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Research papers

# Combining Landsat observations with hydrological modelling for improved surface water monitoring of small lakes

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A R T I C L E  I N F O

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A B S T R A C T

Small reservoirs represent a critical water supply to millions of farmers across semi-arid regions, but their hydrological modelling suffers from data scarcity and highly variable and localised rainfall intensities. Increased availability of satellite imagery provide substantial opportunities but the monitoring of surface water resources is constrained by the small size and rapid flood declines in small reservoirs. To overcome remote sensing and hydrological modelling difficulties, the benefits of combining field data, numerical modelling and satellite observations to monitor small reservoirs were investigated. Building on substantial field data, coupled daily rainfall-runoff and water balance models were developed for 7 small reservoirs (1–10 ha) in semi arid Tunisia over 1999–2014. Surface water observations from MNDWI classifications on 546 Landsat TM, ETM+ and OLI sensors were used to update model outputs through an Ensemble (n = 100) Kalman Filter over the 15 year period. The Ensemble Kalman Filter, providing near-real time corrections, reduced runoff errors by modulating incorrectly modelled rainfall events, while compensating for Landsat's limited temporal resolution and correcting classification outliers. Validated against long term hydrometric field data, daily volume root mean square errors (RMSE) decreased by 54% to 31 200 $m^3$ across 7 lakes compared to the initial model forecast. The method reproduced the amplitude and timing of major floods and their decline phases, providing a valuable approach to improve hydrological monitoring (NSE increase from 0.64 up to 0.94) of flood dynamics in small water bodies. In the smallest and data-scarce lakes, higher temporal and spatial resolution time series are essential to improve monitoring accuracy.

## 1. Introduction

### 1.1. Hydrology of small water bodies

Small reservoirs have developed across semi-arid areas to reduce transport of eroded soil and mobilise water resources for local users. Their reduced costs favoured significant bottom-up development, resulting in several million small reservoirs worldwide (Lehner et al., 2011). Due to their modest size and large numbers, field monitoring of small water bodies remains rare except for scientific purposes (Albergel and Rejeb, 1997), limiting their hydrological understanding.

Local studies in Sub-Saharan Africa (Desconnets et al., 1997; Martin-Rosales and Leduc, 2003), Brazil (Molle, 1991), Mexico (Avalos, 2004), India (Massuel et al., 2014b) and Tunisia (Grunberger et al., 2004; Zammouri and Feki, 2005) performed water balance modelling to quantify available resources and hydrological processes illustrated in Fig. 1. These exploit field measurements of rainfall, reservoir stage and pan evaporation but difficulties occur due to the uncertainties in estimating inflow, infiltration and groundwater inflow, withdrawals and lake evaporation (Li and Gowing, 2005), which must be modelled, extrapolated and/or neglected based on reasonable assumptions. Inflow due to diffuse runoff is often assessed indirectly by closing the water balance or through rainfall-runoff modelling. The latter notably suffer from the spatial variability of semi-arid rainfall regimes, leading to model performance of NSE = 0.5 or less, even with site specific field data (Lacombe et al., 2008; Neppel et al., 1998; Ogilvie, 2015). Difficulties increase when seeking to upscale site specific data and model water resources in ungauged small reservoirs (Cudennec et al., 2007;

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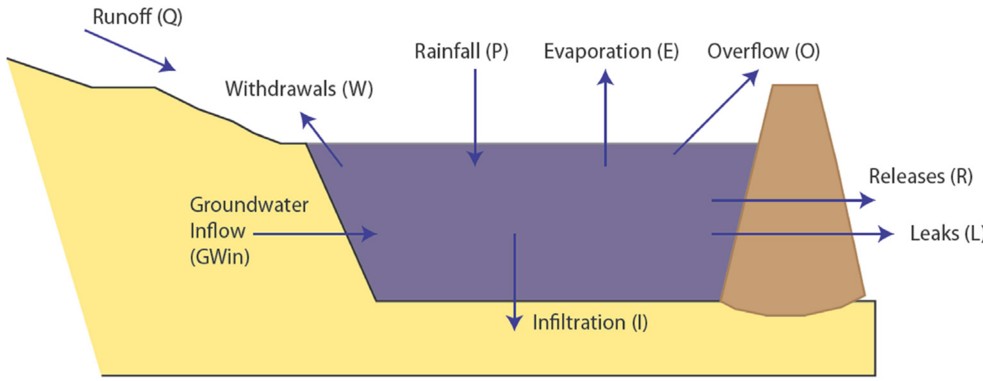


**Fig. 1.** Water balance fluxes in small reservoirs.

Hrachowitz et al., 2013).

As a result, limited information exists on their water resources, preventing the optimisation of farming practices and local stakeholder investments (Wisser et al., 2010). Capturing runoff and favouring evaporation and infiltration, these reservoirs also modify the spatio-temporal distribution of resources. Hydrological studies have shown these can reduce downstream flows by up to 80% in small catchments and highlighted their cumulative influence in larger catchments (Ma et al., 2010; Nyssen et al., 2010). Studies in China (Gao et al., 2011; He et al., 2003) and Tunisia (Kingumbi et al., 2007; Lacombe et al., 2008; Ogilvie et al., 2016b) on catchments over 1000 $km^2$ identified reductions ranging between 1% and 50% over the same periods and catchments, highlighting the uncertainties resulting in part from hydrological data scarcity on small reservoirs.

### 1.2. Remote sensing and data assimilation of small water bodies

Satellite imagery is increasingly exploited to provide input data or to calibrate hydrological models, with remotely sensed values of evaporation, rainfall and soil moisture (Soti et al., 2010; Zribi et al., 2011) or assessments of surface water areas (Leauthaud et al., 2013; Ogilvie et al., 2015; Swenson and Wahr, 2009), lake and river stages (da Silva et al., 2014), and lake water volumes (Baup et al., 2014; Crétaux et al., 2015; Frappart et al., 2018). Used extensively across large wetlands, lakes or rivers, and at continental or global scales, remote sensing has also been applied to provide insights across smaller water bodies.

Studies using Landsat 30 m or pansharpened 14.5 m (Feng et al., 2016) notably enabled mapping numerous water bodies and their storage capacities (Liebe et al., 2005; Sawunyama et al., 2006). Long term Landsat time series have also recently been used to monitor surface water variations over time. Pekel et al. (2016) developed a publicly available global data set of surface water at a monthly scale over 1984–2015. Ogilvie et al. (2018) showed the benefits of a specific approach to monitor small reservoirs (<10 ha) and account for the greater presence of flooded vegetation (Mueller et al., 2016; Yamazaki and Trigg, 2016) and difficulties resulting from limited spatial (30 m) and temporal resolution (up to 8 day from the combination of Landsat 8 and Landsat 7 satellites). These succeeded in reducing mean surface water RMSE to 9300 $m^2$ (NRMSE = 24%) but the presence of clouds reduced image availability reducing the method's ability to detect rapid floods and reproduce coherent flood declines.

Data assimilation seeks to combine external sources of data or observations to beneficially correct or calibrate in real time (i.e. as observations become available) model outputs. Widely relied on in meteorology, it has become increasingly used in other scientific fields, including hydrology (Beven and Freer, 2001; Boulet et al., 2002; Clark et al., 2008; Emery et al., 2017; Moradkhani et al., 2005; Xie and Zhang, 2010) notably to combine the benefits of increasingly available and valuable (precise, accurate, higher temporal and spatial resolution) remote sensing data.

To overcome the difficulties in monitoring surface water variations in small reservoirs through hydrological modelling and satellite imagery, the benefits of combining field data, numerical modelling and remote sensing were investigated here. A daily hydrological model to simulate volumetric changes in small reservoirs combined with an Ensemble Kalman filter to reevaluate in real time model outputs based on Landsat observations was developed here. The benefits of this combined model on daily values and mean annual availability were assessed against field data on 7 gauged reservoirs and compared with results obtained using only hydrological modelling or Landsat observations. Finally, the sensitivity of the approach to downgrading the confidence in input values and moving towards conditions found on ungauged reservoirs was investigated.

## 2. Methods

### 2.1. Study sites

This research focussed on seven small reservoirs in semi-arid central Tunisia (Fig. 2) benefiting from long term hydroclimatic data acquired through research collaboration with government agencies (Albergel and Rejeb, 1997; Leduc et al., 2007; Ogilvie, 2015). Field instrumentation on each lake consisted of automatic stage pressure transducers and tipping bucket rainfall gauges, supplemented by daily limnimetric (ladder) and rainfall readings by local observers. Thirteen lakes in the vicinity had also been equipped with evaporation pans. Complementary pressure transducers and automatic rainfall gauges were installed as part of this research in 2011 on three lakes (Hoshas, Morra, Guettar) to extend time series (Fig. 3) and tend to the declining monitoring network exacerbated by the Tunisian revolution.

Stage and surface area were converted using site specific Height-Surface-Volume relations (Fig. 3) acquired and updated since the 1990s to account for silting (Albergel and Rejeb, 1997). Complementary surveying was also carried out on Hoshas in 2014. Fig. 4 illustrates the shift in the rating curves from silting, which can be used to assess the level of uncertainty associated with volumes in recent years. On Gouazine, after 6 years (2001 vs. 2007) the obsolescence of the rating curve results in a mean RMSE of 4900 $m^3$, while on Fidh Ali it reaches 25 000 $m^3$ on volumes under 80 000 $m^3$. On lakes where rating curves could not be updated (Guettar and Morra) for logistical reasons (cost, access to lakes and presence of water and/or vegetation on lake bed), GPS contours nevertheless highlighted that errors in the H-S rating curves only reached 11–12% after 12 and 22 years respectively (Ogilvie et al., 2018).

These are inferior to errors generated from extrapolating capacity loss based on studies on 15 nearby surveyed reservoirs (Fig. 2), due to the strong disparities in silting rates and the difficulties in erosion modelling, especially over extended periods (Albergel and Rejeb, 1997;