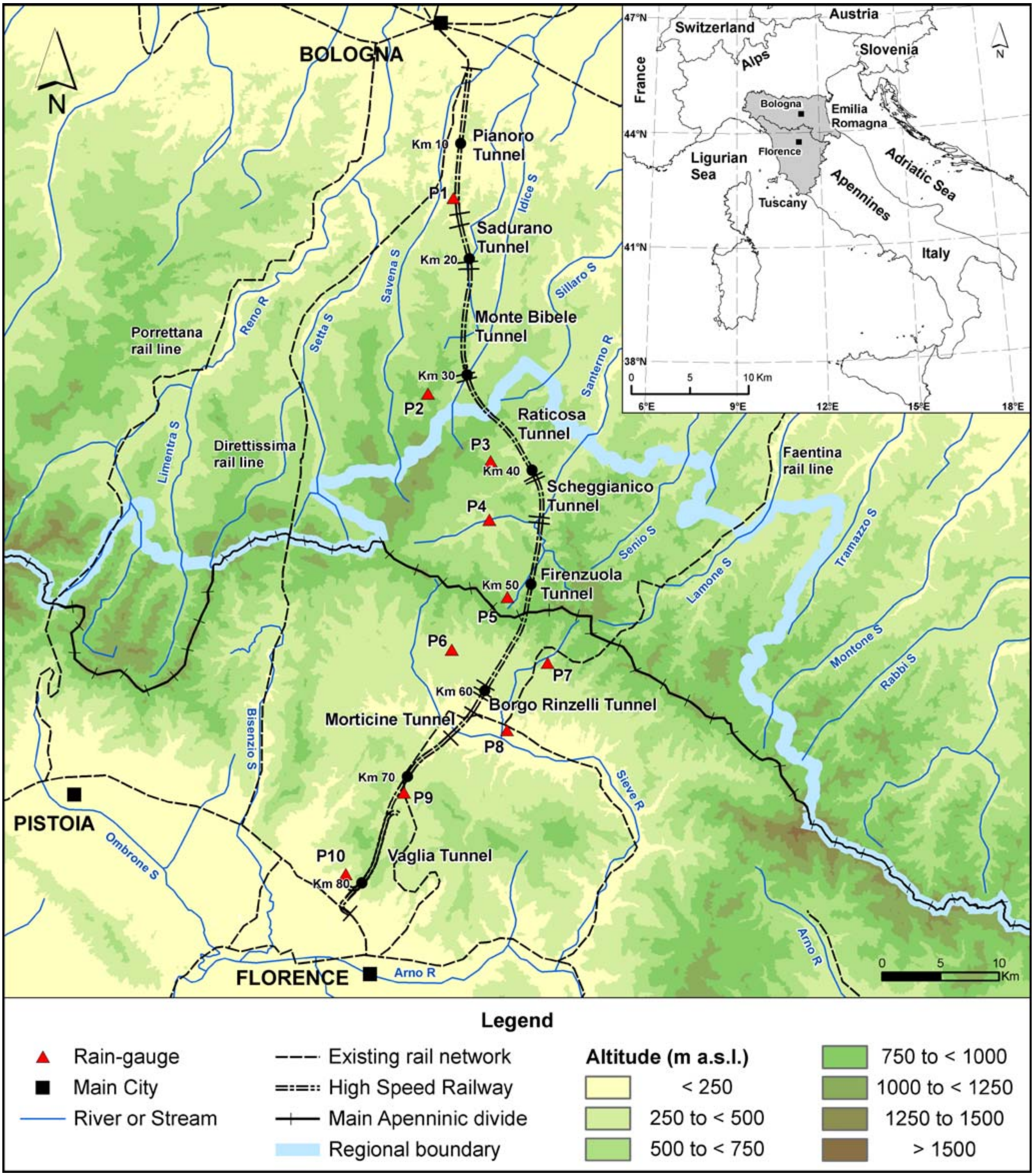

Fig. 1 Geographic setting of the central sector of Northern Apennines chain in the regions of Tuscany and Emilia-Romagna (*shaded grey in the index map*) together with the high-speed railway (*HSR*) line between Bologna and Florence and existing railway lines through the Northern Apennines

research on fractured aquifers (Boni et al. 1986; Angelini and Dragoni 1997; Scozzafava and Tallini 2001; Petitta and Tallini 2002). For this reason, a clear conceptual model of groundwater flow systems (GFS), following the work of Tóth (1963, 1999), inside these units is lacking; springs were considered simply an expression of shallow GFS related to the weathered rock cap or to landslide deposits (Pranzini 1994; Gargini 2000).

This point of view changed quickly during the tunnel boring for the high-speed railway (HSR) connection

 DOI 10.1007/s10040-008-0352-8

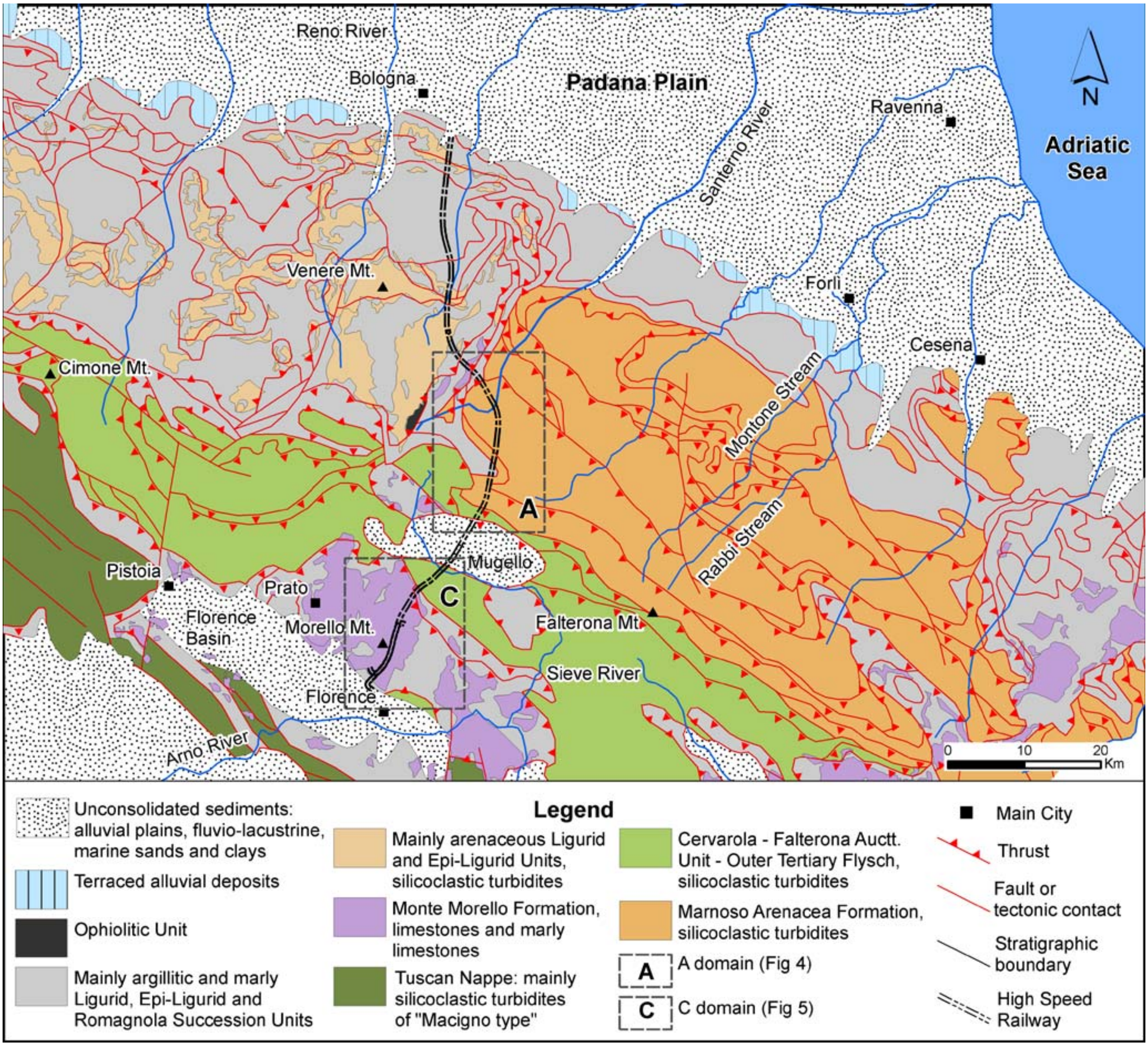

Fig. 2 Geological sketch map of the Northern Apennines between Bologna and Florence; redrawn and simplified from Cerrina Feroni et al. (2002)

between Bologna and Florence (Figs. 1 and 2). Between 1996 and 2005, nine main tunnels and 14 access tunnels or "windows" (W.) were drilled on a total underground length of 73 km, 92% of the entire track of about 79 km. The completed new track begins 4,384 m to the south of Bologna railway station, at the kilometric progressive (p.) 4+384 km along the line, and ends at about 4,000 m distance from Florence railway station at p. 83+356 km from Bologna (Lunardi 1998; Figs. 1 and 3). Locally, huge and steady amounts of drained groundwater (flowing out from the turbidites), together with severe seasonal effects on the hydrogeologic system (such as drying out of springs and permanent streams; Canuti et al. 2002), have provided evidence for an "aquifer-like" behaviour, renewing interest in the study of turbidites hydrogeology.

Since 1995, 1 year before the beginning of tunnels excavation, a monitoring programme has been performed by the project contractors (Agnelli et al. 1999), involving 678 water points (402 springs, 180 wells and 96 stream sections) located on an approximate 2-km-wide strip along the tunnel path and monitored at a variable time frequency (depending on the importance of the water point and on its distance from the drilling face); at the same time discharge from the tunnels has been recorded. A preliminary analysis of the huge amount of raw data (mostly water discharges and hydraulic heads) was limited to four watersheds and monitoring data from 1995 to 2003, and was particularly related to the geological interpretation of tunnel drainage and surface interferences (Gargini et al. 2006). This analysis provided evidence for the key role of post-orogenic extensional tectonics (at macro-scale) and the importance of the arenite/pelite ratio of turbidites (at mesoscale).

The report presented improves and refines the analysis, by including all the Tuscan sector of the line and the

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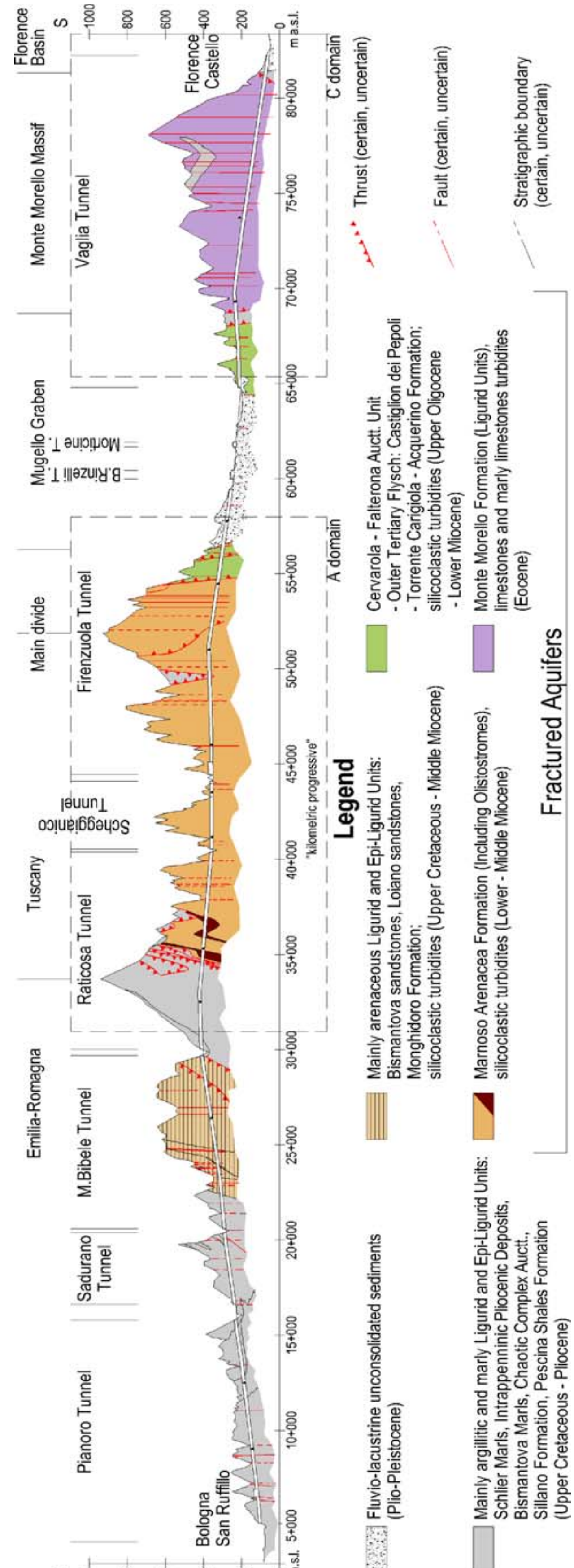

Fig. 3 Geological cross section along the tunnels of the Bologna-Florence HSR connection; trace in Fig. 2; redrawn and modified from Lunardi (1998)

whole set of monitoring data up to now available (1995–2006). Hydrochemical data analyses, environmental isotopes and a stream-tunnel tracer test contributed further, supporting the presented conceptual model; selected results are presented in this main report and supporting results are provided in the electronic supplementary material (ESM).

Hydrogeological setting of the railway line

The Northern Apennines chain is a typical thrust-folds belt of sedimentary rocks with a series of nappes thrusting over each other (Castellarin 2001). From the tectonically inner part of the chain (south west) to the outer part (north east), more allochtonous Ligurid units (Mesozoic-lower Tertiary) overthrusted the Oligo-Miocenic flysch cover of the Tuscan units (Tuscan Nappe unit-TN and Cervarola-Falterona unit-CFU) and this, in turn, overthrusted a more authoctonous and tectonically less disturbed unit represented by Umbro-Marchean-Romagnola succession (UMR). Whereas Ligurid units (Mesozoic-lower Tertiary) are a chaotic shaly melange, including slabs of lithoid bodies (calcareous and silicoclastic turbidites), the remainder units are made mainly, as outcropping lithology, by silicoclastic turbidites. After this compressive tectonic phase (which occurred in middle Miocene (Bendkik et al. 1994)), in the Messinian Stage, an extensional block-fault tectonic phase developed, involving the sector of the chain to the south west of the main divide (Boccaletti et al. 1997).

The HSR line cuts through the entire Apennines chain from Bologna (Emilia-Romagna region) to Florence (Tuscany region), crossing the main divide. From Bologna to the regional border, tunnels pass through aquicludes and aquitards, while in the remainder of the line to Florence, fractured aquifers of turbidites prevail. Two main domains of fractured aquifers have been defined (Figs. 2 and 3): silicoclastic turbidites domain (arenite or "A domain") and marly calcareous turbidites domain (calcareous or "C domain").

A domain (Fig. 4) is affected by main tunnels (t.) from p. 35+000 km to p. 56+300 km; it involves 5.4 km of Raticosa t., the whole 3.5 km long Scheggianico t. and 11.2 km of Firenzuola t., for a total underground length of about 20 km. From p. 35+000 to p. 52+000 km, the line runs inside the upper reaches of Santerno River watershed, flowing toward the Adriatic Sea, whereas from p. 52+000 km to p. 56+300 km, the line runs inside the upper reaches of Arno River watershed, flowing to the Ligurian Sea.

Fig. 4 Geological map of A domain (silicoclastic turbidites) with tunnels and monitoring/sampling water points (geology simplified from CARG project survey—Carta Geologica d'Italia, National Geological Map of Italy, 1:50,000 scale, sheet 253 "Marradi", not yet published; courtesy of Geological, Seismic and Soil Service of Emilia-Romagna Region)

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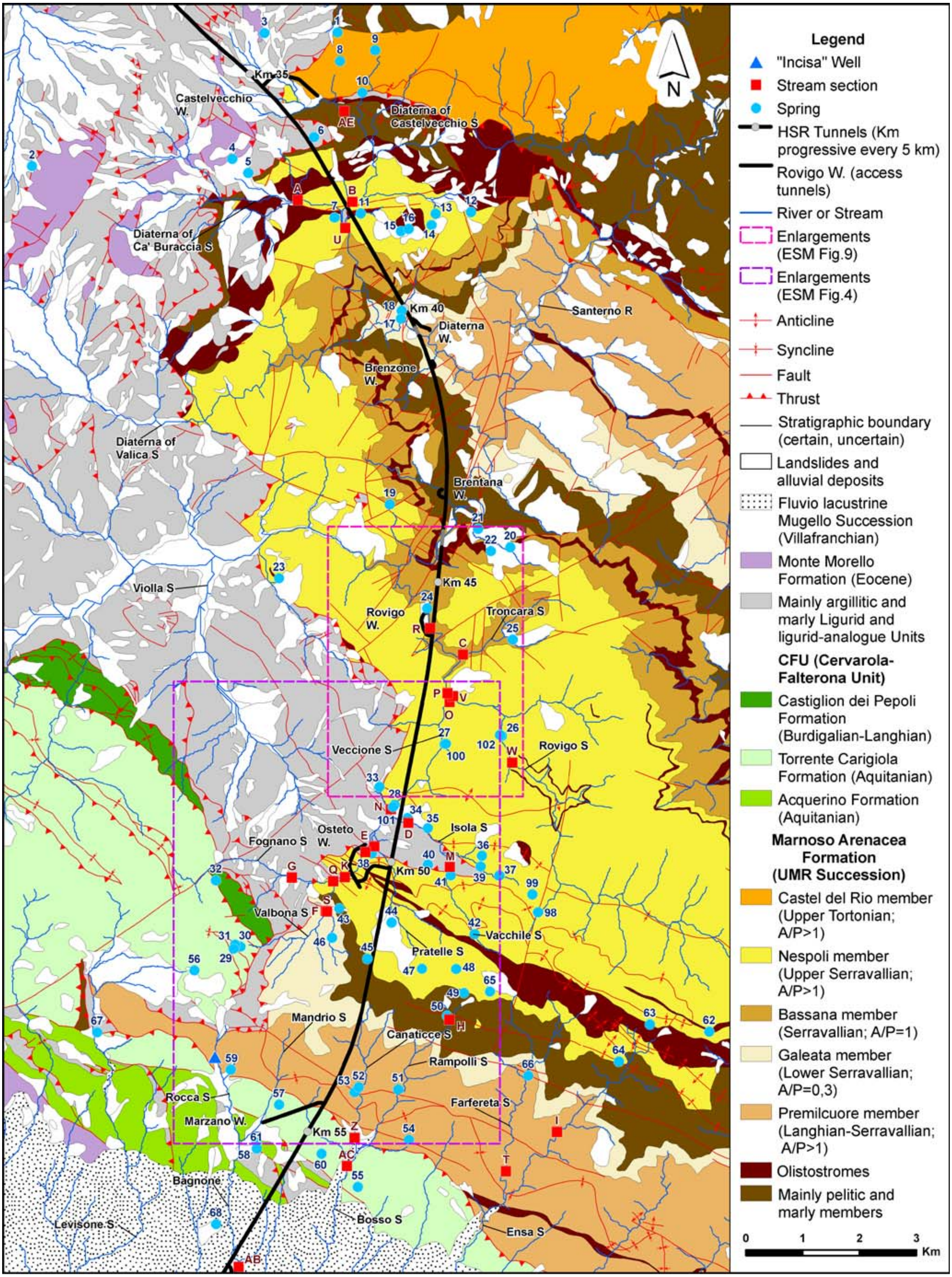

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The main aquifer lithology is represented by upper Oligocene to middle Miocene silicoclastic turbidites pertaining to the upper part of CFU and UMR succession; marly-calcareous turbidites outcrop as isolated slabs inside the shaly melange of Ligurid units at the north-western edge of A domain (see legend in Fig. 4). The dominant outcropping unit is Marnoso Arenacea Formation (FMA); A domain is located along the western edge of the widest FMA outcrop (Fig. 2) with a total area of 4,500 km^2 and 3 km estimated maximum thickness (Cerrina Feroni et al. 2001). FMA is a deep marine basin silicoclastic cone formed by a more or less regular alternance of silicoclastic arenaceous beds, originated by submarine sediment-laden density flows, and marly emipelagic beds (Cibin et al. 2004; Amy and Talling 2006). Different lithostratigraphic members have been identified according to the arenite/pelite thickness ratio (A/P) (Campbell 1967); the higher the A/P value, the more "aquifer-like" is the behaviour of the unit (Gargini et al. 2006).

C domain is affected only by Vaglia t., from about p. 66+000 km to the end for a total length of about 15 km. Monte Morello Formation (MMF) is the relevant aquifer unit (Fig. 5); it is an Eocenic turbidite included in Ligurid Units (Bortolotti et al. 2001), formed by an irregular alternance of marly limestones, limestones and shales. Locally the unit denotes karst and dissolution phenomena (Forti et al. 1990), even if shaly and marly layers fragment the continuity of the aquifers.

From a hydro-structural point of view, at the mega-scale, A domain, being located on the western termination of a double-plunging NW-SE oriented regional antiform (FMA tectonic window) and with axial culmination in the upper Rabbi and Montone streams watersheds (Fig. 2), is downgradient with respect to regional groundwater flow (Cerrina Feroni et al. 2002). The main regional tectonic lineaments affect the domain, either of compressive or extensional nature, like normal faults bordering Mugello graben at the southern edge (Figs. 2 and 3). C domain involves the eastern half of Morello Mt. massif (Fig. 2) affected by block-fault tectonics and less continuous regional lineaments (Coli and Fazzuoli 1983).

Materials and methods

Natural discharge, artificial discharge (induced by tunnel drainage) and the effects (impacts) of artificial discharge, either at water point scale or watershed scale, have been analysed in order to define a GFS rationale in turbidites. After a critical review of the huge amount of data produced by the monitoring programme, integrated by three hydrogeological surveys performed directly by the authors during summer 2000, 2002 and 2006, a total of 82 perennial springs and 11 stream sections have been identified as deserving analysis in natural discharge conditions. Most of the springs (61) are located in the A domain (Fig. 4; ESM Table 1); 16 springs (Fig. 5; ESM Table 2) occur in the C domain.

In order to compare turbidites with a different type of aquifer, five more springs were considered, even if far from the tunnel and not impacted (ESM Table 3): they flow out from the ophiolitic series of "Sasso di Castro unit" (Jurassic oceanic floor basalts and overlaying pure fine-grained Calpionella limestones; Calanchi et al. 1987), included as a big slab (about 0.4 million m^3) in the dominant clayey tectonic melange of Ligurid Units (about 10 km westward from the line, in the southern half of the outcropping area called "Ophiolitic series" in Fig. 2). One of these springs is the most important in this sector of Northern Apennines (ID 70 in ESM Table 3). By characterising these springs, a hydrogeologically representative transect crossing the chain has been defined.

Among all the discharge values measured at stream sections, only those recorded at least 5 and 10 days after rainfall events, respectively in summer and in the remainder of the hydrological year, have been selected and analysed (ESM Table 4; location in Figs. 4 and 5); in such a way overland flow or interflow "noise" have been taken out, leaving only baseflow (as defined in Hall 1968) as the runoff component related to the reach upstream of the monitoring section.

Discharge analysis has been integrated with available precipitation data along the HSR line, recorded by 10 representative rain gauges for the 1960–2005 time span (Table 1, location in Fig. 1); the localities of Borgo S. Lorenzo and Firenzuola have also a complete record of air temperature data for the same period.

Two separate data sets are available concerning tunnel drainage data: average tunnel drainage flow from the sector drilled every month and total drainage flow from all the tunnel sectors drilled from the beginning; in this way, either the integral or the monthly derivative of outflow were analysed.

Results

Analysis of recharge-discharge relationship in turbidites

The discharge regime in a fractured aquifer is affected, basically, by depth of the GFS, rock mass permeability distribution and direct recharge regime (Freeze and Cherry 1979; Halford and Mayer 2000); as a consequence of the dominant shallow nature of GFS in turbidites, the key role of the effective precipitation regime, i.e. of water availability at the surface for direct recharge, is enhanced. In such a system, groundwater discharge becomes practically a "mirror" of recharge, having very fast travel time from the input signal (rainfall) to the output (spring flow); only during the recession season, with no active recharge, does discharge output become totally representative of aquifer intrinsic properties.

Direct recharge regime

The climatic regime of the area is typical Mediterranean with slight mountainous-continental influence: rainfall

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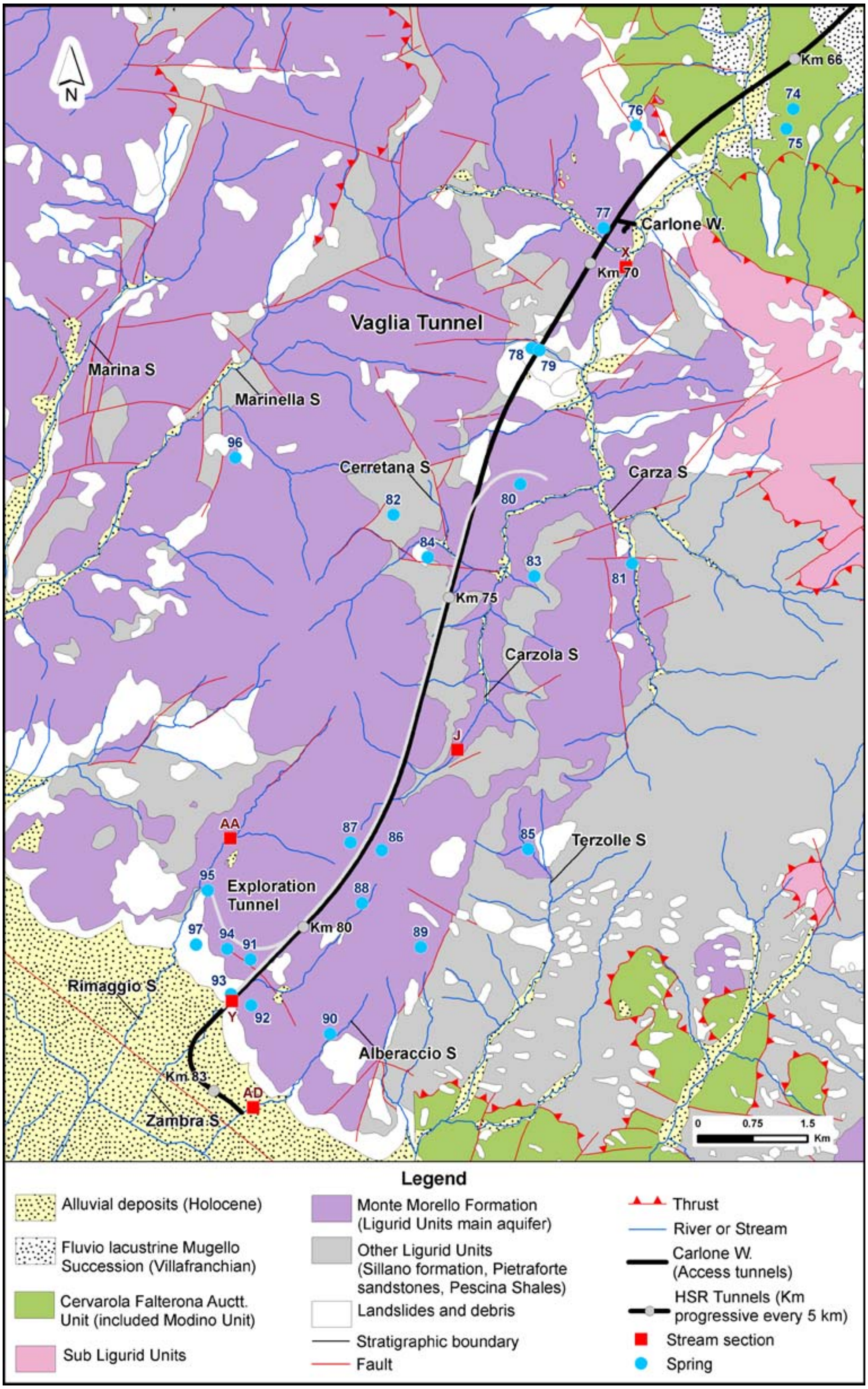

Fig. 5 Geological map of C domain (marly-calcareous turbidites) with tunnels and monitoring/sampling water points (geology redrawn from CARG project survey—Carta Geologica d'Italia, National Geological Map of Italy, 1:50.000 scale, sheet 263 "Prato", not yet published; 1:10,000 scale maps, available at Tuscany Region website (Tuscany Region 2004)

peaks in autumn (November), with a secondary peak in spring (April), and there is a dry-hot summer starting in June, with scattered thunderstorms in August–September (Fig. 6). Mean annual precipitation and air temperature (1960–1994), northward and southward of the main divide (climatic barrier protecting from northerly cold winds), are 1,245 and 1,046 mm respectively (average value of the representative rain gauges) and 11.3°C (422 m a.s.l.;

 DOI 10.1007/s10040-008-0352-8

Table 1 Rain gauges and mean precipitation data (annual, for November–April period); rain gauge locations in Fig. 2

ID	Rain gauge name	H (m a.s.l.)	P_0 1960–1994 (mm)	P_m 1995–2005 (mm)	P_m/P_0	N–D 1960–1994 (mm)	N–D 1995–2005 (mm)	J–F 1960–1994 (mm)	J–F 1995–2005 (mm)	M–A 1960–1994 (mm)	M–A 1995–2005 (mm)	P_{E0} 1960–1994 (mm)	P_{Em} 1995–2005 (mm)	P_{Em}/P_{E0}
P1	Pianoro	187	892	845	0.95	190	217	113	86	173	124	476	427	0.90
P2	Monghidoro	841	1,090	1,180	1.08	230	326	160	142	203	202	593	670	1.13
P3	Pietramala	845	1,410	1,372	0.97	346	378	235	176	269	232	850	786	0.92
P4	Firenzuola	422	1,263	1,236	0.98	296	357	225	184	228	212	749	753	1.01
P5	Barco	741	1,569	1,400	0.93	373	409	271	306	282	316	926	1,031	1.11
P6	Ronta	364	1,091	1,069	0.98	243	289	164	165	199	186	606	640	1.06
P7	S.Agata	341	1,069	966	0.90	246	269	197	146	172	159	615	574	0.93
P8	Borgo	193	996	962	0.97	232	253	162	149	176	168	570	570	1.00
P9	Vaglia	350	1,217	1,106	0.91	300	304	216	181	211	191	727	676	0.93
P10	Sesto F.	55	857	857	1.00	193	221	127	130	142	145	462	496	1.07

H elevation; *P* total precipitation; P_E effective precipitation; *N–D* November–December; *J–F* January–February; *M–A* March–April; subscripts: *0* before tunnel excavation; *m* tunnel excavation period

Firenzuola) and 13.4°C (199 m a.s.l.; Borgo S.Lorenzo). From the soil-water budget analysis, performed according Thornthwaite and Mather (1957), the coincidence between highest air temperature and water deficit conditions is evident (Fig. 6); effective precipitation is produced mainly during November–April period with October, notwithstanding summer thunderstorms, being the hydrological year starting month (6 October is the mean streams recession ending day in 1994–2004 period; Gargini et al. 2006).

Total and effective precipitation comparison between 1960–1994 and 1995–2005 periods (Table 1) provides evidence that, even if during the excavation (1995–2005) precipitation was a bit lower than in the preceding 35 years (97% and 95% on average north and south of the divide, respectively), effective precipitation has remained practically the same because the decrease in precipitation has not occurred in the active recharge period (November-April). By the way, effective precipitation southward of the divide, at similar elevation, is about one half than northward of the divide (611 mm surplus value for Firenzuola compared to 369 mm for Borgo S.Lorenzo in 1995–2005 period).

Discharge regime and parameterization

Some examples of spring and stream discharge regimes, in relation to the precipitation regime, are shown in Fig. 7 for both domains. Active groundwater circuits restart in October, attain peak discharge in spring, also with the contribution of snow melting, and go toward a typical hydrologic recession from late May-early June until the end of the hydrological year (HY). Uniformity and regularity of recession behaviour contrast with strong discharge variability during active recharge periods in relation to quick flow originated from rainfall events (Padilla et al. 1994).

Parameterization of this variability has produced the following data in relation to 82 analysed springs (ESM Tables 1–3, ESM Figs. 1 and 2): mean annual discharge (Q_A), mean baseflow season discharge (Q_S; from July 1st to HY end), Meinzer's class (Meinzer 1923) either for Q_A or Q_S values, Discharge Variability Index (DVI) and mean recession coefficient α. For 64 springs mean specific electrical conductivity value at 20°C (EC) was recorded. DVI has been determined according to Meinzer (1923):

$$DVI = (Q_{max} - Q_{\min})/Q_A$$

where $Q_{\max}$ and $Q_{\min}$ are, respectively, the highest and lowest discharge value ever recorded during monitoring activity.

For determination of α value, the exponential recession model of Maillet (1905) has been adopted, being proven as the most effective to fit monitoring data in many empirical studies (Tallaksen 1995). It is the first experimental confirmation of the analytical exponential recession model originally defined by Boussinesq (1904) and furtherly verified by other authors (Amit et al. 2002).

DOI 10.1007/s10040-008-0352-8

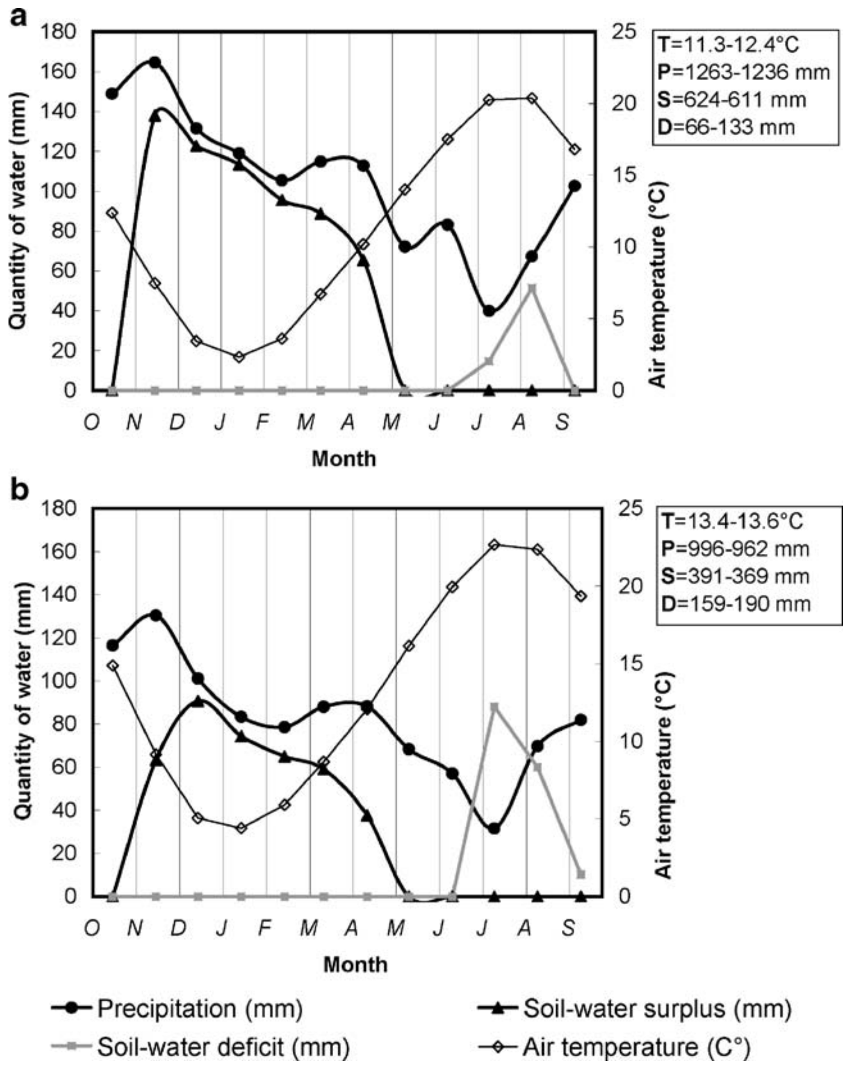

Fig. 6 Air temperature (*T*), soil-water average regime (after Thornthwaite and Mather 1957) and precipitation (*P*) for two rain gauges (1960–1994): **a** Firenzuola; **b** Borgo S.Lorenzo. Soil-water surplus from soil-water budget (*S*), soil-water deficit from soil-water budget (*D*). Time starts at the beginning of the hydrological year, *O* (October)–*O*). In the data boxes mean values comparison between periods 1960–1994 and 1995–2005

The linearized Dupuit-Boussinesq equation takes the form:

$$Q_{\mathrm{t}} = Q_o e^{(-\alpha t)}$$

where Q_{t} is the recession flow at time t, Q_0 is the flow at t=0 and α is the Maillet recession coefficient related to rate of discharge lowering during recession. α is also given by:

$$\alpha = -[(\ln 0.5)/t_{0.5}]$$

where $t_{0.5}$ is the time required to halve the discharge.

α value, expressed in (day^{-1}), was obtained by averaging values of each single available recession. The majority of springs showed a uniform recession (springs ID 59 and 78 in Fig. 8), with a dominance of the baseflow component with respect to quickflow. Exceptions were noted for some springs flowing from the MMF (like ID 76 in Fig. 8), which showed a typical dual fracture porosity discharge behaviour (Moore 1992; Tallaksen 1995); in this case the lower α value (lower aperture and more pervasive fracture network) has always been considered as the more representative of groundwater discharged during the recession (Amit et al. 2002).

Even if the monitoring performed is actually a discontinuous recording of hydrological data (measurements taken in accordance with a predetermined timetable completely independent of climatic conditions), the resulting parameters have good statistical meaning despite there being no chance of analysing spring flow behaviour on a daily basis (Floreal and Vacher 2006); this is because there is a huge time span of data acquisition (11 monitoring years in some cases, from 1995 to 2006) and a generally high number of discharge measurements (shots) per year (s/y number). However, to take into account temporal dishomogeneity of data collecting, mean Q_{A} and EC values do not simply come from the aritmetic averaging of all available data, but rather from a preliminary disaggregation

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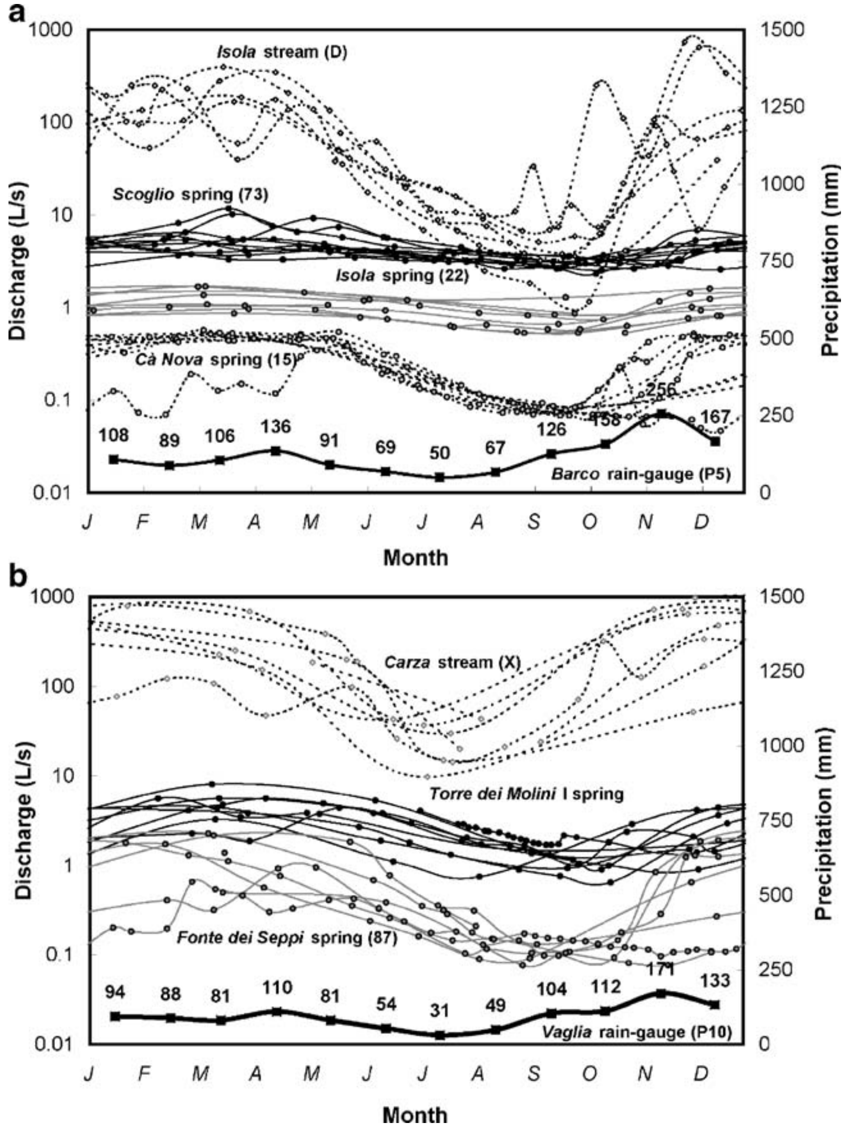

Fig. 7 Examples of pluriannual discharge regimes (one measure *each dot*) in natural conditions and mean monthly precipitation (*black squares*) for 1995–2005 period; name and ID for each water point. **a** A domain; **b** C domain

according to four "hydrological" seasons: "fall" (from HY start to the end of December); "winter" (January–March); "spring" (April–June); "summer" (from July to HY ending). Mean annual values originate from the averaging of four mean seasonal values.

Springs have generally low discharge: most represented spring Meinzer's class, either for Q_A and Q_S, is relative to the discharge range between 0.1 and 1 L/s. Factors like A/P (Premilcuore and Nespoli members of the FMA) and the MMF aptitude to dissolution increase the outflow, whereas even a little outcrop of a highly fractured aquifer that is prone to dissolution (basalts and limestones of the ophiolitic Sasso di Castro unit) is enough to "produce" a consistently higher discharge. Practically all springs have been considered "variable" with DVI > 1 and oligomineral (EC value between 400 and 600 μS/cm). Higher EC values in springs are found at specific sites: these are associated with mixing with deeper GFS, or with low pH value and high bicarbonate concentration if shallow circulation is affected by soil biological activity. α distribution is log-normal with dominant values around 1×10^{-2} day^{-1}.

For a single watershed, stream average baseflow at a monitoring section is always much higher than the total of the discharge contributions coming out from all the springs in the same watershed (compare Q_A values between ESM Table 4 and ESM Tables 1–3); also taking into account a few springs missed from the monitoring activity, this is explainable with the dominance of groundwater discharge process directly to streams through stream bed fractures (Oxtobee and Novakowski 2001).

Springs and groundwater flow systems

Conventional approaches to hydrogeological classification of springs (Alfaro and Wallace 1994) are not particularly

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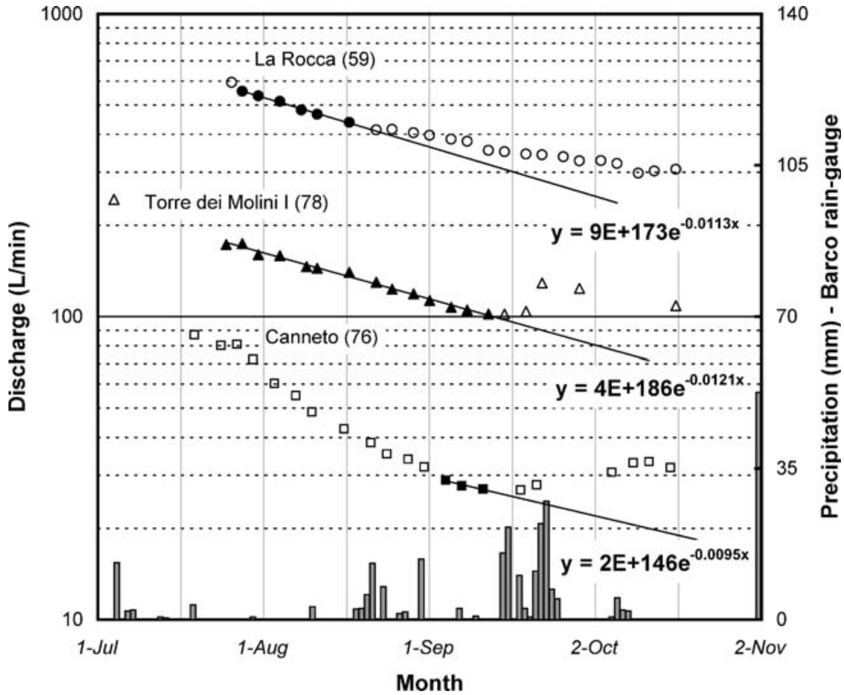

Fig. 8 Analysis of hydrologic recession for three springs (1995 year), with exponential model fitting to *black symbols*, and total daily precipitation (*bars*). Springs *59* and *78* are in A domain; spring *76* is in C domain

appropriate for turbiditic GFS; a ranking based on Q_A value, like Meinzer's class, is deeply affected by peak values (in the Apennines often related to rainfall and permeability distribution in the shallow portion of the rock mass), whereas a ranking based on hydrogeological structure, according to predetermined conceptual models (Civita 1973), is much more effective in karst.

Outlining the importance of recession behaviour, a graphic methodology to differentiate spring type based on Q_A and α values is here proposed. It is recognized that, independent of what happens from HY start to the beginning of summer recession, depth and regional importance of a GFS discharging into a spring is directly related either to spring magnitude during low flow season or to the reciprocal of the rate at which discharge itself decreases during recession (Swanson and Bahr 2004); for this reason a new empirical index is introduced to take into account, in an integrated way, mean spring flow and its recession rate during low flow season. The index is called "base-yield" (B_y) and is given by:

$$B_y = -[\log_{10}(\alpha) \times Q_S]$$

with Q_S in L/min and α in 1/day; the "minus" sign makes the B_y value positive. A high spring flow in summer and a low rate of spring flow deplenishment during summer drought suggest that the spring yield is reflecting a more developed GFS cell discharge. So, integrating the Meinzer ranking approach with hydraulic recession behaviour, a new spring ranking parameter allows one to differentiate GFS.

B_y value for all springs was thus evaluated (ESM, Tables 1–3). Springs differentiation must also take into account elevation of the discharge point above local base level; according to a topographic-driven conceptual model of groundwater flow (Tòth 1999), low elevation discharge outlets correspond to more developed GFS. For this reason, also the ΔH parameter (differential elevation between spring and the outlet of the watershed where the spring is located; ESM, Tables 1–3) has been taken into account in the proposed methodology, as spring elevation above local hydrologic base level.

In Fig. 9 two semi-log "springs-graphs" are plotted, as bubble diagrams, in terms of the above-mentioned parameters: ΔH (*y*-axis) versus B_y (*x*-axis). Bubble size is proportional to DVI in Fig. 9a and to EC in Fig. 9b.

Springs distribution in the graphs is rather structured with a general increase of B_y value with decreasing ΔH, as expected, but with a remarkable "anomaly" that contributes to a clear distinction of different hydrogeological settings for major springs. Defining the spring clusters with a specific position in the graph as "spring types"—two main assemblages, called "S type" and "T type" springs—can be recognized: S type forms the "structured group" of springs on the left hand side of the graph with the expected inverse correlation between ΔH and B_y and with bubbles converging downward and rightward toward a "pole" of springs with B_y value > 100; T type occurs on the right half of the graphs with B_y>100 and is clearly differentiated from the others. Among these two main spring types, a total of five subtypes have been recognized, reflecting GFS typology and spring occurrence in the watershed (see the following).

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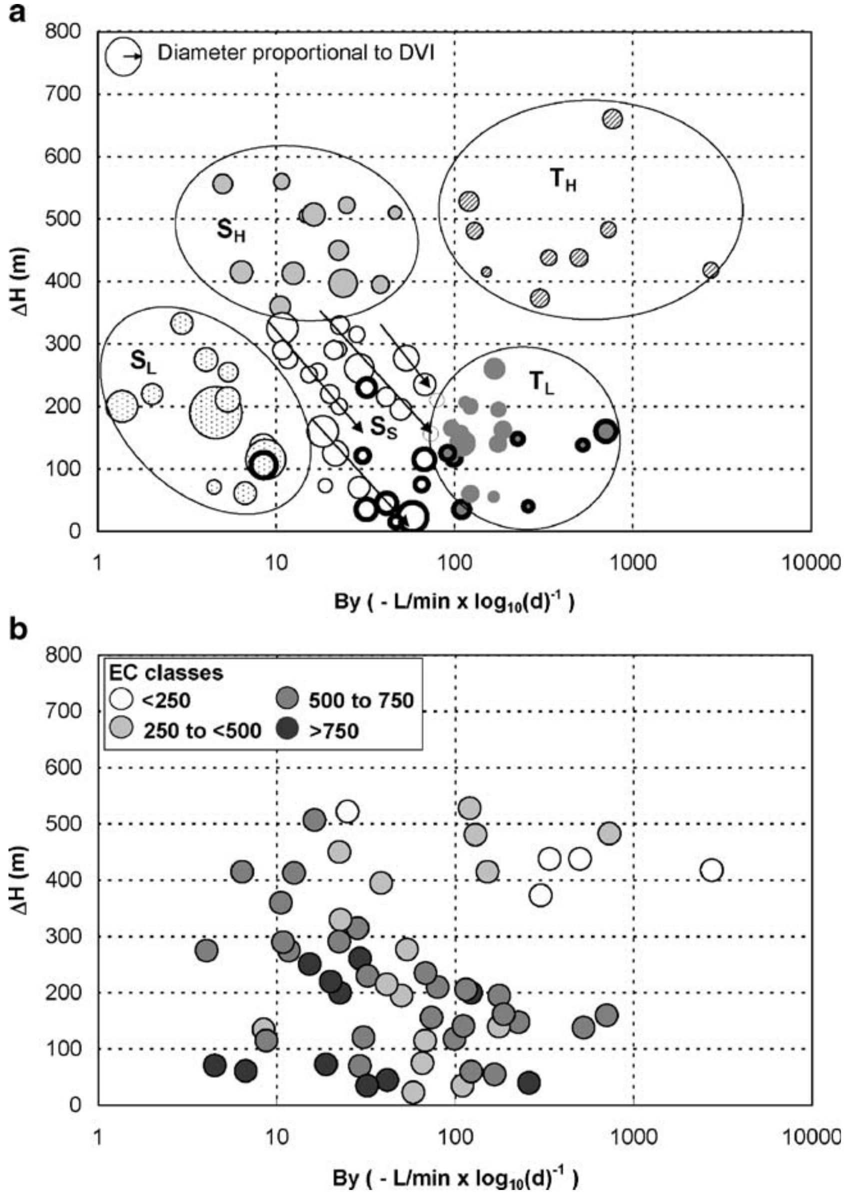

Fig. 9 Bubble diagrams showing spring ΔH versus B_y. **a** Bubble diameter is proportional to DVI value (82 springs); **b** bubble shade is related to mean EC (μS/cm) value (64 springs). Springs are enveloped and evidenced in graph (**a**), with different shaded patterns, according the spring type; *black-circled bubbles* refer to tunnel impacted springs. See text for explanation of *S type* and *T type* springs

Intra-watershed or "slope" flow systems (S type)

S type springs are the majority in turbidites and form the "structured group" in the left half of the graph; baseflow rate is < 1 L/s and, at ΔH decreasing, EC tends to increase and DVI tends to decrease. The springs have been further differentiated into three sub-types: local high altitude (S_H sub-type), local low altitude (S_L sub-type) and whole "slope" (S_S sub-type).

The S_H sub-type ones are to be considered peculiar anomalies of the S_S sub-type springs: at high relative elevation (ΔH>350 m) S_H springs denote higher B_y, lower DVI (mean 2.8) and EC values (mean 470 μS/cm), as a consequence of more abundant and evenly distributed effective precipitation (included hidden precipitation) and of lower CO_2 production by soil organic activity. In contrast, S_L springs denote higher DVI (with an average value of 6) and EC value (with an average value of 630 μS/cm).

Trans-watershed or "tectonically"-driven flow systems (T type)

Low DVI (mean 1.3) and α values (mean 7×10^{-3} day^{-1}) are an expression of large aquifer volume and regulatory capacity. These fewer springs are generally exploited for public water supply. Two main sub-types can be differentiated on the basis of ΔH value: high altitude (T_H sub-type) and low altitude (T_L sub-type). T_H sub-type EC value is very low as a result of high elevations (mean between 437 μS/cm for turbiditic units and 222 μS/cm for ophiolitic unit), whereas in T_L sub-type springs EC value is relatively higher as a result of a deeper flow circuit (mean 600 μS/cm).

Recession analysis

Hydrologic recession is thus the key factor to rank discharge in such a setting (Amit et al. 2002). α value reflects aquifer hydraulic diffusivity, ratio between hydraulic transmissivity and storativity of the medium (Rorabaugh 1964; Schoeller 1967; Hall 1968; Tallaksen 1995; Domenico and Schwartz 1997). Concerning those springs considered in the analysis, mainly connected to medium/low permeability turbiditic aquifers, it is mainly storativity that affects the α value with low α values implying high storativity and vice versa. T type springs denote low α value (high storage), whereas S type springs denote high α value (low storage, reflected also by low Q_S and high DVI values).

The role of α in mediating discharge response is also established by the experimental relationship, on a log-log scale, between Q_S and Q_A for the 82 springs and 11 stream sections (Fig. 10a). Direct correlation is clearly controlled by α value: at the lowering of α value, Q_A and Q_S tend to be equal, because there is a gentler lowering of discharge from the beginning of the recession to the

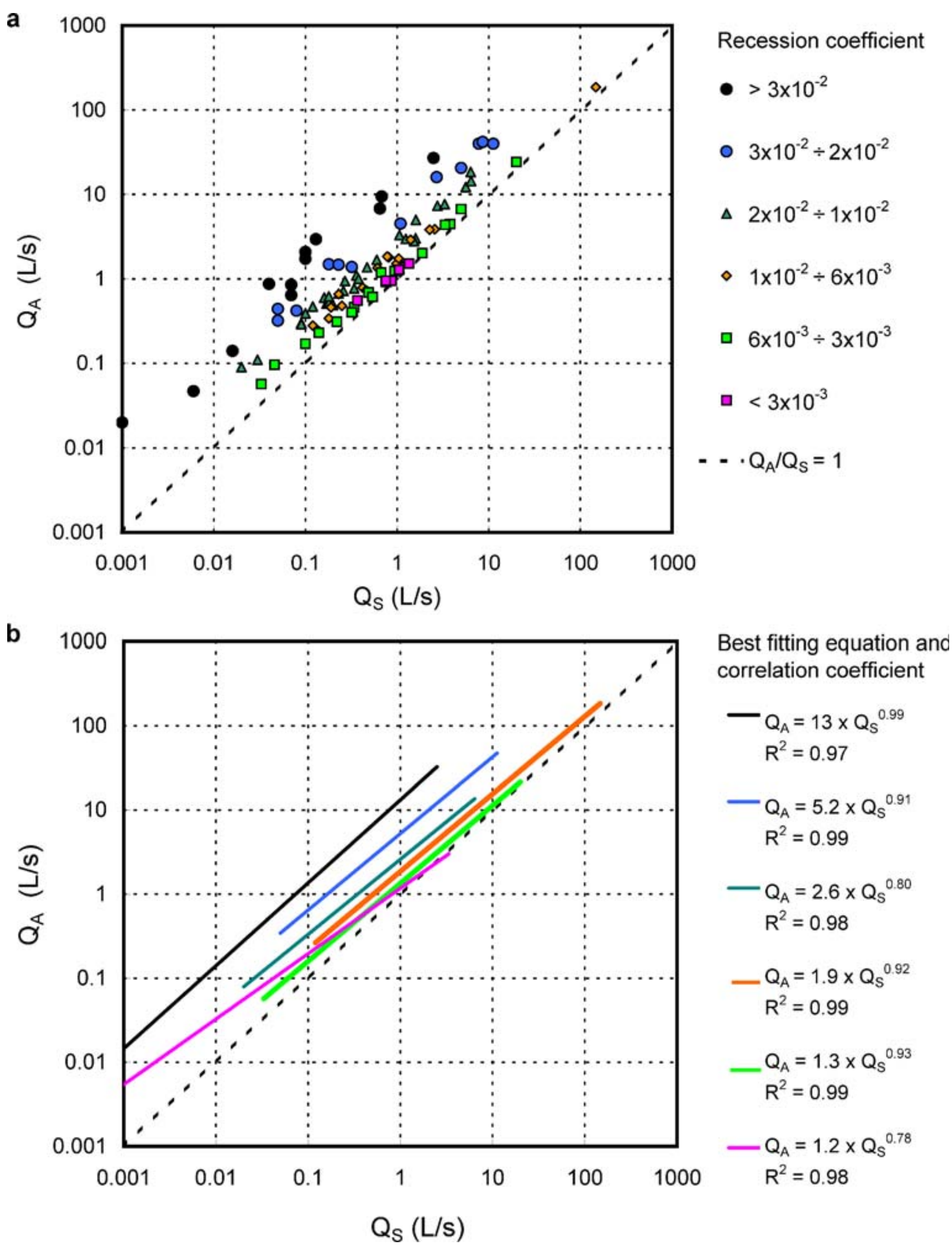

Fig. 10 Recession coefficient (α) driven power-law correlations between Q_S and Q_A on log-log scale. **a** Scatter plot with α value classes; **b** power-law best fitting for each α class in the same order as in **a** (best fitting equations and correlation coefficients R^2 are shown)

 DOI 10.1007/s10040-008-0352-8

summer minimum. Streams baseflow follows the same correlation as expression of the whole groundwater discharge upstream (Appleby 1970).

Considering the high values of R^2 in power-law correlations of Fig. 10b, the possibility of estimating Q_A value on the basis of Q_S and α is proved; so, these power-law correlations represent useful analytical tools to obtain Q_A (which needs a huge amount of data throughout the whole year for its estimation) from only two summer parameters that can be obtained more easily: Q_S and α. Q_A, in the case of streams, is the average baseflow discharge, to be considered equal, in first approximation, to the groundwater recharge upstream to the measuring section (Korkmaz 1990; Foster 1998; Scanlon et al. 2002). As a consequence, a useful tool to estimate recharge in Apenninic aquifers in turbidites has been defined on the basis of recession parameters.

Recession analysis must be fully representative of natural discharge conditions, not affected either by hot air temperature and high evapotranspiration (affecting streams or shallow groundwater circulation; Daniel 1976) or by man-made water abstraction from streams and aquifers; in these cases an anomalous steepening of the recession curve slope is recorded and α value has no physical sense in reflecting natural discharge.

Analysis of tunnel discharge and its effects

It is well known that tunnel drainage can significantly affect natural discharge and can represent a high risk factor for the integrity of the surface hydrologic system, particularly when huge groundwater inflows occur at the intersection of the tunnel with main faults and fractures; these phenomena are often unpredictable on the basis of surface geological evidence (Mabee et al. 2002). The way inrushes of groundwater in the Bologna-Florence tunnels affected groundwater, as recorded by the monitoring activity, has contributed further to better understanding of GFS in the turbidites.

Bologna-Florence tunnels are draining tunnels, designed to abate hydraulic loading; so, even after the definitive lining with concrete, they continue to drain groundwater through a drainage system. The system collects groundwater by a PVC water-proofing foil, which envelopes the concrete on the outside, and a series of 25-m-long fully-screened tubes, conveying water to two main pipes at the base of each tunnel side-wall and running toward the outlets, according to tunnel gradient (3‰ on average). To provide evidence for the hydrogeological interpretation of the tunnel discharge regime, in comparison with the natural discharge analysis, first, the effects of inrushes on springs have been analysed and, second, tunnel drainage effects on the hydrogeologic system and its capacity to keep baseflow discharge, have been evaluated.

Groundwater effects of tunnel inrushes

Since the beginning of the tunnel excavation, 31 springs have been certainly impacted by the drainage; 18 of these springs are located in A domain (Table 2; location in Fig. 4), 13 springs in C domain (Table 3; location in Fig. 5). The impact means either complete flow-rate extinction (22 springs) or summer drying (9 springs) with a maintenance of natural discharge values during fall, winter and spring periods. In some cases (less than 10 springs, not reported in this report), a quite evident decreasing of discharge values has occurred, particularly during the recession season. For 14 of the 31 impacted springs, a meaningful monitoring in natural conditions was not performed, so they were not considered for the natural discharge analysis; the 17 springs analysed are marked in the springs graph of Fig. 9a.

The impact source is a tunnel inrush, the impact receptor is a certain spring; main features of the space/time relationship between inrush and spring have been derived from monitoring data, taking also into account the position of main tectonic lineaments derived from detailed maps, and reported in Tables 2 and 3. Approximately two-thirds of the impacted springs are located less than 700 m from the tunnel (Fig. 11a), 153 m being the mean value; along the normal faults bordering Mugello graben (with linear persistence of many km) an interference up to 2800 m distance from tunnel was reported (ID 23 spring; A domain). About 75% of impacted springs are located less than 200 m above the tunnel pavement; maximum attained spring elevation is 527 m above the tunnel pavement but only three springs are above 240 m (Fig. 11a). Half of the springs respond very quickly to the interference (Fig. 11b) notwithstanding the distance (delay time less than 1 month, time determination threshold being based on tunnel drainage monitoring performed each month); propagation speed of the hydraulic interference is estimated as varying between about 1000 m/month and 200 m/month (respectively solid and dashed correlation line in Fig. 11b). The highest interference propagation speed (highest hydraulic diffusivity) is related to T_L sub-type springs (ID 51 and 59, highest B_y value of all impacted springs) connected to the normal faults bordering Mugello graben. It is interesting to note that the hydraulic diffusivity value, derived from hydraulic conductivity (K) and storativity (S) values—obtained by a long duration pumping test performed with the tunnel acting as an analogue pumping well (see ESM, chapter 2)—is 926 m/month, very similar to the interference propagation rates graphically obtained in Fig. 11b.

Tunnel drainage and hydrogeological budget

Tunnel drainage started to be recorded on a monthly basis in 1998, even though excavation began in 1996; in March 2007, with all tunnels completed, drainage was huge if compared to the natural discharge rate (note, autumn 2006 was characterized by exceptionally low precipitation). Eighteen months after the completion of all tunnels in 2005 (but 3–4 years after the last major inrushes; Tables 2 and 3) drainage has attained pseudo-steady state conditions, characterized by an evident correlation with the precipitation regime (a peak in spring and a minimum at

 DOI 10.1007/s10040-008-0352-8

Table 2 Impacted springs in A domain

ID	Spring name	Dominant unit	Spring type	Impact type	Impact (month)[a]	Tunnel	Q_A^b (L/s)	Inrush (km)[c]	Inrush (month)[d]	Distance (m)[e]	ΔH (m)[f]	Delay time (months)[g]
8	Castelvecchio	Castel d.Rio	S_S	s	7/98	RA	1.4	35+950	5/98	1,300	240	2
10	Molino	Castel d.Rio	ND	s	ND	RA	0.03	36+400	2/99	1,600	140	ND
11	Biguglio	Nespoli	S_L	s	5/03	RA	1.7	38+185	5/03	170	90	0
23	Selva	Nespoli	ND	s	ND	FIR. N	0.2	45+000	5/99	2,800	120	ND
24	Cà di Sotto	Nespoli	ND	p	11/96	ROV W.	1.5	45+450	ND	200	65	ND
27	Veccione III	Nespoli	T_L	p	3/00	FIR. N	1.8	47+780	3/00	520	120	ND
28	Veccione I	Nespoli	S_S	p	3/01	FIR. N	0.7	48+880	3/01	60	160	0
34	Moscheta I	Nespoli	S_S	p	11/01	FIR. N	0.6	49+165	11/01	130	200	0
45	Fossa di Pietrone	Nespoli	ND	p	ND	OST W.	0.3	51+752	6/99	1,300	465	ND
51	Frassineta	Premilcuore	T_L	p	2/01	FIR. S	1.5	53+765	1/01	1,050	190	1
52	Casa d'erci II	Premilcuore	T_L	p	3/00	FIR. S	4.5	53+950	3/00	400	180	0
53	Casa d'erci I	Premilcuore	T_L	p	3/00	FIR. S	1.7	54+000	3/00	350	175	0
54	Alicelle	Premilcuore	ND	p	ND	FIR. S	0.8	54+205	1/00	1,600	220	ND
59	La Rocca	Premilcuore	T_L	p	5/00	FIR. S	12.3	54+670	3/00	2,100	222	2
60	Belvedere	T. Carigiola	ND	p	5/01	FIR. S	0.07	55+200	4/01	400	215	1
57	Marzano	T. Carigiola	S_S	s	ND	MAR W.	0.3	55+800	4/99	250	198	ND
61	Giuncaia II	Acquerino	ND	p	7/01	FIR. S	0.6	55+900	4/01	650	144	3
68	Guazzini	Fluvio-Lac.	T_L	s	ND	FIR. S	1.2	57+300	1/00	600	30	ND

Aquifer units according to the legend of Fig. 4 (all are FMA members except those in last four rows). *s* summer drying; *p* perennial drying; *RA* Raticosa; *FIR* Firenzuola North/South; *ROV* Rovigo window; *OST* Osteto window; *MAR* Marzano window; *ND* not determined

[a] Impact occurrence month and year at the spring

[b] Not perturbed spring mean annual discharge

[c] Inrush progressive (p.)

[d] Inrush occurrence month and year

[e] Linear distance between spring and inrush location

[f] Spring elevation above tunnel at the inrush location

[g] Delay time between d and a

the end of the recession season) and a subtle progressive decreasing of lower flow rates, evident in Scheggianico and Raticosa tunnels (Fig. 12).

A comparison between tunnel and natural discharge has been conducted relative to the 2005–2006 hydrological year, with all tunnels completed (Table 4). The power-law correlation of Fig. 10b was applied to estimate Q_A of the tunnel, equal to average active recharge (R) to the area subjected to hydraulic influence by the tunnel. The correlation was based on Q_S of the tunnel (summer 2006 average tunnel drainage discharge) and α value, calculated for 2006 tunnel summer recession (very long, until end of November). Tunnel "active recharge/total groundwater reserve" ratio (R/G) is between 0.89 and 0.63 with an average value of 0.84 (weighted according the outflow from each tunnel system).

The ratio between the R value (L/s) for the tunnel system in 2005–2006 HY and the 'natural average baseflow discharge' D (L/s) in affected watersheds (i.e. ratio R/D), quantifies the volumetric groundwater fractions subtracted from tunnel to natural discharge to springs and streams (Table 4). The D value was estimated relative to different time periods for each watershed so R/D values in Table 4 are simply a raw estimate of the tunnels impact on

Table 3 Impacted springs in C domain

ID	Spring name	Unit	Spring type	Impact type[a]	Impact month[b]	Tunnel	Q_A^b (L/s)	Inrush km[c]	Inrush month[d]	Distance (m)[e]	ΔH (m)[f]	Delay time (months)[g]
74	Case Frilli	Carigiola	ND	T	ND	Vaglia N	ND	66,400	8/00	600	50	ND
75	Mozzete	Carigiola	ND	T	10/00	Vaglia N	0.15	66,700	10/00	700	60	0
77	Carlone	MMF	T_L	T	ND	CARL	1.7	69,464	ND	150	50	ND
80	Case Carzola	MMF	ND	S	7/00	Vaglia S	1.0	73,250	5/00	530	145	2
81	Cementizia	MMF	ND	S	ND	Vaglia S	0.2	73,879	5/01	2,282	160	ND
82	Sitriano	MMF	ND	T	5/01	Vaglia S	ND	74,098	5/01	1,050	314	0
86	Le Torricelle	MMF	ND	T	ND	Vaglia S	ND	78,551	7/01	211	527	ND
90	Casale	MMF	ND	T	4/01	Vaglia S	1.0	80,517	3/01	1272	117	1
91	Fontemezzina	MMF	S_S	T	2/01	EXPL	1.1	80,817	1/01	140	17	1
94	Ginori	MMF	S_S	T	12/00	EXPL	0.5	80,929	12/00	130	60	0
97	Colonnata	MMF	ND	T	5/01	EXPL.	0.3	81,186	3/01	400	38	2
92	Moreni	MMF	S_S	S	5/03	Vaglia S	9.5	81,300	5/03	220	38	0
93	Pozzaccio	MMF	S_S	T	2/03	Vaglia S	0.5	81,350	2/03	70	18	0

MMF Monte Morello Formation; *N* north; *S* south; *EXPL* exploration tunnel; *CARL* Carlone window. Other superscripts/footnotes same as Table 2 legend

DOI 10.1007/s10040-008-0352-8

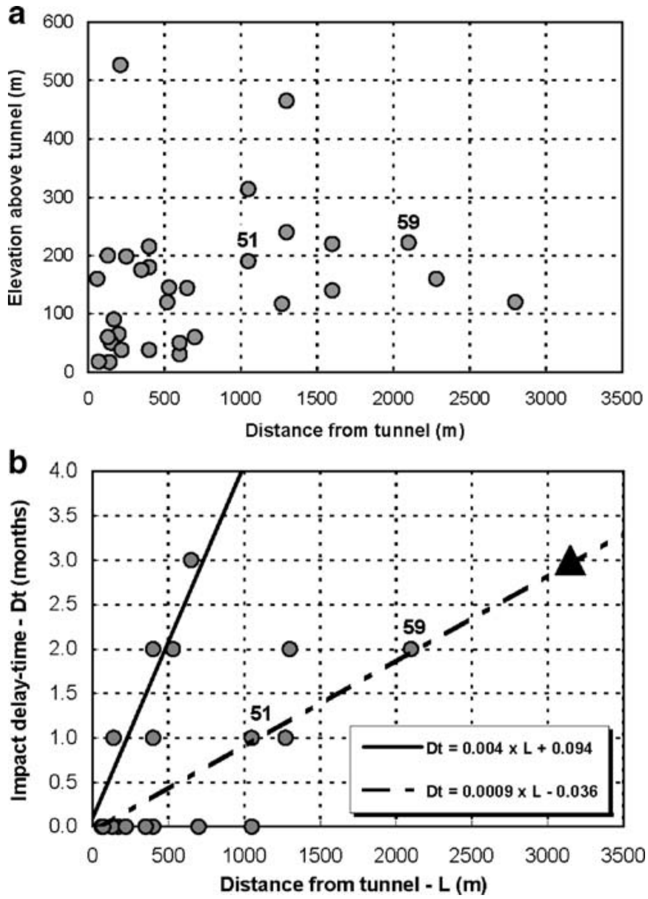

Fig. 11 Relationship between impacted spring distance from the tunnel and: **a** elevation of the spring above the inrush location in the tunnel (31 springs); **b** impact delay time (18 springs). *Black triangle* in **b** is related to Farfereta stream; 51 and 59 are ID for, respectively, Frassineta and La Rocca springs; for correlation lines see text

the hydrogeologic budget. *R*/*D* values vary between 0.33 (Raticosa system) and 0.66 (Firenzuola and Vaglia system); on average about 50% of total recharge is no longer discharged in a natural way but now discharges through the tunnels.

A major effect on streams is complete disappearance of baseflow during the summer: if tunnels divert groundwater and lower the piezometric level, streams are no longer able to maintain minimum summer flow rates. All streams of watersheds presented in Table 4 have been impacted in such a way (even if *R*/*D* value is less than 0.5); so the impact on springs occurs only for certain spring types and the vanishing of base flow in streams in the summer is widespread.

Supplementary investigation tools: hydrochemistry, isotopes and artificial tracers

Hydrochemical analyses of water samples collected inside the tunnels during drilling advancement confirmed independently the mixing proportions of active recharge and reserve groundwater in tunnel waters, indicating that two-thirds of drainage belongs to alkali-earth bicarbonate facies, whereas one-third represents the deep alkaline groundwaters of the rock mass (piper diagram of Fig. 13). Details about hydrochemical data analyses and interpretation, together with environmental isotopes analyses, are presented (see ESM chapter 3).

A stream-tunnel tracer test, performed in November 2002 by injecting uranine in Veccione stream and recovering it inside Firenzuola tunnel, has further proven the hydraulic connection between streams and tunnels; methodology, results and interpretation of the tracer test are presented in ESM chapter 4. This qualitative tracer test was the first one ever performed in turbiditic aquifers. A specific investigation that applied this methodology took place 4 years later: quantitative multi-tracer tests were performed in Veccione and Rampolli streams, to improve the knowledge of the whole system and characterize the hydrogeological connections between streams and tunnel (Vincenzi et al. 2008).

Conceptual model of groundwater flow systems in turbidites

Taking into account the results of monitoring, hydrochemical and isotopic surveys and the tracer test, a schematization of the GFS pattern in turbidites is proposed along two directions: transversal (Fig. 14a) and parallel (Fig. 14b) to the Apenninic chain, either in natural conditions (before tunnel excavation) or after tunnel drainage. GFS in turbidites may be considered "topographically controlled" and so may reflect nested patterns (regional, intermediate and local flow cells) with both horizontal and vertical components of flow (Haitjema and Mitchell-Bruker 2005). The development of active local and intermediate flow cells is enhanced by the quite strong permeability contrast of soil and shallow weathered and detensioned rock mass respect to underlying fractured aquifer. Thus, three separate hierarchically grouped GFS types may be defined (Fig. 9a).

Slope-controlled (S type) systems develop along slopes and are generally shallow in nature. The GFS cell is recharged in an uphill location and discharges downhill where a permeability contrast occurs; the greater the distance between the recharge and discharge areas, the deeper is the GFS depth. Most of the springs in turbidites are S type.

S_H and S_L sub-type systems are connected to very local GFS with aquifers originated by gravity driven processes (landslides, debris deposits) or connected to weathered and fractured regolith: generally they flow out at the contact between aquifer and bedrock. They can be considered expression of interflow (Fetter 1994) or landslide/colluvium groundwater flow. Flow cell maximum attained thickness is less than 10–20 m.

S_S sub-type systems can be considered expression of deep interflow or down-slope flow, a topographically driven GFS occurring inside a tectonically or gravity driven detensioned slope. At the maximum, this flow can develop down to 100–150 m depth as a consequence of tectonically driven or gravity driven (layer's dipping-

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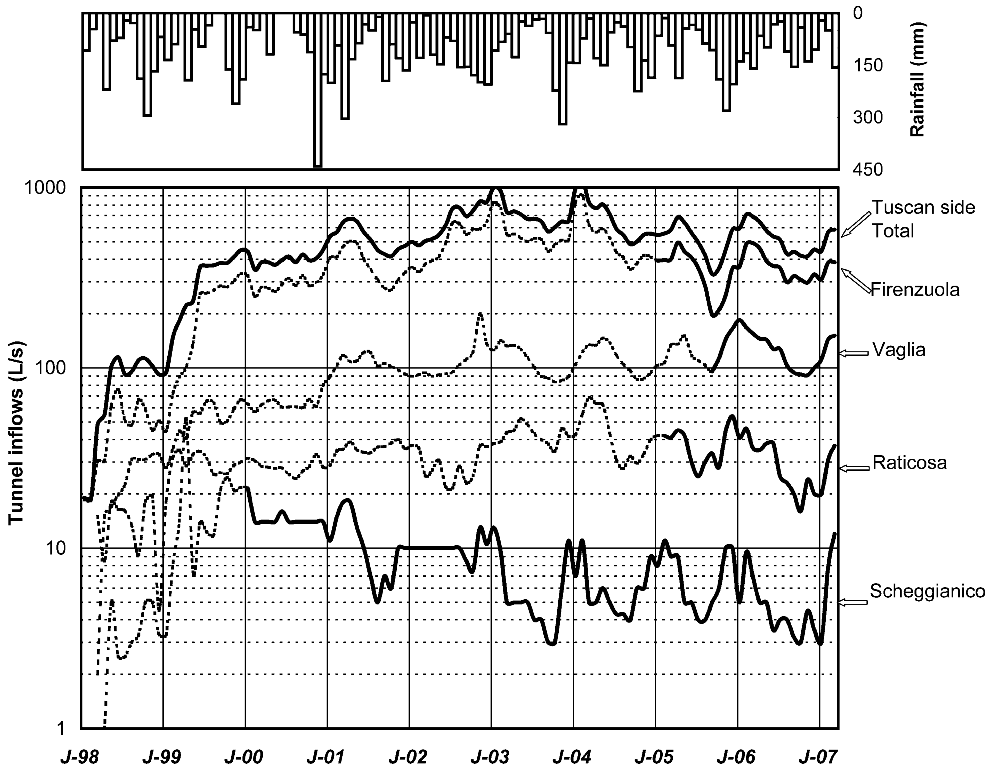

Fig. 12 Tunnel drainage regime from January (*J*) 1998 to March 2007 for each of four tunnel systems (main tunnel + access windows; for Vaglia the exploration tunnel is also included) on the Tuscan side of the HSR line; continuous line indicates drilling completion conditions. Total monthly precipitation (mm) of Barco rain gauge in the *bar diagram* at the top

direction matching slope aspect) stress-field relaxation of the slope (see left-hand edge of the section in Fig. 14a). S_S springs show the typical inverse correlation between ΔH and B_y; the lower the discharge point, the deeper is the GFS cell. Spring location is generally related to a permeability threshold where a low permeability unit acts as a barrier to groundwater flow along the slope. GFS discharge is focused on springs or often directly to streams (particularly when the streambed is at the base of a detensioned slope).

Tectonically-controlled (T type) systems, even if still actively connected to direct recharge (low salinity, alkali-earth bicarbonate facies), are strongly controlled by tectonic lineaments and structural history of the area,

Table 4 Hydrogeological budget for the tunnel system and impacted watersheds; watersheds column indicates stream sections identified with letters and located in Fig. 4 (A domain; Raticosa to Firenzuola) and Fig. 5 (C domain; Vaglia)

Tunnel System	DR 2005/2006 (L/s)[d]	α 2006 (day^{-1})[e]	R 2005/2006 (L/s)[f]	R/DR	D Before excavation (L/s)[g]	R/D	Watersheds
Raticosa[a]	35	4.8×10^{-3}	22	0.63	67 (1995–2000)	0.33	Diaterna Casatelvecchio (B) Cà Buraccia (A)
Firenzuola[b]	355	1.6×10^{-3}	317	0.89	474 (1995–1998)	0.67	Rovigo (R) Bagnone (AB) Bosso (AC) Farfereta (T)
Vaglia[c]	132	2.9×10^{-3}	101	0.77	150 (1995–2000)	0.67	Carza (X) Rimaggio (AA) Zambra (Y) Alberaccio (AD)

t tunnel; *W* access tunnel (pertains to a–c of the following)

[a] Raticosa t, Castelvecchio W, Diaterna W

[b] Firenzuola t, Rovigo W, Osteto W, Marzano W, S.Giorgio W

[c] Vaglia t, Carlone W, exploration t

[d] Average total drainage outflow rate

[e] Tunnel drainage Maillet recession coefficient

[f] Average active recharge component of tunnel drainage rate

[g] Average annual groundwater discharge before excavation (watershed data)

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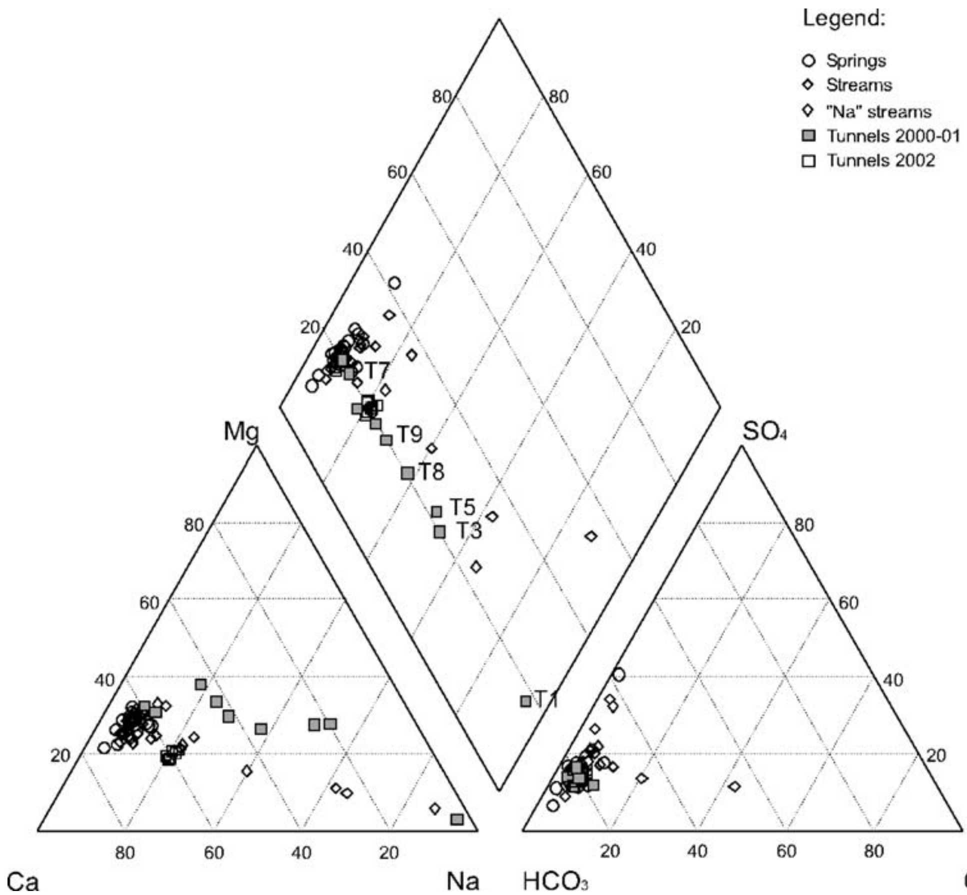

Fig. 13 Piper diagram for springs, stream sections and tunnel inflow samples. Most of the 2002 survey tunnel samples and some of 2000–2001 samples are clustered in the same alkali-earth bicarbonate pole. Sample *T1* was collected inside Raticosa tunnel and belongs to the sodic bicarbonate facies, while samples *T3, T5, T8* and *T9* fall along the mixing line between this facies and the alkali-earth bicarbonate one, indicating that Firenzuola tunnel in 2000–2001 was draining a mixture of two-thirds alkali-calcic waters with one-third alkaline waters; this process is no longer recognizable in 2002 samples, because after 1–2 years of drilling advancement, only 17% of drained groundwater is alkaline, with an evident shift in the relative mixing proportion

denoting a "huge area" pattern (low α value); they are typically trans-watershed in nature, similar to karst springs, so there is no coincidence between topographic and hydrogeologic boundaries.

T_L sub-type springs are expressions of low elevation GFS related to main post-orogenic extensional tectonic lineaments bordering the aquifer reliefs (right-hand portion of section in Fig. 14a,b), for example at the northern edge of tectonic depressions like Mugello graben in A domain and Florence basin in C domain; the discharge point is located where a main fault outcrops or where the aquifer is subjected to a low permeability threshold (overlapping unconsolidated sediments, clayey tectonic units). EC value is relatively higher as a result of flow length (mean 600 μS/cm).

T_H sub-type springs are expression of high-elevation GFS, developed along topographic divides, in some instances tectonically driven (groundwater flows along main tectonic axis from the structural highs, or culmination of tectonic windows, to structural lows; T_H springs in Fig. 14b) and hydraulically sustained by low permeability thresholds (clayey units, marly-clayey turbiditic members; T_H spring in Fig. 14a).

Base Regional (R type) system is the deep regional GFS of the chain with discharge focused, through tectonic lineaments, either on some isolated springs (S_R spring in Fig. 14a) or directly into the stream bed, in both cases generally located where topography is more hollowed out (minimum ΔH).

Ca-bicarbonate S and T type GFS (low in Na^+, high in redox potential Eh), being always dynamically interconnected to direct recharge, coexist with R type deeper GFS (well represented by T1 sample of Raticosa tunnel) belonging to Na-bicarbonate facies (relatively warmer, high in Na^+ and low in Eh, relatively depleted in ^{18}O and ^{2}H) and discharging at the surface in rare and scattered sulphur-smelling springs. R type GFS, at the whole chain scale, are involved in the deep and slow flow toward alluvial plains bordering the Apennines.

Tunnel drainage affects, in different ways, different GFS, confirming the conceptual model. Big inrushes are related to interceptions of main extensional lineaments (right-hand portion of Fig. 14a) with significant impact against T_L springs and streams (whereas a lineament is cutting the stream bed). Where tunnels run inside detensioned rock mass, rather high inflows occur, and

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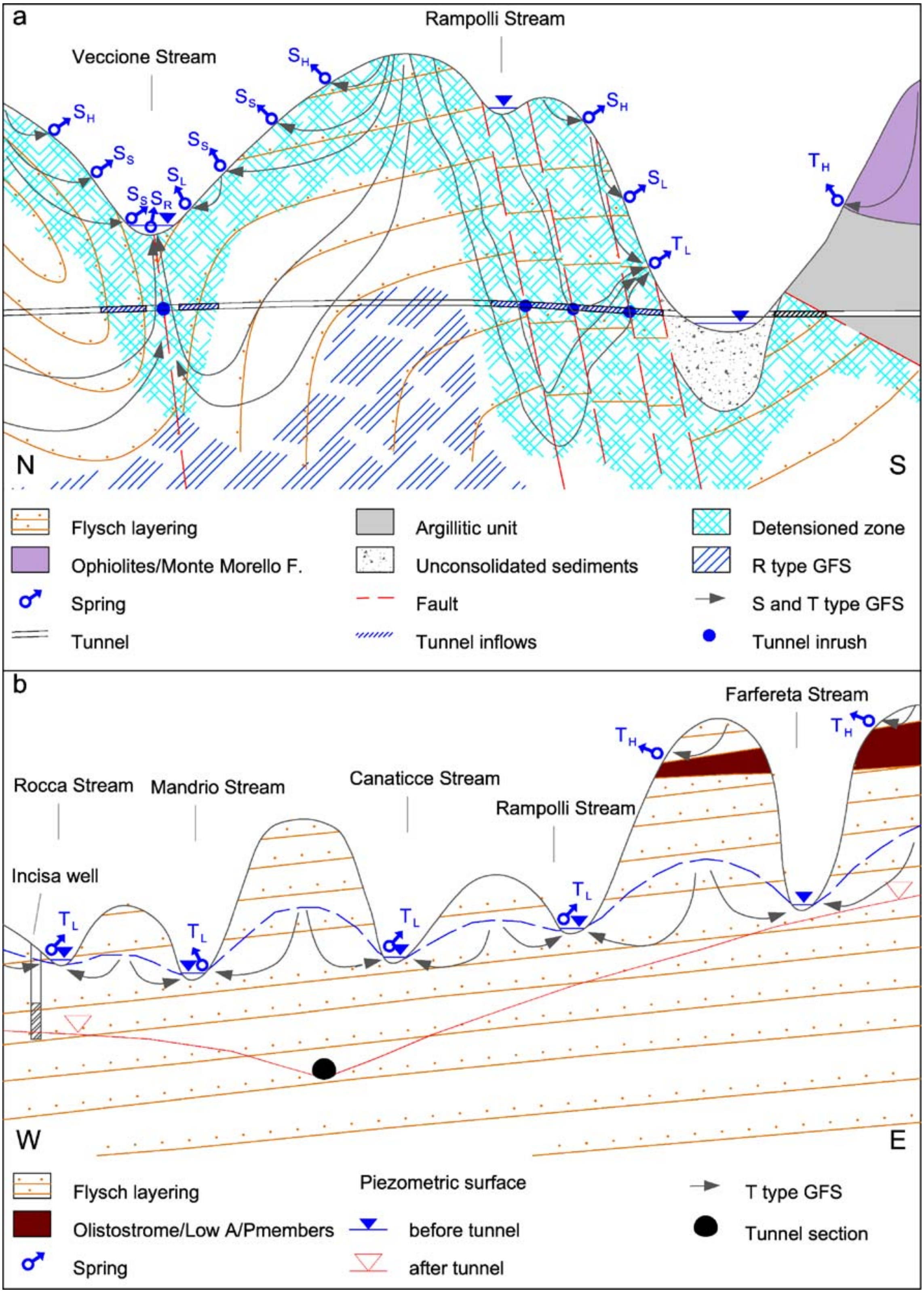

Fig. 14 Hydrogeological sections (idealized and not in scale) in the Northern Apennines setting, showing the main GFS and tunnel interference. **a** Section transversal to the main divide from Veccione Stream through Rampolli Stream to the Mugello graben; **b** section parallel to the main tectonic lineaments bordering Mugello graben and crossed by the southern sector of Firenzuola tunnel

 DOI 10.1007/s10040-008-0352-8

there is an impact on low ΔH S_S sub-type springs and on streams where the valley is cut inside the detensioned rock (left-hand portion of Fig. 14a); piezometric level lowering is greater where the A/P ratio is high and tectonic lineaments occur at regional scale. T_H type springs maintain the natural discharge regime because they are fed by perched aquifers not connected to the tunnels (Fig. 14b).

Tunnel waters originate from a transient state ephemeral GFS activated at the beginning of the boring, through a sort of hydraulic short circuit induced by tunnelling; for a short time after the inrush tunnel waters are similar in composition to the "aged" endpoint, showing subsequently a progressive mixing between shallow recharge waters and deep confined waters; shallow waters percentage increases progressively with time.

T_L sub-type and low ΔH S_S sub-type springs get impacted (Fig. 9a), except for one S_L sub-type spring (ID 11), where the tunnel runs a few metres below slope surface. On the other hand, all involved streams denote a full deplenishment of summer flow, providing strong evidence that all streams act as discharge spots for T_L and/or S_S sub-type GFS (Fig. 14b).

Conclusions

The integration of large amounts of hydrogeological data, originating either from natural flow conditions or from tunnel drainage perturbed conditions of the groundwater system, has given the chance to define a new rationale of groundwater flow systems inside turbidites in the Northern Apennines, demonstrating that they can locally behave as high yield aquifers, notwithstanding, up to now, scant consideration by hydrogeologists.

Active groundwater circulation develops in turbidites where the following geological conditions occur or coexist: dominance of arenites with respect to pelites or of more soluble limestones with respect to marls, extensional post-orogenic faults and fractures and tectonic stress relaxation zones in chain tectonic windows.

Three distinct and hierarchically nested GFS can be identified in Apenninic turbidites: shallow, intermediate and deep. The shallow system, from a few metres to maximum 150–200 m depth, is hosted in the regolith and shallower and detensioned portion of the rock mass, and discharges to S type springs and directly to streams where they are cut into the active groundwater circulation rock mass; strong analogy between the precipitation and spring discharge regimes, and high S type spring discharge variability, outline the rather high permeability and dynamics of GFS cells.

The intermediate system, developed down to 300–400 m depth (maximum differential elevation in Apenninic watersheds), is disconnected from a simply "topographic-driven" intra-watershed down-slope flow, being related to major tectonic lineaments and permeability thresholds, and discharges to fewer and comparatively higher yield T type springs or directly to streams where they intersect main tectonic structures; however intermediate GFS still have high permeability and dynamics, as proven by the short impact delay time of tunnel inrushes.

For both shallow and intermediate systems, taking into account that discharge values during the recession period are relatively low, it can be argued that, during one hydrological year, GFS cells discharge corresponds to the direct recharge received in the November-April period, i.e. water budget balance is practically zero.

The deeper system, an expression of the base regional groundwater circuit, is slow, aged and connected to the faults and fractures network of the deeper portion of the Apennines chain (down to more than 2,000 m depth, average thickness of outcropping silicoclastic turbidites); discharge points (springs or streams) are located at the lowest elevations of the landscape, near to the local base level.

Spring discharge in turbiditic aquifers is poorly relevant with respect to total groundwater discharge and this emphasizes the role of streams as main receptors for either local, intermediate or regional GFS. Turbiditic groundwater discharge is stream-focused, so relatively high stream baseflow during recession season is assured. Hydrochemistry and environmental isotopes reflect well the distinction between shallow/intermediate flow systems and the deep systems, with the clear occurrence of two mother waters in turbiditic aquifers: the alkali-earth bicarbonate pole, associated with the shallow and intermediate GFS (cold, low mineralised, oxidizing waters) and the alkali-bicarbonate pole, associated with the deep GFS (isothermal, mineralised, reducing, sulphur-smelling, relatively depleted in ^{18}O, oversaturated in calcite and consequently equilibrated with lower CO_2 partial pressures).

The Florence-Bologna high-speed railway connection tunnels have deeply affected and destroyed the above-mentioned hydrological and hydrochemical ordered array of GFS. The typology of water inrushes and the effects at the surface has contributed indirectly to the confirmation of the proposed rationale; severe effects on the natural recharge–discharge relationship have occurred within a landscape strip 3 km linear distance from the main tunnel. Consider also that the system, probably, has not yet reached the steady state.

Several pieces of evidence outline the severity of the impacts and confirm how the aquifer's strong deplenishment and the adverse ecological effects on streams are due exclusively to tunnel drainage:

- Uniformity of the direct recharge regime: the amount of effective precipitation was not substantially modified during tunnel excavation (according to the historical record) and cannot explain the monitored discharge deplenishment during the low flow season.
- Hydrologic regime of tunnel drained waters: there is an absence of any tendency towards progressive decreasing of tunnel discharge; on the contrary discharge regime of tunnels is in evident relationship with direct recharge regime (particularly for Firenzuola and Vaglia ones).
- Tunnels recession analysis and hydrologic budgeting: applying to tunnel drainage recession data the same analysis performed for springs and streams, it was

 DOI 10.1007/s10040-008-0352-8

found that an average 85% of the tunnel waters originate from direct recharge (89% for Firenzuola tunnel); moreover, applying a water budget calculation to the watersheds affected by tunnel interference, it was found that up to about two-thirds of natural groundwater discharge, on an annual average, is captured by the tunnels and this proportion increases to more than 90% during the low flow season, diverting completely water necessary to sustain environmental flows and leaving many streams completely empty of water, like semi-arid land wadis.

– Hydrochemical composition and evolution of tunnel waters: immediately after the excavation, the tunnel waters hydrochemistry was representative of the deep flow system but, through the interception and diversion of intermediate and even shallow GFS cells, hydrochemical facies turned very rapidly to the alkali-earth bicarbonate, which is the same as the majority of springs and streams; according to the last available analyses on mixing between groundwater endpoints (direct recharge and aged facies) 83% of Firenzuola tunnel water was derived from active recharge and this proportion is very similar to the value obtained independently by a water budgeting approach.
– Tracer test results: direct connection between an impacted stream (Veccione) and the underlaying tunnel (Firenzuola) was undoubtedly proved by a tracer test (see ESM chapter 4), with maximum transfer rate varying between 240 and 900 m/month (value comparable with hydraulic diffusivity obtained independently for the rock mass from a long duration pumping test); tracer-conveying fractures are the same fractures that contribute to stream baseflow in natural conditions. An improved and quantitative application of tracer tests took place four years later and is discussed in Vincenzi et al. (2008).

Different types of general and "transferable" conclusions may be derived from the here presented study. First of all, the hydrologic recession, with no active recharge occurring and so without a "noise signal", must be emphasized as the only hydrologic period that provides representative intrinsic properties of the aquifer. The hydrologic recession, therefore, constitutes the key to rank springs and groundwater flow systems in such a dynamic and direct-recharge-affected hydrogeologic setting. The summer discharge regime is more stable, not affected by high precipitation variability and reflects only the intrinsic diffusive properties of the rock mass and the typology of the GFS discharging there.

A new empirical index, called Base-yield (B_y), is proposed for an easy and reliable springs ranking on the basis of mean summer spring flow and recession coefficient: through a graphic methodology, springs, as an expression of GFS discharge, can so be differentiated according to more stable and easy-to-measure parameters. The effectiveness of the proposed methodology was verified by comparing spring type with tunnel interference effects: for the most part, only T_L type and lower differential elevation S_S springs were impacted, as representative of discharge of more developed groundwater flow systems. A site-specific methodology to calculate stream average annual baseflow on the basis of recession parameterization is proposed. If enough monitoring data are available during low flow season, a useful tool to estimate recharge, in an analogue hydrogeologic setting, so can be used.

To support the mapping of the potential impact of inrushes to springs and in implementing monitoring schemes related to tunnels, some important items of note resulted from the study: impacted springs are, for the most part, not more than 150–200 m from the tunnel axis (with a possible increase of radius of influence up to some kilometres along regional extensional lineaments); it is rare that a spring located at an elevation higher than 200–250 m from the tunnel could be impacted; impact is irreversible and propagates very rapidly, almost instantaneously at the monitoring time operating scale, with an interference propagation speed between 200 m/month and 1000 m/month.

If GFS discharge is stream-focused, most of the impact will be addressed to surface waters, inducing the more problematic consequences in ecological terms; also if not more than 50% of the watershed direct recharge is diverted from the tunnel (and even if the value is around 30%, as in the case of the Diaterna watershed impacted by Raticosa tunnel) complete vanishing of stream baseflow is expected during the recession season.

A promising tool for directly demonstrating the connection between streams and tunnels, also over half-km-scale linear distance, is represented by tracer tests using fluorescent dyes.

The main results of this study, given either huge outcropping extension of turbiditic units, not only in Northern Apennines but in many chains worldwide, or poor international hydrogeological references about the considered topic, could improve the research in this peculiar hard-rock investigation field, verifying the proposed conceptual model and contributing to the evaluation and protection of a still generally unknown groundwater realm.

Acknowledgements The authors wish to thank the Geological, Seismic and Soil Service of Emilia-Romagna Region (L. Martelli, R. Pignone), CAVET Consortium (G. Bollettinari, G. Bernagozzi), E.G.S. Florence (A. Agnelli, P. Innocenti), Prof. O. Vaselli of the Earth Sciences Department of the University of Florence and Geological Sciences graduated students (M. Rorato, A. Messina, L. Criscione) of the University of Ferrara.

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