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Research papers

The impact of lake and reservoir parameterization on global streamflow simulation

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ABSTRACT

Lakes and reservoirs affect the timing and magnitude of streamflow, and are therefore essential hydrological model components, especially in the context of global flood forecasting. However, the parameterization of lake and reservoir routines on a global scale is subject to considerable uncertainty due to lack of information on lake hydrographic characteristics and reservoir operating rules. In this study we estimated the effect of lakes and reservoirs on global daily streamflow simulations of a spatially-distributed LISFLOOD hydrological model. We applied state-of-the-art global sensitivity and uncertainty analyses for selected catchments to examine the effect of uncertain lake and reservoir parameterization on model performance. Streamflow observations from 390 catchments around the globe and multiple performance measures were used to assess model performance.

Results indicate a considerable geographical variability in the lake and reservoir effects on the streamflow simulation. Nash-Sutcliffe Efficiency (NSE) and Kling-Gupta Efficiency (KGE) metrics improved for 65% and 38% of catchments respectively, with median skill score values of 0.16 and 0.2 while scores deteriorated for 28% and 52% of the catchments, with median values −0.09 and −0.16, respectively. The effect of reservoirs on extreme high flows was substantial and widespread in the global domain, while the effect of lakes was spatially limited to a few catchments. As indicated by global sensitivity analysis, parameter uncertainty substantially affected uncertainty of model performance. Reservoir parameters often contributed to this uncertainty, although the effect varied widely among catchments. The effect of reservoir parameters on model performance diminished with distance downstream of reservoirs in favor of other parameters, notably groundwater-related parameters and channel Manning's roughness coefficient. This study underscores the importance of accounting for lakes and, especially, reservoirs and using appropriate parameterization in large-scale hydrological simulations.

1. Introduction

Lakes and man-made reservoirs are key components of terrestrial hydrological systems. They affect flow regimes by changing the magnitude and timing of streamflow, usually by attenuating and delaying flows, but also through releases from reservoirs which can result in severe downstream floods. The impact of reservoirs on global streamflow has become considerable over the 20th century (Vörösmarty et al., 1997; Chao et al., 2008; Lettenmaier and Milly, 2009), during which the storage capacity of global reservoirs increased from less than 100 km^3 in 1900 to approximately 8300 km^3 in 2000 (Chao et al., 2008; ICOLD, 2007). The majority of large river systems around the world are fragmented by dams (Gao et al., 2012; Nilsson et al., 2005). The spatio-temporal quantification of the impacts of lakes and reservoirs is essential in terms of assessment of water-related hazards such as droughts and floods and hydrologic models may serve as essential tools for this purpose (Zhou et al., 2016; Oki and Kanae, 2006).

Some of the currently used global and continental scale hydrological models (GHMs; Bierkens, 2015; Bierkens et al., 2015; Döll et al., 2003; Coe, 2000; Meigh et al., 1999) that explicitly represent lakes and reservoirs, were used to assess the impacts of lakes and/or reservoirs on global- or regional-scale streamflow simulations (Biemans et al., 2011; Coe, 2000; Coe and Foley, 2001; Döll et al., 2009; Haddeland et al., 2006; Hanasaki et al., 2006;

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Meigh et al., 1999; Vörösmarty et al., 1997; Zhou et al., 2016). Above all, these previous studies highlighted the considerable impact of dams and reservoirs on the large-scale hydrological simulations. However, these studies mainly assessed the effect of dams on long-term (monthly – seasonal) streamflow, aggregated to catchment or regional scales. In this study we focus on estimating lake and reservoir effects on fully spatially distributed (at 0.1° resolution), daily streamflow simulations suited for global flood forecasting. Our overall objective is to improve streamflow simulations within the Global Flood Awareness System (GloFAS; Alfieri et al., 2013)—a probabilistic, medium-range flood forecasts at the global scale with a forecast horizon of 30 days (see www.globalfloods.eu). Within the GloFAS, the LISFLOOD hydrological model (De Roo et al., 2000; van der Knijff et al., 2010; Burek et al., 2013a) is used to simulate river routing and groundwater processes. The LISFLOOD lake and reservoir routines were developed specifically to provide realistic streamflow simulations at lakes and reservoirs outlets with a (sub-) daily time steps with the objective of improving flood forecasting for river sections downstream of large water bodies. These routines are parameterized with information contained within global-scale datasets, using a methodologically consistent approach, in order to avoid data bias due to political and geophysical boundaries (Arheimer et al., 2012). Although existing global inventories such as the Global Lakes and Wetlands Database (GLWD; Lehner and Döll, 2004) and the Global Reservoir and Dam Database (GRanD; Lehner et al., 2011) provide extensive metadata, some information necessary for parameterization and validation of lake and reservoir routines is not available. This includes for example descriptions of hydrographic conditions for lakes (e.g., outlet characteristics) and historical operation records for reservoirs. Openly shared reservoir records for deriving case-specific operation rules (and related model parameters) are only available in some developed countries (CEDEX, 2016, Gao et al., 2012; Hanasaki et al., 2006). We attempt to overcome these data limitations by relating some parameters to global-extent auxiliary data. For example, we estimate the outflow characteristics of lakes based on the channel width at the lake outlet, and we derive reservoir parameters based on simulated ‘naturalized’ streamflow. However, such an approach is associated with considerable uncertainty around parameter values which may adversely affect model performance.

To examine how uncertainty of lake and reservoir parameters propagates through the model and, as a result, affects model performance we use global sensitivity and uncertainty analyses (GSA/UA; Saltelli et al., 2004). River flow in sections downstream of lakes and reservoirs is controlled by a combination of factors relating to the natural variation of river flow and the lake and reservoir processes. GSA provides means of exploring the magnitude and spatial extent of influence of lake and reservoirs processes on the model response. Understanding the relative importance of lake and reservoir parameters is essential to advance global streamflow simulation. Our work has two specific objectives: 1) to quantify the effect of lakes and reservoirs on the performance and the extreme value statistics of the global daily streamflow simulations, and 2) to quantify the relative contributions of lake and reservoir parameters to the uncertainty.

2. Materials and methods

2.1. Modeling framework

2.1.1. Hydrological modeling

The hydrological simulations in GloFAS (Alfieri et al., 2013) were performed using a land surface scheme coupled to a river routing model (Fig. 1). The Hydrologically modified Tiled ECMWF Scheme for Surface Exchanges over Land (H-TESSEL; Balsamo et al., 2009) was used for generating surface and subsurface runoff, and a simplified version of the LISFLOOD hydrological model was used for flow routing and simulation of groundwater processes. LISFLOOD is a spatially distributed, partly conceptual and partly physically-based model, primarily developed to simulate major hydrological processes in large catchments (De Roo et al., 2000; van der Knijff et al., 2010). The simplified version of the model simulates groundwater processes and flow routing, human water use, and lakes and reservoirs. The daily global runoff fields produced by H-TESSEL were resampled from ~80 km (see Section 2.2.3) to the LISFLOOD resolution of 0.1° (approximately 10 km at the equator), and routed using the kinematic wave approach (Chow et al., 1988) with a time sub-step of 4 h.

Spatial physiographic inputs were derived from various sources. Global river network and other river characteristics (e.g., flow direction, upstream area, and flow length) were taken from the global river network database of Wu et al. (2012), the river width map was taken from the Global Width Database for Large Rivers (GWD-LR; Yamazaki et al., 2014), while channel Manning’s roughness coefficient was calculated from land surface elevation and upstream area (De Roo et al., 2000; Burek et al., 2013a).

2.1.2. Lake and reservoir routines

The lake routine simulates the outflow from lakes at each time step based on: (i) upstream inflow, (ii) precipitation over the lake, (iii) evaporation from the lake, (iv) the lake’s initial level, and (v) lakes outlet characteristics (defined by the α parameter which is derived based on the channel width at the lake outlet, following Burek et al. (2013a)). Groundwater flow (lateral or vertical) between lakes and surrounding aquifers is not simulated. The procedure is described in more detail in Appendix A.

Reservoir outflow is calculated based on: (i) upstream inflow, (ii) precipitation over the reservoir surface, (iii) evaporation from the reservoir, and (iv) reservoir-specific characteristics and operation rules, represented by a number of parameters. Specifically, the outflow is calculated following four different set of rules depending on the current filling fraction of a reservoir (described in Appendix A). The rules attempt to reach the desirable level, called the normal filling level, by promoting either recharge (if storage is below normal) or release (if storage is above normal). Moreover, the approach applied in the routine guarantees a minimum outflow (to sustain downstream riverine ecosystems) and a non-damaging outflow (to prevent overtopping of the dam). Parameterization of the reservoir routine requires the specification of: (i) the reservoir storage capacity, (ii) the three threshold filling levels (conservative storage limit, normal storage limit, and flood storage limit), and (iii) the three streamflow release thresholds (minimum, normal outflow, and non-damaging outflow; Burek et al., 2013a). Values for the storage capacity were extracted from global datasets (see Section 2.2.1), while the threshold filling levels were estimated based on expert opinion and the streamflow release thresholds from naturalized simulations (see Appendix B).

2.2. Data

2.2.1. Lakes and reservoirs dataset compilation

We used three datasets containing the characteristics and geographical distribution of global lakes and/or reservoirs: 1) the Global Lakes and Wetlands Database (GLWD; Lehner and Döll, 2004), which contains the largest lakes (area > 50 km^2) and reservoirs (storage capacity $\geq$ 0.5 km^3); 2) the Global Reservoir and Dam Database (GRanD; Lehner et al., 2011), which contains reservoirs with a storage capacity >0.1 km^3, as well as many smaller ones; and 3) the World Register of Dams (WRD), compiled by the International Commission on Large Dams (ICOLD), which contains