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Dynamic attribution of global water demand to surface water and groundwater resources: Effects of abstractions and return flows on river discharges

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ABSTRACT

As human water demand is increasing worldwide, pressure on available water resources grows and their sustainable exploitation is at risk. To mimic changes in exploitation intensity and the connecting feedbacks between surface water and groundwater systems, a dynamic attribution of demand to water resources is necessary. However, current global-scale hydrological models lack the ability to do so. This study explores the dynamic attribution of water demand to simulated water availability. It accounts for essential feedbacks, such as return flows of unconsumed water and riverbed infiltration. Results show that abstractions and feedbacks strongly affect water allocation over time, particularly in irrigated areas. Also residence time of water is affected, as shown by changes in low flow magnitude, frequency, and timing. The dynamic representation of abstractions and feedbacks makes the model a suitable tool for assessing spatial and temporal impacts of changing global water demand on hydrology and water resources.

1. Introduction

Worldwide water demand increased substantially over the past decades as a results of growing population numbers, expanded irrigation areas, and economic development, raising water scarcity in many parts of the world [1]. As a result, an increasing number of rivers run dry for substantial periods of the year before reaching the sea [2]. In regions with frequent water stress and large aquifer systems groundwater is often used as an additional resource to meet water demands. In many of these areas groundwater abstractions exceed groundwater recharge, depleting existing groundwater stores, thereby negatively affecting stream flow of groundwater fed rivers, ecosystems, and depths of local attainable groundwater [3].

Previous model studies that focused on global-scale water consumption and its effects had to deal with the fact that little to no information exists on the attribution of water demand to surface water and groundwater abstraction. Therefore, between studies different assumptions have been made about this attribution. Limiting ourselves to models that explicitly account for human water abstractions, examples of attribution rules are: H08 [4], where surface water is preferentially abstracted, WBMplus [5], where water from reservoirs and groundwater is preferentially abstracted, LPJmL [6], where irrigation demand is attributed to surface water and groundwater resources using temporal invariant fractions, WaterGap [7] where sector specific abstractions are calculated with temporally invariant but country-specific fractions of total water demand, and PCR-GLOBWB [8] where also sector specific gross and net abstractions are calculated, and where groundwater abstractions are constrained to reported values (i.e. IGRAC www.un-igrac.org). Thus, none of these attribution rules take into account the abundance of both surface water and groundwater resources at the same time. The distribution rules of these models are potentially not very robust under changes in water availability, be it from climate change or water consumption. Wada et al. [9] attempted to include such changes in PCR-GLOBWB and improved the previous scheme to account for feedbacks between water supply and demand. The fraction between baseflow and long-term average river discharge is used to allocate water demand to surface water and groundwater resources. However, the used fraction does not reflect actual changes in available surface water. Also return flows are still static and thus do not affect actual water availability in groundwater and surface water resources.

The goal of this study is to explore a dynamic attribution scheme that is able to mimic changes in exploitation intensity of surface and groundwater. This scheme explicitly considers the feedbacks connecting surface water and groundwater systems and their exploitation. More specifically, compared to previous

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work the following features are added in this study: (1) dynamic attribution of water demand to surface water and groundwater based on the actual availability of surface water and groundwater; (2) including the effects of groundwater and surface water abstractions as well as the return flows on the surface water and groundwater system at run time (full integration of the hydrological cycle); (3) including a two-way interaction between surface water and groundwater by allowing both drainage of groundwater to surface water bodies, as well as suppletion of groundwater by surface water through riverbed infiltration. By means of these additions we will be able to simulate adjustments of preferred water use based on changes in availability of surface water and groundwater due to climate change or increased water consumption. Apart from the validation of the abstraction rates produced by this scheme we specifically focus on the effects of return flows on river discharge.

We use the global hydrological model PCR-GLOBWB [10] to simulate water storages and river discharges over the period 1960–2010 (daily time step, 0.5° resolution, about 50 km at the equator). In this study, total water demand stems from irrigation, industry, and domestic use and defines the total abstraction if sufficient water is available. Abstractions are variably taken from surface water and groundwater driven by simulated water availability and are sector independent. Return flows of unconsumed abstracted water are simulated at the same time as the abstractions. Return flows are sector specific and return to a single source; those of irrigation to the groundwater, those of industry and domestic use to the surface water. In other words, return flows cause a redistribution of abstracted water over the water resources. Three model runs are used to test for the effects of abstractions and return flows on water allocation and river discharges: (1) no abstractions (NA), (2) abstractions only (AB), (3) abstractions and return flows (ABRE).

The suggested dynamic allocation scheme is validated by comparing simulated groundwater abstraction magnitudes and fractions for the year 2000 to reported values on global and continental scale. The impacts of abstractions on river discharges, especially during low flows, are analyzed globally by looking at changes in flow magnitudes, frequency, and timing of low flows. Past trends of abstractions are given. These trends show temporal changes in abstraction intensity under the influence of feedback mechanisms.

2. Methods

2.1. Hydrological model

The global hydrological model PCR-GLOBWB [10] is used to calculate water storages and fluxes of the terrestrial part of the hydrological cycle for the period 1960–2010. A schematic representation of the model is given in Fig. 1. Only a summarized model description is given here, for details we refer to [10].

PCR-GLOBWB is a grid-based hydrological model (here 0.5° grid resolution globally) that operates at a daily time step. Each grid cell contains surface water elements and a vertically structured representation of the canopy, two soil layers, and an underlying groundwater reservoir. Sub-grid variability is used to represent fractions of different vegetation (i.e. short and tall), saturated soil (to quantify surface runoff and lateral outflow from the unsaturated zone), and surface water (i.e. lakes, reservoirs, wetlands, floodplains). Precipitation can be stored as canopy interception and as snow when temperatures are below 0 °C. Throughfall and meltwater are passed to the upper soil layer. Actual evapotranspiration is calculated from potential evaporation and soil moisture conditions. Vertical exchange between the soil and groundwater layers occurs by percolation and capillary rise. Drainage from the soil column to the river network takes place as overland flow, subsurface flow from the two soil layers, and baseflow from the groundwater reservoir. This last reservoir is parameterized based on lithology and topography, and is represented as a linear reservoir model [11]. Thus, for each time step and each grid cell the water balance of the soil column is calculated. The combined runoff is accumulated and routed as river discharge along the drainage network based on DDM30 [12] using a kinematic wave approximation on a sub-daily time scale. Open water evaporation, water storage in lakes, and attenuation by floodplains and wetlands are taken into account within the routing scheme. Reservoirs are located on the river network based on GLWD1 [13]. Reservoir storage and release are dynamically calculated by evaluation of the downstream water demand. This encompasses all blue water demand within an area 600 km downstream of the reservoir outlet (approximately a week with an average discharge velocity of 1 m s^{-1}). When more than one reservoir is present directly upstream, demand is partitioned proportionally to reservoir capacity. PCR-GLOBWB was forced with daily fields of precipitation, temperature, and reference potential evapotranspiration over the period 1960–2010. For the period 1960–2000 precipitation and air temperature were prescribed by the CRU TS 2.1 monthly dataset [14,15], which was downscaled to daily fields by using the ERA-40 reanalysis [16]. For the period 2000–2010 climate data were retrieved for the ERA-Interim [17] reanalysis. Reference potential evapotranspiration was calculated using the Penman–Monteith equation according to FAO guidelines [18]. For the period 1960–2000 radiation and wind speed were prescribed by CRU CLIM 1.0 climatology data [19]. For compatibility, data from ERA-Interim (precipitation, temperature, potential evaporation) was bias-corrected by scaling the long-term monthly means of these fields to the CRU TS 2.1 dataset over the overlapping period (1979–2001).

The model concept of PCR-GLOBWB and used allocation scheme. Middle part: the soil compartment, divided into two soil layers (S1 and S2) and one linear groundwater reservoir (S3). Precipitation (Prec) falls as rain or snow (temperature dependent) and can be stored in canopy or as snow accumulation (Ss). Vertical transport within the soil column appears from percolation or capillarity rise (P). The total local gains from all cells, i.e. drainage (QDr), subsurface flow (QSf), and baseflow (Qbf), are routed along the drainage direction to yield the channel discharge (Qchannel). In every grid cell water can be abstracted from surface water or groundwater. Return flows go to surface water or groundwater, dependent on the water use.

2.2. Water demand

Throughout the paper total water demand is used to denote the water requirements for three sectors: irrigation, industry, and households. It denotes potential water withdrawal, i.e. the water that would be abstracted if sufficient water were available (gross water demand).

Data on sectoral water demand for the model period were adopted from the previous study of Wada et al. [8]. To overcome the lack of available spatially explicit data, sectoral water demands were estimated using country statistics on the extent of irrigated areas and population numbers downscaled to 0.5° resolution. To approximate economic development over the period 1960–2010 data of Gross Domestic Product (GDP), electricity produced, and household consumption were used.

Industrial demand is kept constant over the year. Domestic demand reflects seasonal variability according to air temperature fluctuations. Water recycling ratios for industry and domestic use are adopted from [8] and were calculated per country, on the basis of by GDP and the level of economic development, i.e. high income (80%), middle income (65%), and low income (40%) economies.