HYDROLOGICAL MODELING IN UNGAUGED BASINS USING SAR DATA

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ABSTRACT

In this paper we propose a methodology devoted to exploit high resolution radars for monitoring water bodies in semi-arid countries. The proposed approach is based on appropriate registration, calibration and processing of SAR data, producing information ready to use by end-users. The obtained results were used to (i) estimate a relationship between surface and volume of water stored in reservoirs and (ii) validate a hydrological model that simulates the time evolution of water availability.

Index Terms— Synthetic Aperture Radar, semi-arid regions, small reservoirs.

1. INTRODUCTION

In semiarid regions, building small reservoir is a typical measure taken by farmers, in order to face the effects of a semi-arid climate, which is characterized by the alternation of a short rainy season with long periods of dryness.

Small reservoirs are used for water harvesting in the rainy season and water storage in the dry season. Despite their crucial importance, they are not appropriately monitored, and in many cases, they are not catalogued or the relative data are not kept up-to-date. The use of remote sensing tools could provide fruitful value added in monitoring and planning applications, thanks to the available high coverage and fine resolution.

In low-income countries watersheds are poorly gauged or completely ungauged. Thus, there is a lack of runoff measurements, which can be compensated by monitoring water volumes retained in reservoirs.

A multidisciplinary approach that couples hydrological modeling and remote sensing is proposed. The use of COSMO-SkyMed data allowed outperforming the previously available methods for the monitoring of small reservoirs in semi-arid environment [1]. In particular, two hydrologic model are implemented and compared.

In this paper, the authors present the developments of the aforementioned applications thanks to a dataset acquired in 2010 and 2011 under the aegis of 2007 Italian Space Agency Announcement of Opportunity for the scientific use of COSMO-SkyMed data.

2. SAR PROCESSING

The case study was implemented using a set of COSMO-SkyMed stripmap images. All the data were acquired with medium look angle (almost 30°) and HH polarization, also for increasing the land-water contrast.

Calibration, registration and despeckling procedures were applied as dictated by the MAP3 framework introduced in [3]. In particular, the optimal weighting multitemporal De Grandi filter [4] was adopted in order to allow an effective extraction of water surfaces contour. This operation was carried out with a change detection-based approach based on the Level-1α products which consists in a simple bands ratio, as suggested in [5] using multispectral data.

In Fig.1 we show an example of the water bodies extraction processing chain. In particular, in Fig. 1a we show the Level-1α product relevant with a small reservoir of Yatenga region, Burkina Faso. The reference image (blue band) was acquired at the peak of the dry season on April 2010, while the test image (green band) was acquired on August 2010, during the wet season. Surface water is rendered in blue color. In fact, at the end of the dry season, small reservoirs are completely empty. Therefore, the response of bare soil is dominant in the basin area with respect to that of surface water, exhibited during the wet season (see [3]). In Fig. 1b the basin contour has been manually extracted. In Fig. 1c we show the water index map, which is defined by a weighted bands ratio involving the reference and test images. Finally, in Fig. 1d, we apply a threshold to the water index map in order to extract the area covered by surface water. Besides the water surfaces mask, the estimation of water volumes retained by reservoirs

requires information about the scene topography, Therefore, an interferometric chain was developed to obtain a DEM (9 m resolution) of the area from a couple of COSMO-SkyMed images. The couple was appropriately acquired at the peak of the dry season in order to exploit the fact that the scene is almost completely dry and highly coherent.
The coupling of DEM and water surfaces mask allowed for bathymetric analysis and retrieval of water volume stored in reservoirs as explained in [2].

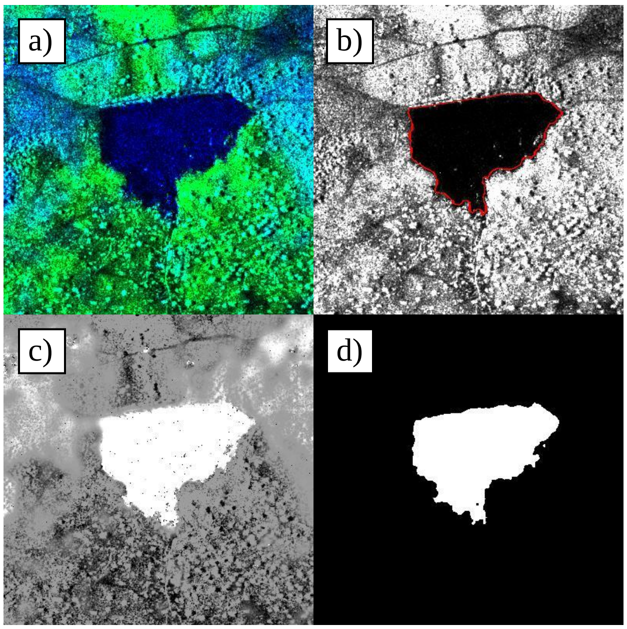

Fig. 1: A small reservoir of Yatenga region, Burkina Faso: (a) Level-1α product, (b) manually extracted contour, (c) water index map and (d) water surface mask after water index threshold.

3. HYDROLOGICAL MODELING

The development of hydrological models is crucial in order to improve the management of the water resource, mainly in contexts where *in situ* measurements are limited. The peculiar context of the semiarid regions of West Africa is characterized by scarcity of environmental data and particularly of hydrological data.
Therefore, it is necessary to improve data availability through the development of cost effective monitoring technics and to adapt hydrological models to the limited available data.

A runoff model was tested by remotely sensing reservoir water volumes over time. This approach was followed in Ghana in [6], where remote sensing data were used for estimating reservoir sizes over time in order to test a runoff model and characterize runoff processes. Reservoir surface areas were extracted from twelve Envisat advanced synthetic aperture radar (ASAR) images at a spatial resolution of 30 m and reservoir's retention volumes were derived through an empirical relationship.

In this study the reservoir's retention volumes were used to evaluate the performances of two hydrological models: the first one is the Soil Conservation Service Method (SCS), a simple, widely used model that don't need any parameter's calibration; the second is a modified Thornthwaite-Mather Procedure, as used in Ghana in [6], that needs the calibration of two parameters. For both of the models the water volumes retained in the reservoirs were modeled, on a daily basis, as a balance between runoff, evapotranspiration and previously stored volumes, until the maximum retention volume of the reservoir is reached.

3.1. The SCS-Curve Number Method

The SCS Runoff Curve Number method was developed by the United States Department of Agriculture (USDA) Soil Conservation Service (SCS). The data requirements for this method are very low, rainfall amount and curve number. The curve number is an empirical parameter based on the area's hydrologic soil group, land use, treatment and hydrologic condition.

By simply applying a daily water budget to the watershed the water volumes retained in the reservoirs can be obtained.

3.2. The Thornthwaite-Mather Procedure

The Thornthwaite-Mather water budget (TM) [7] is a simple and frequently applicable tool to estimate surpluses of water not stored in the soil profile. A modified version of this procedure was applied in this study in order to predict the increasing fraction of the percolation water reaching the reservoirs with increasing rainfall quantities.

The water balance can be written as follows

$$S_t = S_{t-\Delta t} + \left(P - E_{act} - P^*\right)\Delta t \qquad (4)$$

where P is precipitation (Lenght/Time), E_{act} is actual evaporation (L/T), and $S_{t-\Delta t}$ is the previous time step storage in the root zone per unit area (L). P* is the percolation (L/T) out of the root zone, Δt(T) is the time step, and S_t (L^3/L^2) is the volume of water stored in the root zone above wilting point per unit area at time t.

Percolation occurs when rainfall exceeds potential evaporation (i.e., $P > E_{pot}$), and actual evaporation, E_{act}, is equal to potential evaporation, E_{pot}. Percolation, P*, can then be written as

$$P^* = S_{t-\Delta t} - S_{\max} + \left(P - E_{pot}\right)\Delta t \qquad (5)$$

where S_{max} is the volume of water between field capacity and wilting point in the root zone per unit area.

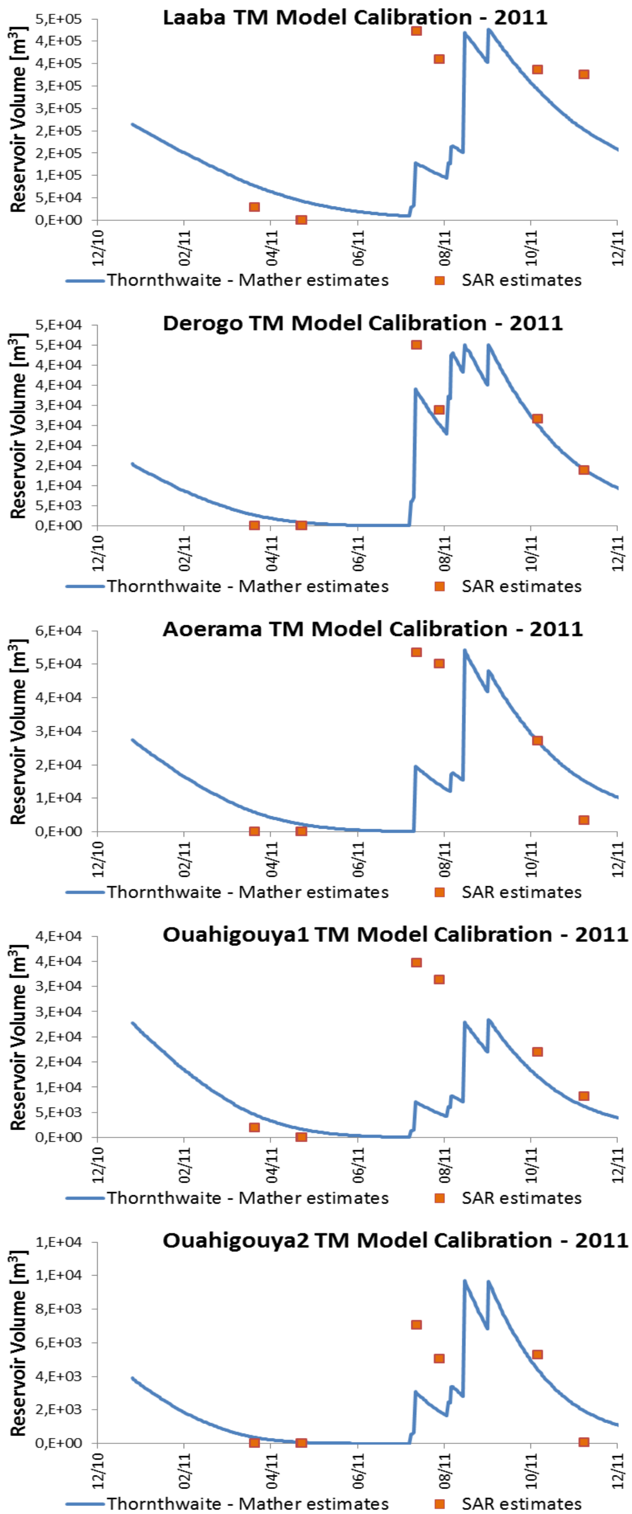

Fig. 2: Plots of model calibration results for the five reservoirs

The amount of percolation that reaches the reservoir is the Quick flow, Q_f, whose expression is the following

$$Q_f = P^* \left(1 - \exp\left(-a \times P^*\right)\right) \quad (6)$$

where a is a constant, which is an indicator of how fast the contributing area of the watershed is increasing.

4. RESULTS

4.1. Calibration of TM model's parameters

The records for the five reservoirs (Laaba, Derogo, Aoerama, Ouahigouya1, Ouahigouya2) are divided into 2 years. The parameters S_{max} and a are calibrated using the 2011 data, and then validated using 2010 data. We used year 2011 for the calibration because in that year we have SAR acquisitions in each season and all the storage process is monitored, while for 2010 dataset we have the first image in advanced wet season.

The 2011's water volumes stored in the five reservoirs obtained as explained in Section 2, and more deeply in [2], were used as reference for the numerical calibration of the parameters. The numerical calibration was performed by imposing that the differences between modeled and measured volumes were as much lower as possible. In Fig.2 are plotted the results of this calibration. With the blue line are represented the modeled volumes, while with orange dots are represented the volumes estimated by SAR.

4.2. TM and CN models implementation: comments

Once calibrated the parameters the TM model was implemented on the 2010 dataset. Also CN method was implemented over all the period of observation (2010-2011) and for all the reservoirs studied. As clearly shown in Fig. 3 we did not obtain enough improvements by using TM model, that needs the calibration of some parameters, instead of using a more simple but already calibrated model like CN method.

5. CONCLUSIONS

Coverage, resolution, and revisit time of available SAR systems allow a detailed, continuous and wide observation of the land that deserves to be exploited in regions where *in situ* measurements are impervious and expensive. Despite these potentialities, the diffuse use of SAR data in applicative scenarios is still limited by the lack of images interpretation tools that could help non expert users to exploit the instrument. In this paper we presented a new multidisciplinary methodology devoted to extract meaningful physical information from SAR data. The obtained information is used to feed appropriate hydrological models applied to the monitoring of small reservoirs in semi-arid regions.

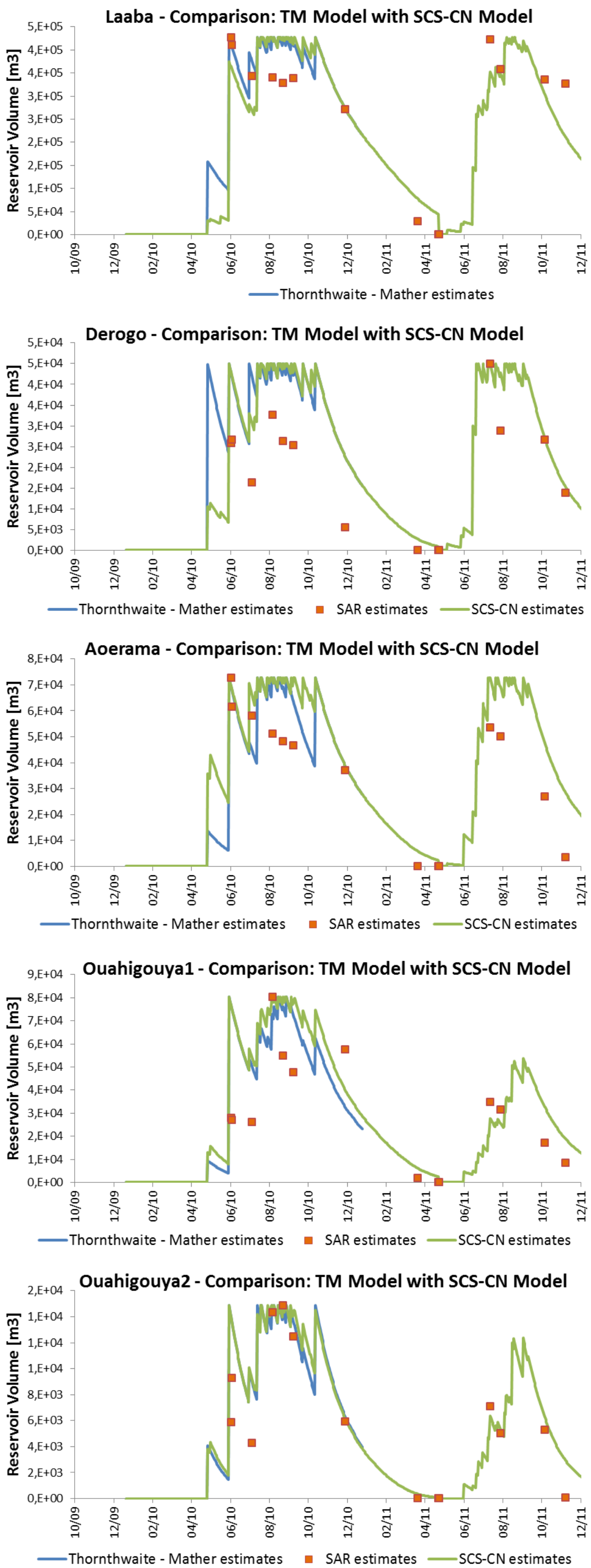

Fig. 3: Plots of TM and CN models' comparison

The proposed approach is based on the appropriate processing of a set of Cosmo-Skymed stripmap images, devoted to retrieve the volume of small reservoirs in Burkina Faso. An interferometric chain allowed to retrieve an estimation of the topography and of the bathymetry of the smallest reservoirs. In addition, a multitemporal despeckling approach supported the extraction of shorelines of the basins of the observed areas.

The comparison between the two hydrological models adopted allowed to make evaluations on the appropriateness of the different models depending on the kind of application, data availability, computing time and quality of the model results.

6. ACKNOWLEDGMENTS

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