Modelling the interaction between groundwater and river flow in an active alpine floodplain ecosystem

WOLFGANG RUF, LAURA FOGGLIA, PAOLO PERONA, PETER MOLNAR, ROLAND FAEH & PAOLO BURLANDO

Abstract
Many alpine valleys are strongly affected by streamflow regulation due to hydropower operation. This is also the case for the Maggia riverine corridor, which contains one of the last remaining braided river systems with a riparian floodplain forest in Switzerland, and where regulation has led to a strong reduction in flow magnitude, variability and a drop in groundwater levels. Aerial photographs show an alteration in riparian vegetation after the hydropower system went into operation. Long-term effects of the altered surface and subsurface water flow regime on riparian vegetation is investigated in the MaVal project. Uprooting of plants due to flooding as well as deeper groundwater levels are postulated to be significant factors for vegetation growth. Therefore, hydrological variables such as inundation depth, flow velocity, duration of inundation, rate of water level rise and fall and depth to groundwater must be known in order to understand riparian vegetation development. For this purpose, we describe here a modelling framework which simulates the rainfall-runoff processes in the watershed (hydrological model), the streamflow in the floodplain (2D hydrodynamic model) and the groundwater flow (groundwater model). The core of the modelling system is the coupling between the hydrodynamic and the groundwater model, which is necessary due to the strong interaction between river and groundwater. Some preliminary results are shown here to illustrate the potential of the modelling framework to study the interaction between hydrological and vegetation dynamics in the floodplain and to develop recommendations for the establishment of new environmental flow requirements.

Keywords: Environmental flow requirements, river-aquifer exchange, model coupling, ecohydrology, Maggia valley

1. Introduction
Large hydropower dams and reservoirs are being operated in many alpine valleys of Switzerland, resulting in significant water abstraction and alteration of the flow regime downstream of the dams and intake stations since the mid 1950s. The Maggia Valley (Canton Ticino, Switzerland) with its reservoirs in the upstream part of the catchment is an example of an alpine environment highly affected by this anthropogenic intervention. Its riverine corridor is one of the environmentally most important in Switzerland, characterized by a largely undisturbed braided gravel-bed river with a highly permeable river bed and aquifer. At present, most of the tributaries from the side valleys are either diverted into the hydropower water supply system, or their discharge completely infiltrates into the coarse alluvial aquifer of the main valley before reaching the Maggia River in dry periods. Vice versa, under flood conditions, almost all water is released into the main channel. Thus, the influence of the hydropower regulation on the hydrological regime is mainly limited to low and moderate flow conditions (see also Molnar et al. 2008, this issue).
When hydropower system operation started in 1953, no environmental flow requirements were imposed. This resulted in partly dry reaches of the Maggia River. Aerial photographs show a strong alteration in floodplain vegetation during the last decades (e.g. Favre 2004, Molnar et al. 2008, this issue). Since 1982, there is an imposed constant minimum release of 1.2 m$^3$/s in winter and 1.8 m$^3$/s$^{-1}$ in summer in Bignasco, which is at the upstream end of the floodplain. The effects of the flow regulation on the floodplain aquatic ecosystem have not yet been well understood, observations are often inconclusive or insufficient to quantify them. A comprehensive modelling system of the floodplain is the most attractive alternative for understanding the response of the riverine corridor to changes in the streamflow and groundwater regimes.

Accordingly, a coupled modelling system of the river hydrodynamics and its interactions with the groundwater system is presented here. The paper focuses on a technical description of the modelling framework. Some results are presented to illustrate how this essential modelling tool will help future assessment of the impact of the altered flow regime on the floodplain vegetation dynamics. This study is conducted within the framework of a larger research project (MaVal, www.maggia.ethz.ch), which focuses on the formulation of an integrated approach including hydrological and ecological analyses at large spatial and temporal scales. The final aim of this modelling system is to investigate the long-term effects of different scenarios of the alteration of the hydrological regime on the floodplain vegetation of the Maggia’s riverine corridor, and to understand how the floodplain vegetation reacts and develops due to water stress (dropping groundwater levels) and changing flow (and flood) pulses in the main river (Foglia 2006, Ruf 2007).

Because of the braided river system with a highly variable inundation area, a 2D modelling approach for the surface water is needed (see section 3.2). Moreover, coupling this with a groundwater model is also required in order to describe the complex river-aquifer interaction dynamics (see section 3.3). The modelling system provides the temporal and spatial variability of the key hydrological variables for the dynamics of the corridor vegetation, such as surface water level, flow depth, flow velocity, piezometric groundwater head and inundated area. The results of the hydrodynamic-groundwater coupled system provide the location and rate of river-aquifer exchange in the whole river floodplain. Along with recent findings suggesting that not only flood pulses but also flow pulses below bank-full discharge are an important ecological factor for the aquatic habitat (e.g. Benke 2001), the results of these investigations will serve a comprehensive identification of the most suitable environmental flow requirements.

2. Study area

2.1. Maggia River basin

The Maggia watershed upstream of Ponte Brolla (216 m a.s.l.) with an area of 592 km$^2$ lies in the southern part of the Swiss Alps and rises up to 3272 m a.s.l. at Mount Basòdino. The main valley in the lower part of the catchment (up to Bignasco) has steep rocky slopes on both sides and was filled with deep coarse alluvial material to around 150 m after the last period of glaciation. The riverine corridor in the main valley with a length of 22 km and a width of approx. 500 m is our study area (Fig. 1). The river bed is characterized by strong dynamics and high sediment transport rates, resulting in a braided river morphology (over a length of around 7.5 km near the village of Someo in the central part of the riverine corridor)
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with altering branches after large flooding events. The Maggia riverine corridor is characterized by a narrow but deep aquifer, where the river-aquifer interaction and the hillslope contribution play by far the most important role in terms of groundwater recharge. Groundwater observations show a strong and rapid response to fluctuations of the river flow and hillslope contribution into the aquifer. Streamflow regulation by the hydropower system has led to the reduction of mean annual flow in the riverine corridor from 520 mill. m³ in the pre-dam period to 128 mill. m³ between 1954 and 1974 and 132 mill. m³ presently (1982 to 2003).

Fig. 1 Study area with the riverine corridor. The map in the inset shows the hydropower system in the same region.
2.2. Instrumentation and data

Daily runoff data in Bignasco at the upstream end of the riverine corridor are available since 1929. Additional runoff gauging stations were installed within this research project. Hydroclimatic data are available at 9 stations in the catchment (Fig. 1). The groundwater table was measured weekly between 1964 and 1978 and hourly since 2001. Eleven runoff measurements along the entire longitudinal profile of the Maggia River were carried out, along with a survey of the water level and the shoreline boundary under low flow conditions with constant runoff in Bignasco of 1.2 m$^3$ s$^{-1}$ in June 2005. A high-resolution digital terrain model (DTM) of the riverine corridor was produced by combining different data sources. The DTM vertical resolution within the braided parts of the river system is 0.5 m, whereas outside the resolution is determined by a horizontal regular grid spacing of 25 m.

3. Modelling system

3.1. MaVal project

The MaVal modelling framework (Burlando et al. 2004) accounts for the following components (Fig. 2): (1) hydrological model (TOPKAPI, Ciarapica & Todini 2002) for the entire watershed, in the future also accounting for the operation of the hydropower system (Alfieri et al. 2006), (2) hydrodynamic model for the simulation of flow and inundation in the main river bed and floodplain, (3) groundwater model for the aquifer in the main valley (Foglia 2008, Foglia et al. 2007) and a (4) vegetation growth model for simulating the floodplain vegetation dynamics (Perona et al., submitted).

![Fig. 2 Modelling framework: the gray scales represent the different modelling domains (left: entire catchment; right: riverine corridor).](image-url)
3.2. Hydrodynamic model

The hydrodynamic model »2dMb« used in the modelling system solves the shallow water equations in 2D with depth-averaged variables (Faeh 1996). The numerical scheme is an explicit finite volume one using a rectangular domain with a regular grid size of 6.25 m. The model outputs are water level and depth-averaged flow velocity in each grid cell. The hydrodynamic model is used to represent the surface water flow in the river bed and in the floodplain during inundation. The runoff in the tributaries of the main valley is considered as lateral inflow into the river system and represents a boundary condition for the hydrodynamic model. In future model developments, this lateral flow contribution will be provided either by the hydrological model TOPKAPI (in the context of the MaVal project) or directly using measured data. The hydrodynamic model can account for infiltration and exfiltration by specifying source and sink terms in each cell of the domain.

3.3. Groundwater model

MODFLOW-2000 (Harbaugh et al. 2000, Hill et al. 2000) is used to construct and calibrate the model first for steady-state conditions. Using borehole information, results from pumping tests and a geological map for the northern part of the valley, the domain is subdivided into five planar zones with different hydraulic conductivities. The model was implemented with a regular grid spacing of 25 m. Overland and subsurface flow from the hillslopes adjacent to the riverine corridor contribute directly into the aquifer. In the groundwater model, we currently use a fraction of the subsurface flow simulated by TOPKAPI as a recharge rate distributed across the appropriate boundary of the groundwater model domain.

3.4. Linkage between the hydrodynamic and groundwater model

Traditionally, hydrodynamic and groundwater models run uncoupled from each other. However, because both models have a spatial representation of the water levels and flow rates in each of their cells, a coupling of the two can be established to model the water exchanges and thus the mutual interaction between the models. The water exchange rate \( q_{ex} \) is calculated according to the difference of hydraulic head in the river cell (i.e., the output of the hydrodynamic model) and the corresponding groundwater cell, that is

\[
q_{ex} = \begin{cases} 
C_{river} (h_{river} - h_{groundwater}); & \text{for } h_{groundwater} > z_{river \text{ bottom}} \quad [\text{river aquifer connected}] \\
C_{river} (h_{river} - z_{river \text{ bottom}}); & \text{for } h_{groundwater} \leq z_{river \text{ bottom}} \quad [\text{river aquifer unconnected}]
\end{cases}
\]

with

\[
C_{river} = \frac{K \cdot A}{M}
\]

where \( q_{ex} \) is the exchange rate (positive, if infiltration, i.e. river \rightarrow\) groundwater; negative, if exfiltration, i.e. groundwater \rightarrow\) river), \( C_{river} \) is riverbed conductance, \( h \) is hydraulic head, \( z_{river \text{ bottom}} \) is elevation of bottom of riverbed, \( K \) is hydraulic conductivity of riverbed material, \( A \) is wet area within the grid cell and \( M \) is thickness of the riverbed layer (see also Ruf 2007 for details).
In turn, $q_{ex}$ acts as a boundary condition for the hydrodynamic model, implemented there as a sink or source term. Since the grids of the two models are different in orientation and size, a transfer matrix was built to match the two model grids. For the work presented in this paper the exchange rate was carried out in an off-line mode, i.e. with the models running separately, and the steady-state solution was reached using an iterative coupling procedure. This coupling was compared here with results of the Streamflow Routing Package (SFR), already included in MODFLOW-2000 (Prudic et al. 2004). SFR is a fully coupled procedure for the river-aquifer interaction, however using a simple 1-D uniform representation for the streamflow.

4. Results and discussion

Outputs of the hydrodynamic and groundwater models are spatially distributed water level and flow depth, flow velocity in the river and floodplain cells, dry and wet cell boundaries, piezometric head in the aquifer cells and the location and magnitude of the exchange of water between river and aquifer cells. This exchange flux $q_{ex}$ can either be from the river to the aquifer (infiltration), or from the aquifer to the river (exfiltration). A calibration procedure was developed for the hydrodynamic and the groundwater model parameters jointly, considering the coupled models as a single system.

Model outputs were used to derive maps of the depth to groundwater, inundated area, shoreline length and river-aquifer interaction patterns for different flow rates in the river using detailed river and floodplain topography within a geographic information system. We also analysed statistical distributions of flow rates and velocities along the modelling domain. Although the modelling framework provides data over the whole domain of the riverine corridor (shown in Fig. 1), for the sake of clarity, only those related to the braided area are presented and discussed in this paper.

The observed flow rates in the valley range from 0.7 to 1000 m$^3$ s$^{-1}$. Here, the flow depth for 1.2 m$^3$ s$^{-1}$ (minimum flow requirement in winter) and 300 m$^3$ s$^{-1}$ (flood peak with a return period of approximately 5 years) are shown as an example (Fig. 3). The effect of inundation and braiding is well represented in the braided area around Someo. The inundated area increases with flow rate, while the shoreline length approaches a maximum at a flow rate of

![Fig. 3 Simulated flow depth in the braided area near Someo with different flow rates.](image-url)
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approximately 300 m³ s⁻¹ and decreases for both higher and lower flows (Fig. 4). Water is constrained to the main channels at low flow, while abundant bars and islands in the river that increase the shoreline become flooded at high flow. Such shoreline dynamics have been observed in other braided gravel-bed streams such as the Tagliamento (Nat et al. 2002). Shoreline length is an indicator of habitat biodiversity and its dependence on flow rate is an important consideration for managing flow regulation.

The simulated depth to groundwater (Fig. 5) reflects the patterns of inundation as well as the topography of the floodplain and the vegetated islands. The observed patterns of vegetation (Fig. 6) are coherent with those of the simulated inundation depth and depth to groundwater, although the spatial distribution of vegetation is also shaped by longer term dynamics of flood pulses and water-table fluctuations (see Favre 2004 ined. diploma thesis, Molnar et al. 2008, this issue, Perona et al., submitted).

Fig. 4 Fraction of inundated area and shoreline length in the braided area of Someo.

Fig. 5 Simulated depth to groundwater for a flow rate of 1.2 m³ s⁻¹ (left: whole valley; right: braided area around Someo).
To illustrate the connection between water flow and vegetation, contingency tables of the variables of depth to groundwater and surface cover type area (exposed sediment or different vegetation types) under low flow conditions (1.2 m³ s⁻¹ in Bignasco) as well as inundation depth and surface cover type area for flooding conditions (300 m³ s⁻¹ in Bignasco) were determined. The Pearson-Chi²-test shows that both variables are statistically significantly related with surface cover type ($p < 0.001$ for flow depth and $p < 0.025$ for groundwater).

Tab. 1 shows the ratio of the observed and expected frequencies assuming independence. Values larger than 1 indicate that the given combination is observed more frequently than in a random selection, and vice versa.

<table>
<thead>
<tr>
<th>Vegetation Type</th>
<th>% of total area</th>
<th>(a) inundation depth [m]</th>
<th>(b) depth to groundwater [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>dry</td>
<td>&lt; 0.25</td>
<td>0.25 – 0.5</td>
</tr>
<tr>
<td>Water &amp; exposed sediment</td>
<td>19.2</td>
<td>0.13</td>
<td>0.85</td>
</tr>
<tr>
<td>Herbaceous vegetation</td>
<td>4.1</td>
<td>0.98</td>
<td>1.47</td>
</tr>
<tr>
<td>Shrubs</td>
<td>21.5</td>
<td>0.87</td>
<td>2.09</td>
</tr>
<tr>
<td>Young trees</td>
<td>18.3</td>
<td>1.12</td>
<td>1.21</td>
</tr>
<tr>
<td>Mature trees</td>
<td>37.0</td>
<td>1.47</td>
<td>0.29</td>
</tr>
<tr>
<td>% of total area</td>
<td>100</td>
<td>62.3</td>
<td>13.6</td>
</tr>
</tbody>
</table>

Fig. 6 Vegetation types in the braided area around Someo (delineated from areal photography from 26 July, 1999).
Some interesting observations can be made from Tab. 1. First, at shallow groundwater tables (< 1 m) near the stream, all vegetation types are under-represented and bare sediment is over-represented. Herbaceous vegetation is positively correlated with groundwater depths between 1.5 and 3 m, while young trees occur mostly at depths > 2 m and mature trees at depths > 3 m. Shrubs appear to occupy predominantly areas where groundwater depths range between 1 and 3 m. Second, both exposed sediment and vegetation are strongly related to inundation depth. All vegetation types are under-represented in areas with over 1 m inundation depth, in fact mature trees are unlikely to be found in inundated areas. Interestingly, although herbaceous vegetation shows a comparably small correlation with inundation depth < 1 m, shrubs are significantly over-represented in the infrequently flooded zone with inundation depth < 25 cm. A possible explanation is that this is the range where water-borne seeds are often deposited and germinate and that shrubs are more resistant to erosion by shallow water flow. However, these are qualitative statements, and the extent to which floods or groundwater levels are the driving forces for the vegetation development in the floodplain will be the subject of further investigation.

Fig. 7 Simulated spatial pattern of infiltration and exfiltration with a runoff of 300 m³ s⁻¹ (left: whole valley; right: braided area around Someo).
The direct result of coupling the hydrodynamic and groundwater models are the exchange rates $q_{ex}$ along the reach. Large-scale zones of both infiltration and exfiltration are visible, which vary with flow rate. However, the spatial changes between infiltration and exfiltration are also evident at a smaller scale (Fig. 7). The simulated exchange rates of the fully coupled 1D streamflow package (SFR) and the 2D hydrodynamic model 2dMb under low flow conditions ($1.2 \text{ m}^3 \text{s}^{-1}$) agree in the basic pattern, although SFR results generally give higher magnitude $q_{ex}$ and in a few reaches SFR and 2dMb results disagree on the direction (sign) of $q_{ex}$. The general patterns for high flow rates ($300 \text{ m}^3 \text{s}^{-1}$) are similar. The basic correspondence between SFR and 2dMb in steady-state simulations is expected and it gives confidence in the performance of the rather complex 2D model. However, differences between the two modelling approaches are expected to be greater in unsteady conditions for the braided area, i.e. where more active reaches are the result of larger inundation. This point underlines the need to use 2D modelling in such situations.

5. Conclusions

The modelling framework presented here is a meaningful tool for modelling surface and groundwater flow processes with high spatial variability, which have consequences for riverine ecological processes. In fact, the spatial pattern of infiltration and exfiltration rates that is captured by the models is important for the spatial distribution of the riverine habitat. Moreover, the depth to groundwater is an important factor with respect to the growth of riparian vegetation. The modelling system allows the simulation of flow pulses and also of the associated variation of inundated area with flow rate. The general dependence of inundated area and shoreline length on flow rate is consistent with field observations (see e.g. Nat et al. 2002, for the Tagliamento River, Northern Italy). In addition to its importance for riverine habitat, simulated inundated area combined with flow velocities may allow the investigation of flow patterns that are relevant for modelling the uprooting mechanism of plants during floods.

The modelling tool developed here should not be restricted to the case of the Maggia valley, but is meant to be transferable to application in other areas, where sufficient data for the model calibration are available (especially a detailed DTM, runoff data and piezometric head data). Its application is beneficial in areas with pronounced river-groundwater interaction and irregular or natural river profiles, which require a 2D hydrodynamic surface water model, such as in morphologically natural floodplains or in river restoration projects. It is robust enough to be applied in areas with riverbed slopes up to a few per cent and with high temporal and spatial dynamics of wetting and drying areas.

Effort is presently being undertaken to achieve an automatic full coupling of the hydrodynamic model with the groundwater model within one code, which is able to handle both transient and long-term simulations (see Ruf 2007). On the one hand, this will provide information on inundation time and rate of water level rise and fall during flood events, which is an important ecological factor for the recruitment and survival of riparian plants. On the other hand, it will enable further analysis of the interaction between the variability of the streamflow regime and the dynamics of the floodplain ecosystem on a larger time-scale. The surface water-ground water modelling framework presented here has the potential to provide hydrological factors that are relevant to riparian vegetation growth and ultimately to provide a more profound basis for the establishment of eco-compatible environmental flow requirements.
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7. References


Authors’ addresses:

Wolfgang Ruf*
ETH - Institute of Environmental Engineering
HIL G 28.2
8093 Zurich
Switzerland
Present address:
Federal Office for Environment – Risk Management
3003 Bern
Switzerland

Laura Foglia
ETH - Institute of Engineering
Zurich
Switzerland

and:
SUPSI - Istituto Scienze della Terra
Canobbio
Switzerland

Present address:
University of California
Department of Civil and Environmental Engineering
Davis, U.S.A.

Paolo Perona, Peter Molnar, Paolo Burlando
ETH - Institute of Environmental Engineering
Zurich
Switzerland

Roland Faeh
Laboratory of Hydraulics, Hydrology and Glaciology
ETH, Zurich
Switzerland

*corresponding author: e-mail: wolfgang.ruf@bafu.admin.ch