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A near real-time water surface detection method based on HSV transformation of MODIS multi-spectral time series data

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ABSTRACT

In the face of global population growth and the uneven distribution of water supply, a better knowledge of the spatial and temporal distribution of surface water resources is critical. Remote sensing provides a synoptic view of ongoing processes, which addresses the intricate nature of water surfaces and allows an assessment of the pressures placed on aquatic ecosystems. However, the main challenge in identifying water surfaces from remotely sensed data is the high variability of spectral signatures, both in space and time. In the last 10 years only a few operational methods have been proposed to map or monitor surface water at continental or global scale, and each of them show limitations. The objectives of this study are to develop, demonstrate and validate the adequacy of a generic multi-temporal and multi-spectral image analysis method to detect water surfaces automatically, and to monitor them in near real-time at the African continental scale as a first step towards global scale coverage. The proposed approach, based on a transformation of the RGB color space into HSV, provides dynamic information at the continental scale. Two different validations were done at the continental scale over Africa: i) The algorithm validation checked the ability of the proposed algorithm to perform as effectively as human interpretation of the image: it showed an accuracy of 96.6% and no commission errors. ii) The product validation was carried out by using an independent dataset derived from high resolution imagery: the continental permanent water surface product showed an accuracy of 91.5% and few commission errors. Potential applications of the proposed method have been identified and discussed. The methodology that has been developed is generic: it can be applied to sensors with similar bands with good reliability, and minimal effort. Moreover, this experiment at the African continental scale showed that the methodology is efficient for a large range of environmental conditions. Additional preliminary tests over other continents indicate that the proposed methodology could also be applied at the global scale without too many difficulties.

1. Introduction

In the face of global population growth and the uneven distribution of water supply, a better knowledge of the spatial and temporal distribution of surface water resources is critical to support sustainable development policies and activities (Vörösmarty et al., 2000). As changing climate impacts the hydrological cycle and interferes with freshwater resources (Ohmura & Wild, 2002), lake maps and water level are two recognized critical parameters among the Essential Climate Variables (ECV) required to support climate change analyses called for by the Convention on Climate Change (UNFCCC) (GCOS, 2011). Beyond the ECV, a timely global water surfaces monitoring capacity would provide all countries with access to critical information on floods and droughts, both of which have dramatic economic and human impacts (Alsdorf & Lettenmaier, 2003). Such monitoring is crucial for many applications including human and animal health (Ceccato, 2010; Lacaux, Tourre, Vignolles, Ndione, & Lafaye, 2007), food security (agriculture, cattle breeding, aquaculture, and gardening) (Breman, Groot, & Van Keulen, 2001; Brouwer, 2003, Haas, Bartholomé, Lambin, & Vanacker, 2011; Hein, 2006; Thebaud & Batterbury, 2001), and biodiversity protection (UNESCO, 2009; Vörösmarty et al., 2000).

Besides all of these, an accurate time-dependent depiction of land and water is critical for the production of land surface parameters from remote sensing data products. The accuracy of other parameters, such as land surface temperature, active fires and surface reflectance, can be improved by defining whether the underlying surface is covered by water or not. Substantial errors in the underlying water mask are known to pervade into these parameters and any product derived from them (Carroll, Townshend, DiMiceli, Noojipady, & Sohlberg, 2009).

Remote sensing provides a synoptic view of ongoing processes, which addresses the intricate nature of water surfaces and allows an assessment of the pressures placed on aquatic ecosystems (Goetz, Gardiner, & Viers, 2008). Large reflectance datasets at medium resolution with high revisit frequency are becoming widely available. It is therefore possible to develop, assess and implement methodologies to

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map water surfaces and monitor their evolution in near real-time at global scale, based on such data.

However, the main challenge in identifying water surfaces from remotely sensed data is the high variability of spectral signatures. The spectral properties of water are determined by the electromagnetic interaction of light with the constituent components of water via absorption or scattering processes. These constituents are: phytoplankton (chlorophyll-a), suspended sediments (i.e. solid particulate matter with a diameter smaller than 2 mm resulting from erosion processes) and colored dissolved organic matter (CDOM) resulting from the degradation of biological organisms. All these constituents vary in character and amount according to the limnological/optical types, season, cyclical change of biological activity and human impact, and play an important role in determining intensity of the absorption and scattering processes (Arst, 2003). Consequently, the water-leaving radiance detected by the sensor shows great spatial and temporal variability, which makes the reliable discrimination of water particularly difficult (Gond, Bartholomé, Ouattara, Nonguierma, & Bado, 2004), specifically at continental scale where a large range of water conditions may be expected.

In the last 10 years, only a few methods applied to datasets with a spatial resolution equal or higher than 1 km, have been proposed to map or monitor surface water at continental or global scale. Among these, the most recent and operational methods (i.e. in production and availability to the user community) which offer satisfactory quality are: (i) the Shuttle Radar Topography Mission Water Body Dataset (SWBD, 2005), (ii) the Small Water Bodies (SWB) monitoring product derived from SPOT VEGETATION (VGT) (Bartholomé, 2008), (iii) the Moderate Resolution Imaging Spectroradiometer (MODIS) 250 m land–water mask (MOD44W) (Carroll et al., 2009) and the on-going NASA JPL wetland project aiming to construct a global-scale Earth System Data Record (ESDR) of inundated wetlands (NASA JPL wetland, 2013).

The SWBD product has a high spatial resolution (30 m), and offers superior performances over spectral data, in cloudy areas such as the humid tropics thanks to the cloud penetrating properties RADAR. However, all observations were made within 11 days in February 2000, meaning that only the specific conditions of that particular period are captured in the product. For instance, February corresponds to the dry season in semi-arid regions of the Northern hemisphere such as the Sahel, a season characterized by low water levels or even drying out in many seasonal water bodies. In addition, this product can be considered as outdated for some applications.

The SWB product is an operational monitoring system of water surfaces at the African scale (Bartholomé, 2008). It makes use of 10 day Normalized Difference Vegetation Index (NDVI), the Normalized Difference Water Index (NDWI), and MIR syntheses of VGT data and is based on a contextual algorithm (Gond et al., 2004) exploiting the local contrast of the water surface with respect to the surrounding region. The product was developed and validated for sub-humid and semi-arid regions in Africa, where it performs well (Haas, 2010). However limitations have been observed over dense vegetation areas which prevent the successful application at continental scale. In addition, the 1 km spatial resolution is an intrinsic limitation of the product. Nevertheless, the combination of 8 years of small water body monitoring data demonstrates the value of the multi-annual approach to capture water bodies that do not replenish every year in relation to seasonal rainfall patterns (Haas, Bartholomé, & Combal, 2009).

The MOD44W, is a global scale 250 m land/water mask that constitutes a valuable improvement over the other masks, specifically considering that the principal purpose of this product is to ensure that terrestrial and oceanic algorithms are applied to the appropriate pixels (Carroll et al., 2009). The main body of the product was created using the SWBD aggregated to 250 m and this was supplemented with MODIS 250 m data as necessary. Nevertheless, the use of this mask for other applications is constrained by its characteristics. Indeed, for temporal consistency reasons, the SWBD was supplemented with MODIS images from the years 2000 and 2001 and is therefore outdated for some applications. In addition, temporary water bodies are not comprehensively mapped, for example, those that do not replenish every year.

The NASA wetland ESDR is comprised of two complementary components: i) Fine-resolution, 100 m, maps of wetland extent, vegetation type, and seasonal inundation dynamics, derived from Synthetic Aperture Radar (SAR) for continental-scale areas. Currently, a map of wetlands in Alaska derived from L-band radar imagery acquired by JAXA's JERS-1 SAR is available (Whitcomb, Moghaddam, McDonald, Kellndorfer, & Podest, 2009). ii) In addition, the project generates a global, 10-day mapping of inundation extent at ~25 km resolution derived from multiple satellite remote sensing observations including passive and active microwave sensors and optical datasets optimized specifically for inundation detection (Chapman, McDonald, & Hess, 2008). A global scale 10 day inundation fraction (from 2002-July to 2009-July) is available (NASA JPL wetland, 2013).

The use of these products is constrained by their characteristics. The 100 m resolution product is specifically planned to cover the major global wetland regions and consists of a static map, while the global 10-day product is more adequate for monitoring activity, but is only available at ~25 km resolution.

The objectives of this study are to develop and demonstrate the adequacy of a generic multi-temporal and multi-spectral image analysis method to detect water surfaces automatically, and to monitor their seasonal variability in near real-time at 250 m. The approach is applied and validated at the African continental scale in order to evaluate the methodology for a large range of ecosystems, as a first step towards global scale coverage.

Three constraints are identified a priori, as follows: (i) In order to achieve a robust and reliable discrimination of water surfaces from other land cover types, a consistent identification of the various targets is required independently of the observation conditions, i.e. the particular location, time and geometry of observations and their intrinsic variations (e.g. cyclic change of biological activity or composition). (ii) The developed methodology has to be generic in order to be applied to similar sensors with a high reliability and with no geographic restrictions. (iii) The processing should not be too time-consuming, to allow real-time image analysis for early warning applications.

The detection algorithm and the African permanent water surface mask were both validated at continental scale. First the ability of the proposed algorithm to perform as well as a photo-interpretation of the image is assessed by applying the proposed methodology to a dedicated sampling including 20,000 points of water and 20,000 points of land surface pixels collected by photo-interpretation. Second, the mask of permanent water surface is validated against an independent dataset including 55,944 objects which were visually delineated and interpreted at 30 m resolution, based on Landsat and Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) imagery distributed all over the African continent.

In the framework of this study, the water surfaces considered are restricted to “free water surface” i.e. water surfaces without vegetation coverage. In other words, swamp vegetation (e.g. swamp forest, bushland and grassland) and floating vegetation areas are not considered by the proposed methodology.

2. Data

This section describes the African continental scale data used for the water surface detection study, i.e. (i) the daily surface reflectance data from MODIS and from VGT, and (ii) the 8-day Land Surface Temperature (LST) product.

For the validation step, the permanent water surface product is compared with the Important Bird Areas (IBAs) dataset (Beresford et al., 2013), described in Section 5.3.2.