Modelling present and future Po river interactions with alluvial aquifers (Low Po River Plain, Italy)
M. Mastrocicco, N. Colombani and A. Gargini

ABSTRACT

A modelling study on a multi-layered confined/unconfined alluvial aquifer system was performed to quantify surface water/groundwater interactions. The calibrated groundwater flow model was used to forecast climate change impacts by implementing the results of a downscaled A1B model ensemble for the Po river valley. The modelled area is located in the north-western portion of the Ferrara Province (Northern Italy), along the eastern bank of the Po river. The modelling procedure started with a large scale steady state model followed by a transient flow model for the central portion of the domain, where a telescopic mesh refinement was applied. The calibration performance of both models was satisfactory, in both drought and flooding conditions. Subsequently, forecasted rainfall, evapotranspiration and Po river stage at 2050, were implemented in the calibrated large scale groundwater flow model and their uncertainties discussed. Three scenarios were run on the large scale model: the first simulating mean hydrological conditions and the other two simulating one standard deviation above and below the mean hydrological conditions. The forecasted variations in groundwater/Po river fluxes are relevant, with a general increase of groundwater levels due to local conditions, although there are large uncertainties in the predicted variables.

Key words | aquifer, climate change, groundwater–surface water interactions, modelling, scenario

INTRODUCTION

Climate change will affect groundwater resources at the watershed scale in many ways (Alley 2001; Earman & Dettinger 2011). Potential impacts of global change on surface water have been studied in detail (IPCC 2007a, b), but these studies address specifically large scale climate patterns and trends. In particular, at the watershed scale, environmental changes might be responsible for the concentration of higher runoff in fewer events during the year and might deteriorate the capacity of rivers to sustain low flow discharge due to the longer duration of drought periods (Brath et al. 2003; Bates et al. 2008). Increased streamflow variability will be induced, also, by the decreasing of snow/ice storage, concurrently causing the decrease of the low flow period’s duration and, consequently, of available surface water resources (Kundzewicz et al. 2008; Weiß 2011).

In addition, there are still large uncertainties about how groundwater resources will react to climate changes, except for global scale studies (Green et al. 2007, 2011; Döll 2009; Bovolo et al. 2009). The studies developed in the last decade to assess the fate of groundwater resources at the watershed scale in response to climatic changes are few (Loaiciga et al. 2000; Candela et al. 2009; Gray & McCabe 2010). Actually there is a lack of groundwater modelling studies that use the downscaled results of global scale models to target aquifers, although the body of literature has been expanding recently (Hanson & Dettinger 2005; Scibek et al. 2007; Essink et al. 2010; Abd-Elhamid & Javadi 2011; Hanson et al. 2012). The need for a downscaled prediction from global climate models to watershed scale models has been highlighted by Flint & Flint (2012).
Beside these issues, future climate scenarios are highly uncertain (Blöschl & Montanari 2010), but their degree of uncertainty is not often discussed or quantified with respect to the observed natural variability of hydrological variables, like streamflow rates (Montanari 2012).

Within the Mediterranean region, Italy is characterized by an intricate pattern of coasts and mountain belts (Alps and Apennines) with a high variability of ground elevations. The complex morphological pattern, together with the bathymetry of the sea floor, affect key parameters of the Mediterranean climate such as lee cyclogenesis (Trigo et al. 2002) and deep water formation (Millot 1999). Consequently, climate change forecasts within the Mediterranean area should use reliable regionalization techniques, like the PROTEUS regional earth system model described and validated by Artale et al. (2010). This model was recently implemented to forecast changes in Po river discharge near Ferrara (Italy) following the A1B scenario calculated by Dell’Aquila et al. (2012) for the Po river catchment; the A1B scenario assumes a rapid economic growth in the developing countries and a stable growth in the other countries, a global population that will attain a peak mid-century, and a balance between fossil and non-fossil energy resources.

The big rivers like the Po are a primary source of water, directly or indirectly through lateral recharge, for a variety of purposes: human consumption, agriculture, industrial activity. This is particularly true in the lowland floodplains near the sea shore where, because of the abundance of fine sediments and the need to avoid the negative effects of salinization and subsidence, the use of groundwater resources often becomes inadvisable (Teatini et al. 2005; Mastrocicco et al. 2013).

In the lower Po river plain, an interesting alternative groundwater resource could be identified in tabular sandy bodies and in paleo-channels constituting a complex multi-layer aquifer system deposited during the Quaternary sedimentary evolution of the plain. These sandy bodies are in direct hydraulic connection with the river and thus laterally recharged by it; moreover, they extend for tens of kilometres away from the Po river and might act as potential natural attenuation reactors of contaminants in solute phase if used as an alternative water resource supply.

The aim of this study is to quantify the impact of future scenarios induced by climate change using a downscaled prediction to 2050 for the Po river lowland, and to discuss the sources of uncertainty that could impact the model post audit. The modelling process presented here provides a representative case study (calibrated against actual high river flow and drought events) about the expected modifications of groundwater resources induced by climate change in temperate Mediterranean lowland settings.

SETTING OF THE AREA STUDIED

The study area is located in the lower sector of the Po river plain, on the eastern side of the Po river (Figure 1), corresponding to the Province of Ferrara (Emilia-Romagna region, Northern Italy), within the Burana Canal-Volano Po artificial drainage basin. This zone has been subjected to mechanical reclamation with pumping stations since 1925. The landscape is flat with elevations ranging between 13 m above sea level (a.s.l.) where mound reliefs of paleo-river beds outcrop and 5 m a.s.l. within morphologic depressions of interfluvial basins.

Hydrogeological conceptual model

Local geology is essentially the result of recent and mainly alluvial geomorphological dynamics, from the Lower Pleistocene to the present day (Castiglioni et al. 1999). The main sedimentary process is the Holocenic progradation of the paleo-Po delta apparatus, formed by an irregular network of channels and fine-grained interfluvial basins above a paleo-erosion surface represented by Würmian (Upper Pleistocene) fluvo-glacial sandy deposits, settled in a cold environment by braided rivers with considerable sediment transport capacity (Amorosi et al. 2005; Simeoni & Corbau 2009).

The resulting hydrogeological setting (Figure 2) is a Holocenic plot of irregular paleo-riverbeds with low gradients and sinuous shapes (braided zone in Figure 2), and depressed areas of interfluvial basins (upper layer, Figure 2), above a Holocenic tabular sandy body of regional extension (lower layer, Figure 2). In historical times the evolution of the study area was conditioned by
the migration of the southern branch of the Po river delta. In Figure 3 the model discretization and boundary conditions assignment are shown. The original meandering course of the Poazzo paleo-channel, dating back to Etruscan times, was followed by the formation of the so-called ‘Ferrara Po’, from Roman times. The Ferrara Po remained the most important channel of the whole Po system at least until the so-called levee breach ‘Rupture of Ficarolo’ (about 900 years ago), after which the present branch of the Po river became the main one. After this flood event, the Ferrara Po began its decline until it became a less important channel about 700 years BP and was finally excluded from the active surface water runoff about 400 years BP (Bondesan et al. 1998).

The complex of the paleo-river beds is fragmented and heterogeneous, consisting of fine to medium sands with a thickness in the range 5–13 m, locally covered by a few meters (maximum 2) of silty clay sediments. These discontinuous sandy bodies (braided zones in layer one Figure 2) constitute the unconfined aquifer called A0 (Molinari et al. 2007). Where paleo-river beds are not present, a silty-clay overbank layer with thickness of 10–15 m, deposited inside interfluvial basins, overlays directly the Würmian sands. Paleo-river channels, where present, are separated by 6–10 m of silt, clayey silt and clay layers (middle layer, Figure 2), from the underlying Holocenic sands. Only locally, in correspondence with the main and deeper paleo-channels, do they merge with the Würmian sands. The latter constitute a 20–25 m thick, southward dipping sandy body called A1. The local merging of the two complexes leads to the formation of a single unconfined aquifer of thickness up to 40 m (Mastrocicco et al. 2011), like in the case of the ‘Poazzo’ paleo-river bed.

Below aquifer A1 there is a thick silty-clay bed (10–25 m) that impedes the hydraulic connection between A1 and A2; this latter bed is the second confined aquifer constituted of 15–25 m thick Pleistocene fluvial sands. The two complexes are hydraulically separated but they merge on the western edge of the study area. The thickness of the Holocenic-Pleistocene sandy aquifers is greater than 150 m where A1 and A2 merge (Figure 2) and rapidly decreases eastward down to about 25 m. The lower limit of the A1–A2 complex is given by a thick clay layer which acts as an aquiclude.

**Water supply**

The two local public water supply authorities (HERA Spa and CADF Spa) utilize the Po river as their primary water

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**Figure 1** | Three-dimensional representation of the model domain, vertical exaggeration 1:100. Shaded areas: model layers; labelled polylines: rivers and canals; black tubes: available stratigraphic logs; the coordinate system is UTM-32 and the Z axis is in m above sea level.
resource, by either river bank filtration or direct abstraction from the river with a total abstraction rate of ≈300 l s⁻¹. Surface waters are subject to a greater risk of contamination and consequently often require expensive purification treatments; in addition, they are exposed to recurrent droughts during the season of greater water demand (as in the case of recurrent extremely low flow summer–early fall periods of the Po river across the 2003–2006 time span). At the same time, river-bank filtration pumping schemes are similarly to be considered at risk for their proximity to the river (due to the possibility of direct exposure of contaminants with no purification effect) and for the associated risk of levee subsidence and decreasing permeability of the river bed (Brunke & Gonser 1997).

The implementation of groundwater abstraction schemes in these sandy bodies could enhance induced recharge from the Po river, maintaining the distance between the river and the pumping site; at the same time they could represent ideal underground reservoirs for siting artificial recharge projects. Locally, further opportunities might arise from abstraction schemes affecting groundwater fed residual lakes formed inside open-hole sand pits, excavated for sand mining purposes inside the path of main paleo-river channels. Substantially these
lakes, via the paleo-channel, are laterally recharged by the Po river and their water is often of good quality, much better than the Po river water (Molinari et al. 2007). For these reasons it is important to manage these alternative water resources with the help of numerical modelling.

MODEL SET UP

The transition from the conceptual model to the numerical model has been developed according to successive refining stages. The finite-differences three-dimensional numerical flow model MODFLOW-2005 (Harbaugh 2005) was used, either in steady or transient state.

The model domain has an extension of 576 km² and has been subdivided into 180 columns and 80 rows with cells of 200 x 200 m (Figure 2); 380 km² of the domain are defined by active cells. The vertical discretization has been completed through subdivision into three layers of variable thickness: the first reproduces the silty clay sediment outcrops and the A0 paleo-river beds complex; the second consists mainly of silty clay sediments interrupted by the paleo-river bed of ‘Poazzo’, connecting the A0 aquifer with the aquifer A1; and the third layer represents the A1 aquifer and the coalescence of A1 with A2 near the western edge of the domain. The topography in the top of the first layer was reproduced using a digital elevation model (DEM) with 50 x 50 m grid and re-interpolated in MODFLOW-2005 (Kriging method with a linear variogram). The thickness of the three layers was reconstructed interpolating 2467 core logs obtained from the Geological, Seismic and Soil Survey of Emilia Romagna Region.

The initial values of the hydraulic conductivity (K) are based on the values reported in Table 1. The K zone assignment is based on stratigraphic logs and the K values are an average of all the available data resulting from 29 pumping tests, 44 slug tests performed in the sandy sediments, and 12 grain-size analyses on clay and silty-clay sediments (Mazzini et al. 2006; Molinari et al. 2007).
At first, a large-scale steady state model was produced, calibrated versus hydraulic heads derived from 96 observation wells in June 2003 (drought conditions) and validated versus hydraulic heads in January 2004 (high level conditions); although, the modelled system cannot be considered fully in steady state, this assumption was justified in order to gain an overall picture of the aquifer system and its main features. As a second step, a transient flow model was performed on the central portion of the domain through a telescopic mesh refinement of the large-scale model. This transient flow model accounted for variable river stage, recharge rate and evapotranspiration (Figure 3) and was calibrated versus continuous data recorded in four piezometers and discontinuous head data recorded monthly in another 24 piezometers from July 2002 to February 2003, and validated from March 2003 to January 2004 using the same observation wells.

The boundary conditions imposed on the large-scale flow domain are represented by a no-flow boundary at the southern edge, due to stratigraphic pinch-out of the aquifers A0 and A1, general head boundaries at the eastern and western sides, and the river boundary (Po river) at the northern side. The general head boundary (GHB) was used since the aquifer is not physically limited to the modelled portion, but piezometric data were not available for the modelled period. In addition, the Panaro river is simulated with the river package and also the Napoleonic canal, since its interaction with the unconfined aquifer is not negligible (Mazzini et al. 2006).

Only pumping wells considered relevant for the flow domain were simulated (with a declared pumping rate > 21 l s⁻¹): public supply well fields (390 l s⁻¹ in June 2003 and 330 l s⁻¹ in January 2004), industrial (20 l s⁻¹ constant) and domestic irrigation wells located only in the western portion of the domain (20 l s⁻¹ in June 2003 and 30 l s⁻¹ in January 2004).

The transient modelling covers a period from July 2002 to January 2004 and is divided into 78 stress periods of variable length, necessary to discretize the variations of the stages of the Po river during the simulated time frame. This period was modelled since it includes both an important high flow event of the Po river in fall 2002 and the intense drought of the summer 2003. The Time Variant Constant Head Package was used to simulate water table fluctuation at the northern (Po river) eastern and western sides of the domain, which allows constant head cells to take on different head values for each time step, linearly interpolating the values of the prescribed hydraulic heads for each time-variant specified head boundary cell. The River package was used to reproduce the stage variations of the Panaro river and Napoleonic canal. The GHB package was used to reproduce the water table fluctuation at the western and eastern boundaries using continuous data from two monitoring wells located near to these boundaries.

Daily reference actual evapotranspiration (ETₐ) was calculated by the FAO recommended Penman–Monteith equation, assuming that grass cover at the site resembles the reference surface as defined by Allen et al. (1998). Potential transpiration and evaporation were split using an estimated surface cover fraction of 0.8 (Ritchie 1972). Runoff was assumed negligible due to the flat topography and according to the results of other studies in the area (Mastrocicco et al. 2010). Meteorological parameters (daily rainfall, wind speed, temperature and humidity) were derived from four stations located in the area; solar radiation data were recorded in another station located in Ferrara town. Meteorological data are available online from the Emilia-Romagna meteorological regional service (www.dexter.it).

For each model (steady state and transient) described above, a calibration process was carried out using the numerical inverse modelling code, PEST (parameter estimation) (Doherty 2002). This process has been performed on the following parameters: horizontal K of the four hydrogeologic units (see Table 1), rivers hydraulic conductances, evapotranspiration and recharge (direct from precipitations and from irrigation systems). The K and rivers hydraulic conductance values were optimized for the steady state model (using both piezometric campaigns), since they

<table>
<thead>
<tr>
<th>Assigned K values (m s⁻¹)</th>
<th>PEST optimized K values (m s⁻¹)</th>
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</thead>
<tbody>
<tr>
<td>Clay 1.0 × 10⁻⁹</td>
<td>Clay 1.0 × 10⁻⁹</td>
</tr>
<tr>
<td>Silty-clay 1.0 × 10⁻⁸</td>
<td>Silty-clay 1.0 × 10⁻⁸</td>
</tr>
<tr>
<td>Medium sand 2.3 × 10⁻⁴</td>
<td>Medium sand 2.5 × 10⁻⁴</td>
</tr>
<tr>
<td>Coarse sand 6.2 × 10⁻⁴</td>
<td>Coarse sand 5.0 × 10⁻⁴</td>
</tr>
</tbody>
</table>
were considered intrinsic parameters of the aquifer that did not change with time. The recharge and evapotranspiration rate were optimized in each steady state model and in the transient model, while in the transient model the $K$ and rivers hydraulic conductances values were not optimized, but kept fixed from the optimized steady state model shown in Table 1. Prior information on isotropic distribution of $K_x$ and $K_y$ values and on the ratio between horizontal and vertical $K$ values were used in order to constrain parameters estimation; the objective function consisted of all available piezometric heads. Each screen interval was subdivided with the layer proportion to ensure that calculated heads were related to the observed heads. If an observation borehole is screened over more than one model layer, and the observed hydraulic head is affected by all screened layers, then the associated simulated value is a weighted average of the calculated hydraulic heads of the screened layers. The $K$ parameters were log-transformed, while the other parameters were left linear for the inverse modelling. The calculated ET$_a$ and observed precipitation were used as an initial guess for the recharge rate and evapotranspiration parameters in both steady state and transient models. The specific storage and yield for transient simulations were set to $5 \times 10^{-6}$ m$^{-1}$ and 0.17, respectively; from a preliminary sensitivity analysis they were judged to be fairly insensitive and thus not included in the model calibration.

**Climate change scenario modelling**

The model was run using forecasted precipitation, evapotranspiration, and Po river stages at 2050 and their predicted variability, as derived from downcaled regional simulation ensembles of the PROTEUS model (Dell’Aquila et al. 2012). The downcaled simulation on the Po river watershed, based on the A1B development scenario of IPCC, considered the most probable one, shows very little change in precipitation and evapotranspiration within the modelled domain. Three transient state scenarios were run at the large scale model domain: one simulating mean hydrological cycle conditions forecasted by the PROTEUS model for the years 2048–2052, and the other two simulating one standard deviation above and below the mean hydrological cycle conditions. Since the PROTEUS model output is expressed in discharge rate, this was converted into Po river stage using the relationship developed by Zanchettin et al. (2008) and linearly interpolated along the simulated river branch.

The simulation time was split into 48 stress periods of 30 days each with every stress period further subdivided into four time steps. Pumping well rates, general head boundaries and Dirichlet type boundary conditions (Panaro river and Napoleonic canal) were left unchanged with respect to the current conditions, in order to provide insight on only effects caused by the forecasted Po river discharge variations. Since the piezometric heads of the GHB are unknown in the future due to possible changes induced by both natural and anthropogenic variability, two additional scenarios were implemented using the base case scenario with mean forecasted Po river discharge to account for these sources of uncertainty. In the two scenarios, the western and eastern GHB stages were increased and lowered by 1 m with respect to the actual values.

**RESULTS AND DISCUSSION**

**Steady state groundwater flow model**

Initially, the steady state numerical model was run without the GHB in the middle of the eastern portion (Figure 3), resulting in a very poor performance of calibration: the largest residual between calculated and observed hydraulic head was limited to the western side of the domain, where the simulated head contours are perpendicular to the Po river course. Actually, head contours derived from the 2003 and 2004 surveys generate an apparently ‘anomalous’ piezometric divide, parallel to the Po river course. Actually, head contours derived from the 2003 and 2004 surveys generate an apparently ‘anomalous’ piezometric divide, parallel to the Po river course, in the western side of the domain. This anomaly was not correctly modelled using a uniform hydraulic parameter distribution in the aquifer. Thus, different hypotheses were proposed: an unexpected heterogeneity of the aquifer structure, due to clay lenses or the occurrence of a main paleo-channel of higher hydraulic conductivity, or the coalescence between the A1 and A2 aquifers.

To test the soundness of the different possible conceptual models, three numerical flow scenarios were implemented in the framework of the steady state model:
both the conceptual models about aquifer heterogeneity were rejected because of a very poor calibration attained, supported also by no geological or geomorphological clues such as stratigraphic logs, aerial photographs and historical reconstructions indicating strong aquifer heterogeneities. Much better results were obtained taking into account coalescence between the A1 and A2 aquifers; Table 1 shows the comparison of the average $K$ values derived from all the available observed dataset given as initial estimate and the optimized $K$ values from PEST. There is little variability from the initial guess and the optimized $K$ values for the sandy units, while no appreciable changes are given for the aquitard units. This information also leads to exclude other different conceptual models.

The calibration was performed against either an exceptional drought head survey in June 2003 or in January 2004 (Figure 4). The mean absolute error of the residual between observed and calculated values is 0.13 m for the 2003 scenario and 0.15 m for the 2004 scenario (Figure 5); this last scenario has a slightly higher variance due to the effects of a flood of the Po river which occurred a few days before the piezometric survey (basically this system cannot be defined as stationary).

Numerical steady state modelling improved the interpretation of the piezometric distribution over the area with respect to a simple interpolation. Simulated head contours are similar for 2003 and 2004 with the occurrence of pumping depressions in the eastern side of the model domain, a mound in the middle portion, related to lateral

![Figure 4](https://iwaponline.com/jwcc/article-pdf/5/3/457/375109/457.pdf)
recharge of the Napoleonic canal, and a piezometric divide at the western side of the domain, related to seepage from the A2 to the A1 aquifer. The Po river is always draining the aquifer system except for aquifer lateral recharge induced by bank filtration plants.

The budget performed on the whole flow domain satisfied the continuity equation of the system (Table 2).

Aquifer recharge was less than one order of magnitude compared to the summation of the pumping rate and Po river lateral/induced recharge; out of an estimated mean flow rate of 466 l s⁻¹ entering into the aquifer system, about 75% came from the Po river leaching. Water leaching from the Napoleonic canal was relevant, attaining values of 25 and 27 l s⁻¹, in June 2003 and January 2004, respectively, while it did not drain groundwater from the aquifer system. By contrast, water leaching from the Panaro river was null, while it drained groundwater from the aquifer system. The upflow from aquifer A2 to A1 was limited and attained approximately 7% of the total aquifer inflow.

River bank filtration plants seemed to collect water in large amounts directly from the Po river and this explains how the capture zone was not so widespread despite the high pumping rates; however, the most important external stress, particularly in the 2003 summer period, was represented by public water supply pumping wells along the right river bank near Ferrara (Figure 3) with a total abstracted rate of 270 l s⁻¹.

The recharge, as fitted from inverse modelling, was higher in summer 2003 than in winter 2004, most probably due to the large use of irrigation during June for water exigent crops like maize, while evapotranspiration was 10 times higher in summer than in winter.

Table 2 | Entire domain budget for the steady state models; fluxes are expressed in m³ s⁻¹ (June 2003; January 2004)

<table>
<thead>
<tr>
<th>FLUXES (m³ s⁻¹)</th>
<th>June 2003</th>
<th>January 2004</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IN</td>
<td>OUT</td>
</tr>
<tr>
<td>Wells</td>
<td>0.00</td>
<td>4.30 × 10⁻⁰¹</td>
</tr>
<tr>
<td>Recharge</td>
<td>4.08 × 10⁻⁰²</td>
<td>0.00</td>
</tr>
<tr>
<td>Actual evapotranspiration</td>
<td>0.00</td>
<td>9.34 × 10⁻⁰³</td>
</tr>
<tr>
<td>Flow from A2</td>
<td>3.45 × 10⁻⁰²</td>
<td>0.00</td>
</tr>
<tr>
<td>Western boundary (GHB)</td>
<td>1.76 × 10⁻⁰²</td>
<td>6.04 × 10⁻⁰³</td>
</tr>
<tr>
<td>Eastern boundary (GHB)</td>
<td>1.99 × 10⁻⁰²</td>
<td>0.00</td>
</tr>
<tr>
<td>Po river</td>
<td>3.72 × 10⁻⁰¹</td>
<td>4.81 × 10⁻⁰²</td>
</tr>
<tr>
<td>Panaro river</td>
<td>1.19 × 10⁻⁰⁴</td>
<td>1.63 × 10⁻⁰²</td>
</tr>
<tr>
<td>Napoleonic canal</td>
<td>2.49 × 10⁻⁰²</td>
<td>0.00</td>
</tr>
<tr>
<td>TOTAL</td>
<td>5.10 × 10⁻⁰¹</td>
<td>5.10 × 10⁻⁰¹</td>
</tr>
<tr>
<td>DISCREPANCY (%)</td>
<td></td>
<td>7.65 × 10⁻⁰⁵</td>
</tr>
</tbody>
</table>

Figure 5 | Plot between calculated and observed heads of observation points (monitoring piezometers and pumping wells) for the two steady state scenarios.
Transient groundwater flow model

The calibration process by inverse modelling was based on head data collected on four boreholes in the continuous monitoring network and also on the monthly head recording carried out, by the Regional Technical Service of Reno Basin, in 24 boreholes located along the route of the Napoleonic canal. In the first stage of the transient model calibration, evapotranspiration and river (Panaro river and Napoleonic canal) packages were not activated, but they had to be included since otherwise a very poor match between observed and calculated heads was obtained (not shown). This is because they act directly on the shallow unconfined aquifer, in particular not taking into account direct evapotranspiration from the water table would produce simulated head values systematically higher than the observed ones. The achieved calibration performance was good with a mean absolute error of only 0.072 m (comparison between simulated and observed data in the four continuous monitoring boreholes).

The transient modelling allowed testing the effects of the Po river flood events on the groundwater flow system. The distance of influence on the hydraulic heads extends only up to 2 km away from the Po river, considering that only the behaviour of P1 borehole (Figure 6) is accurately described taking into account the Po river interactions alone. During a flood event the average groundwater flow direction, relative to the portion of the affected model domain, changes from a seaward East-West axis to a Northwest-Southeast axis. On the other hand, the head variations

of other monitoring boreholes, also during a Po river flood event, are principally affected by local factors such as recharge, evapotranspiration from the water table or Napoleonic canal leakage.

**A1b scenario models**

Given a set of linked models from a regional downscaled climate model to a local groundwater flow model, such as those presented here, the feedback and sensitivity of a specified hydrologic system to possible climate changes might be assessed in order to manage the groundwater resources for different purposes like agricultural, industrial and drinking supply.

The lowland Po river valley numerical flow model, once integrated with forecasted climatic data derived from downscaled models, delivers insights into the consequences of climate change on groundwater resources within the complex aquifer system highly linked with the surface water hydrologic system. The aim was to verify how downscaled precipitation and temperature regimes, produced as output from the PROTEUS climate change scenario, drive the Po river discharge and stage regime so affecting the modelled groundwater domain. The hydraulic behaviour of the middle and lower portion of the Po river is rather complex, particularly during high flows, making one-dimensional hydrodynamic models sometime unsuitable for an accurate representation (Castellarin et al. 2011a, b). Also, the natural stream-flow regime can be heavily impacted by anthropogenic effects (withdrawals, multi-purpose water retention in a number of reservoirs located in the headwater subcatchments, etc.) particularly during low-flows, and these human interactions and their change in time are very difficult to predict.

Surface water levels exert a very important control on the groundwater recharge of alluvial aquifers and they may change dramatically independently of climate change due to the construction of river engineering works (e.g., backwater effects associated with the construction of a weir), or differential land-subsidence, that can be very important over a 40-year time interval (Bissoli et al. 2010).

In general, these sources of uncertainties affect the variability of natural river cross-sections in time, that alters the cross-section rating-curve (Domenechetti et al. 2012). This is particularly important, since the predicted future water level stage of the Po river is derived from a rating-curve observed for the last 200 years, but this relationship could change in the future due to the above-mentioned reasons and the magnitude of these changes cannot be established a priori.

In the light of these uncertainties, it is rather difficult to predict groundwater levels or discharges, but keeping in mind all these unknown variables, some conclusions can still be drawn considering that the assumed Po river rating-curve remains the same for the next 40 years.

The forecasted variations of Po river–groundwater exchange fluxes are relevant: in average hydrologic annual conditions, an increase of aquifer inflow is expected (+90 l s⁻¹ with respect to 2004) whereas the other two scenarios determine a large variability in the response of the predicted fluxes (+127 and −128 l s⁻¹ compared to 2004, respectively). The increase of lateral recharge from the Po river into the aquifer system is due to the higher forecasted Po river discharge during late winter/beginning of spring for the A1B scenario.

Figure 7 shows simulated hydraulic head in two monitoring boreholes located in the centre of the model domain (P4) and 2.4 km from the Po river (P1). P4 is not affected by the Po river stage fluctuations for both scenarios whereas it is directly influenced by the leakage of the Napoleonic canal; for this reason the variability of forecasted heads in the A1B scenario is very low. By contrast, in P1 the head excursion is relevant, being affected by the Po river discharge; a head excursion of 1.5 m is forecasted for the piezometer P1.

Analysing the results of the additional scenarios implemented to account for the sources of uncertainties in the selected boundary conditions, the effect of the GHB variation in the piezometers P1 and P4 shown in Figure 7 was negligible (less than ±0.02 m), since they were located far away from these boundaries; clearly in piezometers located near these boundaries the effect was more evident with a maximum head change of ±0.87 m. What is most interesting to note is that the flow budget showed a negligible change of the aquifer’s inflow from the Po river in both the scenarios (Table 3), a remarkable increase in the aquifer’s outflow towards the Po river in the scenario with higher GHB, and an equal decrease in the aquifer’s outflow
towards the Po river in the scenario with lower GHB. These simple scenarios show that the uncertainties in the boundary conditions do not dramatically affect the model results in terms of predicted heads and flows, but these results are only qualitative and a more extensive set of scenarios with different forcing to all of the boundaries implemented should be done to extend the findings to similar alluvial aquifers, which is beyond the aims of this study.

The analysis presented suggests the importance of also taking into account groundwater dynamics in forecasting global change effects. In the modelled area, a head rise of about \(0.7 \pm 0.24\) m is expected for scenario A1B when the Po river stage is high and, as a consequence, water table outcropping at ground surface is expected where the aquifer is unconfined, with possible impacts on the drainage network and agricultural practices. Counter mitigation schemes need to be planned in order to prevent waterlogging conditions in agricultural lands during the cropping season. On the other hand, in order to mitigate the effects of prolonged droughts, water management plans should be prepared accounting for groundwater and surface water combined use.

Either in flood or severe drought conditions it should be stressed that mitigation measures should keep the wells’ pumping rate constant and the stage of the Napoleonic canal unchanged with respect to current conditions, otherwise the groundwater level far away from the Po river may change dramatically, with relevant effects in terms of subsidence or drying of shallow wells.

**CONCLUSIONS**

Water resources in the Mediterranean basin are first of all needed for agricultural and industrial uses, and secondarily for civil purposes. These needs are in contrast with environmental requirements like the preservation of minimum
ecological stream flow. The sustainable development of water-related infrastructures necessitates an integrated water management approach. This approach needs to be supported by numerical modelling that accounts for variable scenarios to quantify possible drawbacks of actual and future water management strategies.

In the presented case, the modelling approach emphasizes the potential to explore the long-term sustainability of complex aquifer system exploitation linked with surface water bodies in relationship to expected climate change effects. The assumption made at the base of all the simulated scenarios must be verified; in fact, if they change in the near future (e.g., the Po river rating-curve), the post audit of the model results could be rather inaccurate. For the simulated scenarios, a general increase of lateral recharge from the Po river into the aquifers system is predicted, induced by the higher forecasted Po river discharge during winter/spring for the A1B scenario. This aspect is particularly relevant for areas located at low elevations and at risk of flooding.

The comparison between the supply’s potential and demand components, as forecasted in the future, could address alternate sources, uses or policies. This comparison should be considered feasible and robust only if based upon quantitative and predictive numerical groundwater flow models, prone to facilitate physically based and physically constrained environmental adaptations to climate changes. An application in a series of physically based, climatic and groundwater flow models, should become a widespread technical instrument to assist the decisions on water governance and management in lowland areas.

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