
Surface water/groundwater interaction in the Piora Aquifer, Switzerland: evidence from dye tracing tests

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Abstract Results of seven dye tracing tests done from 1993–1997 to investigate the extent to which lakes and surface water interact with the underlying Triassic Piora Aquifer, Switzerland, are reported here. Two of the dye tracing tests showed that groundwater flows in the Piora Aquifer from the Piora Valley to springs in the adjacent Santa Maria Valley, and even further east to the di Campo Valley considerably outside of the Piora Valley surface water divide.

Lake Ritom located in the Piora Valley loses water only to the Canaria Valley outside of the lake's surface-water watershed at the lake's western margin when lake levels are above 1,835 m above sea level. Dye tracing tests show that a major sinkhole in the Piora Valley, Calderoni Sinkhole, is located precisely on the water divide where subsurface flow in the Piora Valley and surface water diverge and move in opposite directions. The dye tracing results also showed no hydraulic connection between surface water in the Piora Valley and the famous Pertusio Spring, located in the upper Santa Maria Valley. Only a small amount of dye from the two dye tracing tests done in 1993 and 1997 entered an exploratory gallery built to test the viability of the AlpTransit tunnel, being built in competent rock under the Triassic Piora Aquifer, effectively perched above.

Résumé Cet article présente les résultats de sept essais de traçage réalisés entre 1993 et 1997 pour étudier l'étendue sur laquelle les lacs et les eaux de surface interagissent avec l'aquifère triasique sous-jacent de Piora

(Suisse). Deux des essais de traçage ont montré que les eaux souterraines s'écoulent de la vallée de Piora vers des sources de la vallée voisine de Santa Maria, et même plus à l'est vers la vallée Di Campo, bien au-delà de la limite du bassin superficiel de la vallée de Piora.

Le lac Ritom, situé dans la vallée de Piora, perd de l'eau uniquement vers la vallée de Canaria, hors du bassin versant du lac, sur la rive ouest du lac, lorsque les niveaux du lac sont supérieurs à l'altitude 1835 m. Des essais de traçage montrent qu'une perte majeure dans la vallée de Piora, la perte de Calderoni, est située exactement sur la limite de partage des eaux où l'écoulement souterrain dans la vallée de Piora et les eaux de surface divergent et coulent dans des directions opposées. Les résultats des traçages montrent également qu'il n'existe pas de connexion hydraulique entre les eaux de surface de la vallée de Piora et la fameuse source Pertusio, située dans la haute vallée de Santa Maria, et que seulement une petite quantité de traceur des deux traçages faits en 1993 et 1997 parvient dans une galerie d'exploration percée pour tester la faisabilité du tunnel transalpin, creusé dans des roches compétentes sous l'aquifère triasique de Piora, perché au-dessus.

Resumen Se informa en el presenta artículo de los resultados obtenidos a partir de la ejecución de siete ensayos de trazadores con colorantes entre 1993 y 1997, con el fin de investigar la interacción entre las aguas superficiales y los lagos con el acuífero Triásico de Piora (Suiza). Dos de los ensayos mostraron que las aguas subterráneas fluyen en el acuífero desde el Valle de Piora hasta los manantiales situados en el valle contiguo de Santa María,; incluso, descargan más hacia el Este, en el Valle di Campo, situado a una distancia considerable de la divisoria del Valle de Piora. El Lago Ritom, ubicado en este Valle, sólo infiltra agua al Valle de Canaria, que se halla fuera de la cuenca superficial del propio lago – en el margen occidental – cuando los niveles del lago están por encima de la cota 1.835 m. Los ensayos de trazadores muestran que existe un sumidero principal en el Valle de Piora, denominado Calderón, precisamente en la divisoria de aguas, donde el flujo subsuperficial del Valle de Piora y las aguas superficiales divergen y se mueven en sentidos opuestos. Los resultados también confirman la ausencia de conexión hidráulica entre las aguas superficiales del Valle de Piora y el famoso manantial de Per-

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tusio, que está en la parte alta del Valle de Santa María. Además, sólo una pequeña cantidad del colorante utilizado en los dos ensayos realizados en 1993 y en 1997 penetró en la galería exploratoria construida para comprobar la viabilidad del túnel AlpTransit, perforado en roca competente bajo el acuífero Triásico de Piora, el cual se comporta como un nivel colgado.

Keywords Piora · Lake Ritom · Pertusio · Dye tracing · Surface water

Introduction

Since construction of the hydroelectric power plant and dam at Lake Ritom over 80 years ago, dye tracing tests have been used to evaluate the hydrologic flow paths in aquifers of the Piora Valley of southern Switzerland. The valley is interesting hydrogeologically because of the morphology of its very permeable karst-like sedimentary Triassic rocks, termed the Piora Zone, wedged between crystalline gneisses of the Pennine Lucomagno Nappe and granites of the crystalline Gotthard Massif (Fig. 1). The Piora Valley is noted for losing streams and leaking lakes. In addition, galleries have been built through the bedrock to transport water to and from adjacent valleys.

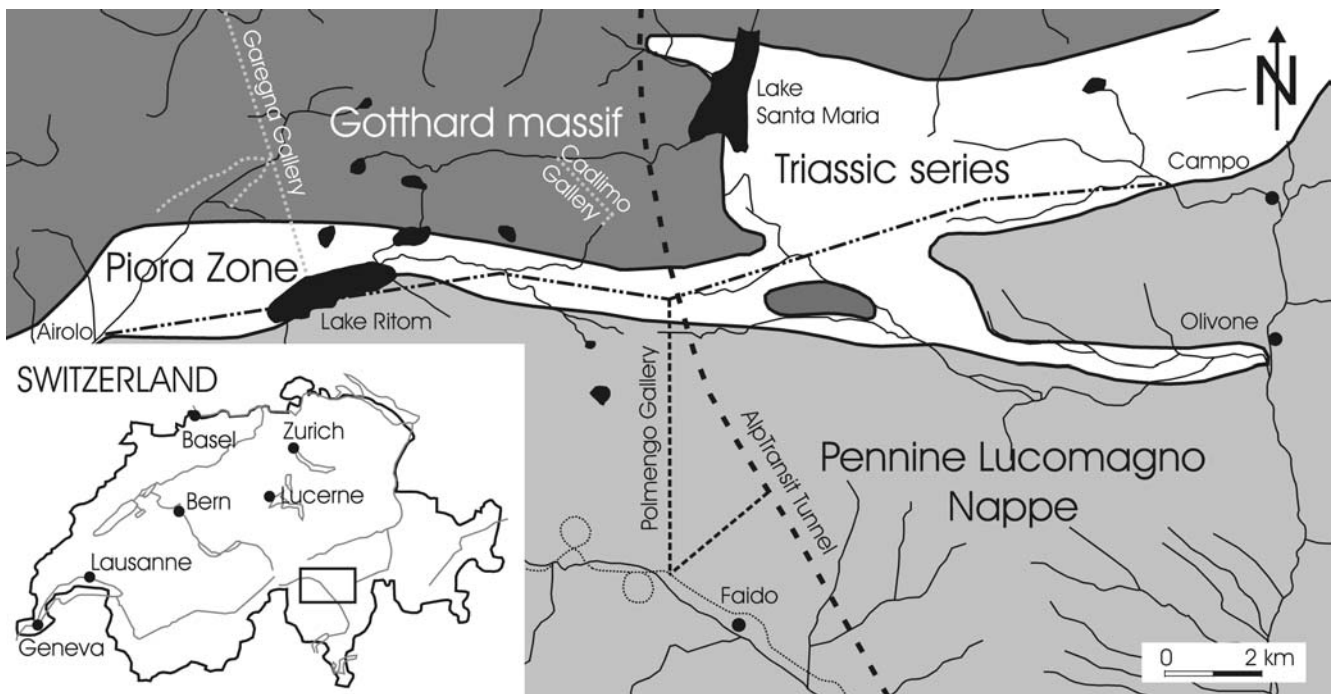
Fig. 1 The Triassic Piora Zone is wedged between the Gotthard massif on the north and the Pennine nappes in the south. The proposed new railway tunnel (AlpTransit) (dashed black line) crosses the Piora Zone at its most narrow zone between large lakes. The E-W transect from Airola to Campo shows the location of the cross-section represented in Fig. 9

The first dye tracing tests were done in the Piora Valley in 1920 to locally test the integrity of a pressure line connecting Lake Ritom and the first surge tank below the dam. Several days after injection, Na-fluorescein dye reached the Canaria Valley (Fig. 2), 3 km to the west (Winterhalter, written communication 1949). In 1944, dye tracing tests were done near the Lucomagno Pass east of the Piora Valley and it was determined that there was no hydraulic connection between the Pertusio Spring and Lake Santa Maria located upgradient (Fig. 2; Wyss, written communication 1945). Subsequently, tritium and sulforhodamine B tracer introduced to Lake Chiera in 1969 (Fig. 2) showed no leakage into the Piora Zone from the Leventina Valley on the south (H. Otz, personal communication).

These dye tracing tests provided local information on the hydrogeologic mosaic of the Piora Zone, but still no comprehensive understanding of the overall hydrodynamics of the Piora Aquifer. The objective of this study was to clarify and quantify water loss from major streams and lakes using additional dye tracing tests and to determine whether flow paths are regional in scale.

Regional Hydrogeology

The Piora Valley is bounded on the north by the Cadlimo Valley, to the southwest by the Leventina Valley, to the northwest by the Canaria Valley, and to the east by the St. Maria Valley (Fig. 2). The ~250-m-broad, Triassic-age, E-W trending Piora Zone under the valley separates the crystalline rocks of the Gotthard Massif from the metamorphic Pennine Lucomagno Nappe over a distance of tens of kilometers, as shown in Fig. 1. During the Alpine Orogeny, 50 to 25 million years ago, the carbonate



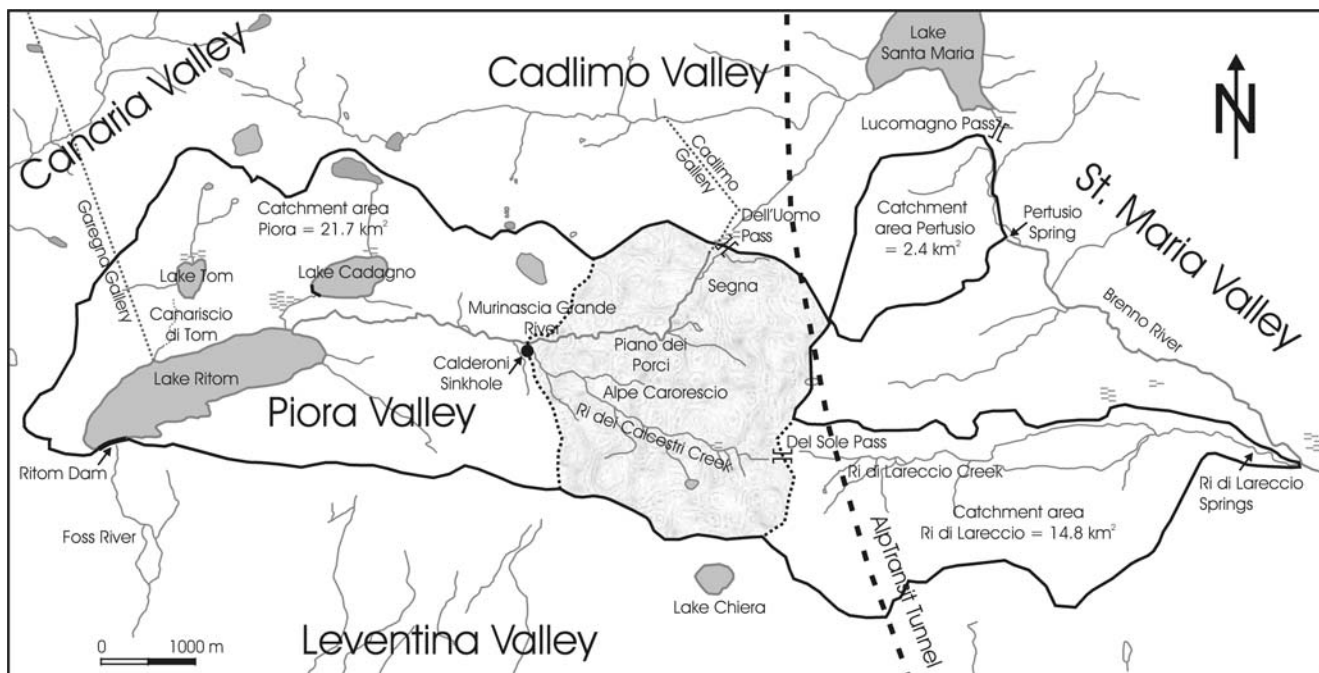


Fig. 2 The shaded area divided by a dashed line shows the overlapping of the Piora and the Ri di Lareccio catchments. The catchment area of the Pertusio Spring is separated from the other catchments. Lake Cadagno's catchment area is part of the Piora catchment area. The Calderoni Sinkhole lies exactly on the hydrologic divide (dotted line)

rocks of the Triassic sediments of the Piora were a glide horizon between the Gotthard Massif and the Pennine Lucomagno Nappe, and therefore they have a complexly deformed internal structure. Weathering of the Piora Zone has exposed Triassic "cargneules", carbonate sedimentary rocks containing cavities filled with soft, friable gypsum that easily dissolves, leaving rough corroded surfaces (Herwegh and Pfiffner 1999). Extensive karst-like zones occur in the weathered Piora Zone, making it a significant aquifer.

Two second-order drainages, the Murinascia Grande River and the Ri dei Calcestri Creek drain the Piora Valley and have their headwaters near a N-S topographic divide, the del Sole Pass (Fig. 2). The Murinascia Grande River flows westward into Lake Ritom. Most seepage (average volume loss ~100 L/s per 300 m) from the Murinascia Grande River occurs where it is in direct contact with the highly weathered Piora Zone downgradient of Piano dei Porci (Fig. 2). The river then continues to flow westward through unconsolidated Quaternary glacial deposits until it reaches Lake Ritom. In addition to water from its own watershed, the Murinascia Grande River also receives water from the adjacent Cadlimo Valley through the constructed Cadlimo Gallery (Fig. 2). The Ri dei Calcestri Creek flows to the west from the del Sole Pass. West of the Alpe Carorescio the creek becomes intermittent and generally loses water (30 to 90 L/s) into the subsurface along its entire length.

Murinascia Grande River, the discharge of the Garegna Gallery, the outflow of Lake Cadagno, and the perennial Canariscio di Tom creek all discharge into Lake Ritom, the largest lake in the Piora Valley. The Garegna Gallery (Fig. 2), built in 1948–1953, brings an additional ~200 L/s water from the Canaria Valley to the lake. Lake Ritom formed in a glacially eroded basin with a rim not deeply eroded enough to drain the lake. In 1918, the Swiss Federal Railway built a 10.5-m-high dam on the crystalline rim of the lake (Eggenberger 1923), and raised the dam in 1950 to its present height of 23 m. Since then, major water losses (115–270 L/s in 1993) occurred from Lake Ritom when the water level was high (Jäckli Inc. 1994). Significant water loss through the well-consolidated clayey lake bottom is unlikely.

A second large lake in the Piora Valley, Lake Cadagno, formed behind two recessional moraines enhanced by an artificial dam, 3 m high (Fig. 2). A third lake, Lake Tom, is located on a cirque step where Triassic sediments outcrop. This lake is only ~15 m deep and its outflow (~45 L/s) to the south vanishes into cargneules. During periods of peak discharge, Canariscio di Tom flows into Lake Ritom (Fig. 2).

Finally, the Piora Valley contains hundreds of sinkholes, the largest of which is the Calderoni Sinkhole located on the west side of the Ri dei Calcestri Creek. East of the sinkhole is the catchment area of the Ri di Lareccio, and to the west, the catchment of the Piora, as shown in Fig. 2. The surface and subsurface hydraulic boundaries between the two catchment areas may be complex because of the underlying karst-like drainage system, the details of which are addressed in the dye tracing experiments.

The Ri di Lareccio Springs in the Santa Maria Valley are hydraulically connected to the main streams in the Piora Valley (Otz 1998; Otz et al. 2001). The springs

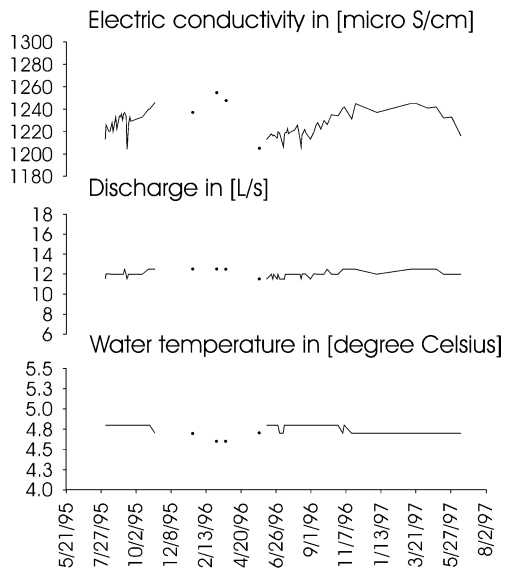


Fig. 3 The graph of this Ri di Lareccio Spring is representative for the entire spring horizon. The spring reflects a nearly constant water temperature and discharge

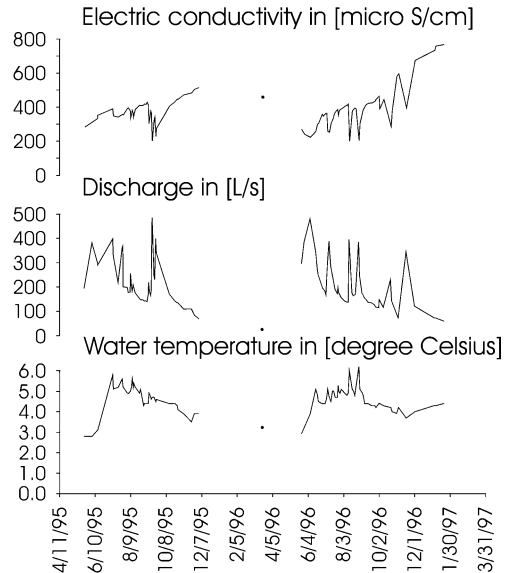


Fig. 4 The electric conductivity of Pertusio Spring water mirrors the Pertusio discharge. Pertusio's water is a mixture of slowly percolating stagnant groundwater and rapid channel discharge

have nearly constant discharge, water-temperature, and specific conductance, as shown in Fig. 3. For example, the temperature and specific conductance for the largest Ri di Lareccio Spring from 1995 to 1997 remained nearly constant at ~ 4.8 °C and $\sim 1,235$ $\mu\text{S}/\text{cm}$, respectively. During the same period, discharge was ~ 12 L/s (Otz 1998). In contrast, discharge and specific conductance of the Pertusio Spring in the upper Santa Maria Valley (1,830 m a.s.l.) varied greatly (Fig. 4). Discharge ranged from negligible to about 500 L/s throughout the year. The electric conductivity (reflecting major ion concentrations) decreased with increasing stream flow, as shown in Fig. 4 (Otz 1998).

Water temperatures of the Pertusio Spring are not affected by variations in discharge. Commonly, in karstic hydrologic systems, large changes in discharge coincide with significant fluctuations in water temperature (Käss 1998; Binggeli 1961). Water in the flow system must have a long enough residence time to allow temperature to equilibrate. During dry seasons, the slowly discharging groundwater from Triassic cagneules largely controls the discharge of the Pertusio Spring. During storms, water discharging from the smaller episodic creeks that vanish into sinkholes shows up a few hours later in the Pertusio Spring (Binggeli 1961; Otz 1998).

Methods

A variety of organic fluorescent dyes were used to evaluate the hydrogeologic flow system in the Piora Valley and the adjacent valleys, as shown in Table 1. The nature and chemical characteristics of the dyes and standard tracing procedures are described in Käss (1998). Briefly,

multiple dyes were placed in different parts of the Piora flow system and the dye breakthrough curves were monitored at possible discharge points. From the breakthrough curves, maximal flow velocities for the dyes to move from places of introduction to reemergence were calculated, as shown in Table 1.

Dye Tracing Test Piora-1993

Prior to Piora-1993 (Table 1), it was known that Lake Ritom, the Murinascia Grande River, and the Ri dei Calcestri Creek lose up to ~ 400 L/s through seepage to the Piora Aquifer (Jäckli Inc. 1994). The goal of the Piora-1993 dye tracing test was to identify where the seepage was going. Five different fluorescent dyes were used to identify discrete flow paths from potential sources to potential sinks. Dyes were placed in the following places:

On 24 August 1993, 4 kg of liquid eosine dye was poured at once into the Murinascia Grande River in Piano dei Porci (A), as shown in Fig. 5.

On 29 August 1993, 10 kg liquid pyranine dye was pumped for 4 h into the deep waters of Lake Ritom (B) through a hose. In the afternoon, 10 kg of liquid duasyn dye was poured at once in the Ri dei Calcestri Creek, south of Alpe Carorescio (C), as shown in Fig. 5.

A day later, 30 August 1993, 40 kg of liquid Na-fluorescein dye was inserted throughout Lake Ritom in the upper waters (D), which were colored within 4 h. On the same day Lake Tom (E) was also colored completely with 10 kg of Na-naphtionate dye using the same approach.

Table 1 Summary of all dye tracing test done in the Piora Valley

Year	Date/ time	Name of dye test	Dye injection in	Amount and name of dye injected	Dye found or not found	Traveling time
1920			Pressure line Ritom		Canaria Valley	Several days
1944	9/28		Cuolm Creek	0.25 kg Na-fluorescein	Not found in Pertusio Spring	
	9/30–10/8		Brenno by Alpe Croce	2 kg Na-fluorescein in total	Not found in Pertusio Spring	
	10/10 10/19		Brenno by Alpe Croce Sinkhole 3 near Pertusio Spring	1.3 kg Na-fluorescein 1 kg Na-fluorescein	Pertusio Spring Pertusio Spring	25 h
	10/21		Sinkhole 1 near Pertusio Spring	1 kg Na-fluorescein	Pertusio Spring	
1951	9/24		Murinascia Grande River by Segna	40 kg Na-fluorescein	Pertusio Spring	3 days
1969			Lake Chiera	150 Ci tritium and 2 kg sulfurhodamide B	Not found in any spring in the Piora Valley	
1993	8/24	Piora-1993	Murinascia Grande River by Piano dei Porci	4 kg eosine	Ri di Lareccio Creek in Santa Maria Valley	14 days
	8/29		Monimolimnion of Lake Ritom	10 kg pyranine	None	
	8/29		Ri dei Calcestri Creek by Alpe Carorescio	10 kg duasyn	Ri di Lareccio Creek in Santa Maria Valley, and in the Polmengo Gallery in 1995	14 days
	8/30		Mixolimnion of Lake Ritom	40 kg Na-fluorescein	Ce di fuori Springs and Spring AIR 148	15 days 29 days
	8/30		Lake Tom	10 kg Na-naphtionate	Caregna Gallery and upper Canaria Valley (Ronco)	1 h 27 days
1995	9/5	Pertusio-1995	South end of Lake Santa Maria	25 kg Na-naphtionate	Not found in Pertusio Spring	
	9/5		Brenno by Alpe Croce	0.2 kg Na-fluorescein	Pertusio Spring	12 h
	9/5		Valletta di Croce Creek	0.2 kg sulfurhodamine B	Pertusio Spring	9 h
	9/5		Pond Foppe di Pertusio	0.2 kg duasyn	Pertusio Spring	12.5 h
	9/5		Losing creek west of Foppe di Pertusio	0.2 kg pyranine	Pertusio Spring	7 h
	9/5		Losing creek south of Foppe di Pertusio	0.2 kg eosine	Not found in Pertusio Spring	
1995	5/15	Ritom-1995	Piezometer S1	0.2 kg lissamine	Not found in Spring AIR 148	
	5/15		Piezometer S2	5 kg Na-naphtionate	Not found in Spring AIR 148	
1995	31/5	Canaria-1995	Canaria Creek	0.1 kg sulfurhodamine B	Found in Spring AIR 148	20 mins
1996	7/25	Pertusio-1996	Mottrone Creek	5 kg Na-fluorescein	Not found in Pertusio Spring	
1996	8/27	Ritom-1996	Piezometer S1	0.2 kg lissamine	Spring AIR 148 and Ce di fuori Springs	28 days 18 days
	8/27		Piezometer S2	0.2 kg pyranine	Not found in Spring AIR 148	
	8/27		Piezometer S3	0.2 kg duasyn	Not found in Spring AIR 148	
	8/27		Piezometer S4/5	0.2 kg Na-fluorescein on top	Spring AIR 148 and	48 days
				0.2 kg sulfurhodamine B at bottom	Ce di fuori Springs	37 days
			Piezometer S5/6	0.2 kg eosine on top	Not found in Spring AIR 148	
1997	8/17	Piora-1 997	Calderoni Sinkhole	5 kg Na-naphtionate 5 kg amidoflavine	Not found in Spring AIR 148 Ri di Lareccio Creek in Santa Maria Valley di Campo Valley and Polmengo Gallery	18 days 43 days 22.5 days 25 days
	8/17		Mixolimnion of Lake Ritom	50 kg Na-fluorescein	Canaria Valley (Spring AIR 148)	
	8/18		Murinascia Grande River by Segna	10 kg pyranine	Ri di Lareccio Creek in Santa Maria Valley, di Campo Valley and Polmengo Gallery	19 days 45 days 23.5 days
	8/18		Ri dei Calcestri Creek by Alpe Carorescio	54 kg Na-naphtionate	Ri di Lareccio Creek in Santa Mari Valley, di Campo Valley and Polmengo Gallery	14 days 38 days 24.5 days

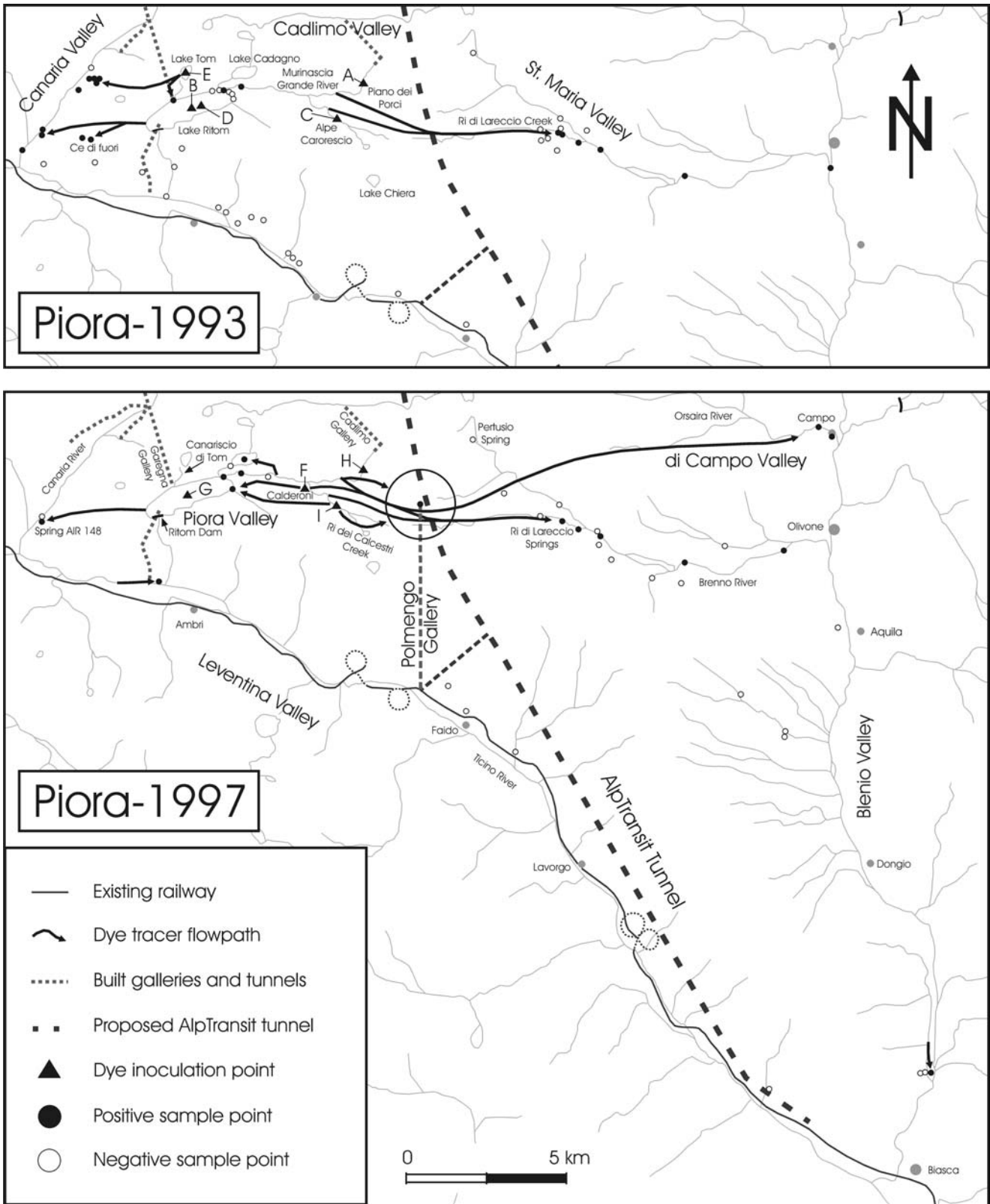
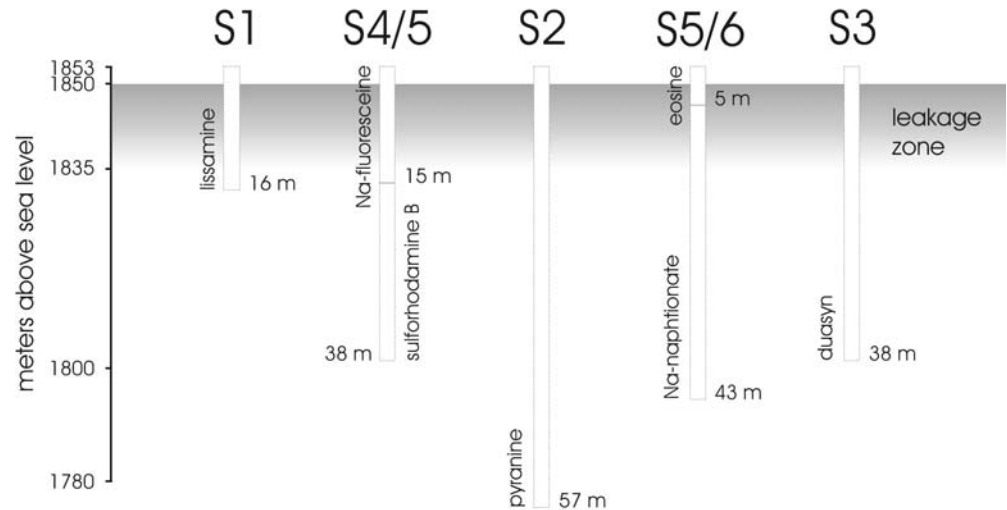
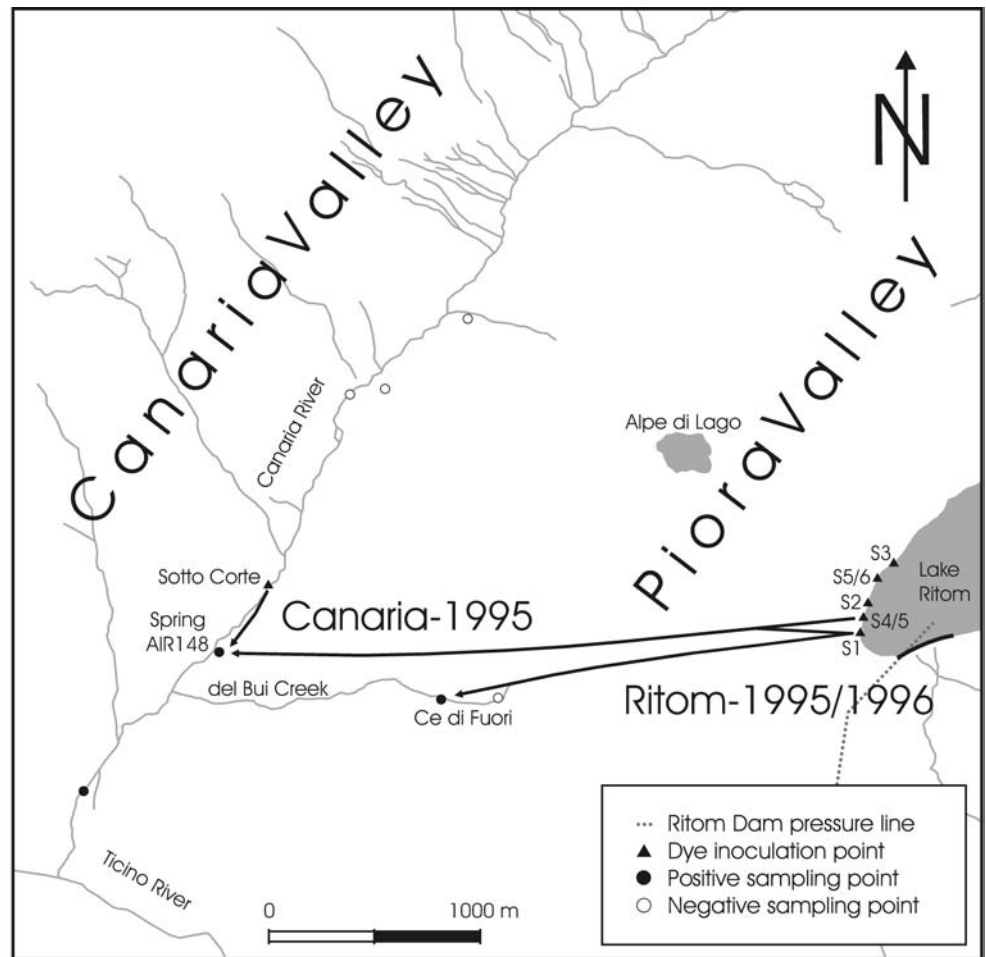


Fig. 5 Location map for dye tracing tests. The *black arrows* show the general flow paths for injected dyes in dye tracing test Piora-1993 and Piora-1997. The *small black dots* are the sampling points

where dyes were found. *Open circles* are where dye was not found. The extensive Piora-1997 test included sites over five valleys

Fig. 6 Flow paths to the Canaria Valley of the injected dyes of Ritom-1995, Ritom-1996, and Canaria-1995 clearly repeated the results of dye tracing test Piora-1993. With the first and second tests, the leakage zone could be described more precisely



Dye Tracing Tests Ritom-1995, Ritom-1996, and Canaria-1995

To determine where on the western lakeside Lake Ritom loses water to the adjacent groundwater, five groundwater monitoring wells from 15 to 60 m depth were installed after dye tracing test Piora-1993. The wells were

screened over their entire length. On 27 August 1996, 200 g lissamine dye was inserted in S1; 200 g pyranine dye in S2; and 200 g duosyn dye in S3, 200 g Na-fluoresceine dye in wells S4/5 from the water table to 15 m depth, and 200 g sulforhodamine B dye from 15 to 38 m. In addition, 200 g eosine dye were inserted in the top

5 m below the water table of S5/6 and 5 kg Na-naphtionate dye from 5 to 43 m depth, as shown in Fig. 6. To quantify the amount of Canaria Creek water discharging in a spring, labeled Spring AIR 148, located in the lower Canaria Valley, 100 g sulforhodamine B was poured in Sotto Corte into Canaria Creek on 31 May 1995, as shown in Fig. 6.

Dye Tracing Tests Pertusio-1995 and Pertusio-1996

Two dye tracing tests, Pertusio-1995 and, Pertusio-1996, were done to define the catchment area of the Pertusio Spring. On 2 September 1995, Otz (1998) colored the south end of Lake Santa Maria with 25 kg Na-naphtionate. On the same day, several vanishing creeks (these creeks received Na-fluorescein, pyranine, and eosine respectively), a ravine creek (sulforhodamine B), and a pond (duasyn), all located in Foppe di Pertusio (the Lucomagno Triassic unit) were colored. One year later Mari (1996) poured 2.5 kg Na-fluorescein in total in a intermittent creek southeast of the Lucomagno Pass.

Dye Tracing Test Piora-1997

A second large dye tracing test, Piora-1997, was done to further evaluate the results from Piora-1993 and Pertusio-1995. Twenty-eight sampling sites were used to measure dye breakthrough in the Piora Valley, the Santa Maria Valley, the di Campo Valley, the Blenio Valley, the Leventina Valley, and in the Polmengo Gallery, as shown in Fig. 5. For this test, 5 kg of liquid amidoflavine dye was injected all at once on 17 August 1997 into the Calderoni Sinkhole (F) and flushed with 12 m³ of water over a 20-h period. Fifty kg of liquid Na-fluorescein dye was then spread over the thermocline in Lake Ritom (G) in stripes, and the lake became thoroughly colored, from the surface down to the thermocline, within 2 h.

On 18 August 1997, 10 kg of liquid pyranine dye was injected at once in the Murinascia Grande River (H) at the same location as was done in the dye tracing test Piora-1993. As the pyranine-colored water reached the inflow of Lake Ritom, it dispersed under the thermocline (located at 20 m depth) because of the colder temperature and higher density of the water. On the same day, 54 kg of Na-naphtionate salt was injected into the Ri dei Calcestri Creek (I), in the same location as in dye tracing test Piora-1993, as shown in Fig. 5.

Results and Discussion

Dye Tracing Test Piora-1993

The dye tracing test showed considerable groundwater flow, up to 150 L/s, from west to east to the Ri di Lareccio Springs in the Santa Maria Valley. No dye was found in any of the springs in the Leventina Valley. Neither was dye found in the Pertusio Spring. The results therefore conflict with those of Sonderegger (written commu-

nication 1952) that suggested that part of Murinascia Grande River water discharges into Pertusio Spring.

The Na-fluorescein dye injected in Lake Ritom first appeared within 15 days in springs in Ce di fuori. In the Spring AIR 148 (Fig. 6), located in the lower Canaria Valley, Na-fluorescein from Lake Ritom appeared after 29 days. According to Jäckli Inc. (1994) Lake Ritom lost between 180 to 250 L/s during this time. Over the sampling time, almost all of the injected Na-naphtionate in Lake Tom reached the Garegna Gallery, as shown in Fig. 7. The dye first appeared in the Garegna Gallery 1 hr after insertion. As the Garegna Gallery water flows into Lake Ritom the dye reached the lake a few minutes later. Less than 1% Na-naphtionate dye discharged to springs in the upper Canaria Valley (Jäckli Inc. 1994).

The eosine dye injected in the westward-flowing Murinascia Grande River and seeping into the Piora Aquifer passed eastward under the topographical divide to the east, into the Santa Maria Valley. It then emerged in the Ri di Lareccio Springs (aerial distance to the injection site: ~6.5 km) in only 14 days, as shown in Fig. 7. During the test the Murinascia Grande River lost 300 L/s through seepage (Jäckli Inc. 1994).

The Ri dei Calcestri Creek water colored with duasyn dye appeared 14 days later at the Ri di Lareccio Springs. These data combined compellingly document a large, complicated, and fast moving hydrogeological system to the east in the Piora Aquifer, as shown in Figs 5 and 9. During the dye tracing test, Ri dei Calcestri Creek lost 43 L/s water along its flow from Alpe Carorescio to the Murinascia Grande, as shown in Fig. 2. Only 4 L/s of the Ri dei Calcestri Creek water drained into the Murinascia Grande River at the dye tracing time (Jäckli Inc. 1994).

The dye breakthrough curve in Fig. 7 for the Ri di Lareccio Springs shows dye concentrations much smaller than that found throughout the entire Ri di Lareccio Creek. Since only 1 of 12 springs was sampled, the other springs likely provided the bulk of the dye to the creek. The low dye recovery is probably due to hydrodynamic dispersion and diffusion into the older "stagnant" water zone in the lower part of the Piora zone, as shown in Fig. 9 (Fellner 1999).

Dye Tracing Tests Pertusio-1995 and Pertusio-1996

Dye tracing test Pertusio-1995 clearly defined the catchment area of the Pertusio Spring, as shown in Fig. 2 (Otz 1998). In addition, the results of Pertusio-1996 showed that the left side of the upper Santa Maria Valley does not contribute any water to the Pertusio Spring. These waters drain to the east, probably into the di Campo Valley. Several additional investigations, such as speleology, geophysics and geomorphology studies support this hypothesis (Mari and Otz 1997; Otz 1998).

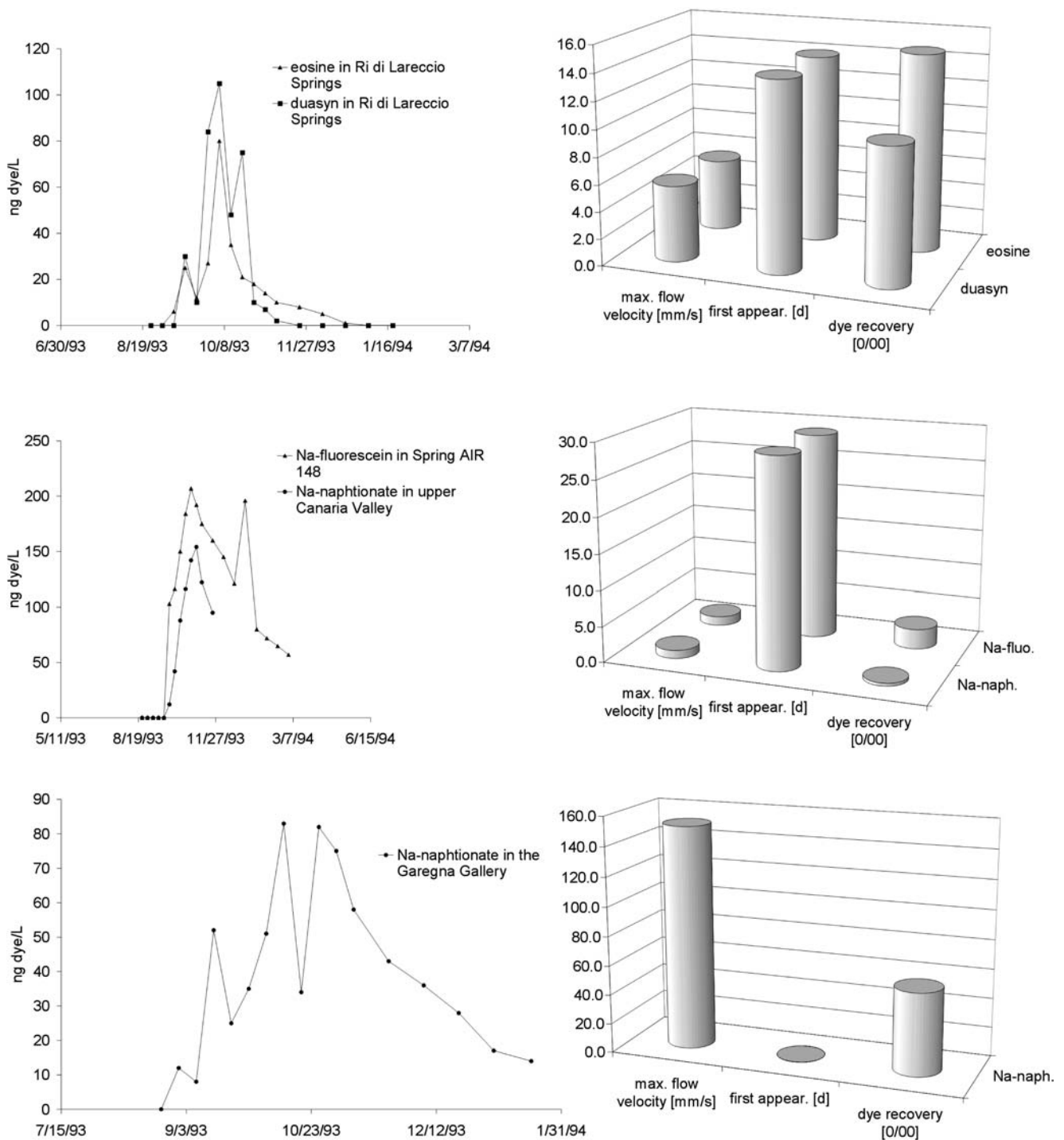


Fig. 7 Piora-1993: maximal flow velocities, breakthrough curves, first appearance and dye recoveries in the Santa Maria Valley, the Canaria Valley, and in the Garegna Gallery

Dye Tracing Tests Ritom-1995, Ritom-1996, and Canaria-1995

Dye tracing test Ritom-1996 confirmed that the upper Lake Ritom waters are hydraulically connected to the springs in Ce di Fuori and in the lower Canaria Valley, as shown in Fig. 6 (Jäckli Inc. 1994). Based on these tests, Lake Ritom loses water only at its western lakeside be-

tween piezometers S1 and S4/5, and at elevations between 1,850 to 1,835 m a.s.l. In other words, Lake Ritom begins to significantly lose water in its nearshore area when its water level is 15 m below its maximum height (1,850 m a.s.l.). Below 1,835 m a.s.l., water losses from Lake Ritom are unlikely. This conclusion was clearly shown by dye tracing test Ritom-1995. Then, the lake level was at 1,833 m a.s.l., and no dyes reached the Val Canaria surface waters.

Test Canaria-1995 further showed that ~80% of the spring's (AIR 148) discharge (~500 L/s in total) was pro-

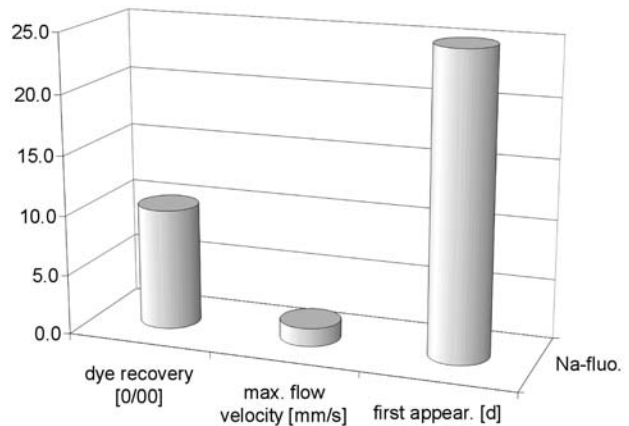
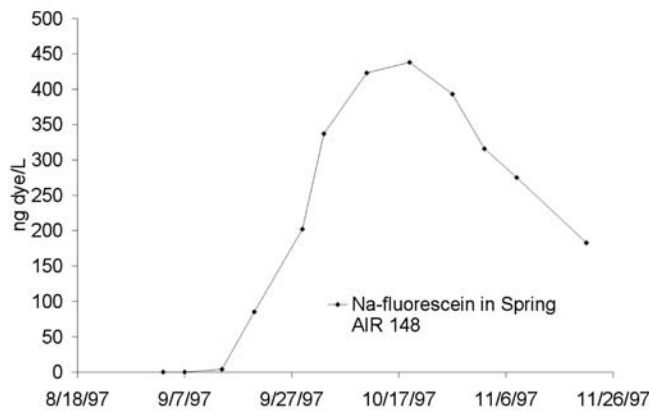
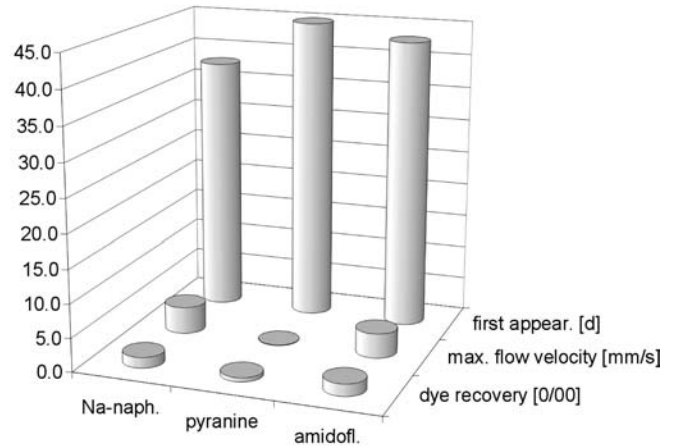
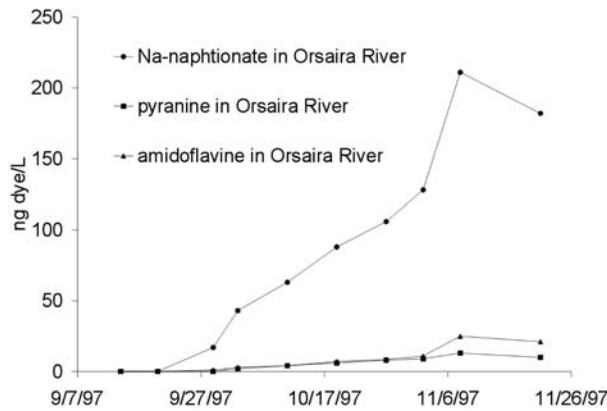
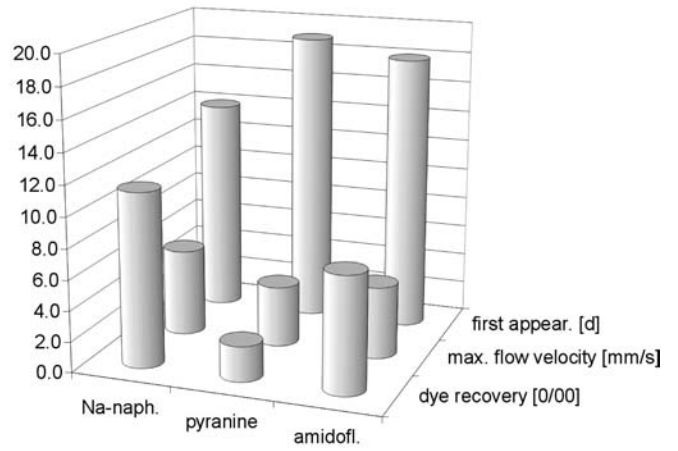
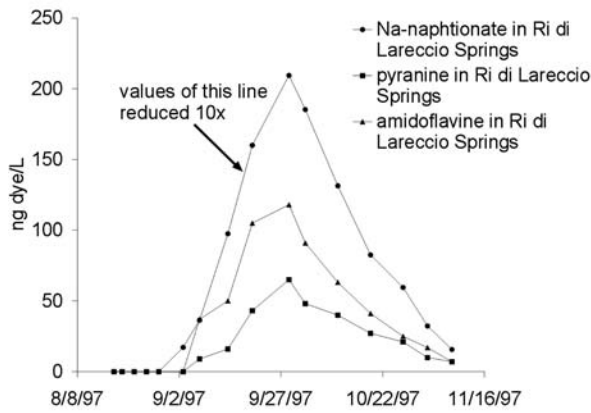


Fig. 8 Piora-1997 below shows the maximal flow velocities, breakthrough curves, first appearance and dye recoveries graphs for Spring S11 (Ri di Lareccio Springs) in the Santa Maria Valley, the di Campo Valley, and the Spring AIR 148 in the Canaria Valley

Dye Tracing Test Piora-1997

The more detailed repetition of the dye tracing test from 1993 gave comparable results. Once the dyes appeared in the Ri di Lareccio Springs they flowed into the Brenno River, and they were flushed from the Blenio Valley into the Ticino River at Biasca. The low recovery percentage of the dyes is consistent with the results from the Piora-1993 test, as shown in Figs 7 and 8, and Table 1. Much of the dye still remains in the flow system, possibly quenched by the higher saline stagnant water zone or at the interface between the stagnant water zone and fresh water in the Piora Aquifer, as shown in Fig. 9.

vided by infiltrated Canaria Creek water. The rest of the spring water comes from the southeastern Canaria Valley side. At the time of the test, no Lake Ritom water reached Spring AIR 148, because the head of the lake was below its leaking zone, as shown in Fig. 6.

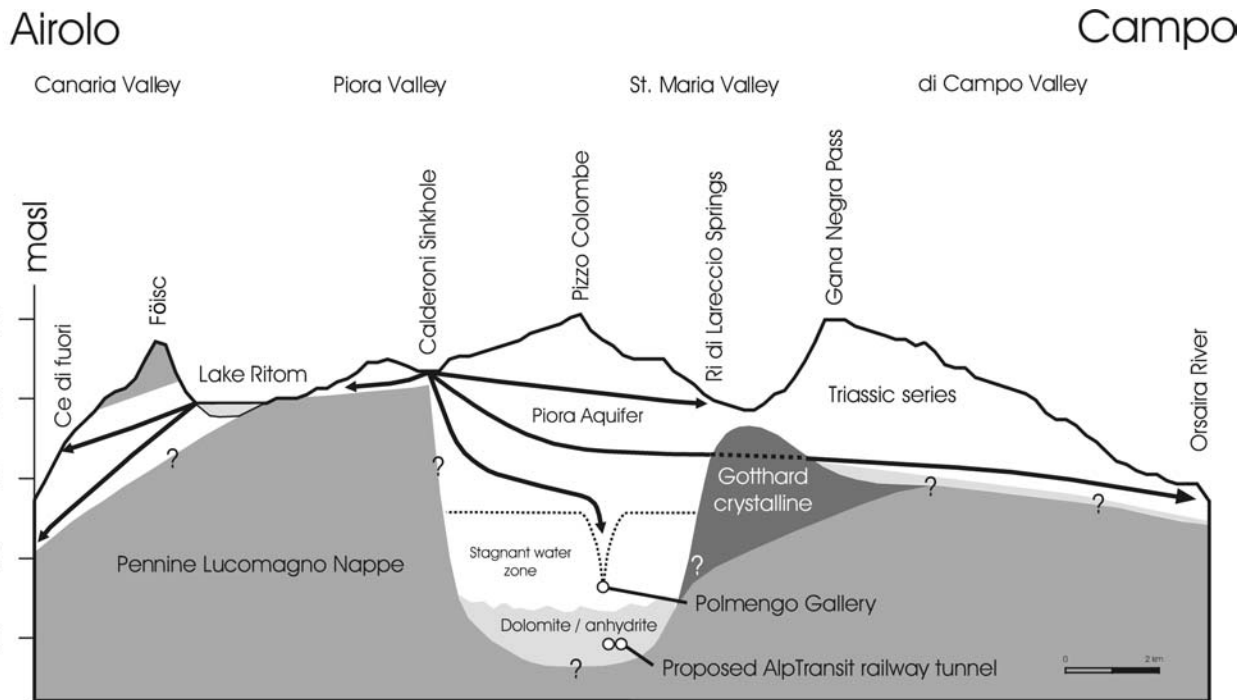


Fig. 9 West to east hydrogeologic cross section along the Piora Zone. *Question marks* show uncertainty of the depths of the geologic units. The cone of depression, inferred from changes in the physical-chemical characteristics of discharge to the Polmengo exploratory gallery tunnel, provided the tunnel with “fresh” groundwater from the leaking rivers above

The results of dye tracing tests Piora-1993 and Piora-1997 show that the hydrogeologic divide between the Piora Valley and the Santa Maria Valley falls on the Calderoni Sinkhole, as shown in Fig. 2.

The dyes amidoflavine, pyranine, and Na-naphtionate injected into the Calderoni Sinkhole, Murinascia Grande, and Ri dei Calcestri, respectively, drained into the Polmengo Gallery within ~23 days, as shown in Fig. 8. A quantitative analysis of dye recovery was impossible due to the small amount of total drainage (8 L/s) compared to the volume of water in the Piora Aquifer. No Na-fluorescein or pyranine dye from Lake Ritom was ever found in the Polmengo Gallery or in the Santa Maria Valley. Lake Ritom most probably does not lose any water to the Piora Aquifer.

Within 14 to 19 days the dyes amidoflavine, pyranine, and Na-naphtionate injected into the Calderoni Sinkhole, Murinascia Grande, and Ri dei Calcestri, respectively, reached the Ri di Lareccio Springs in the Santa Maria Valley. The breakthrough and recovery of the dyes were similar to Piora-1993, as shown in Figs. 7 and 8. The low recoveries of the dyes in Santa Maria and Campo Valley are due to the strong hydrodynamic dispersion of the dyes in the large Piora Aquifer. During the pyranine dye injection, the Murinascia Grande lost 92 L/s of water (Otz and Otz 1998). The entire Na-naphtionate-colored Ri dei Calcestri (60 L/s) vanished into the weathered cagneules of the Triassic Piora Zone be-

fore it reached the confluence with the Murinascia Grande River.

The most striking discovery was that the dyes amidoflavine, pyranine, and Na-naphtionate injected into the Calderoni Sinkhole, Murinascia Grande, and Ri dei Calcestri, respectively, reached the di Campo Valley more than 13.5 km away in only 38 to 45 days, as shown in Figs. 8 and 9. From the recovered concentrations, 40 to 50 L/s of ‘Piora water’ reaches that valley.

In August of 1999, pyranine dye was found in the anoxic monimolimnion of Lake Cadagno, as shown in Fig. 5. This dye was injected in the Murinascia Grande River during dye tracing test Piora-1997. The residual dye in the lake is consistent with the fact that the Murinascia Grande River once flowed through Lake Cadagno (Lautensach 1914). Several subaquatic springs with high, dissolved solids content discharge in Lake Cadagno on its south shore. A dry gorge on the surface is the sole morphological remain of past times (Otz et al. 2000).

Conclusion

There is a large and complex eastward flowing water system in the weathered Triassic Piora Aquifer, located on the southern rim of the Gotthard massif in southern Switzerland. Two dye tracing tests, Piora-1993 and Piora-1997, showed that the direction of groundwater flow in the Piora Aquifer is from the Piora Valley to the Ri di Lareccio Springs in the Santa Maria Valley, and even further east to the di Campo Valley.

Lake Ritom located in the Piora Valley loses water only to the Canaria Valley at the lake’s western margin when lake level is above 1,835 m a.s.l., 15 m under the

maximal height. Above 1,835 m a.s.l., nearshore water losses increase exponentially. To avoid major water losses, the hydroelectric power plant Ritom stopped filling the lake above 1,835 m a.s.l.

Calderoni Sinkhole is located precisely on the water divide where subsurface flow and surface water diverge and move in opposite directions. Consequently, the upper Piora Valley includes two subsurface groundwater watersheds: the catchment area of the Piora Valley and that also of the Ri di Lareccio in the Santa Maria Valley. The dye tracing tests showed no hydraulic connection between the Piora Valley and the Pertusio Spring, located in the upper Santa Maria Valley.

The AlpTransit Authority recognized that the hydrogeology of the Piora Zone is very complex, and in 1993, they constructed an exploratory tunnel, the Polmengo Gallery (Figs. 5 and 9), 300 m above the base of the future AlpTransit tunnel to evaluate the hydrogeology and engineering properties of the Piora Zone before the AlpTransit is built (Fellner 1999). These investigations showed that a dry, compact, and unfractured dolomite and anhydrite sequence forms a no-flow boundary at the base of the Triassic Piora Aquifer. This mechanically competent and unweathered rock should serve as an effective barrier to significant seepage into the tunnel when it is built (Fellner 1999).

Some dye from earlier tests did enter the exploratory tunnel. As the drilling of the Polmengo Gallery reached the Piora Aquifer in 1996 (Fig. 9), stagnant waters, which contained dasyn dye in low amounts (2 ng/L water) drained for 4 h into the tunnel before discharge rapidly decreased. This dye had been injected in the dye tracing test Piora-1993. Due to minor drainage into the Polmengo Gallery a cone of depression formed, and the draining water temperature decreased from 12 to 9.5 °C. Rock temperatures at this depth should be normally ~30 °C. The low temperatures imply a large active hydrologic system above the stagnant water zone in the Piora Aquifer, as shown in Fig. 9 (Fellner 1999).

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