Water resource monitoring in semi-arid environment through the synergic use of SAR data and hydrological models

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ABSTRACT

In semi-arid regions, small reservoirs are widely employed for facing seasonal in water availability due to the alternation of a short rainy season and of a very long dry season. Therefore, their monitoring is fundamental for local rural communities wellness. In this paper, we present a novel framework for water resources management exploiting the synergy of synthetic aperture radar (SAR) data and hydrological models. The pilot project was implemented in Burkina Faso, showing good potentialities for cheap and continuous monitoring of the environment through the exploitation of a multi-disciplinary framework.

Keywords: synthetic aperture radar, semi-arid regions, small reservoirs, multitemporal synthetic aperture radar, hydrological modeling

1. INTRODUCTION

In semi-arid regions, the exploitation of small reservoirs is a common practice of farmers to face extreme climatic conditions, characterized by the alternation of a short rainy season and long periods of drought.

Despite their crucial importance for local rural communities wellness, small reservoirs are not appropriately monitored. They are often built for the initiative of small local communities and even basic data as their location and capacity are not available. In this context, the most important problem to be addressed is the soil erosion due to water and consequent reservoirs' sedimentation that reduces the amount of available water and the life span of reservoirs.[1]

In low-income countries, watersheds are poorly gauged or completely ungauged. This lack of data prevents the implementation of strategies for the optimization of water resources management. Therefore, it is necessary to improve the data availability through the development of cost-effective monitoring techniques and to adapt the hydrological modeling to the limited available data.

The use of satellite data can highly contribute to the achievement of crucial information at low costs, and with high temporal and spatial resolution. In particular, synthetic aperture radar (SAR) data can represent an effective tool for the monitoring of reservoir extension. This information, integrated with a bathymetric survey, can compensate the lack of runoff measurements, giving an estimate of the water volume retained in reservoirs.[2–4]

In a multi-disciplinary context, such as remote-sensing-assisted hydrology, it is highly desirable the adopted algorithms, as well as the satellite products in use, are as much as possible user-oriented, i.e. not demanding a high level of technical expertise with satellite imagery.[5–7] Therefore, one of the aim of the framework we are going to present, is to provide a tool easily manageable by hydrologist, exploiting end-user oriented SAR products and information extraction algorithms.

The work is organized as follows. In Section 2, SAR interferometric processing for the extraction of a high resolution digital elevation model (DEM) is briefly recalled. A simple procedure for small reservoirs' shoreline extraction using innovative RGB multitemporal SAR products and change-detection is described in Section 3. Estimation of the retained water volume in reservoirs through the coupling of the DEM and of the extracted shoreline is addressed in Section 4. Hydrological modeling of the study area and its validation through SAR-derived results is presented in Section 5. Conclusions are drawn at the end of the work.

2. DEM RETRIEVAL

Interferometry is one of the most assessed applications of spaceborne SAR. In this case, we exploited a standard interferometric chain,[8] whose block diagram is depicted in Figure 1, to a couple of COSMO-SkyMed stripmap images (3 meter spatial resolution) acquired at the peak of the dry season of the year 2011.[1] At this time, in the study area, the environment is almost completely dry, and the small reservoirs are empty. This makes possible to retrieve their bathymetric profile.

However, the selection of the most performing algorithm for the implementation of processing block of the diagram of Figure 1 is an important issue. In SAR interferometry, two fundamental steps are the filtering of the flattened interferogram (i.e. after the removal of the flat earth ramp), and the unwrapping. As for the phase filtering, we suggest the usage of the Lee filter presented in Reference 9. As for the unwrapping, the *snaphu* algorithm proposed in Reference 10.

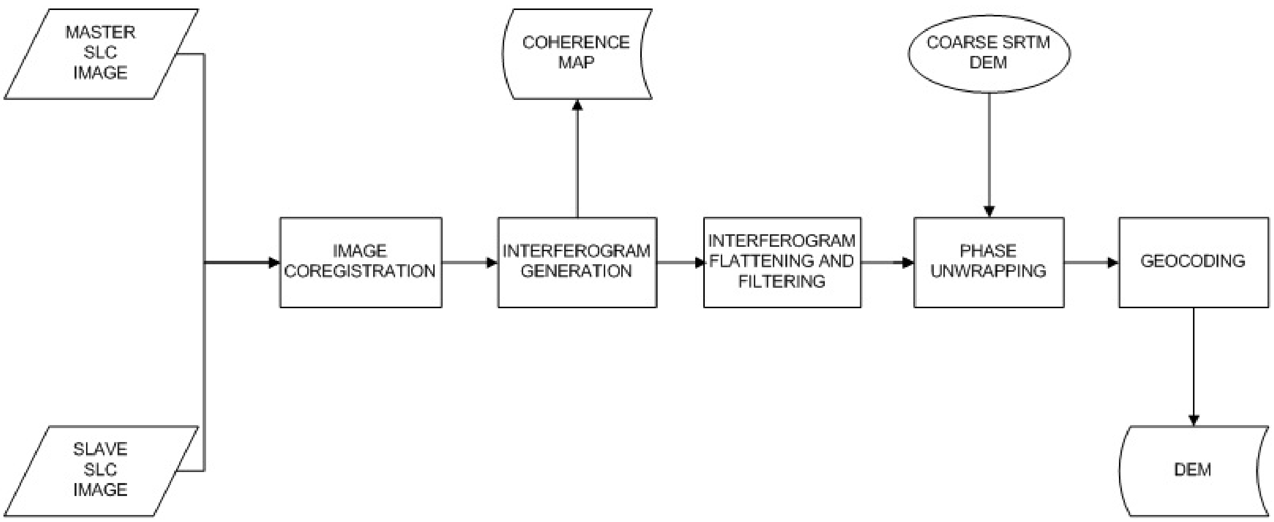


Figure 1: Processing chain for SAR interferometric DEM generation.

In Table 1, we report a comparison between the proposed DEM (9 meters resolution) and two among the most used global coverage DEMs (the SRTM DEM -90 meter resolution- and the ASTER DEM -30 meter resolution-), referring to 4 GPS measurement points. From this table, it arises a good agreement between the proposed DEM and those taken as reference (and with the in-situ measurements, as well), with the advantage of a significant improvement of the spatial resolution, which is fundamental for monitoring reservoirs with extension of few thousand square meters.

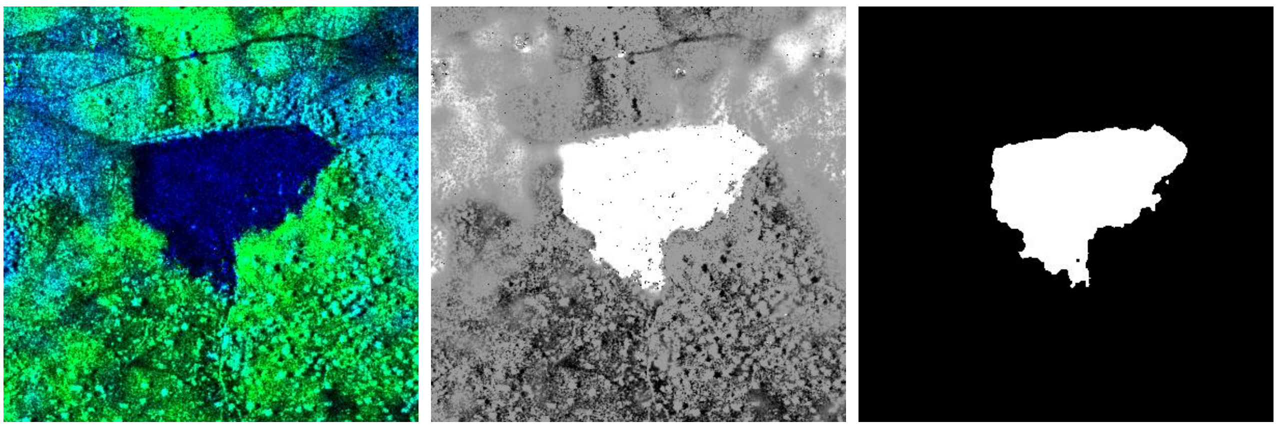
Table 1: Comparison between the proposed DEM (9 meters resolution), the SRTM dem (90 meters resolution), the ASTER DEM (30 meters resolution), and 4 GPS points assumed as ground truth. In parentheses, the difference expressed in meters between the DEM and the GPS measurement is reported.

Position (GPS)	ASTER (m)	SRTM (m)	Proposed (m)
$13°55'03.6''N$, $2°29'40.1''W$, 309 m	307 (-2)	312 (3)	312 (3)
$13°53'38.8''N$, $2°29'49.6''W$, 312 m	306 (-6)	316 (4)	314 (2)
$13°50'04.9''N$, $2°24'38.8''W$, 358 m	354 (-4)	359 (1)	356 (-2)
$13°41'45.8''N$, $2°11'57.5''W$, 333 m	327 (-6)	335 (2)	335 (-1)

3. BASINS' EXTENSION RETRIEVAL

In order to estimate water volume retained within the reservoirs, the altimetric information of the DEM must be integrated with the one about basins' extension over the time.[2] To this end, multitemporal Level-1α products, presented in Reference 11, can be effectively exploited to extract reservoirs' shoreline through band comparison in a change detection framework.[12]

In Figure 2, we show the process of basins' shoreline extraction. The starting point, see Figure 2a is a Level-1α product. It is composed as follows: on the blue band, an image acquired during the dry season is loaded. The green band is reserved to an image acquired during the wet season. The red band carries the information related to the interferometric coherence (which is useful in the identification of the built-up feature). This configuration allows for displaying the most important features of the study area (i.e. water and vegetation) in natural colors. Therefore, the blue color is associated to water (because it acts as a reflector for the electromagnetic field during the wet season), and the green color to the vegetation (due to the dominance of the wet season image backscattering triggered by the growth of vegetation in this period of the year).



(a) (b) (c)

Figure 2: Basins' shoreline extraction process. (a) Input Level-1α product. (b) Water probability map. (c) Basin mask after thresholding of the probability map.

In Figure 2b, we show a probability map linked to the presence of surface water. The map is in gray-scale, thus the brighter the pixel, the higher the probability that the area is covered by water. Finally, in Figure 2c, the basin mask, after thresholding of the probability map, is reported.

This processing chain have been designed looking at simplicity and repeatability, and is particularly oriented toward multi-disciplinary users, usually having a limited expertise with radar imaging.

4. ESTIMATION OF THE WATER VOLUME RETAINED IN THE RESERVOIRS

Once the information concerning basins' bathymetry and extension is available, they can be easily coupled to estimate the retained water volume.[2] Each pixel classified as belonging to a reservoir is assumed to be a water column, whose height h_{wc} is given by:

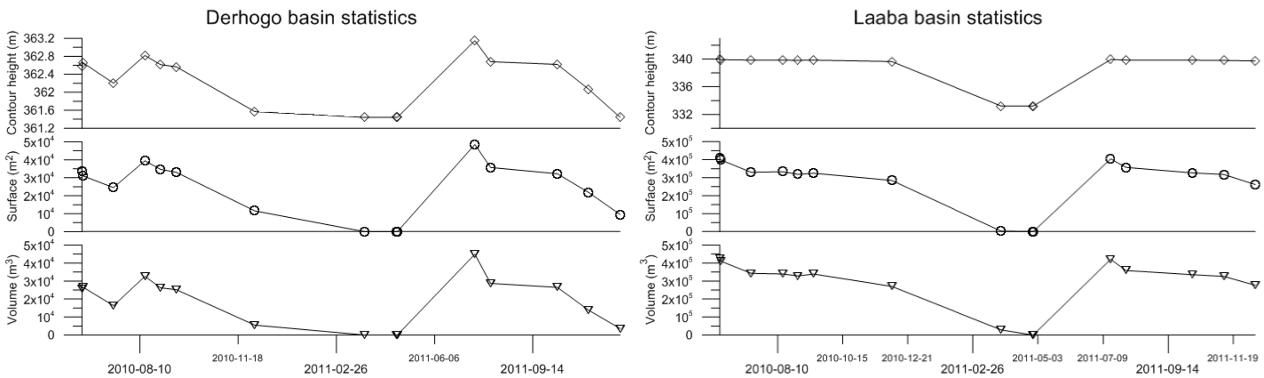
$$h_{wc} = h_c - h, \tag{1}$$

where h_c is the elevation of the equipotential surface identified by the basin contour and h is the DEM height corresponding to the considered pixel. Finally, the water volume is estimated by summing up all the contribution brought by the water columns as follows:

$$V = \sum_{i=1}^{N} S_i \times h_{wc}, \tag{2}$$

where S_i is the surface of the $i-th$ pixel belonging to the reservoir and N is the total number of pixels belonging to it.

The estimate has been performed for several reservoirs in a time span covering about one year and half between June 2010 and December 2011. In Figure 3, the statistics concerning the contour height, the surface area, and the retained volume for two of the considered basins are reported.



(a) (b)

Figure 3: Statistics for two of the considered basins in the study area. (a) Derhogo basin. (b) Laaba basin.

5. HYDROLOGICAL MODELING

The retrieved database was exploited to extract a semi-empirical relation between basins' surface area and retained volume. In particular, the following relation was found through regression analysis of the available data:[2]

$$\text{Volume} = 0.10120\text{Area}^{1.1670} \left[m^3\right] \tag{3}$$

These relations (see also Reference 13) are very useful in applications. In fact, if reservoirs' surface area can be estimate through satellite acquisitions, the retrieval of their bathymetric profile requires the implementation of expensive in-situ campaigns.

SAR-derived results was used to validate an hydrological model of the study area, constituted by a water balance between the water flows entering and exiting the reservoir. The input flow is the surface runoff, while the outputs are the evaporations, the spill downstream the dam, and the water withdrawn by the users. The model adopted to express the involved variables was the soil conservation service method (SCS), which is suitable for the simulation of runoff in small ungauged watersheds.[14–16]

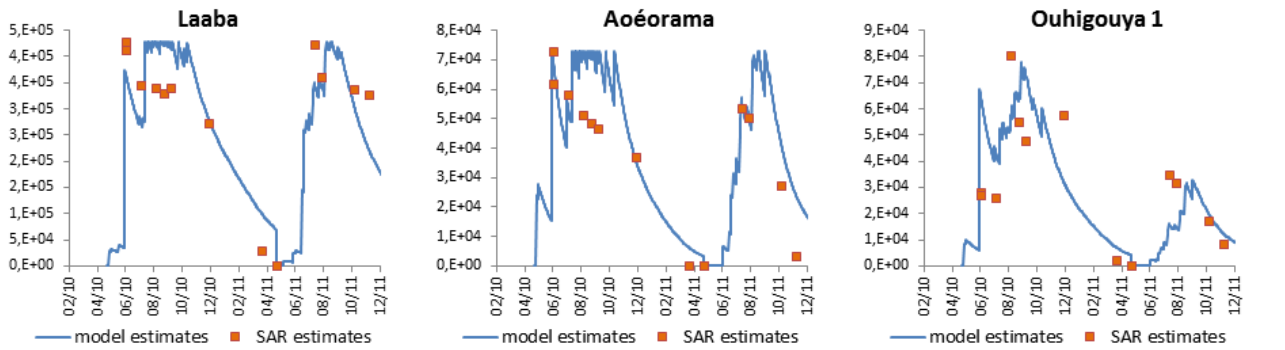
In Figure 4, the results of the above described analysis for three of the analyzed reservoirs is reported. Although the extreme simplicity of the model, the agreement with the SAR-derived estimation is quite good.

6. CONCLUSIONS

In this paper, we presented an operational framework for small reservoirs monitoring in semi-arid environment. It was designed to provide a simple, remote-sensing assisted tool for hydrologist through the exploitation of end-user SAR products and information extraction algorithms.

The pilot project was implemented in Burkina Faso, and showed significant potentialities for a cheap and continuous monitoring of the environment. Operatively, we faced several challenges, such as the retrieval of a high resolution DEM, suitable to catch the bathymetry of reservoir with few thousand meters of extension, the extraction of basins' shoreline, and the estimation of the retained water volume.

The DEM was retrieved using a standard interferometric processing. Most of the algorithms used to carry out each processing block can be found in commercial/open source software suites. Suggestion about the selection



(a) (b) (c)

Figure 4: Simulated retention volumes expressed in m^3 compared to the ones extracted by SAR images for three of the analyzed reservoirs.

of the most performing techniques for the filtering of the flattened interferogram and for the unwrapping was provided.

Shoreline extraction was implemented exploiting innovative RGB SAR products in a change detection framework. This processing chain is particularly oriented toward non-expert SAR users.

Estimation of retained water volume was implemented both using SAR-derived data and a simple hydrological model. The obtained results showed a good agreement, testifying the reliability of the proposed framework.

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