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Filling the gaps: Calibrating a rainfall-runoff model using satellite-derived surface water extent

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ABSTRACT

Calibration is a crucial step in the application of hydrological models and is typically performed using in situ streamflow data. However, many rivers on the globe are ungauged or poorly gauged, or the gauged data are not readily available. In this study, we used remotely-sensed surface water extent from the Global Flood Detection System (GFDS) as a proxy for streamflow, and tested its value for calibration of the distributed rainfall-runoff routing model LISFLOOD. In a first step, we identified 30 streamflow gauging sites with a high likelihood of reliable GFDS data. Next, for each of these 30 sites, the model parameters related to groundwater and routing were independently calibrated against in situ and GFDS-derived streamflow time series, and against the raw GFDS surface water extent time series. We compared the performance of the three calibrated and the uncalibrated model simulations in terms of reproducing the in situ streamflow time series. Furthermore, we calculated the gain achieved by each scenario that used satellite-derived information relative to the reference uncalibrated scenario and the one that used in situ data.

Results show that using the raw GFDS data as a proxy for streamflow for calibration improved the skill of the simulated streamflow (in particular the high flows) for 21 of the 30 sites using correlation as a metric. Furthermore, we discuss a calibration strategy using a combination of in situ and satellite data for global hydrological models.

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1. Introduction

Hydrological models are indispensable tools for increasing our understanding of the hydrological cycle, for assessing the hydrological implications of climate and land-use change, and for flood and drought forecasting. Model calibration and validation are essential prerequisites to obtain reliable streamflow estimates from hydrological models (Minville et al., 2014; Werner, Blazkova, & Petr, 2005) and are typically performed using in situ streamflow data. However, in situ streamflow data are unavailable for the majority of the land surface, particularly for the most flood vulnerable countries, and the number of operational stations is rapidly decreasing (Hannah et al., 2011; Sivapalan, 2003; Wohl et al., 2012).

Satellite remote sensing has the ability to provide information on hydrological fluxes and state variables at (near-)global coverage and (near-)real time, and at frequent temporal intervals, and as such provides unique opportunities for enhancing model simulations in remote areas (van Dijk & Renzullo, 2011). In recent decades, there have been increasing efforts to improve models by incorporating remotely-sensed data on hydrologic variables such as evaporation (Zhang, Chiew, Zhang, & Li, 2009), surface soil moisture (Beck, De Jeu, Schellekens, Van Dijk, & Bruijnzeel, 2009; Hirpa, Gebremichael, Hopson, Wojick, & Lee, 2014; Wanders, Bierkens, de Jong, de Roo, & Karssenberg, 2014), total water storage (Jiang et al., 2014; Ramillien, Famiglietti, & Wahr, 2008), and snow and ice cover (Bergeron, Royer, Turcotte, & Roy, 2014; Dietz, Kuenzer, Gessner, & Dech, 2012), as well as vegetation-related variables such as leaf area index (LAI; Zhang, Vaze, Chiew, & Liu, 2011) and normalized difference vegetation index (NDVI; Donohue, Roderick, & McVicar, 2007). In addition, various studies have examined the value of remotely-sensed variables related to surface water, including inundation extent, river width, and water levels (see overview in Table 1). Some of these studies used satellite-derived information to calibrate model parameters or to derive empirical rating curves, while others focused on the direct use of changes in water level or width for calibration, using a variety of hydrodynamic or hydrological models. Although these studies reported promising results, a major drawback from the point of view of global hydrological modelling is that they often focused on a small region. Most studies focused on single river reaches and the validation was performed using a relatively small number of gauges ($n < 6$) (Di Baldassarre, Schumann, & Bates, 2009; Domeneghetti et al., 2014; Hostache et al., 2009; Mason, Bates, & Dall' Amico, 2009; Milzow, Krogh, & Bauer-Gottwein, 2011; Montanari et al., 2009; Sun, Ishidaira, & Bastola, 2010, 2012a, 2012b;

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Table 1
Summary of relevant studies where satellite-derived inundation extent, river width, and/or water levels were used to calibrate a hydrodynamic and/or hydrological model. Studies are listed in alphabetical order of author.

	Study	Satellite and sensor/Acquisition frequency	Model	Study area and no. of in situ river gauges used	Study period	Objective/Approach	Key findings
1	Di Baldassarre et al. (2009)	ENVISAT ASAR and ERS-2 SAR (1 image each used)	LISFLOOD-FP	10-km of the Dee and 8-km of the Alyn River (UK) (3 gauges)	Dec. 2006 flood event	Use inundation map derived from satellite imagery	Need to move from deterministic binary wet/dry maps to probabilistic fractional flood extent maps
2	Domeneghetti et al. (2014)	ENVISAT and ERS-2/35-day	HEC-RAS	~140 km reach of the Po River (northern Italy) (2 gauges)	16 years	Identification of Manning's roughness coefficient	Combine satellite time series with hydrometric data to increase the reliability of the hydraulic model
3	Getirana (2010)	ENVISAT altimetric data/35 days	MGB-IPH model	Branco River (northern Amazon Basin, Brazil) (11 gauges)	10 years	Use empirical equations to estimate river depth from modelled streamflow	Pioneering use of spatial altimetry data in the automatic calibration of hydrological models
4	Getirana et al. (2013)	ENVISAT altimetric data/35 days	HyMAP (based on CaMa-Flood + ISBA)	Amazon Basin (Brazil) (4 gauges)	10 years	Use of altimetric data to calibrate four parameters: the subsurface runoff time delay, Manning's roughness coefficient, river width, and bankfull height	Demonstrated use of altimetric data in the automatic calibration of model parameters
5	Hostache et al. (2009)	ENVISAT SAR/A few days to 30 days (1 image used)	HEC-RAS	18-km reach of the Alzette River (Luxembourg) (6 gauges)	Jan 2003 flood event	Estimation of spatially distributed water levels from remote-sensing observations and integration of satellite-data information in a hydraulic model in order to reduce model uncertainties	It provides distributed water levels with a high spatial density and provides more reliable hydraulic models thanks to these water levels that allow a spatial evaluation of model performances
6	Mason et al. (2009)	ERS-1 SAR (1 image used)	LISFLOOD-FP	12 km of the Thames River (UK) (No gauges, comparison with LiDAR)	1992 flood event	Comparison of water level probabilities based on flood waterline estimates derived from both SAR and LiDAR data to that derived from only SAR data	The use of water levels unable to restrict the parameter range of acceptable model runs and hence reduce the number of runs necessary to generate a flood inundation uncertainty map
7	Milzow et al. (2011)	ERS-2, and ENVISAT SAR altimetric data/35 days	SWAT	Okavango catchment (Southern Africa) (3 gauges)	11 years	Satellite altimetry was used to derive water level fluctuations at three locations in the catchment for channels approximately 150 m wide	The combination of multiple independent observational datasets improves the parametrization of the hydrological model
8	Montanari et al. (2009)	ERS-2 and ENVISAT SAR altimetric data/35 days (1 image each used)	Nash IUH + HEC-RAS	Alzette River basin (Luxembourg) (2 gauges)	Jan. 2003 flood event	Assessment of the value of remote-sensed water levels in an aggregated modelling system	A first step toward a systematic remote sensing-based surface water monitoring system that may quasi-continuously provide valuable information for sequentially updating coupled H–H models
9	Sun et al. (2012a)	JERS-1 SAR images (1 image used)	HYdrological MODel (HYMOD)	Mekong River (Asia) at Pakse (1 gauge)	4 years	Develop a conceptual framework for rainfall-runoff models in ungauged basins using satellite-derived river width or water surface elevation	Illustrates that under both the average and low designed satellite observational frequencies, the simulated streamflow had an acceptable degree of accuracy
10	Sun et al. (2012b)	TOPEX/Poseidon (T/P)/~10 days	HYMOD	Upper Mississippi Basin at Clinton (US) (1 gauge)	5 years	Attempt to use water surface elevation data obtained from satellite radar altimeters	Comparison with calibration using streamflow data shows that for the new calibration method, the uncertainty in the modelling process is higher, and the parameter space is less constrained
11	Sun et al. (2010)	JERS-1 SAR (16 images used)	HYMOD	Mekong River (Asia) at Pakse (1 gauge)	4 years	Minimize the difference between river widths observed from space and simulated widths by tuning parameters of rainfall-runoff model and at-a-station hydraulic geometry relation simultaneously	Wide applicability for reproducing river streamflow time series on the daily scale in ungauged basin if satellite data is available
12	Tarpanelli et al. (2013)	ENVISAT ASAR (1 image used)	Modello Idrologico Semi-Distribuito (MISD)	20-km reach of Genna stream (Italy) (1 gauge)	6 flood studies (1 day long each)	Calibration of Manning's roughness coefficient by comparing the flooded areas derived from ASAR imagery and hydrologic- hydraulic modelling.	The assessment of the Manning's roughness for the main channel and the floodplain is obtained from hydraulic simulations and satellite data for a flood event on a small basin (90km^2).
14	This study	Passive microwave (AMSR-E, TRMM)/daily	LISFLOOD (GloFAS System)	Africa, Europe, North America, and South America (30 gauges)	13 years	Assess the value of satellite-derived surface water extent for calibration of a hydrological model	Improvement in the timing of the simulated flow peak, and of the model skill in term of volume accuracy using satellite-derived river streamflow, when available

Tarpanelli, Brocca, Melone, & Moramarco, 2013), while others applied the calibration to more locations ($n < 12$) but all within the same catchment (Getirana, 2010; Getirana, Boone, Yamazaki, & Mognard, 2013). In addition, the calibration periods used in these studies are not long enough, if the aim is to improve rainfall-runoff simulations of models at multi-decadal time scales, since in many cases the focus has been on specific flood events of short duration. In these studies, the satellite data were derived from multiple sensors, and ranges of the electromagnetic spectrum, and at different spatial and temporal resolutions. The limitations described are in most cases due to the infrequent overpass

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