# K&C Science Report – Phase 2
# Characterisation of inland wetlands in Africa

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*Abstract*— **Inland wetlands occur extensively across Sub-Saharan Africa. These ecosystems typically play a vital role in supporting rural populations and their sustainable management is thus critical. In order to prevent depletion of resources and ecosystem services provided by these wetlands, a balance is required between ecological and socio-economic factors. The sustainable management of wetlands requires information describing these ecosystems at multiple spatial and temporal scales. However, many African countries lack regional baseline information on the temporal extent, distribution and characteristics of wetlands. PALSAR data provides invaluable information related to the flooding patterns and vegetation characteristics of these wetlands. Due to political instability in Sudan and the inaccessible nature of the Sudd, recent measurements of flooding and seasonal dynamics are inadequate. Analyses of multi-temporal and multi-sensor remote sensing datasets are presented in this paper, in order to investigate and characterize flood pulsing within the Sudd wetland over a twelve month period. Wetland area has been mapped along with dominant components of open water and flooded vegetation at five time periods over a single year. The total area of flooding over the twelve months was 41,334 km$^2$, with 9,176 km$^2$ of this constituting the permanent wetland. Mean annual total evaporation is shown to be slightly higher and with narrower distribution of values from areas of open water (1718 mm) than from flooded vegetation (1641 mm). While the exact figures require validation against ground based measurements, the results highlight the relative differences in inundation patterns and evaporation across the Sudd.**

***Index Terms*— ALOS PALSAR, K&C Initiative, Wetland Theme, Africa, flooding patterns, vegetation.**

## I. INTRODUCTION

Originating in Lake Victoria, the White Nile, one of the two major tributaries of the Nile River, flows from Uganda into Southern Sudan where it enters a shallow depression and forms the vast Sudd wetland. Beyond the Sudd the river flows to Khartoum where it merges with the Blue Nile, forming the main stem of the Nile River which subsequently flows through Egypt and into the Mediterranean Sea. While wetland ecosystems occur extensively across the basin, from Lake Victoria in the south to the Nile Delta in the north, the swamps and floodplains of the Sudd constitute the largest wetland ecosystem in the Nile Basin and one of the largest tropical wetlands in the World. The Sudd is dependent on the outflow from Lake Victoria, but exhibits large seasonal changes as a consequence of variation in flow downstream of the lake. The "Flood Pulse Concept" (FPC; [1]) describes the importance of the hydrological pulse to the functioning of wetlands, and states that it is the annual inundation pattern which is primarily responsible for the high productivity of, and the biotic interactions within, such systems.

In addition to supporting high levels of biodiversity, the Sudd provides many other ecosystem services. It is estimated that more than 1 million people are almost entirely dependent on the wetland. The socio-economic and cultural activities of the Nilotes living within and adjacent to the Sudd region are entirely dependent on the Sudd wetland [2]. It is a major source of water for domestic use, and for livestock, and is an important source of fish. The Sudd is one of the only water bodies of the Nile which is not overfished and the potential yield (based on a surface area of 30,000–40,000 km$^2$) has been estimated at 75,000 tons per year [3]. Many fish species migrate from the surrounding rivers to the nutrient rich flood plains to feed and breed during the seasonal floods [4]. The socio-economic and cultural activities of local people are dependent on the annual floods to regenerate the floodplain grasses which feed their cattle. However, due to the protracted civil war in the region with the latest episode lasting from 1983 till 2005, very little is known about the current status of the biodiversity or the livelihood practices which are supported by the wetland.

The Comprehensive Peace Agreement (CPA), signed in 2005 ended 22 years of civil war, and subsequently in 2006 a core area of 57,000 km$^2$ of the Sudd was designated as a Ramsar wetland site of International importance. Despite this status, recent discovery and exploitation of oil reserves in the Sudd threatens the diversity of the wildlife, aquatic macrophytes and floodplains, as well as the hydrology of the intricate ecosystem [5]. With the signing of the CPA another major threat to the wetland is the completion of the Jonglei Canal. The original aim of the canal was to divert inflows to the Sudd in order to reduce evaporation from the wetland, thereby gaining approximately 4,700 Mm$^3$ of water for downstream use, as well as to reclaim approximately 100,000 ha of land for agriculture [6]. Construction of the canal started in 1980 but was stopped by the onset of the civil war in 1983, after 260 of the total 360 km had been completed. In 2008, discussions to continue the work were resumed. If completed the canal is likely to have a significant impact on groundwater recharge, silt and water quality; it is also likely to result in the loss of biodiversity, fish habitats and important grazing areas, all of which will have an effect on the livelihoods of the local populations.

An understanding of the links between the hydrological pulse and the ecosystem is a prerequisite for deriving management plans for flood pulse wetlands such as the Sudd. While it is known that the size of the Sudd varies substantially in response to seasonal and inter-annual changes in inflows, maps of recent flood extent and seasonal changes are unavailable for the total Sudd area, and figures in the literature on the areal extent of the wetland vary considerably [7,8,9]. This is due to variations in the definition of what constitutes the wetland, as well as differences in the approach used to map the area. In addition the area of wetland increased dramatically after the early 1960's due to increases in outflows from Lake Victoria. Different techniques have been applied to determine the size of the Sudd including hydrological modelling [10], thermal remote sensing [8], and a combination of hydrological modelling and remote sensing of evaporation [9]. While an area of 30,000 to 40,000km$^2$ is frequently cited in the literature [7,8,9], figures range from approximately 7000 km$^2$ of permanent swamps to 90,000 km$^2$ of seasonal floodplain [6].

Due to the political instability in the region as well as the inaccessible nature of the Sudd, recent analyses have typically focussed on the use of remote sensing datasets. Remote sensing technologies are essential in providing up-to-date spatial and temporal information about wetlands and their catchment basins, and should be seen as a fundamental component in the development of wetland management plans for conservation and sustainable utilization [11]. While mapping of wetlands has proved difficult in many areas due to the lack of temporally and spatially consistent datasets, the systematic data acquisition strategy of new satellites such as the Advanced Land Observing System (ALOS) seek to redress this. The acquisition of data at a high temporal frequency is essential for the analysis of wetlands such as the Sudd, which are defined by seasonal flows.

## II. Description of the Project

### A. Relevance to the K&C drivers

The project aims to generate knowledge to assist in the sustainable management of wetlands which are utilised for agriculture and fisheries activities, and to assist the countries concerned to put in place or enhance mechanisms that minimize degradation of the wetlands, in order to optimize the ecosystem and livelihood benefits. Project objectives also include the provision of baseline wetland information from remote sensing and GIS data, and the generation of generic guidelines, tools and methodologies for wetland mapping and characterisation.

The Wetlands Theme of the K&C Initiative focuses on the provision of remote sensing datasets that can be used to assist the global mapping and monitoring of wetlands and identifying and quantifying the threats to which these are exposed. Specifically, it aims to develop a suite of products which may be used to improve the understanding of carbon cycle science, assist the implementation of conservation and management strategies and support national and international obligations to multi-national conventions [12]. The work reported here is of relevance to all three of the thematic drivers: **C**arbon, **C**onservation, and **C**onventions i.e. the three C's. The draining and transformation of wetlands for agricultural (as well as for other) uses is likely contributing to the carbon imbalance in the atmosphere [13]. Wetlands contain and cycle a significant amount of carbon and play a key role in the global carbon cycle, not least because of the large turnover of methane within these systems; it is estimated that natural wetland sources emit about 20% of the methane entering the atmosphere each year [14] and they are responsible for a significant proportion of biogeochemical fluxes between the land surface, the atmosphere, and hydrologic systems [15]. A basic requirement for modelling regional to global methane or carbon dioxide emissions from wetlands is information on their type and distribution.

In Africa where wetlands are utilised extensively for agriculture and fisheries activities, the loss of these ecosystems will also have a more direct effect on local populations. Long-term preservation and sustainable use of these resources is therefore critical for the economic and social well being of current and future generations. Key requirements include the establishment of regional and temporal datasets of wetland extent and condition which incorporate an understanding of the inundation dynamics of an area and spatially quantifiable measures of both anthropogenic and natural pressures and threats to wetland communities [12].

The Ramsar Convention on wetlands of International Importance promotes the conservation and wise use of all wetlands through local, regional and national actions and international cooperation, as a contribution towards achieving sustainable development throughout the world (Ramsar COP8, 2002). The Convention aims to halt and reverse the global trends of wetland degradation and destruction through the dissemination of information, involvement of local communities and establishment of sustainable management plans. While Contracting Parties to the Convention have been encouraged to undertake better and more efficient wetland inventory, and to establish and maintain national inventories, many African countries lack the resources to achieve this. Remote sensing technologies are essential in providing up-to-date spatial and temporal information about wetlands and their catchment basins, and should be seen as a fundamental component in the development of wetland management plans for conservation and sustainable utilisation. While mapping of wetlands has proved difficult in many areas because of the lack of temporally and spatially consistent datasets, the systematic data acquisition strategy of ALOS PALSAR seeks to redress this [13].

### B. Site Description

The analyses have been conducted in the Nile Basin, with a focus on the Sudd wetland. Located on the Bahr el Jebel (the White Nile) in southern Sudan, the Sudd is one of the largest floodplain wetlands in the world. The total catchment area of the Sudd is nearly 3 million km$^2$. Located between 6° to 9° 8' N and 30° 10' to 31° 8' E, the Sudd consists of a diverse range of habitats which support a rich array of aquatic and terrestrial fauna [16]. Biodiversity within the Sudd is high, supporting over 400 bird and 100 mammal species. Located on the eastern flyway between Africa and Europe/Asia, the Sudd is one of the most important wintering grounds in Africa for Palaearctic migrants, providing essential habitats for millions of migrating birds [7]. During the 1980's the region was listed as supporting the highest population of Shoebill Storks (*Balaeniceps rex)* [17] and the greatest numbers of antelopes in Africa [18]. Many of the antelopes undertake large scale migrations across the Sudd, following the changing water levels and vegetation. The wetland also has a high density and diversity of aquatic plants [19].

As the objective of the work was to characterize seasonal patterns of inundation and evapotranspiration from the Sudd, the study area was defined as the Bahr el Jebel contribution to the Sudd wetland, i.e. excluding the neighbouring Bahr el Gazal swamps and the Sobat marshes. The Sudd area was determined by delineating the catchment for the main stem of the Bahr el Jebel between Juba in the south and the confluence with the Sobat in the north (see Figure 1).

### *C. Datasets*

Delineation of the Sudd wetland is extremely difficult due to its dynamic nature as well as due to the presence of adjoining wetland systems. In this study, the area of interest was derived from elevation data and catchment boundaries. The boundaries were delineated using the Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM) and standard processing steps using the HydroSHEDS GIS Toolkit [20]. The elevation at Juba (455m on the SRTM Digital Elevation Model) was used to define the southern boundary.

Inundation patterns were mapped over a twelve month period from PALSAR data. K&C ScanSAR strips with a pixel spacing of 70 x 50m acquired at five time periods were used as input to the analysis; June, September and December 2007, and January, May 2008. Three paths were required to cover the study area; RSPs 250, 253 and 256. These were provided by JAXA in ORT format, and were processed to geotiffs and mosaicked across the area of interest following the

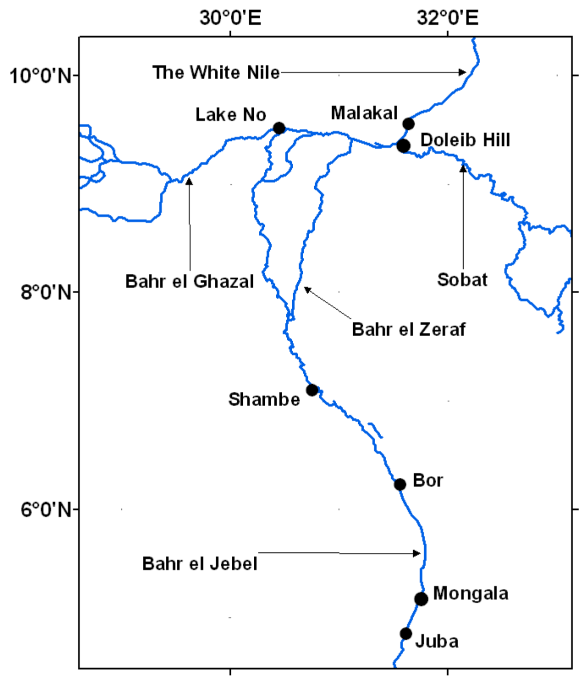


Figure 1. The Sudd region, southern Sudan; river network and settlements

processing chain in Figure 2. The mosaics used in the analysis for three of the observation periods are shown in Figure 3. A principal components analysis over the three months of peak inflow (June, September and December 2007) is shown in Figure 4. The PALSAR amplitude data were converted to normalized backscatter coefficients ($\sigma^0$) following Equation 3, where DN is the Digital Number and CF refers to the calibration co-efficient provided by JAXA [21].

$$\sigma^0 = 10 * \log_{10}(DN^2) + CF \qquad \text{Equation 1}$$

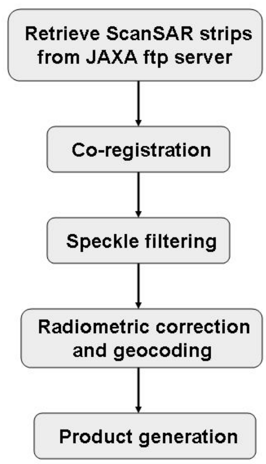


Figure 2. ScanSAR processing chain

The data were filtered using a 3x3 median filter, followed by a 5x5 Enhanced Lee filter in order to reduce speckle and smooth areas of the image with similar ground cover [22].

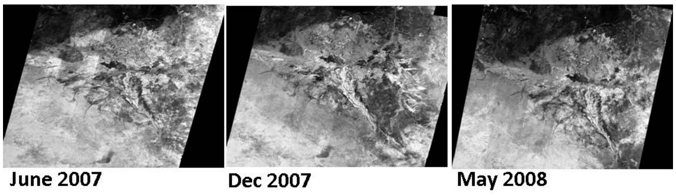


Figure 3: ScanSAR strips over the Nile Basin © JAXA/METI 2007, 2008

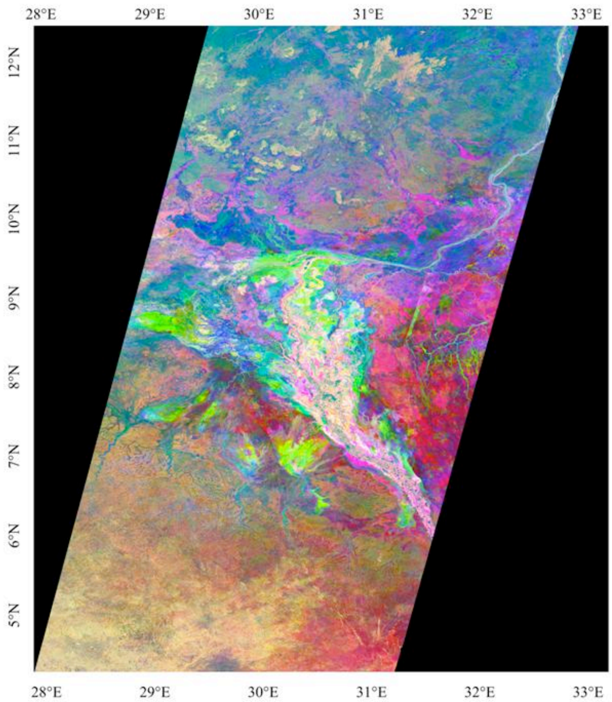


Figure 4: Principal components analysis of three dates (June, September and December 2007) of ScanSAR strips over the Sudd wetland, southern Sudan © JAXA/METI 2007, 2008

The detection of open water and flooded vegetation from SAR data is well established, and time series of SAR images have been used successfully to map flood dynamics in different ecosystems [23,24,25]. The backscatter response from open water and from flooded vegetation at L-band is well understood. The signal exhibits i) high returns in areas of flooded vegetation due to the double bounce effect as the radar signal is reflected off both the vegetation and the water surface, ii) intermediate returns for dry land due to diffuse scattering from the ground and/or volume scattering within vegetation canopies, and iii) very low returns from open water due to specular reflectance [26,27]. Open water bodies and flooded vegetation have traditionally been detected in SAR images through thresholding, with class boundaries set through empirical evaluation of the image histograms [28]. This is the approach followed in this study, with threshold levels identified through histogram analysis. While an absolute measure of soil moisture is not achieved, this approach provides a means of monitoring spatial and temporal changes in the hydrological state [29]. The histograms indicate a high level of separation between the three classes, with open water exhibiting very low returns, dry land intermediate values, and flooded vegetation high values (Figure 5). The horizontal lines show the selected thresholds with an upper value of -15 db for open water, and a lower value of -9 for flooded vegetation. The overlap between the histogram classes gives an indication of the errors associated with the threshold values.

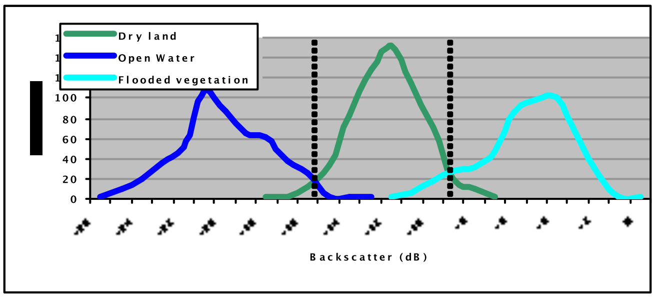


Figure 5: Frequency distribution of backscatter coefficients for different landcover types

Monthly maps of actual evapotranspiration (ETa) for the study area were generated using the Simplified Surface Energy Balance (SSEB) model [30] for the period between 2001 and 2009 (Figure 6). The SSEB model uses a combination of thermal data sets to develop ET fractions and reference ET (ETo) generated using weather data sets from NOAA's global data assimilation system (GDAS), as described in detail in [31]. The Land Surface Temperature (LST) is derived from satellite thermal data and suggested value of alpha is 1.2 when ETo is based on clipped grass reference ET. Rn is net radiation; T is air temperature; U is wind speed; RH is relative humidity; P is atmospheric pressure.

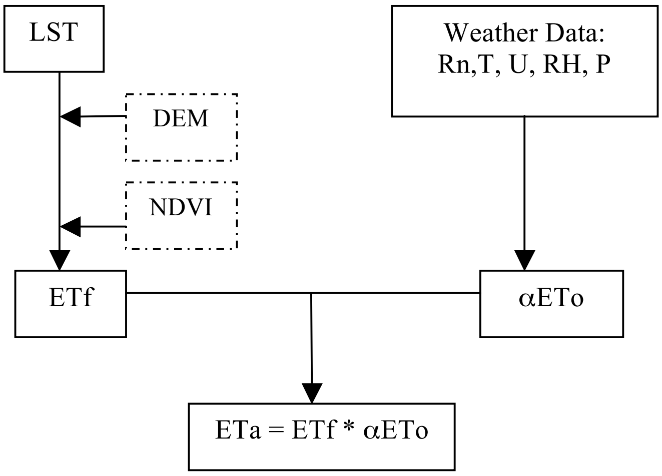


Figure 6: Schematic Representation of the SSEB modeling setup

## III. Results and Summary

The area of the Sudd and the components of open water and flooded vegetation vary considerably over the twelve month period. Lowest areas of open water are identified in September (4,313 km$^2$), whilst the highest expanse of flooded vegetation (27,186 km$^2$) is also evident during this month. In contrast the greatest expanses of open water occur in December and January, when the area of flooded vegetation is lower. The monthly total area of wetland within the study site ranges from a minimum in June of 22,892 km$^2$, to a maximum of 32,701 km$^2$ in January (Table 1). Note however that the latter figure does not refer to the total flooded area within the study site as different areas may flood at different times of the year. The total area of the wetland, defined here as areas which were detected as either open water or flooded vegetation for any of the five dates during the twelve month period, is 50,510 km$^2$ (Figure 7). It should be noted that the flooding identified is not limited to river-fed flooding only, but also to rain-fed flooding. Temporary flooding due to rainfall may occur locally in the rain-fed grasslands adjacent to the wetland [32]. Of the 50,510 km$^2$, 9,176 km$^2$ constitutes the area of "permanent" swamps, i.e. the locations where open water or flooded vegetation (Figure 7) is detected in each of the five dates during the twelve month period. The ratio of permanent to seasonal swamps is thus 18%, with the wetland area expanding to more than 4 times the size of the permanent swamps with the annual flood pulse and rainfall in the catchment.

Table 1: Seasonal variations in inundated areas (km$^2$)

| Month | Open water | Flooded vegetation | Wetland |
|---|---|---|---|
| June 2007 | 5850 | 17,042 | 22,892 |
| September 2007 | 4313 | 27,186 | 31,499 |
| December 2007 | 10947 | 18,873 | 29,821 |
| January 2008 | 10601 | 22,100 | 32,701 |
| May 2008 | 5365 | 19,892 | 25,257 |

The ET varies substantially both spatially across the study site), as well as temporally, over the twelve month period. Between June 2007 and May 2008 the estimated total ETa is 1449 mm while the annual rainfall for the same period was 779 mm meeting 54% of the ETa demand. The minimum ET occurs at the end of the dry period in April. The deficit ET months were August to April, with the maximum deficit occurring in December with the lowest rainfall and a relatively high ET period. The peak ETa occurred in October. Mean ET values were calculated for areas of permanent wetland, i.e. pixels which were either classified as open water or flooded vegetation in *each* of the images, i.e. their status did not change during the twelve month period, as well as for the areas which were seasonally flooded (Table 2).

Table 2: Mean ET values for open water and flooded vegetation

| | Total ET (Mm$^3$) | Mean ET (mm) | Area (km$^2$) |
|---|---|---|---|
| Open water | 1,162 | 1718 | 692 |
| Flooded vegetation | 14,098 | 1641 | 8488 |
| Seasonally flooded | 59,763 | 1422 | 41334 |
| Terrestrial | 9,075 | 1311 | 6823 |

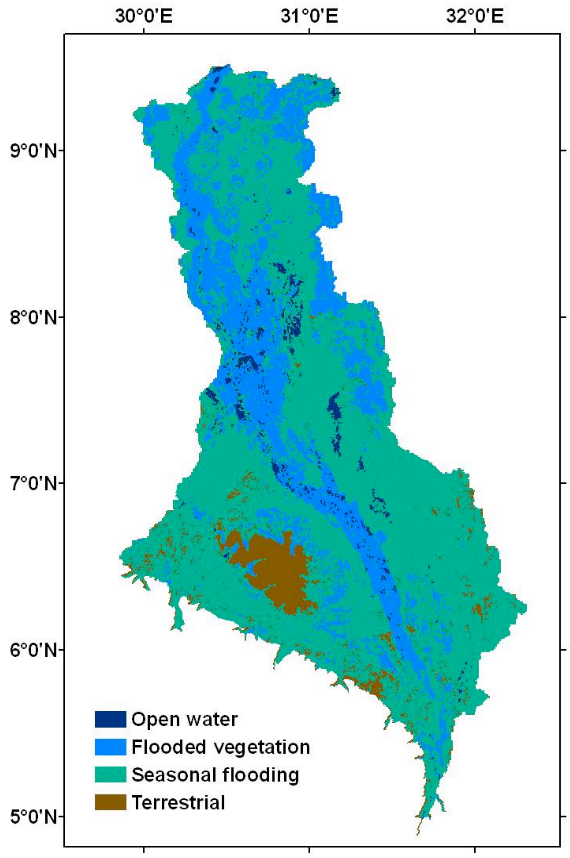


Figure 7: Spatial patterns of inundation (both river- and rain-fed), analysed at five time periods between June 2007 – May 2008.

Two parameters which are widely debated in the literature on the Sudd are the area of, and the evaporation from, the wetland. Within the defined study site, the total wetland area (50,510 km$^2$) constituted 85% of the land surface between June 2007 and May 2008. Flooding in the Sudd wetland exhibits a distinct seasonal pattern which is determined by the level of the Bahr el Jebel and rainfall in the catchment. While a core area of 9,176 km$^2$ of permanent wetland was identified during the period June 2007 – May 2008, at 41,334 km$^2$, the area of seasonal flooding over the twelve months was four times larger. The total wetland area is thus composed of 18% of permanent and 82% of seasonally flooded wetlands. The wetland was at its greatest expanse between September 2007 and January 2008 and at its lowest in June 2007 and May 2008, suggesting a 3-4 month lag following inflow at Juba and torrents in the catchment.

It has been emphasized in previous studies of the Sudd that one of the complexities in determining regional scale evaporation has been the variability in the boundaries of, and seasonal changes in, the wetland [9]. While mapping of tropical wetlands has proved problematic with the use of optical satellite images due to the presence of cloud cover at the time of maximum inundation, this study has mapped the seasonal changes in the Sudd wetland using radar remote sensing data, which are unaffected by cloud cover. The systematic acquisition strategy of ALOS PALSAR has enabled characterization of wetland dynamics at a high temporal resolution. Analysis of this data has provided high resolution (70m) maps of inundation patterns in the Sudd over the twelve month period June 2007 to May 2008. Combining these with spatially explicit monthly calculations of ET over the Sudd has provided insights into variations in ET from the different wetland components. While the exact figures presented require validation against ground based measurements and should therefore be treated with caution, the results highlight the relative differences in inundation patterns and evapotranspiration across the Sudd over a twelve month period. Future work will extend the analysis over multiple flood cycles, in order to characterize the intra- as well as inter-annual flood dynamics of the Sudd and provide information which is crucial to the management of this vast resource. Lessons learned here will be applied to the analysis of regional scale inundation patterns across the Nile Basin.


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