Mapping small reservoirs in semi-arid regions using multitemporal SAR: methods and applications

Donato Amitrano*, Gerardo Di Martino*, Antonio Iodice*, Francesco Mitidieri†,
Maria Nicolina Papa†, Daniele Riccio* and Giuseppe Ruello*
*Department of Electrical Engineering and Information Technology
University of Napoli Federico II, Napoli, Italy
†Department of Civil Engineering
University of Salerno, Fisciano, Italy

***Abstract*—In this paper, we introduce an innovative method to map small reservoirs in semi-arid environment. The proposed technique is based on the exploitation of the recently introduced Level-1α RGB SAR composite, and it is based on change-detection. In particular, we introduce a user-oriented water index defined by a weighted ratio of the bands composing the RGB product. The performance of the method are evaluated by comparison with other popular segmentation techniques of the same complexity in order to demonstrate its reliability. Finally, an applications concerning hydrology, i.e the estimation of reservoir bathymetry starting from area measurements, is presented to underline the usefulness of remote sensing in multidisciplinary contexts.**

I. Introduction

Information about the extent of water surfaces is fundamental for water resource monitoring [1], [2], especially in semi-arid regions. These problems are usually faced using multi-spectral sensors, allowing for the exploitation simple indices, very popular in the end-user community, whose amplitude is related to some physical characteristics of the feature they refer to. Dealing with water bodies, the normalized difference water index (NDWI) by McFeeters [3] is probably the most common option in this kind of applications.

In semi-arid environment, the main limitation of this approach is the cloud coverage, which is extremely probable during the wet season. The use synthetic aperture radar (SAR) systems allows for overcoming this problem, provided that simple, user-friendly techniques for information extraction are made available to the end-user community, in which the expertise with radar data is often low. In the last years, several tools looking toward multidisciplinary users have been developed [4], [5], but no water index derived from SAR data has been formulated, yet.

In this paper, we address the problem of small reservoir extraction exploiting multitemporal Level-1α RGB products [6]. They are bi-temporal images combining two acquisitions for change-detection purposes. Principal characteristics of these products are the interpretability (thanks to a consistent rendering of the information), and the possibility to be processed with simple algorithms for feature extraction [7], [8]. Here, we present a temporary water index suitable to be applied in semi-arid environments for extracting small reservoir contours. This way, computational complexity and SAR expertise are moved in the product formation phase, simplifying the feature extraction step which can be carried out by setting just one parameter, that is the threshold to be applied to the index map.

The work is organized as follows. In Section II, the case study is presented, and some experimental results are provided. Section III is devoted to the discussion of an application concerning hydrology, consisting in the retrieval of water volume retained at reservoir basing on the estimated surface area. Conclusions are drawn at the end of the work.

II. Case study

The case study has been implemented in semi-arid Burkina Faso. The study area is approximately 40×40 km^2 wide. In semi-arid regions the identification of surface water is extremely important because human and animal lives as well as the local economy are strictly related with the availability of water. In addition, several studies showed that the presence and distribution of surface water influences the transmission of waterborne diseases such as Schistosomiasis [9], [10].

The presence of temporary surface water can be detected through change-detection by comparing the electromagnetic (EM) response of a reference acquired during the dry season and a test image acquired during the wet season combined in a Level-1α RGB product [6]. An example of such products is provided in Fig. 1. The reference image is loaded on the blue band. The test image is loaded on the green band. The red band is reserved to the interferometric coherence between the two images (it is useful for identifying small settlements). This combination allows for displaying in natural colors the most important features of the study area. In fact, surface water is rendered in blue. This is due to the dominance of the EM scattering from the terrain in the basin area during the dry season. Vegetation is displayed in green, due to the volumetric backscattering contribution triggered by plants during the wet season.

Level-1α products characteristics allow for introducing a water pseudo-probability index defined by a weighted ratio of the bands constituting the product. As explained in [11], this index can be computed as follows:

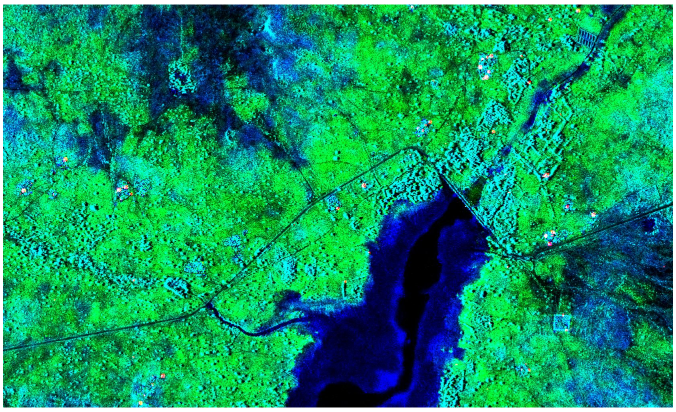


Fig. 1: Study area (subset), Level-1α product. Original image resolution 3×3 meters.

$$\text{SWPP} = \left[1 - \left(\frac{G}{255}\right)^2\right] \frac{B-G}{B+G}, \quad \text{SWPP} \in [-1, 1]\,. \quad (1)$$

In this formula, B and G are the blue and the green band of a Level-1α product, respectively. Roughly, this formulation aims at the enhancement of areas appearing in blue color in the RGB product.

The result of the calculation of such index to some reservoirs of the study area is depicted in Fig. 2. In particular, in the first column of the picture, we reported the subsets of the Level-1α product concerning the considered reservoir. In the second column the water index map of the area. Finally, in the third column, a binary mask obtained after thresholding of the index map is depicted.

The performance of the proposed technique is tested through comparison with those given by other popular segmentation methods oriented to water body extraction having comparable complexity. In particular, we tested a band-ratio (BR) and a maximum likelihood (ML) feature extraction. In all cases, the same information content of a Level-1α product, i.e. a couple of SAR images, was exploited to classify. The result of this comparison is shown summarized in TABLE I.

TABLE I: Comparison between water index-based (WI), band-ratio-based (BR) and maximum likelihood-based (ML) feature extraction. T: applied threshold, OA: overall accuracy, FA: false alarm rate.

Date	Method	T	OA (%)	FA $\times E^{-4}$
31/8	WI	0.3	88.8	2.38
	BR	2.5	82.2	2.00
	ML	na	79.39	7.63
15/8	WI	0.3	89.8	2.64
	BR	2.5	87	4.13
	ML	na	80.7	0.97

The three techniques were applied to two Level-1α products available in our database. They share the reference image, acquired on 28 April 2011 (peak of the dry season). Test images were acquired on 15 and 31 August 2010, respectively.

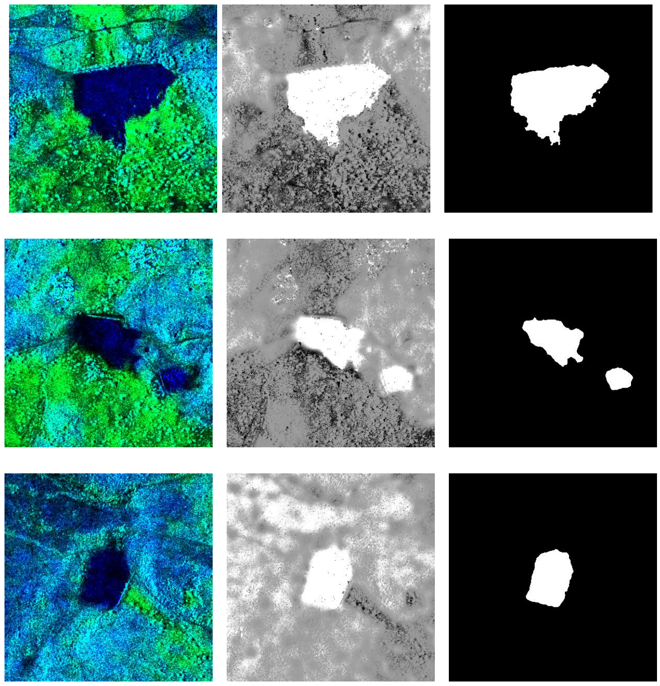


Fig. 2: Results of the application of water index to some reservoirs of the study area.

As a general comment, the water index-based has the highest overall accuracy and a lower false alarm rate with respect to band-ratio-based feature extraction. The lowest false alarm rate is registered using the ML classifier. However, in this case, the overall accuracy is significantly lower with respect to those achieved using both the water index or the band-ratio.

III. Applications

Once the basin contour is known, the water volume contained into the basin can be retrieve considering each pixel of the water mask as a water column whose height h_{wc} is given by:

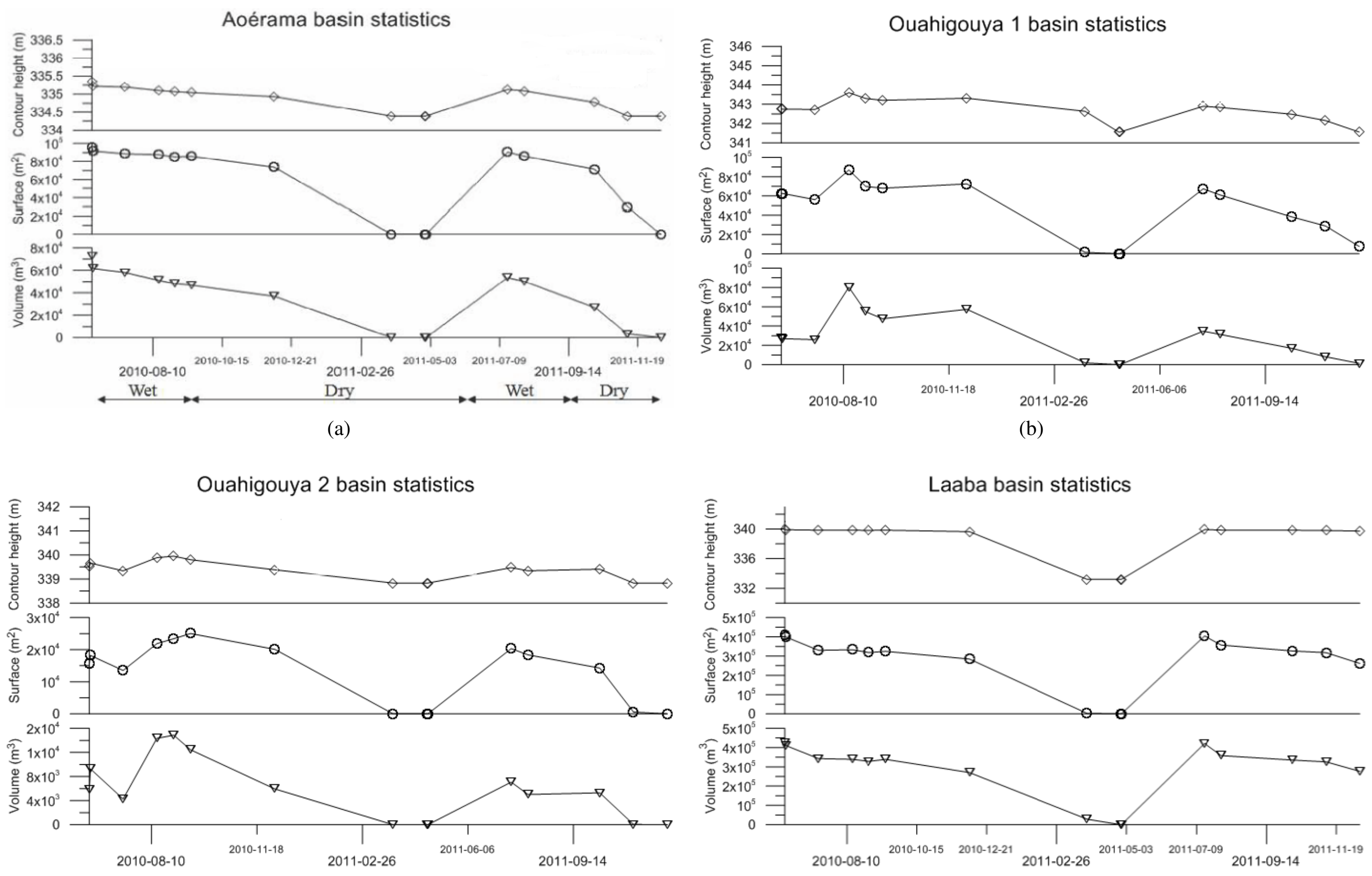
$$h_{wc} = h_c - h, \quad (2)$$

where h_c is the elevation of the equipotential surface identified by the basin contour derived from the SAR intensity maps, and h is the DEM height corresponding to the considered pixel. The water volume contained into the basin is given by the summation of all the elementary contributions brought by the water columns:

$$V = \sum_{i=1}^{N} S_i \times h_{wc_i}, \quad (3)$$

where S_i is the basin surface of the $i-th$ resolution element belonging to the water mask and N is the number of pixels belonging to the water mask.

In Fig. 3 shows the results of our analysis for four basins in the study area considered basins. These diagrams are strictly related to the seasonal variation of rainfall with an abrupt



(a) (b) (c) (d)

Fig. 3: Basins statistics.

increment of volume at the beginning of the rainy season and a continue decrease in the dry season.

The obtained data can be used to find a relation between reservoirs' storage volume and surface area. These relations are very useful since the reservoirs' surface area estimated with good precision through satellite or aerial imagery, while the volume measurement requires more demanding and expensive bathymetric surveys.

Relations area-volume have been developed in literature both theoretically and empirically. As an example, Liebe *et al* [12] obtained the following relationship based on an extensive bathymetric survey in Upper East Region of Ghana:

$$\text{Volume} = 0.00857\text{Area}^{1.4367} \; [m^3] \tag{4}$$

The regression analysis of reservoir volumes and areas obtained using SAR-derived data allowed us to derive the following relation:

$$\text{Volume} = 0.10120\text{Area}^{1.1670} \; [m^3] \tag{5}$$

As shown in Fig. 4, there is only a slight difference between (4) and (5). This confirms that, thanks to the morphological and morphometrical regularity of the regions, the estimation of the retained volume from satellite area measurements is possible with a good approximation.

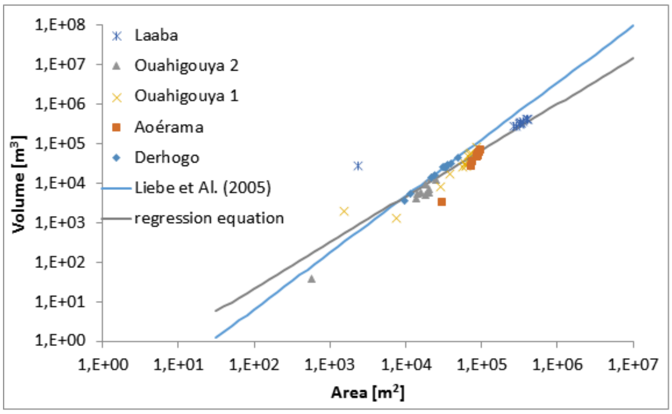


Fig. 4: Reservoirs' storage volumes as a function of their surface areas in a log-log plane.

IV. Conclusions

In this work, we presented an innovative framework for mapping small reservoirs in semi-arid environment exploiting multitemporal SAR RGB Level-1α product. The proposed methodology is based on the introduction of a water index defined by a weighted band ratio of the bands composing the RGB product. The proposed method is particularly oriented toward the end-user, allowing for the retrieval of the reservoir map with just one parameter, that is the threshold value to be applied on the index map.

In the second part of the paper, the suitability of the proposed framework in applicative contexts has been assessed through an application concerning the retrieval of the water volume contained in the reservoirs starting from their surface are measured through the SAR observation. The obtained result, compared with those obtained through expensive field surveys, confirmed that this approach is feasible with a good approximation.

ACKNOWLEDGMENTS

The authors thank the Italian Space Agency (ASI) for providing the Burkina Faso dataset under the aegis of the "HydroCIDOT" project.

REFERENCES

[1] D. Amitrano, F. Ciervo, G. Di Martino, M. N. Papa, A. Iodice, Y. Koussoube, F. Mitidieri, D. Riccio, and G. Ruello, "Modeling Watershed Response in Semiarid Regions with High Resolution Synthetic Aperture Radars," *IEEE J. Sel. Topics Appl. Earth Observ.*, vol. 7, no. 7, pp. 2732–2745, 2014.

[2] S. Zhang, S. Foerster, P. Medeiros, J. Carlos de Araujo, M. Motagh, and B. Waske, "Bathymetric survey of water reservoirs in north-eastern Brazil based on TanDEM-X satellite data," *Sci. Total Environ.*, In press.

[3] S. K. McFeeters, "The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features," *Int. J. Remote Sens.*, vol. 17, no. 7, pp. 1425–1432, 1996.

[4] S. Martinis, C. Kuenzer, A. Wendleder, J. Huth, A. Twele, A. Roth, and S. Dech, "Comparing four operational sar-based water and flood detection approaches," *Int. J. Remote Sens.*, vol. 36, no. 13, pp. 3519–3543, 2015.

[5] S. G. Dellepiane and E. Angiati, "A New Method for Cross-Normalization and Multitemporal Visualization of SAR Images for the Detection of Flooded Areas," *IEEE Trans. Geosci. Remote Sens.*, vol. 50, no. 7, pp. 2765–2779, 2012.

[6] D. Amitrano, G. Di Martino, A. Iodice, D. Riccio, and G. Ruello, "A New Framework for SAR Multitemporal Data RGB Representation: Rationale and Products," *IEEE Trans. Geosci. Remote Sens.*, vol. 53, no. 1, pp. 117–133, 2015.

[7] D. Amitrano, G. Di Martino, A. Iodice, D. Riccio, and G. Ruello, "An end-user-oriented framework for the classification of multitemporal SAR images," *Int. J. Remote Sens.*, vol. 37, no. 1, pp. 248–261, 2016.

[8] D. Amitrano, V. Belfiore, F. Cecinati, G. Di Martino, A. Iodice, P.-P. Mathieu, S. Medagli, D. Poreh, D. Riccio, and G. Ruello, "Urban Areas Enhancement in Multitemporal SAR RGB Images Using Adaptive Coherence Window and Texture Information," *IEEE J. Sel. Topics Appl. Earth Observ.*, vol. 9, no. 8, pp. 3740–3752, 2016.

[9] J. Perez-Saez, L. Mari, E. Bertuzzo, R. Casagrandi, S. H. Sokolow, G. A. De Leo, T. Mande, N. Ceperley, J.-M. Froehlich, M. Sou, H. Karambiri, H. Yacouba, A. Maiga, M. Gatto, and A. Rinaldo, "A Theoretical Analysis of the Geography of Schistosomiasis in Burkina Faso Highlights the Roles of Human Mobility and Water Resources Development in Disease Transmission," *PLoS Negl. Trop. Dis.*, vol. 9: e0004127, no. 10, 2015.

[10] L. Mari, R. Casagrandi, E. Bertuzzo, A. Rinaldo, and M. Gatto, "Floquet theory for seasonal environmental forcing of spatially explicit waterborne epidemics," *Theoretical Ecology*, vol. 7, no. 4, pp. 351–365, 2014.

[11] D. Amitrano, G. Di Martino, A. Iodice, , D. Riccio, and G. Ruello, "Small Reservoirs Extraction in Semi-Arid Regions Using Multitemporal Synthetic Aperture Radar Images," *IEEE J. Sel. Topics Appl. Earth Observ.*, In press.

[12] J. Liebe, N. van de Giesen, and M. Andreini, "Estimation of small reservoir storage capacities in semi-arid environment: A case study in the Upper East Region of Ghana," *Phys. Chem. Earth. Pt. A/B/C*, vol. 30, pp. 448–454, 2005.