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Monthly flooded area classification using low resolution SAR imagery in the Sudd wetland from 2007 to 2011

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ABSTRACT

The annual flood cycle of the Sudd wetland in South Sudan plays an important role in the Nile River Basin water balance. The wetland, however, is extensive and sparsely instrumented, which has inhibited credible understanding of regional flooding across space and time. Here we explore the potential to apply low resolution C-band ENVISAT Advanced SAR imagery for remote estimation of Sudd flooded area. Over a five year study period (2007–2011) the time-averaged flooded Sudd area was found to be 18,033 km^2 with an average annual high of 29,702 km^2 in late September and a low of 10,128 km^2 in early May. Annual peak flood area ranges considerably from 19,259 km^2 in 2009 to 36,649 km^2 in 2007, but we found no systematic trend over the five year study period. Derived flood frequency maps identify areas of open water and permanent flooding (12% of total area), seasonal flooding (29%), and intermittent flooding (48%). To evaluate the certainty of our results, we consider their consistency with (1) prior studies, (2) evapotranspiration estimates from the Atmosphere-Land Exchange Inverse (ALEXI) surface energy balance algorithm, (3) watershed storage anomaly estimates from GRACE, (4) supervised classification of open water area using Landsat, and (5) a rough measure of water availability (antecedent precipitation). The analyses show reasonable temporal and spatial consistency with available lines of evidence. We conclude that low resolution C-band SAR imagery shows promise for study of Sudd wetland flood dynamics.

1. Introduction

Water is a precious resource for the eleven African countries that share the Nile River Basin. At the heart of this water system is the vast Sudd wetland in South Sudan (Fig. 1). The Ramsar Convention on Wetlands designated the Sudd as a Wetland of International Importance in 2006 based in part on its biodiversity, its role in regulating downstream water quality and flow, and its value to local communities as a source of water for household and other beneficial uses (Ramsar, 2014). Water resources in the Sudd wetland are likely to be increasingly stressed by growing upstream pressures including population growth, economic development, and climate change (Nile Basin Initiative, 2012). Despite these looming challenges, the baseline hydrology of the Sudd wetland, including the area, volume, and seasonality of flooding, are poorly understood (Mohamed et al., 2006). Policy makers need a fuller grasp of Sudd hydrology to provide for the long-term health and productivity of the wetland (Mohamed and Savenije, 2014). Of particular interest are inter- and intra- annual variability in Sudd flooding across space and time. Flooded area has been seen as a plausible proxy for the health of the Sudd ecosystem (Mohamed and Savenije, 2014). Most field and remote estimates of flood extent in the Sudd literature, however, have been one-time or short term (<1 year) surveys using different methods and site delineations, making it difficult to compare and compile findings for longer-term trend analysis.

One promising approach for making remote estimates of Sudd flooded area is Synthetic Aperture Radar (SAR). Unlike other remote sensing techniques, SAR flooded area classification can be effective under cloudy conditions and over regions with vegetative canopies (Hess et al., 1990), which are typical in the Sudd. Recent work by Rebelo et al. (2012) demonstrated that high-resolution (70 m) L-band SAR imagery can provide credible remotely sensed estimates of flooded area over a 12 month period (June 2007–May 2008). In order to extend

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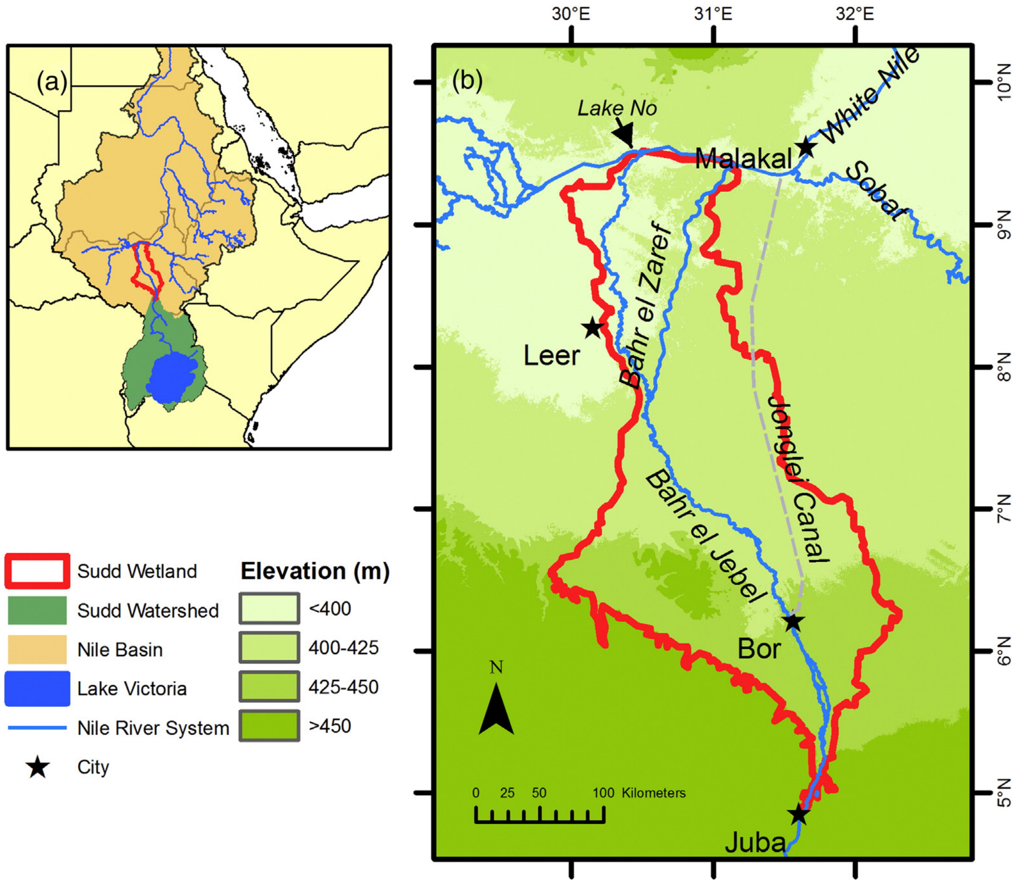

Fig. 1. Map of the study area. **(a)** The delineated area of the Sudd wetland (red), the equatorial lakes region (green), and the entire Nile basin (tan) in Eastern Africa. **(b)** Select cities, rivers, and topography of the Sudd wetland, as well as the planned location of the incomplete Jonglei canal. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and expand the previous SAR analysis of the Sudd, we obtained from the European Space Agency (ESA) 60 relatively low-resolution C-band ENVISAT Advanced Synthetic Aperture Radar (ASAR) images for monthly estimation of Sudd flooded area from 2007 to 2011. Based on prior literature (discussed in Section 3.2.1), we hypothesized that C-band imagery could be as effective as L-band imagery for Sudd flooded area estimation. The study objective is two-fold: (1) to report our C-band SAR-based estimates of the intra- and inter- annual trends in Sudd flooded area from 2007 to 2011 and (2) to evaluate our estimates by considering their consistency with five semi-independent lines of evidence: prior studies, actual evapotranspiration (ET) estimates from the Atmosphere-Land Exchange Inverse (ALEXI) surface energy balance model (Anderson et al., 2007), watershed storage anomaly estimates from the Gravity Recovery and Climate Experiment (GRACE) (Tapley et al., 2004), supervised classification of open water area using Landsat, and antecedent water availability based on estimates of catchment precipitation (P) from three different remotely sensed data products.

To our knowledge, this is the first multi-year study focused on Sudd flood area to exploit SAR imagery and its demonstrated skill at flood classification. Multi-year studies can generate more stable, time-averaged classification thresholds that potentially minimize classification error. In addition, the study showcases how multiple remote sensing products can be used to corroborate flood classification in regions without contemporaneous, in-situ observations. Other contributions of the paper include: (1) the assessment of low-resolution SAR imagery for Sudd classification, (2) the application of a novel seasonally-adjusted thresholding method for SAR-based flood area classification, (3) a practical approach to parameterizing the relationship between Sudd flooded area and water volume, and (4) new insight into the relationship between Sudd flooded area and ET. Useful applications for the SAR-based flooded area estimates are briefly discussed, including flood trend detection, flood monitoring and early warning, and impact assessment of hypothetical White Nile development scenarios on flood dynamics.

The remainder of the paper is split into five sections. The Background Section motivates the work by describing the wetland and previous studies of its area. The Methods Section describes the seasonally adjusted thresholding algorithm that was applied to the ENVISAT ASAR imagery to estimate flooded area, and the subsequent analysis and evaluation work. The Results and Discussion section reports our flooded area estimates and how well they compare with other remotely sensed data. Finally, the Conclusion section summarizes our results and their applications.

2. Background

2.1. Site description

Although its boundaries are poorly defined, the Sudd wetland is immense, covering roughly 10% of the land area of South Sudan (see Fig. 1). The name "Sudd" is derived from an Arabic word meaning barrier or obstacle (Collins, 1990). Indeed, the wetland has long disrupted White Nile flows between upstream Lake Victoria and Lake Albert in Uganda and the downstream juncture with the Blue Nile at Khartoum, Sudan. When the northward flowing White Nile (here called the Bahr el Jebel) reaches Juba, the approximate starting point of the Sudd, the landscape flattens and the flow splits into a shifting network of parallel rivers including Bahr el Jebel (the main river) and Bahr el Zeraf. The Sudd takes form as large shallow lagoons on either side of the rivers, which are seasonally fed by rainfall and flows through naturally forming