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Groundwater thermal monitoring to characterize streambed water fluxes of the Brenta river (Northern Italy)

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Abstract

The work proposed deals with the characterization of temporal and spatial variability of water exchange fluxes from/to the Brenta river streambed (Veneto, Italy), critically important to regional water resources management. The aquifer system evolves from a large undifferentiated aquifer close to the adjacent mountain ranges, later developing into a well-structured multi-layer system made up of six well-defined confined aquifers constituting the noteworthy subsurface reservoirs of the area. A three-dimensional groundwater flow model of the multi-aquifer system of the Central Veneto, within a 3300 km² area, integrating a large amount of data, has been developed to analyze the behaviour of this large, complex and well-monitored sedimentary system. The temporal and spatial variability of the water exchange flux is investigated using heat as a tracer in conjunction with water-level measurements (in the river and in piezometers close to the river): an effective method for estimating groundwater/surface water exchanges. In the study area, 5 groundwater monitoring wells (4 on the right bank, 1 on the left bank) were drilled along the river banks near a pilot transversal ramp (permeable river barrier) built in order to reduce the downstream flooding risk and to increase the river dispersion. A hydrothermal model of the river and of the underlying aquifer was implemented to improve the estimation of the water exchange between the Brenta river and the aquifer system. The contribution of exchange between the river and the underlying aquifer is quantified by comparing simulations of water flow and heat transport to observed temperature and levels in river and in groundwater.

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1. Introduction

The area of interest is located in North-Eastern Italy (fig. 1) encompassing the large, deep multiaquifer groundwater reservoir formed in the quaternary deposits of the Po plain sedimentary basin and the Brenta river system [1] [2]. In this area several projects are under investigation to withdraw water from the Brenta river both for aquifer recharge and anthropic consumption. Wise management of this resource needs to consider potential effects upstream and downstream of the area of interaction of the intimately coupled river and subsurface system. Spring emergence (termed risorgive, i.e. the spring sites where spatially widespread surficial emergence of the first phreatic aquifer occurs ephemerally) characterizes a broad area located roughly in correspondence to the transition from the unconfined to the confined aquifer system (fig. 1).

Recharge is mainly originated from the fractured system forming the Pre-Alps (the Asiago Plateau), by rain and by significant streambed dispersion of the Brenta river flowing from the Alps. A distinct feature of the subsurface basin is the presence of an undifferentiated unconfined aquifer system formed by alluvial deposits developing on a strip of roughly 5 to 20 km bordering the piedmont region and characterizing the entire Venetian plain. Outside this strip, a well-defined confined, multiaquifer system originates from the alternation of silty-clayey layers and sandy fine-grained aquifers. Both the undifferentiated and the multiaquifer systems are heavily exploited for urban, industrial and agricultural uses. The depth of the phreatic surface with respect to the ground level starts at a few tens of meters in the piedmont zone and gradually decreases to zero developing in a strip of spatially distributed plain springs just south of the appearance of the first low permeability lens, called the area of the risorgive (or
All groundwater levels maps realized using several data acquisition campaigns reveal a different behaviour between the upper part of the Brenta river (from Bassano to spring emergence groundwater flux lines are diverging from the river) and the lower part of the Brenta river (from spring emergence to Carturo groundwater flux lines converge towards the river). The upper portion of the river, of about 12 km, is characterized by stream levels greater than groundwater levels and so there is a water flux from river to aquifer through streambed; in the lower part of the Brenta river, of about 13 km, stream levels are lower than groundwater levels (which are close to ground level) and the aquifer recharges the river through streambed. The transition between dispersing and draining streambed depends on groundwater levels: in the periods characterized by high groundwater levels the inversion of the behaviour of the river shifts towards the north because the phreatic surface intersect the ground level further north.

2. Material and Methods

The three-dimensional (3D) flow model of the aquifer system [1] [2] is calibrated through the large number of available observational data, chiefly concerning phreatic and piezometric surfaces, censuses, and evidence gathered from pumping tests. The water balance includes the following components: 1) the net infiltration of the rain, 2) the water discharge dispersed and drained by rivers and 3) by irrigation channels and fields, 4) water discharges from the springs and 5) the water fluxes springing from, or pumped out by, a large number of private and public wells operating in the area. The water flux exchanged between the Brenta river and the underlying aquifer represents an important rate to the recharge of the aquifer system and it is about the 22% of total ingoing water flux (average annual values of about 12 m$^3$/s out of 50 m$^3$/s). The three-dimensional geological model of the system (i.e. its conceptual model), set up by means of extended geological sections and stratigraphies, is used to create the unstructured finite elements grid. Necessary field data concern the local hydraulic conductivity/transmissivity of the aquifers. The steady state calibration is carried out based on real phreatic surface obtained by interpolation of about 100 phreatic observational wells. Estimates of water exchange have been carried out in the past by means of differential discharge measurements along the river (fig. 1).

The investigation campaigns of the past have permitted to extract a correlation between the river discharge and water dispersion through the streambed: if the stream flow discharge is of about 10 m$^3$/s the water exchange toward the aquifer is of about 7 m$^3$/s, when water discharge of the river is of about 150 m$^3$/s, the flux ingoing to the aquifer is about 20 m$^3$/s. The draining nature of the lower part of the river (characterized by a water flux from the aquifer to the river) has not been investigated adequately because of the difficulty to conduct differential discharge measurements in the second portion of the river characterized by large and changeable sections, by a great number of gains and losses from surface channels and by the presence of several expansion areas very close to the river and variously interconnected with it. The drained groundwater discharge from the first unconfined aquifer seems to be equal or slightly higher than the water flux from the river to the aquifer of the upper part of the river. So the discharge of the river at the beginning and at the end of the dispersing and draining streambed is approximately equal, taking into account the uncertainty of these measurements. The accuracy of this type of measurements is limited by partially known river diversions and uncertainties in discharge measurements, especially during extreme events. Moreover, they do not give any information on the temporal and spatial variability of the exchange.

Using heat as a tracer, the simplest and most available natural tracer along the river channel and its aquifers, allows to investigate the temporal and spatial variability of the water exchange flux. In fact, using heat as a tracer, in conjunction with water-level measurements (within the river and in nearby
piezometers) has been shown to be an effective method for estimating groundwater/surface water exchanges [3] [4] [5] [6] [7] [8] [9] [10] [11]. This method requires continuous monitoring in time of the water temperature and the levels of the stream jointly with suitable samples of the temperatures and the piezometric levels of groundwater (if possible, at multiple depths).

In particular, in the study area, 5 groundwater monitoring wells (4 on the right bank: Pz1, Pz1-1, Pz1-2, Pz1-3, 1 on the left bank: Pz2) were drilled along the river banks near a pilot transversal ramp (permeable river barrier) built in order to reduce the downstream flooding risk and to increase the river dispersion; these points have been monitored with automatic head and temperature data loggers since March 2007 (Pz1, Pz2) or since June 2014 (Pz1-1, Pz1-2, Pz1-3). A river stage data logger has also been installed near the permeable check dam in April 2010, in order to obtain hydraulic head and temperature values of the stream (fig. 2).

Then a hydrothermal model has been developed in order to optimize the seepage estimation and to simulate the thermal trends observed in monitoring wells. In such manner it has been possible to calculate the flow rate from the river to the aquifer.

![Fig.2. Monitoring wells, river data logger and S1 ramp.](image)

### 3. Results

Field measurement confirm that groundwater temperature and levels are heavily conditioned by the streambed dispersion, even in furthest monitoring point.

For example, well Pz2 is nearer to the streambed and the observed values reveal a direct relation with river leakage. The further well Pz1 starts to show the stream seepage influence only in post-operam condition, after the realization of a ramp, demonstrating a clear variation in the hydrogeological regime.

Infact, after the completion of the permeable barrier (which consist of the enlargement of the leakage zone upgradient the ramp) persistent rises of water table (of about 4 meters) have been detected in near monitoring wells (fig. 3). This condition seems to be stable during a long-term monitoring period which
includes all the different phases of the hydrogeological regime. Thermal datasets proved to be useful to validate the artificial groundwater recharge effectiveness (fig. 4). For example, in monitoring well Pz1, that was at first barely influenced by the stream leakage because of the greater distance from Brenta river, a marked head and temperature variation was identified after the realization of ramp S1.

The river influence on temperature and hydraulic head of the monitoring well (Pz1 and Pz2) is different in winter or in summer (fig. 5). In winter, a river flood instantaneously raises the hydraulic head of well Pz1 and well Pz2; the water temperature of well Pz2 drops gradually and reaches the minimum value in 8-10 days (events 1 and 2 in fig. 5) due to the arrival of the cold water; the water temperature of well Pz1 does not change due to the great distance from the river (during a flood event). In summer, a river flood instantaneously raises the hydraulic head of wells Pz1 and Pz2 but the impact on temperature is not evident due to the lower temperature of the river water and of the groundwater, similar to the temperature of the flood water (events 3, 4 and 5 in fig. 5). The first model simulations estimate a medium leakage discharge of about 4 m$^3$/s/km. This value is perfectly comparable with the previous field measurements, confirming the numerical tool validity for river seepage evaluation.

![Fig. 3. Groundwater levels and river head (5 years).](image-url)
Fig. 4. Water temperature of the monitoring well Pz1 and Pz2 and of the river (5 years)

Fig. 5. Temperature and hydraulic head of the monitoring well Pz1 and Pz2 and of the river in winter and in summer
References


