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Deriving daily water levels from satellite altimetry and land surface temperature for sparsely gauged catchments: A case study for the Mekong River

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ABSTRACT

Space borne radar altimeters often complement *in-situ* water levels to provide greater insights to hydrodynamic models in sparsely gauged catchments. However, 10-day or 35-day water levels derived from satellite radar altimetry are generally too infrequent for flood forecasting or hydrodynamic modelling purposes. This paper proposes a new approach to find daily water levels for areas where *in-situ* river heights are not available. The new approach is based on the relationship between river height and difference between daytime and night time land surface temperatures (LST). This relationship is first demonstrated using *in-situ* gauge data to explore appropriate statistical models to predict river height using LST differences. The approach is then applied to a number of virtual stations at the intersections between the Mekong River and the ground-tracks of Jason-2 satellite altimetry which gives 10-day water level time series.

The LST difference from the thermal infrared (TIR) observations of Moderate Resolution Imaging Spectroradiometer (MODIS) is shown to have a strong relationship with *in-situ* water levels and a good relationship with the Jason-2 water levels. The models included a simple linear regression model which was then extended to firstly include seasonal terms and secondly assimilate satellite altimetry data. A regression model tree (M5) was also considered but was found to be inferior to the seasonal linear model. The developed regression models were used to predict daily water levels to infill the 10-day Jason-2 altimeters. RMSE of modelled daily water levels at gauges is between 0.3 m to 0.6 m, while RMSE of modelled daily water levels without using *in-situ* data is higher varying from 1.4 m to 1.9 m. The temporal correlation between the modelled water levels using satellite altimeters at virtual stations and *in-situ* water levels at adjacent gauges ranged from 0.72 to 0.86. These results show the potential of the proposed approach to produce high temporal resolution water levels for flood models or other applications using only remotely sensed data.

1. Introduction

River water levels are a fundamental input for hydraulic models. It is common to use *in-situ* river stages to constrain and enhance the implementation of flood models. However, *in-situ* water levels are often not available in remote areas and developing countries (Alsdorf et al., 2007; Di Baldassarre et al., 2011) which causes difficulties in surface water management and flood forecasting in large river systems. For instance, Sun et al. (2012) highlighted the problems when calibrating hydrological models in the ungauged Upper Mississippi River. Hossain et al. (2014) also emphasised the challenge of flood forecasting in a transboundary Ganges-Brahmaputra River where *in-situ* boundary conditions are not available. Similar to other large river basins, surface water assessments in Mekong River are difficult due to the paucity of gauging information (Birkinshaw et al., 2010; Liu et al., 2016). Even if there are *in-situ* gauges on a river, often the data may not be adequate for near-real time flood models in terms of both spatial coverage and latency of the data (Alsdorf et al., 2001). To address the limited available of *in-situ* data, quasi-globally available topographic and remotely sensed data such as digital elevation models (DEM), precipitation, soil moisture, evapotranspiration, river discharges and river heights have been used to provide alternative measurements for model configuration, model calibration and data assimilation (Bates, 2012; Li et al., 2016; Musa et al., 2015; Palmer et al., 2015; Yan et al., 2015).

One such remotely sensed data source is satellite radar altimetry which has been employed to supplement ground-based hydrological

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Table 1
Summary of relevant literature on improving the coarse temporal resolution of satellite altimetry with respect to the study aims, which are (1) to demonstrate water level-ΔLST relationship at *in-situ* gauges to predict daily water levels using *in-situ* data; (2) to estimate daily water levels at virtual stations without using *in-situ* data. The current paper is added for completeness. The studies are sorted in chronological then alphabetical order. The symbol (1) and (2) in Key results column denotes contributions to the first and the second objective.

References	Location/satellite data	Key results
Frappart et al. (2006a)	Amazon River/Jason-1, T/P, ERS-1&2, ENVISAT, and GFO	Improve the number of available data but the temporal resolution is still very coarse (2)
Roux et al. (2010)	Rio Negro River/ENVISAT	Daily interpolated water levels (1)
Biancamaria et al. (2011b)	Ganges-Brahmaputra/Topex/Poseidon	Forecast water levels up to 5, 10-day lead time (1)
Hossain et al. (2014)	Ganges-Brahmaputra/Jason-2	Daily modelled water levels (1)
Schwatke et al. (2015)	North and South America/ENVISAT, ERS-2, Jason-1, Jason-2, T/P, SARAL	Water levels time series for rivers and lakes (2)
Tourian et al. (2016)	Po, Congo, Mississippi, and Danube Rivers/ENVISAT, T/P, Cryosat-2, SARAL, Jason-2	3-day water levels (2)
Boergens et al. (2017)	Mekong River/ENVISAT, Jason-1, SARAL	5-day water levels (2)
This study	Mekong River/Jason-2, MODIS LST, LPRM/AMSR2 LST	Predict daily water levels at gauges (1) Predict daily water levels at ungauged areas (2)

information such as river heights, rating curves and riverbed slopes (Calmant and Seyler, 2006). Available satellite altimetry with 35-day repeat periods includes ERS-1 (1991–2000), ERS-2 (1995–2011) and ENVISAT (2002 – 2012) operated by European Space Agency (ESA), and SARAL (2013-present) operated by the Indian Space Research Organisation (ISRO) and the French Space Agency (CNES). ESA also operates Sentinel-3A (2016–present) and Cryosat-2 (2010–present) which have a revisit time of 27-day and 369-day respectively. Other satellite radar altimetry with higher temporal resolution (10-day return period) includes TOPEX-POSEIDON (T/P) (1992–2006), Jason-1 (2001 – 2013), Jason-2 (2008–present) and Jason-3 (2016–present) that were a joint satellite project between the NASA (United States) and the CNES (France) space agencies. These satellite altimetry data have been widely used to derive water levels in rivers, lakes and reservoirs (Birkett and Beckley, 2010; Dubey et al., 2015; Frappart et al., 2006c; Jarihani et al., 2015; Kuo and Kao, 2011; Liu et al., 2016; Maillard et al., 2015; Papa et al., 2012; Tourian et al., 2016).

Although satellite altimetry has been increasingly used to monitor continental waters, there remain limitations such as incorrect range measurements and corrections, land contamination, and low temporal resolution (Calmant and Seyler, 2006; Frappart et al., 2005; Santos da Silva et al., 2010). The poor temporal resolution of existing satellite altimetry (10-day and 35-day) limits their application in flood forecasting scenarios because flood models typically require high frequency measurements (Calmant and Seyler, 2006; Calmant et al., 2008). To address this issue, Roux et al. (2008) suggested an approach that interpolates *in-situ* river height data of nearby gauges to fill missing data between the 10-day or 35-day altimeter water levels to generate daily water level time series. However, this method interpolates rather than forecasts water level data, meaning that it cannot be used for flood forecasting purposes. To avoid using *in-situ* data to fill gaps, Boergens et al. (2017) used ordinary kriging to spatially and temporally combine multiple satellite altimetry to improve temporal resolution of satellite altimeters over the Mekong River. Although this approach can be applied in ungauged catchments as independent of *in-situ* data, a 5-day predicted water level is still too coarse for forecasting applications. In the context of flood forecasting, Biancamaria et al. (2011b) used the correlation between the T/P altimeter water levels at an upstream site and the *in-situ* river heights at a downstream site to forecast up to 5-day lead time with small errors. Higher errors were found when forecasting at a lead time of 10 days or longer. Hossain et al. (2014) extended the method proposed by Biancamaria et al. (2011b) to estimate the relationship between upstream Jason-2 satellite altimetry water levels and downstream *in-situ* river discharges to also forecast water levels up to 5-day lead time. Although these methods have provided useful hydrological information for flood forecasting models, they do not address the challenge of forecasting daily water levels in areas without *in-situ* river height data. One common approach to circumvent the absence of *in-situ* gauged data is to use a hydraulic model with satellite radar altimetry. For example, Domeneghetti et al. (2014) used satellite altimetry (ERS-2 and ENVISAT) water levels to calibrate a two-dimensional model for the Po River. A simpler, statistical approach was presented by Tarpanelli et al. (2013) who used a relationship between hydraulic conditions at two river sections to estimate a downstream rating-curve using upstream *in-situ* discharge and downstream satellite altimetry water level. Tarpanelli et al. (2017) used this rating curve to forecast discharge from satellite altimetry Jason-2 and ENVISAT. In a more complex approach, satellite altimetry was assimilated in hydrological and hydrodynamic models to estimate river discharge at a single virtual station (Andreadis et al., 2007; Biancamaria et al., 2011a; Neal et al., 2009). Instead of developing relationship at each virtual station, Tourian et al. (2017) used a Kalman filter and smoother techniques to solve a linear dynamic model using multiple satellite altimetry (ENVISAT, Jason-2, and SARAL) and *in-situ* river discharge to estimate daily river discharge over an entire river basin. Whether a simple statistical approach or a complex data assimilation approach is used, such models still depend on *in-situ* data, and hence cannot be used in areas where such data do not exist. Previous approaches to improve the coarse temporal resolution of satellite altimetry are summarised in Table 1.

It has recently been suggested that the difference in land surface temperature (LST) between daytime and night time may act as a suitable surrogate for flood inundation (Parinussa et al., 2016b). Under dry conditions, it has been found that LST heats and cools more rapidly. In addition, due to their lower thermal mass, shallow water bodies emit a smaller heat flux at night time (Alcântara et al., 2010). Thus for dry locations and/or times of year, the difference between daytime and night time LST (ΔLST) increases. When wet conditions are experienced, humidity and cloud cover contribute to a smaller ΔLST due to slower warming and cooling. Deep inundation in the wet season leads to more emissive heat flux at night time due to the higher thermal mass of the water body. Parinussa et al. (2016b) used soil moisture and antecedent catchment wetness when considering ΔLST but it is not known if the relationship extends to river water levels. If the relationship holds, it is expected that large ΔLST values would indicate lower water levels, with smaller ΔLST values occurring when river levels increase.

Here, we extend the concept of using remotely sensed ΔLST to flood forecasting by testing the utility of the approach for predicting daily water levels. The objectives of this study are to: (i) evaluate the potential skill in estimating daily water levels at *in-situ* gauges using satellite-based ΔLST; (ii) assess the ability of satellite-based ΔLST to improve the temporal resolution of water levels estimated using satellite altimetry. The first objective extends the previous work using ΔLST to understand its applicability to water level forecasting, while the second objective will indicate whether the approach can be used in ungauged