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A continuous coupled hydrological and water resources management model

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ABSTRACT

Human exploitation of water resources is widespread and its impact on hydrological fluxes is expected to increase in the future. Water use interacts in a complex manner with the hydrological system causing severe alterations of the hydrological fluxes with multifaceted feedbacks. Implementing this coupling within hydrological models is essential when dealing with the impact of human activities on water resources at all relevant scales. We contribute to the effort in developing models coupling natural and human systems with a distributed continuous model, named GEOTRANSF. The model allows to quantify, within the same framework, alterations in the natural regime and constraints and limitations to water resources availability. After presenting GEOTRANSF, an example of application to a medium-size Alpine catchment with streamflow modified by hydropower and distributed uses is discussed, followed by the analysis of the effect of suitable water uses scenarios in the same catchment.

Software availability

Name of the software: GEOTRANSF
Developer: Department of Civil, Environmental and Mechanical Engineering, University of Trento, Via Mesiano 77, I-38123 Trento, Italy and Smart HydroGeological Solutions Srl, Via Unterveger 52, I-38123 Trento, Italy.
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Hardware: No specific requirements
Software required: FORTRAN compiler
Program Language: FORTRAN
Availability: LGPL licence, source code available upon request to the authors

1. Introduction

Timing and spatial distribution of freshwaters are modified by human intervention almost everywhere in the planet (Sivapalan et al., 2012; Savenije et al., 2014). These modifications are particularly visible in mountain areas due to hydropower exploitation and other distributed uses (i.e., agricultural and industrial, Zolezzi et al., 2009; Botter et al., 2010). A great effort has been devoted in the last decades to gain a better understanding of the processes controlling the terrestrial water cycle, in an attempt to improve hydrological modeling, often focusing on cases with small to negligible human alterations. However, given the widespread relevance of human uses, further effort is needed to gain a better understanding of the interactions between human and hydrological systems (Thompson et al., 2013; Lall, 2014).

Water transfer and storage due to human activities have far reaching implications on the water cycle and water security with feedbacks on climate at local and regional to global scales. For example, intensive agriculture may disturb atmospheric boundary conditions and cause hydroclimatic shifts at a regional scale (see e.g., Destouni et al., 2010, 2013). To address these issues hydrological models should be envisioned that provide full coupling between hydrological process and changes in water fluxes and storage due to human uses. This is particularly relevant for large-scale hydrological models because including water uses at a scale significant and informative for water management is challenging (see e.g., Nazemi and Wheater, 2015a, b for a review on the issues and challenges associated to the incorporation of water resources

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management modules into Earth System Models).

Available models can be classified either as water management-oriented, adopting simplified hydrological kernels (see e.g., IQQM, Simons et al., 1996; MODSIM DSS, Fredericks et al., 1998; RiverWare, Zagona et al., 2001; MFSP, Li et al., 2009) or as hydrological simulation models, which reproduce the relevant hydrological processes with a relatively high level of complexity, but incorporate simplified water management components. Widely used models, such as MIKE SHE (DHI Software, 2009), HEC-HMS (Feldman, 2000) and HSPF (Bicknell et al., 1997; Lampert and Wu, 2015), belong to the latter category, and make use of simplifications in the description of water use and generally ignore dynamic links between natural and human systems. According to Nalbantis et al. (2011) these models can be classified as “monomeric”, since they tend to focus on the hydrological component. Holistic models instead, i.e. models in which all parts of the system are simulated with similar details (Nalbantis et al., 2011), as for example RIBASIM (Deltares, 2010), MIKE HYDRO Basin (DHI Software, 2003) and DSF (MRC, 2004), are in general more appealing for operational and planning applications, though their transferability to contexts different from that in which they have been developed may be problematic (see e.g., Dutta et al., 2013).

Source IMS (Welsh et al., 2013), WEAP21 (Yates et al., 2005), SWAT (Neitsh et al., 2011) and HYDROGEIOS (Efstratiadis et al., 2008) are models which integrate hydrological processes and water management rules. In particular, Source IMS and WEAP21 adopt an object-oriented modeling framework in which natural (e.g., runoff and interactions between rivers and groundwater aquifers) and anthropogenic processes (e.g., water demands, reservoirs and river regulation) are conceptualized through the adoption of nodes and transmission links. In both models a conceptual rainfall-runoff module is used to compute water fluxes at selected nodes, at which specific rules are applied to decide amount and timing of water uses. The hydrologic and human-modified systems are in this case loosely coupled, given that uses within the rainfall-runoff areas can be taken into account only by lumping them to the closest node (e.g., Welsh et al., 2013, Fig. 1).

SWAT is a well known model which includes exchanges between hydrological and human systems as source and sink terms, thereby it does take into account feedbacks between the two systems, such as for example the release of water from reservoirs depending in a nonlinear manner from the water elevation. Similarly, HYDROGEIOS is a modeling tool developed to deal with hydrological systems modified by water uses (Efstratiadis et al., 2008). It is based on the concept of Hydrological Response Units (HRUs) (Ross et al., 1979) coupled with a two-compartment bucket model dealing with infiltration and exchanges with atmosphere and groundwater. An interesting feature of this approach is the inclusion of the groundwater component modeled with a network of connected cells. The human component is more sophisticated than in SWAT and it is represented through a linear network programming approach, in which the priorities of conflicting water uses are accounted for through virtual costs. However, the feedback between the two systems is limited to the stream elements and groundwater cells, while it does not include a specific module for flow regulations due to in line storage elements (e.g. reservoirs). The difficulties encountered in modeling the two systems may be alleviated by taking advantage of the services offered by Geographic Information Systems (GIS), as in JGrass-NewAge (Formetta et al., 2011, 2014), though this latter approach does not provide a full coupling between the two systems.

We contribute to this effort by developing a new modeling framework, we called GEOTRANSF, with characteristics similar to HYDROGEIOS and JGrass-NewAge, but with some additional capabilities. The main difference with respect to these tools is a tighter connection between natural and human systems with the inclusion of their feedbacks. For example, withdrawals for irrigation are included as input in the surface bucket representing soil moisture dynamics at the sub-catchment scale. This may be useful in addressing feedbacks between climate change and irrigation, along the lines suggested in the paper by Destouni et al. (2013). Another novelty is represented by the treatment of small diffuse uses from the streams and groundwater, which cannot be treated at the level of the single withdrawal due to their large number and because of the cutoff introduced in representing the river network (smaller reaches are not included into the river network, in particular when modeling medium to large catchments). Here, we propose a hierarchical approach, which allows for distribute water uses within the sub-catchment respecting the reciprocal constraints between users along the river network. In our view these are essential features for dealing with all the nonlinear interactions between the hydrological system and the variety of water uses including the effects of the market, in particular the energy market, which influences hydropower production (Seekell et al., 2011; Dalin et al., 2012; Sivapalan et al., 2012).

Water withdrawals along the streams should respect Minimum Environmental Flow (MEF) requirements as part of the objectives indicated in national regulations. Several methodologies have been developed to identify minimal flow conditions that should be respected downstream each withdrawal (see e.g., Acreman et al., 2014). In the simplest case the minimum flow is constant, but modulations to mimic the natural variability, yet with a lower mean, is often applied, particularly in areas of high environmental value. The module of GEOTRANSF dealing with the human component of the water cycle is fully integrated with the natural component and local water budgets are established at intake and restitution points along the river network. For example, withdrawals at a given point of the river network are conditioned to upstream transfers and protocols regulating competing uses, such as the limitations imposed to hydropower by recreational activities and agricultural needs. To the best of our knowledge, these characteristics are not included with a similar level of detail in existing modeling approaches.

In addition, GEOTRANSF can be used to develop scenarios of the human component to be used in impact assessment studies of new water infrastructures, decommissioning of reservoirs and other activities that may be of interest to land and water resources managers. Examples of applications range from the analysis of the impact of future climate and land use scenarios on water resources, to effects of changes in water policies, reservoir storage capacity, irrigation techniques and the overall impact of new run-of-the-river hydropower plants. Within the same framework, the effect of new water policies and possible mitigation actions can be explored and evaluated.

Section 2 describes the hydrological conceptual model, while the model components are described in Section 3. Modeling of human systems is presented in Section 4. Data requirements and parameter identification procedure are presented in Sections 5 and 6, respectively, while two examples of applications are discussed in Section 7. Finally, a set of concluding remarks in Section 8 closes the work.

2. Hydrologic system

The model is composed of a hierarchical combination of elements belonging to two morphological units: the sub-catchment and the stream. The former includes the portion of the territory where hillslope processes dominates and the latter is the building block of the river network. The river network is extracted from the Digital Terrain Model (DTM) of the catchment by means of a