Modeling Watershed Response in Semiarid Regions With High-Resolution Synthetic Aperture Radars

Donato Amitrano, Fabio Ciervo, Gerardo Di Martino, *Member*, *IEEE*, Maria Nicolina Papa, Antonio Iodice, *Senior Member*, *IEEE*, Youssouf Koussoube, Francesco Mitidieri, Daniele Riccio, *Fellow*, *IEEE*, and Giuseppe Ruello, *Member*, *IEEE*

***Abstract*—In this paper, we propose a methodology devoted to exploit the outstanding characteristics of COSMO-SkyMed for monitoring water bodies in semiarid countries at a scale never experienced before. The proposed approach, based on appropriate registration, calibration, and processing of synthetic aperture radar (SAR) data, allows outperforming the previously available methods for monitoring small reservoirs, mainly carried out with optical data, and severely limited by the presence of cloud coverage, which is a frequent condition in wet season. A tool has been developed for computing the water volumes retained in small reservoirs based on SAR-derived digital elevation model. These data have been used to derive a relationship between storage volumes and surface areas that can be used when bathymetric information is unavailable. Due to the lack of direct measures of river's discharge, the time evolution of water volumes retained at reservoirs has been used to validate a simple rainfall–runoff hydrological model that can provide useful recommendation for the management of small reservoirs. Operational scenarios concerning the improvement in the efficiency of reservoirs management and the estimation of their impact on downstream area point out the applicative outcomes of the proposed method.**

***Index Terms*—Semiarid regions, small reservoirs, synthetic aperture radar (SAR).**

I. Introduction

IN SEMIARID regions, small reservoirs are widely employed for facing water scarcity and climatic variability [1], [2]. In Sub-Saharian Africa, they are used for water harvesting in the rainy season and water storage in the dry season. In Burkina Faso, it is estimated that almost 1700 small reservoirs are actually used for irrigation, livestock, and other purposes. Despite their crucial importance, small reservoirs are not appropriately monitored, and in many cases, they are not catalogued or the relative data are not kept up-to-date [2]. This is mostly true in low-income countries and, in particular, in Sub-Saharian Africa. Moreover, small reservoirs are often built or modified for the initiative of local communities and even basic data as their location and capacity are not available. For these reasons, it is extremely hard to study the impact of reservoirs on the territory and to optimize their management.

In order to improve the management of water supply, it is necessary to provide hydrological models suitable for the specific environments under study. In literature, there is a lack of environmental and hydrological data concerning semiarid West Africa. 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 remote sensing in this context could really be a breakthrough, allowing dramatic reduction in costs and time needed for achieving crucial information for effective and integrated water management [3]. So far, the use of multispectral [4], [5] and low-resolution radars [6], [7] for reservoir monitoring evidenced not only great potentialities but also poor practical results. The main limit for a continuous monitoring with passive sensors (i.e., optical sensors) turned out to be the dependence of the results on the cloud cover, which is particularly severe in wet season. Conversely, synthetic aperture radar (SAR) systems are independent of illumination and (in particular, those operating at microwave frequencies) atmospheric conditions [8]. In fact, for an X-band system like COSMO-SkyMed, the atmosphere is quite transparent, at least for intensity measurements and in absence of severe weather events [9]. Phase information, instead, could be subject to major distortions, as discussed in [10].

In the recent past, the use of SAR systems for monitoring water bodies has been mainly constrained by the limited resolution of the available sensors [11], [12] and by the fact that the interpretation of SAR images is not easy for nonexpert users [13], [14]. In fact, the low spatial resolution of the previous sensor generation allowed only applications on regional scale, principally oriented on flood monitoring of wide water surfaces. Martinez and Le Toan [15] used multitemporal SAR data for studying flood dynamics in the Amazon floodplain. Tholey *et al.* [16] fused SAR with exogenous and historical data for flood monitoring and prevention purposes. More recently, data acquired by COSMO-SkyMed, the constellation of the Italian Space Agency, powered this kind of applications; thanks to the high resolution and the short revisit time that the new sensors' generation can offer to the scientific community [17]. Indeed, the literature about small reservoirs monitoring is still related with the past sensors'

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D. Amitrano, G. Di Martino, A. Iodice, D. Riccio, and G. Ruello are with the Department of Electrical Engineering and Information Technology, University of Napoli Federico II, Napoli 80125, Italy (e-mail: donato.amitrano@unina.it, gerardo.dimartino@unina.it, iodice@unina.it, dariccio@unina.it, ruello@unina.it).

F. Ciervo, M. N. Papa, and F. Mitidieri are with the Department of Civil Engineering, University of Salerno, Salerno 84084, Italy (e-mail: fciervo@unisa.it, mnpapa@unisa.it, francescomitidieri88@gmail.com).

Y. Koussoube is with the Laboratoire d'hydrogologie–Unité de formation et de recherche en Sciences de la vie et de la terre, University of Ouagadougou, Ouagadougou 7021, Burkina Faso (e-mail: youssouf.koussoube@univ-ouaga.bf).

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generation. In fact, [11], [18], and [19] indicated as small reservoirs water surfaces smaller than 100 hectares. This is almost at the limit of the imaging capability of the sensors used in those investigations. The introduction of the COSMO-SkyMed high-resolution capabilities can strongly reduce the dimension of the observable surfaces allowing studying basins with extension in the order of few thousand square meters. In addition, the limited land–water contrast and the presence of vegetation (reeds on the reservoir tails) further hampered the accuracy of the estimation of the presence of water bodies. Misclassification and underestimation of the available volumes are typical problems in the identification of surface water.

In this paper, we present a flexible, multidisciplinary, and user-friendly approach for exploiting the new possibilities born with the launch of COSMO-SkyMed for monitoring water bodies. It is flexible because it is made of interchangeable modules that can be adapted to the physical or economical needs dictated by the context. It is multidisciplinary because it combines remote sensing and hydrological models and tools in order to complete their strengths. It is user-friendly because it is not limited to the creation of SAR products; it provides new products that can be easily read and used by users that do not have a background on SAR remote sensing. These characteristics allow going beyond most of the existing limits, opening the way to new fields of applications that could provide humanitarian, technological, and economic benefits.

The proposed approach is supported by the results obtained in the frame of the WARM project developed in northern Burkina Faso (a landlocked country characterized by a semiarid climate) under the aegis of the 2007 Italian Space Agency Announcement of Opportunity for the scientific use of COSMO-SkyMed data, "Use of high-resolution SAR data for water resource management in semi arid regions" [20], during which, by exploiting the peculiar local climate, we were able to retrieve topographic information with unprecedented details [21].

The overall methodology is presented in Section II. For sake of clarity, the SAR and the hydrological processing are dealt with separately, in Sections III and IV, respectively. In particular, in Section III, we present the SAR processing, mainly devoted to extract topographic information and the presence of water bodies in the observed area, and we show that the combination of the obtained information leads to estimate the available water volume at the date of acquisition. The proposed procedure is cheaper and quicker than the expensive bathymetric surveys or approximate empiric methods so far used.

In Section IV, the hydrological model is presented. In particular, we showed how it is possible to extract an empirical relationship between the areas and volumes of the observed reservoirs from SAR products. In addition, a model of runoff is developed and validated with the data extracted by the multitemporal set of SAR images. Examples of possible applications of the model to water management are also reported in Section IV-C.

II. Methodology and Case Study Characterization

The study area (see Fig. 1) is located in the northern Burkina Faso, in the Yatenga province, and it is entirely enclosed in the Volta basin ($13°47'50''$ N, $2°23'310''$ W). The region is characterized by a semiarid climate, with precipitation concentrated

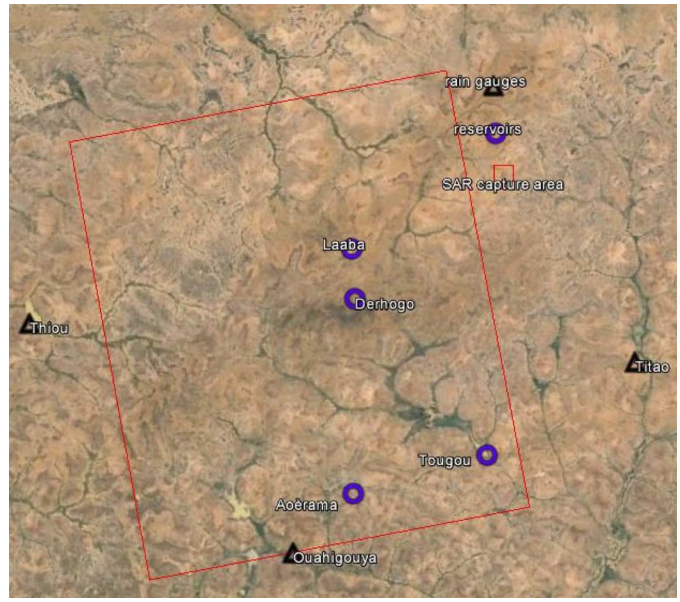

Fig. 1. Study area, Google Earth view.

in the June–September rainy season, which annually range between 500 mm (in the North) and 1000 mm (in the South). This climate calls for appropriate strategies for water storage in the rainy season and water use in dry season.

One of the oldest and most popular technique for water harvesting is the construction of dams that create small reservoirs. The northern Burkina Faso is characterized by an increasing demographic pressure and by soils that are prone to erosion, causing a sedimentation phenomenon that reduces the available water volume [22]. Many reservoirs have been built during the drought occurred between 1974 and 1987 [2], witnessing the importance that this practice assumes to face water shortages. The number of reservoirs frequently changes, due to uncontrolled construction and ruptures, so that an updated inventory of the existing reservoirs with traditional techniques is hard to obtain. The monitoring of the reservoirs would be of great importance in order to optimize their management and also because their effects on the overall water distribution of the Volta basin is still unclear and it is the object of controversies with neighboring countries.

In this project, a set of 15 stripmap (3 m resolution) COSMO-SkyMed images has been acquired. The data cover a temporal interval of almost one year and a half, including two rainy seasons, and are HH polarized, also for increasing the ratio between land and water reflectivity. The block diagram presented in Fig. 2 describes the overall methodology, from the input data through the proposed processing toward the expected output. More details on each block are provided in the following sections. It is worth to note that the modularity of the approach allows choosing the most appropriate technique in accordance with the desired results and the working environment. In this paper, most of the choices have been dictated by the need to obtain accurate results with the simplest techniques. Along with the obtained products, in the last column of the block diagram, a set of applications have been cited for showing the potentiality of the approach.

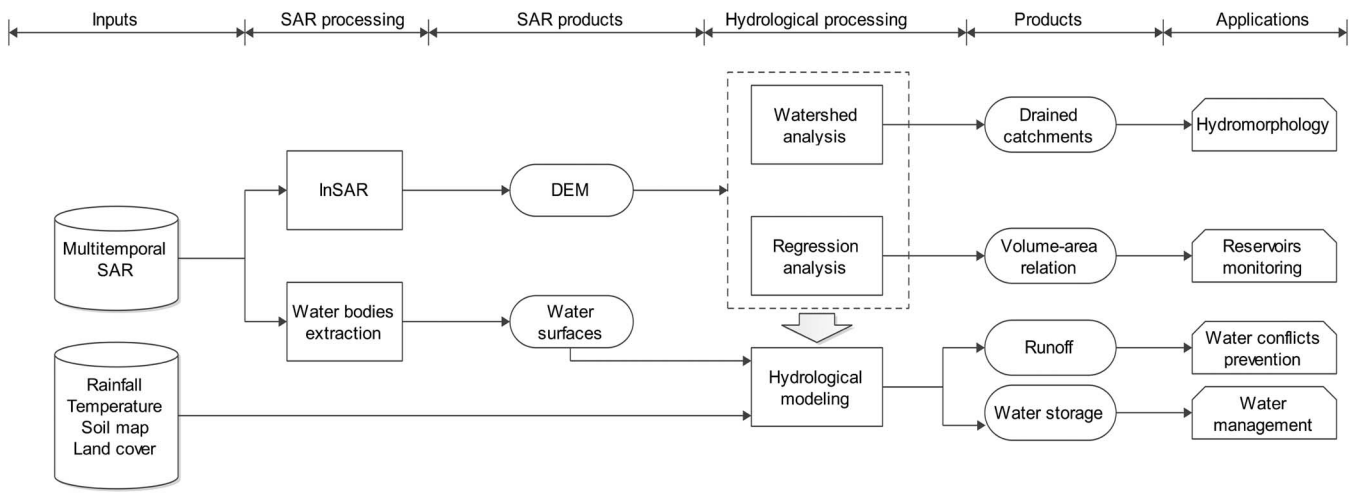

Fig. 2. Block diagram of the proposed processing chain.

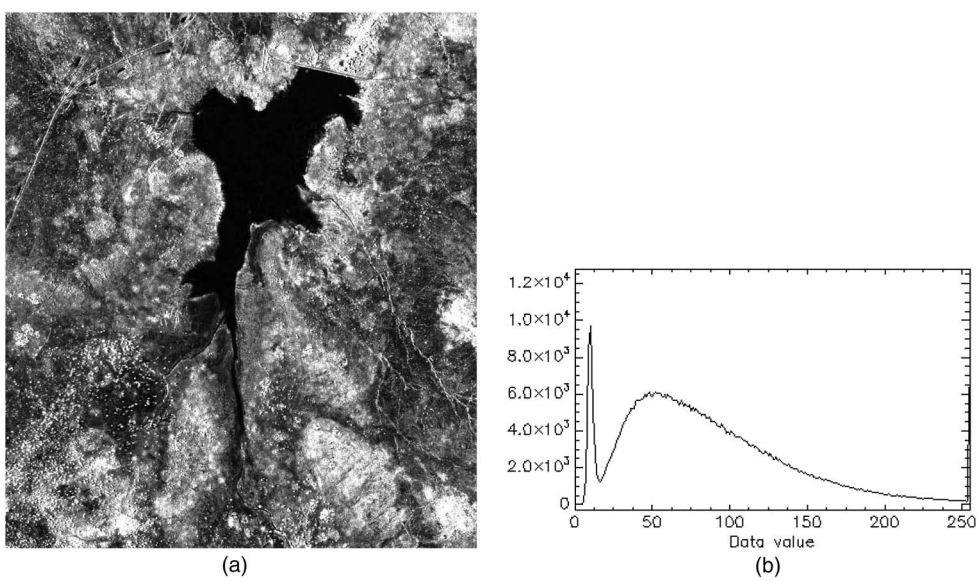

Fig. 3. Gouinre basin intensity map (a) and its 98th percentile histogram (b).

III. SAR Processing

In this section, we present the rationale and the algorithms developed for the estimation of the available water volumes in the monitored reservoirs. The 9-m resolution DEM used for the bathymetric analysis was presented in [21] along with the technique employed for its generation. In particular, it was obtained processing a COSMO-SkyMed interferometric couple acquired on April 28, 2011 and April 29, 2011 at the peak of the dry season when most of the basins are empty and the climatic conditions are very stable. These conditions allow a reliable estimate of elevation and shape of the basins' areas that are covered by water in the rainy season.

A. Preprocessing

In order to exploit the temporal diversity of the SAR images, calibration, registration, and despeckling procedures are required.

According to [23], COSMO-SkyMed SLC balanced products have an absolute radiometric calibration accuracy smaller than 1 dB. However, this requires the application of metadata-based calibration coefficients to the intensity map, which compensate the effects relative to the sensor and to the acquisition geometry. The procedure to be followed to correctly determine these coefficients is explained in [24].

Reduction in speckle is a fundamental aspect in multitemporal SAR processing, since its presence could complicate the identification of a relevant feature and its temporal evolution [25]. In this paper, we adopted the optimal weighting multitemporal De Grandi filter [26], which allowed us to amplify the water–land contrast and, as a consequence, to produce more accurate water–area information. A further speckle reduction has been carried out with a spatial multilooking, which reduced the images' resolution to 9 m, in accordance with the resolution of our DEM, which is the bottleneck of the whole technique.

B. Water Bodies Extraction

1) Segmentation: The application of the multitemporal De Grandi filter allows the enhancement of the land–water ratio and,

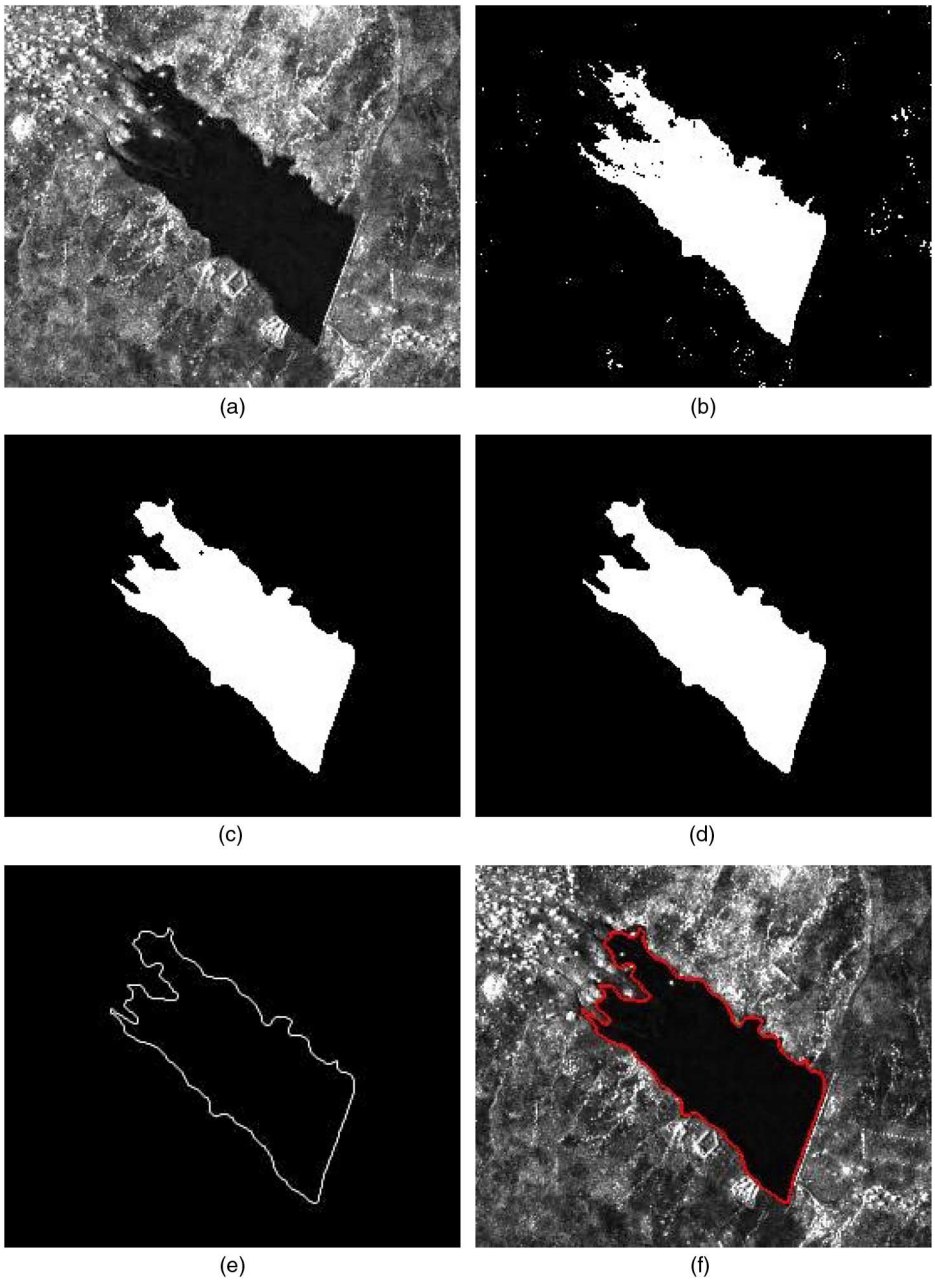

Fig. 4. Shoreline extraction workflow: (a) intensity De Grandi-filtered map; (b) threshold-guided segmentation; (c) mode filter; (d) morphological filtering; (e) roberts edge detector; and (f) superposition of the contour line on the intensity map.

as a consequence, an effective extraction of the shorelines by applying an intensity threshold to separate the class "water" from the class "no water" [27]. The selection of the threshold value is guided by the evaluation of the histogram of a subset taken around the basins under analysis. The constraint to respect is the selection of a subset in which the presence of surface water is relevant, since in this case, the histogram of the intensity map exhibits a bimodal distribution.

In Fig. 3(a), we considered a subset around the Gouinre basin, whose histogram is depicted in Fig. 3(b). It can be appreciated that, thanks to the multitemporal despeckling, low reflectivity objects are well-separated from the rest of the scene and this makes the image pdf bimodal. Note that this distribution emerges after an appropriate histogram clipping. In fact, Fig. 3(b) shows the histogram relevant to the values below the 98th percentile of the pdf. This value has been selected with an entropy-guided criterion as detailed in [13] and [28]. This representation allows an easy identification of the optimal threshold, which is given by the local histogram minimum between the two distribution modes. This threshold is basin- and image-adapted, since water surfaces are not necessarily static objects and their reflectivity could be influenced by local phenomena [29].

2) Shoreline Extraction: The threshold-guided segmentation allows a quick preliminary estimation of the water surface [30], as shown in the example depicted in Fig. 4, where we present the SAR image of the Laaba basin [Fig. 4(a)] and the binary mask [Fig. 4(b)] obtained with the procedure presented in

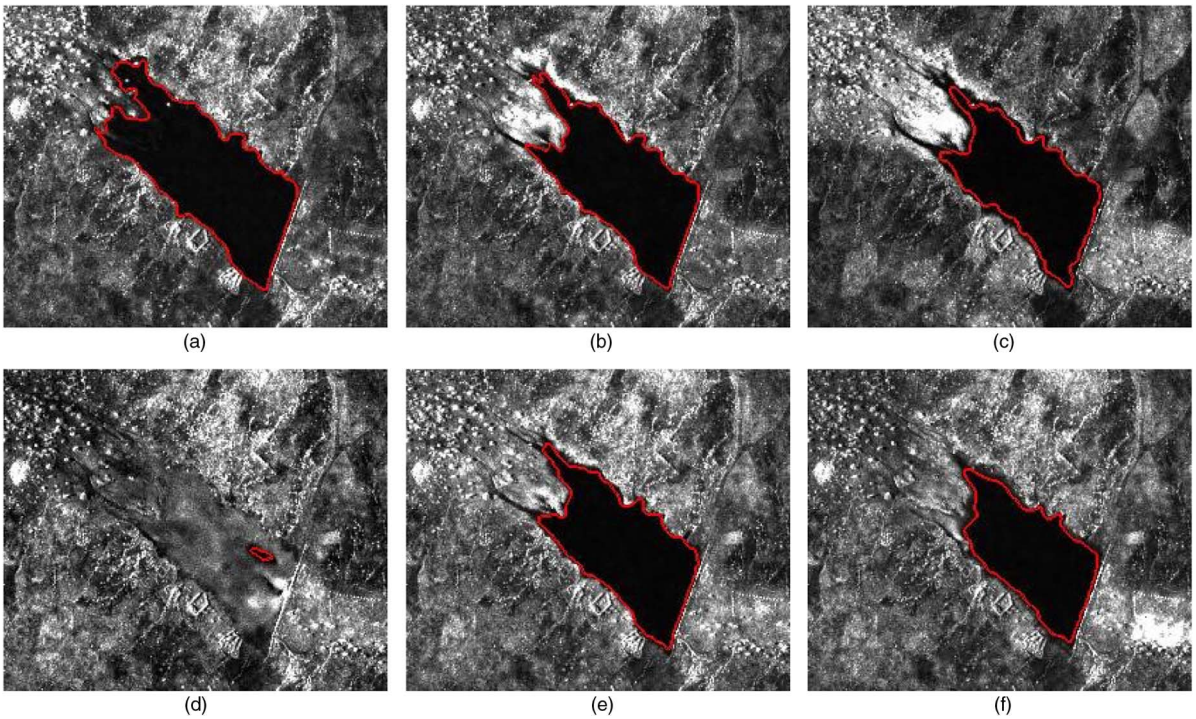

Fig. 5. Laaba basin, shorelines for the acquisitions of (a) 2010/06/12; (b) 2010/07/14; (c) 2010/08/31; (d) 2011/03/27; (e) 2011/11/10; and (f) 2011/12/12.

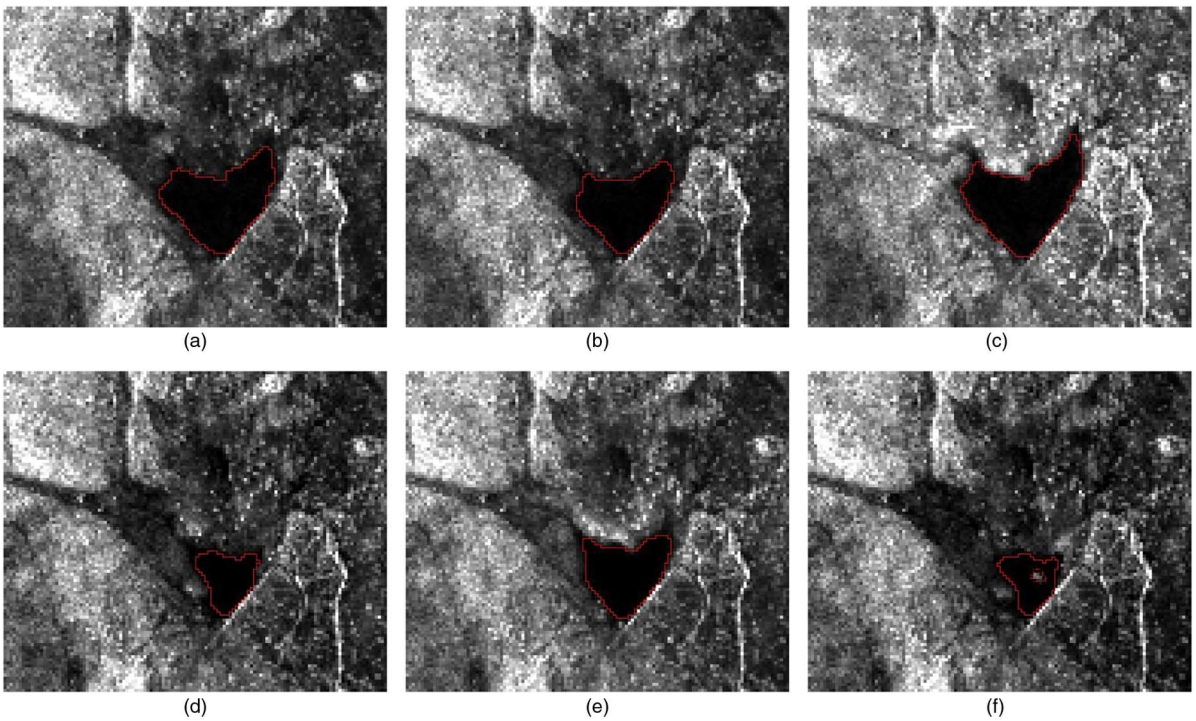

Fig. 6. Derhogo basin, shorelines for the acquisitions of (a) 2010/06/13; (b) 2010/07/14; (c) 2010/08/31; (d) 2010/12/05; (e) 2011/11/10; and (f) 2011/12/12.

Section III-B1. The quality of the mask can be significantly improved, eliminating isolated pixels belonging to the "eroded areas" class [31] and wrongly classified as "water surface" with the application of a mode filter [Fig. 4(c)] and the use of morphological operators [Fig. 4(d)] [32]. Then, the shoreline is extracted with the Roberts operator [Fig. 4(e)] [33]. The result of the whole processing chain is shown in Fig. 4(f), where a good matching between the extracted shoreline and the intensity map can be appreciated.

The extraction of the shorelines has been performed with such a semiautomatic procedure for all the available acquisition for two basins in the nearby of the city of Ouahigouya and the basins

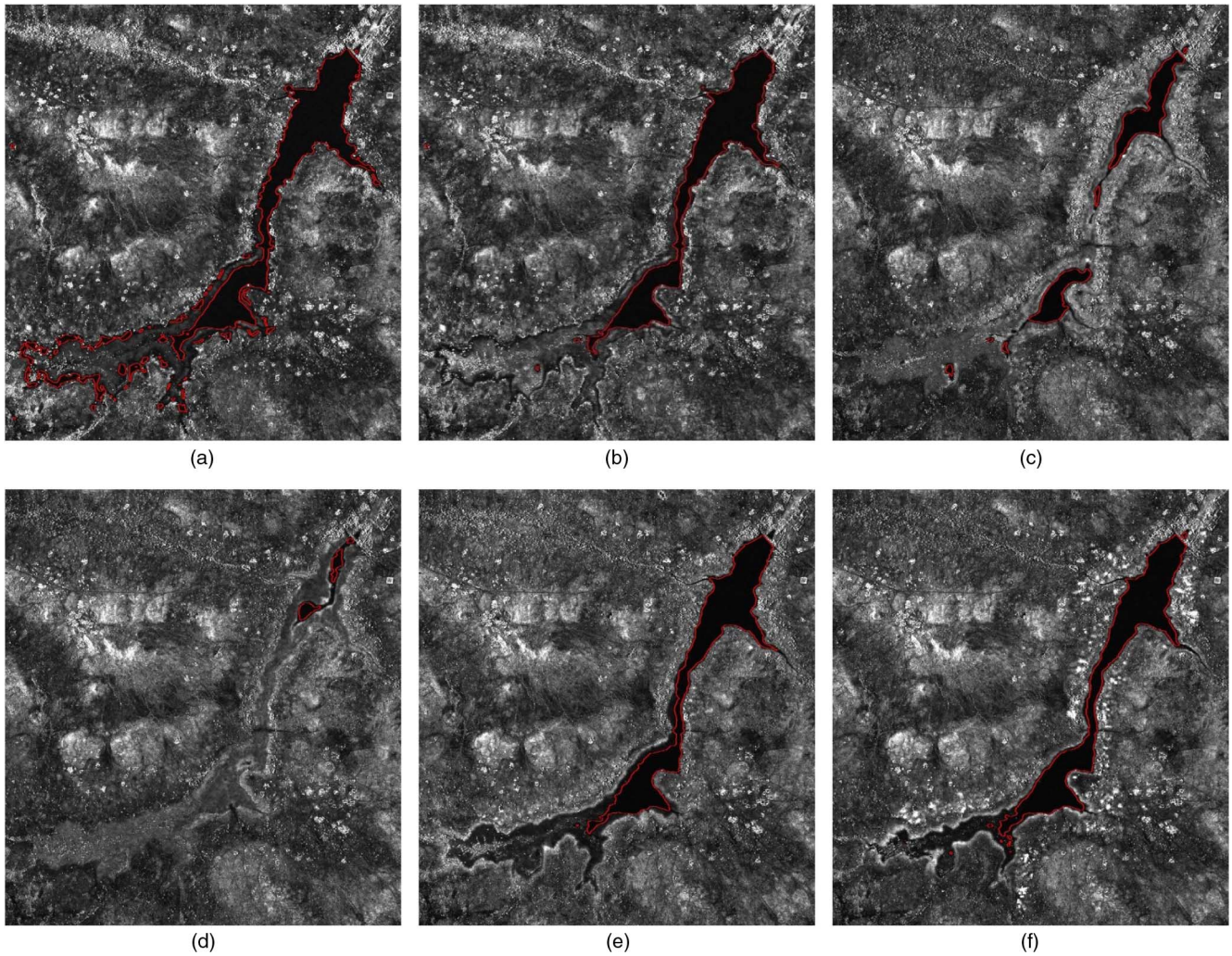

Fig. 7. Tougou basin, shorelines for the acquisitions of (a) 2010/06/13; (b) 2010/07/14; (c) 2011/03/27; (d) 2011/04/28; (e) 2011/11/10; and (f) 2011/12/12.

of Laaba, Tougou, Aorama, and Derhogo for a total of six sites. The results of this procedure are shown in Figs. 5–7 for Laaba, Derhogo, and Tougou basins, respectively.

C. Geocoding

The extracted masks and contours must be reprojected from the SAR azimuth/slant range geometry in a cartographic system through a geocoding operation. This operation is carried out through an iterative solution of the Range–Doppler equations coupled with an Earth model for the point $\underline{\mathrm{P}} = (X, Y, Z)$ [34]. Neglecting the Earth's rotation velocity, the equations to be solved are

$$(\underline{\mathrm{S}}(t_a) - \underline{\mathrm{P}}) \cdot \dot{\underline{\mathrm{S}}}(t_a) = 0 \quad \text{(Doppler equation)} \tag{1a}$$

$$|\underline{\mathrm{S}}(t_a) - \underline{\mathrm{P}}| = t_r \frac{c}{2} \quad \text{(Range equation)} \tag{1b}$$

$$\frac{|\underline{\mathrm{P}} \cdot \hat{e}_x|^2}{(a+h)^2} + \frac{|\underline{\mathrm{P}} \cdot \hat{e}_y|^2}{(a+h)^2} + \frac{|\underline{\mathrm{P}} \cdot \hat{e}_z|^2}{(b+h)^2} = 1 \quad \text{(Earth model)} \tag{1c}$$

where $\underline{\mathrm{S}}$ is the satellite position; t_a, the azimuth time; c, the light speed; t_r, the range time; $(\hat{e}_x, \hat{e}_y, \hat{e}_z)$, the unit vectors of the orbit reference system; a, b, the semimajor and semiminor axis of the ellipsoid; and h is the height of the guess point with respect to the ellipsoid.

D. SAR Postprocessing: Basins' Bathymetry

Once the basin contour is known and reprojected in a cartographic system, the water volume contained into the basin can be computed considering each pixel of the water mask as a water column whose height h_{wc} is given by

$$h_{wc} = h_c - h \tag{2}$$

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. Therefore, the water volume contained into the basin is given by the summation of all the elementary contributions brought by the water columns

$$V = \sum_{i=1}^{N} S_i \times h_{wc_i} \tag{3}$$

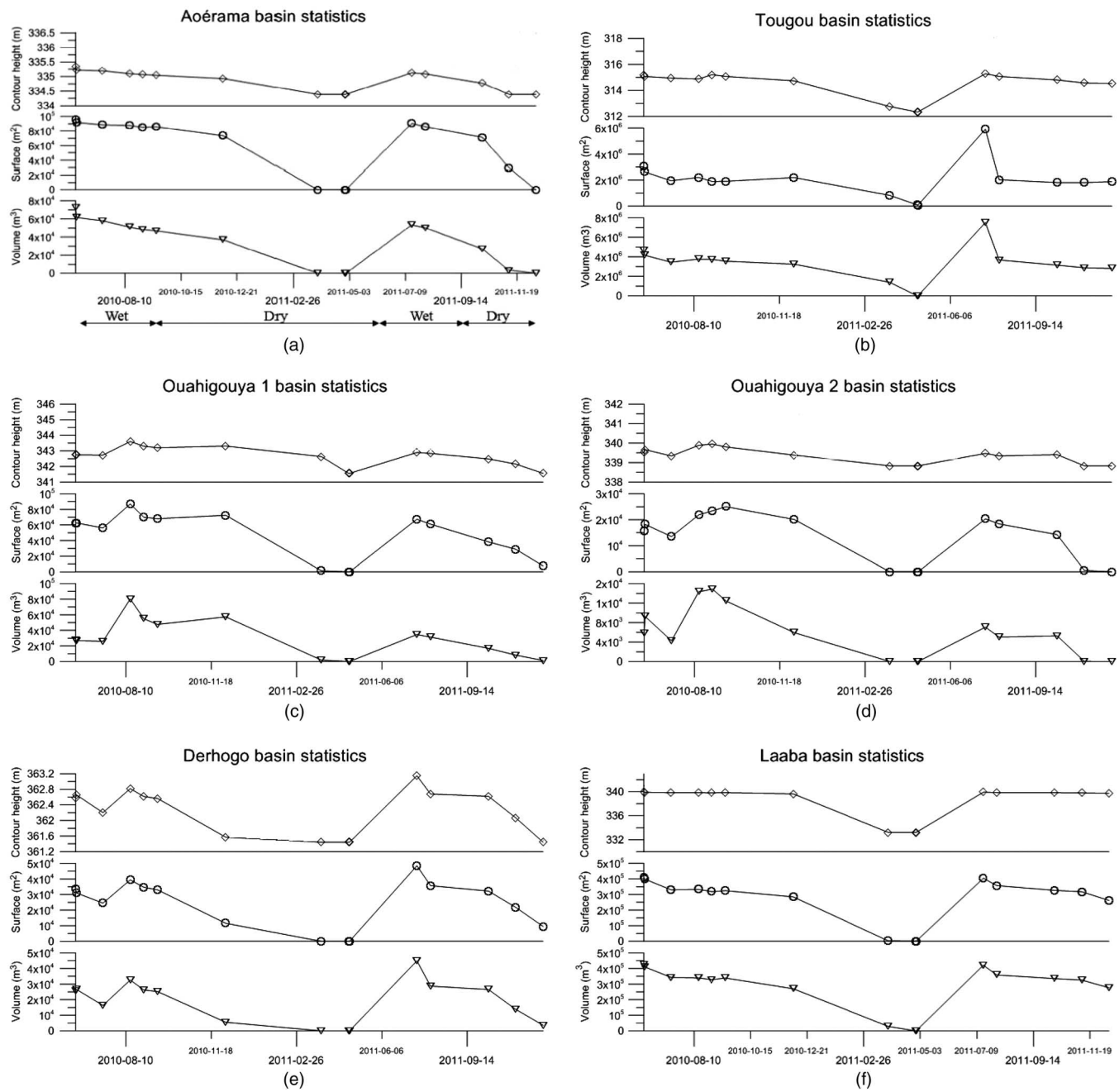

Fig. 8. Basins statistics.

where S_i is the basin surface of the ith resolution element belonging to the water mask and N is the number of pixels belonging to the water mask.

E. Analysis of the Results

Fig. 8 shows the results of our analysis for the six considered basins. As widely discussed in the following section, these diagrams are strictly related to the seasonal variation in rainfall with an abrupt increment in volume at the beginning of the rainy season and a continuous decrease in the dry season.

Note that the Tougou basin does not dry up completely during the dry season [see Fig. 7(d)] and hence its bathymetry can not be estimated in the part of the basin covered by surface water during the acquisitions used for DEM retrieval. Indeed, the DEM elevation for this points is not trustworthy (due to incoherence of water surfaces return) and, therefore, they have been excluded from the analysis using a coherence-derived mask. As a consequence, while the basin surface is correctly determined, the estimated volume represents the variation with respect to the minimum rather than the entire water volume available.

In Table I, the position of the dams and basins maximum surface and volume availability are provided. Note that also the dams' heights could be potentially estimated using the available DEM: however, typical dam's sizes in the study area are

TABLE I
RESERVOIRS DATABASE

Reservoir	Position	Surface max (m^2)	Volume max (m^3)
Laaba	$13°52'23.12''N, 2°.20'44.12''W$	407 430	427 215
Tougou	$13°40'48.68''N, 2°12'52.72''W$	5 918 022	7 511 779
Ouahigouya 1	$13°36'21.44''N, 2°24'42.31''W$	86 994	80 286
Ouahigouya 2	$13°37'78.96''N, 2°24'57.97''W$	25 029	14 871
Aorama	$13°40'10.61''N, 2°21'4.66''W$	96 147	72 723
Derhogo	$13°49'36.53''N, 2°20'34.15''W$	48 519	44 954

comparable to (and frequently lower than) DEM's 9 m resolution. Hence, in most cases, the dam height estimates obtained using the DEM are not reliable. Anyway, this information is not necessary for the calculation of the retained volume. Indeed, it would be needed for the estimation of the maximum retainable volume, which is one of the inputs of the hydrological model. Nevertheless, due to the poor quality of the dam height estimates, we assumed that the maximum retainable volume is equal to the maximum retained volume observed from SAR data, as detailed in Sections III-B1 and III-D.

IV. HYDROLOGICAL MODELS

A. Estimation of Reservoirs Storage Volumes as a Function of Their Surface Areas

A relationship between reservoirs' storage volumes and surface areas can be derived using the obtained database. These relations are very useful since the reservoirs' surface areas can be always estimated with an excellent precision degree by satellite or aerial imagery, while the volume measurement requires more demanding and expensive bathymetric surveys.

Area-volume relations have been developed in literature, both theoretically and empirically. Based on an extensive bathymetric survey in Upper East Region of Ghana, Liebe *et al.* [4] obtained the following relationship:

$$\text{Volume} = 0.00857\ \text{area}^{1.4367}(\text{m}^3). \tag{4}$$

The regression analysis of the reservoirs volumes and areas obtained using SAR-derived data allowed the derivation of the following relationship:

$$\text{Volume} = 0.10120\ \text{area}^{1.1670}(\text{m}^3). \tag{5}$$

The Tougou basin was not used in this derivation since, as explained in Section III-E, it does not dry up completely, thus preventing the DEM extraction for the areas covered by surface water.

As shown in Fig. 9, there is only a slight difference between (4) and (5). This confirms that, thanks to the morphological and morphometrical regularity of the regions, the area-based volume estimation is possible with good approximation.

B. Modeling the Time Evolution of Water Storage

The time evolution of the water storage is computed by the implementation of a water balance among the water flows that

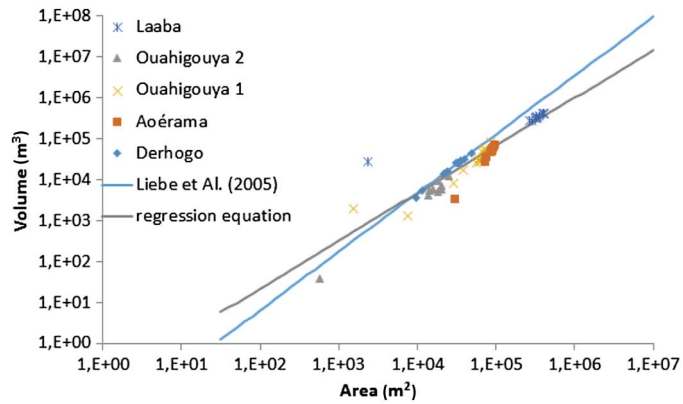

Fig. 9. Reservoirs' storage volumes as a function of their surface areas in a log–log plane.

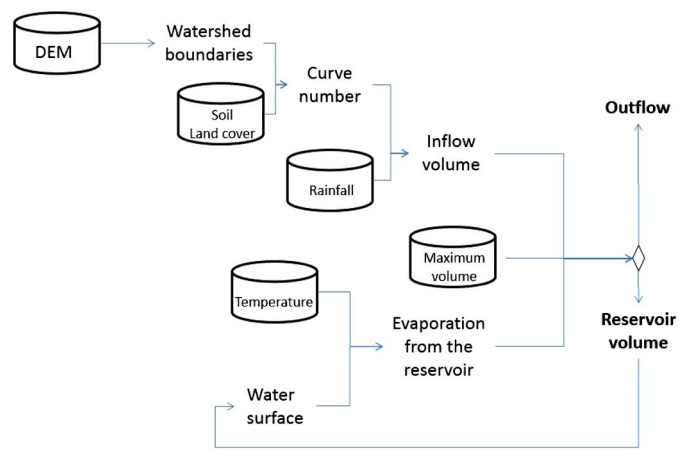

Fig. 10. Block diagram of hydrological model.

enter and exit the reservoir. The input flow is the surface runoff, while the outputs are the evaporation from the reservoir, the spill downstream the dam and the water withdrawn by the users. In order to validate the model, the computed storages are compared with those extracted from SAR data. The overall procedure is depicted in Fig. 10.

The first step of the model is the estimation of the runoff water that inflows the reservoir. The natural process of runoff formation is extremely complex because it is the result of many different phenomena regarding atmosphere, soil, vegetation, and water flows. In literature, many hydrological models that simulate the transformation of rainfall input into surface runoff with different levels of complexity, data requirement, and computational burden are available. In our case, the choice of the most appropriate hydrological model is mainly driven by the available (rather scarce) dataset, i.e., daily measurements of rainfall and temperature and low-resolution maps of soil and land cover. As is often the case, especially for small basins in low-income countries, run-off measurements, to be used for model calibration and validation, were not available. The lack of runoff measures is partly compensated by those of water volumes retained at the reservoirs. Due to the small number of SAR acquisitions (15 images) and the low temporal resolution, we can observe only the cumulate of the flow discharge over a period much longer than the 1 day time-step of the hydrological model. Consequently,

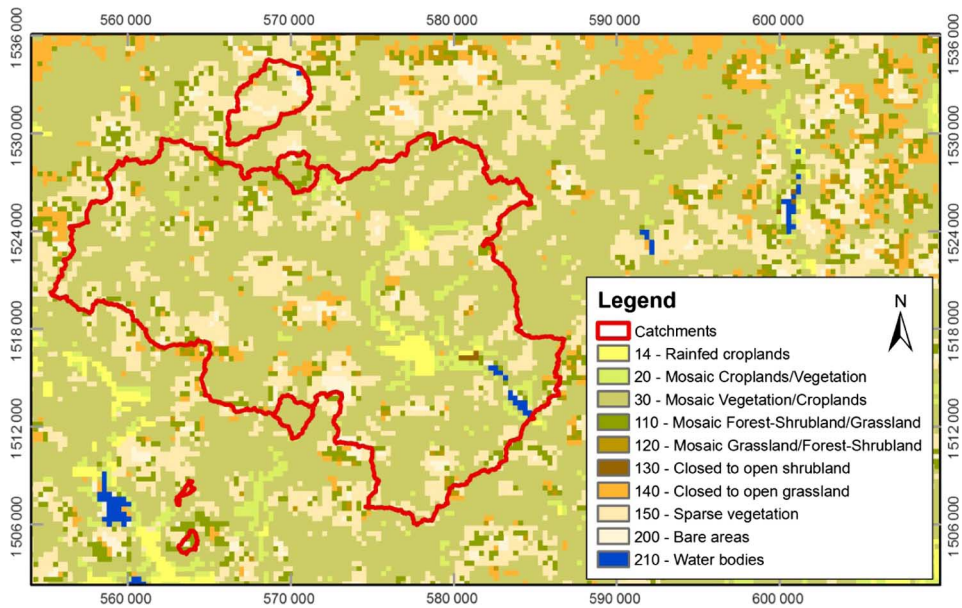

Fig. 11. Watershed boundaries superimposed to land cover map.

the cumulate observed flow discharge cannot be used to calibrate one or more parameters of complex hydrological models. Hence, a simple hydrological model that does not require any calibration was chosen, and the retained water volumes were only used for the validation of the model. It is worthwhile to underline that denser series of SAR images would allow the calibration of more complex models that could better represent the real hydrological response.

Among the models suitable for the simulation of runoff in small ungauged watersheds, which do not require the calibration of the used parameters, we used the soil conservation service method (SCS) [35]–[37], according to which the depth of runoff is given by

$$R = \frac{(P - I_a)^2}{P - I_a + S} \tag{6}$$

where P is the total precipitation; S, the potential maximum retention; and I_a, the initial abstraction given by

$$I_a = \lambda S, \ \lambda = 0.1 \div 0.2. \tag{7}$$

The potential maximum retention S is expressed in the form of a dimensionless runoff curve number CN

$$S = S_0 \left(\frac{1000}{CN} - 10 \right) \tag{8}$$

where S_0 is a scale factor equal to 24.5 mm, for I_a, and R is measured in millimeters.

Using eqs. (6)–(8), the rainfall is converted in runoff through the unique parameter CN for each time step.

The value of CN depends on the soil and on the land cover. The nature of the soil of the basins under analysis was extracted from a soil map produced in 1968 by Orstom agency having a 1/500 000 scale factor. The vegetation cover was derived by the global land cover map released in 2010 by the European Space Agency [38]. In order to estimate the CN parameter for each analyzed catchment, the soil map and the land cover map were superimposed to the watersheds' boundary (see Figs. 11 and 12). The boundaries of the drained catchments were derived in a GIS environment (JGrass) elaborating the InSAR DEM.

The daily precipitation amount were derived by the three rainfall gauge stations (see Fig. 1) of Ouahigouya [13°35′N, 2°26′W, elevation: 329 m above sea level (a.s.l.)], Thiou (13°49′N, 2°40′W, elevation: 303 m a.s.l.), and Titao (13°46′N, 2°04′W, elevation: 329 m a.s.l.). The spatial distribution of precipitation was estimated through the inverse distance-squared method [40], in which the estimate of precipitation in location j is given by

$$P_j = \sum_{i=1}^{n} \frac{d_{ij}^{-2} P_i}{\sum_{i=1}^{n} d_{ij}^{-2}} \tag{9}$$

where P_i is the measured precipitation at the rainfall gauge i and d_{ij} the distance between gauge i and location j.

The reservoirs' storage volume was computed on a daily basis through the following water balance:

$$V_t = \max\{V_{t-1} + R_t W - E_t A_{t-1}; V_{\max}\} \tag{10}$$

where V_t is the reservoir storage volume at day t, V_{t-1} is the reservoir storage volume at day $t-1$, R_t is the depth of direct runoff at day t estimated through (6), W is the drained area of the watershed extracted from the DEM, E_t is the depth of evaporation from the reservoir at day t, A_{t-1} is the reservoir surface at day $t-1$, and $V_{\max}$ is the maximum reservoir capacity. In the absence of records about water withdrawal from the reservoir, this term has been neglected in the balance. As a consequence, the modeling results will overestimate the reservoir storage in the dry season, that is typically the period in which the water is extracted.

The simulation is iterative. The volume at time t is computed from the value at time $t-1$. The initial condition is, for each year, the water volume estimated by SAR acquisitions at the end

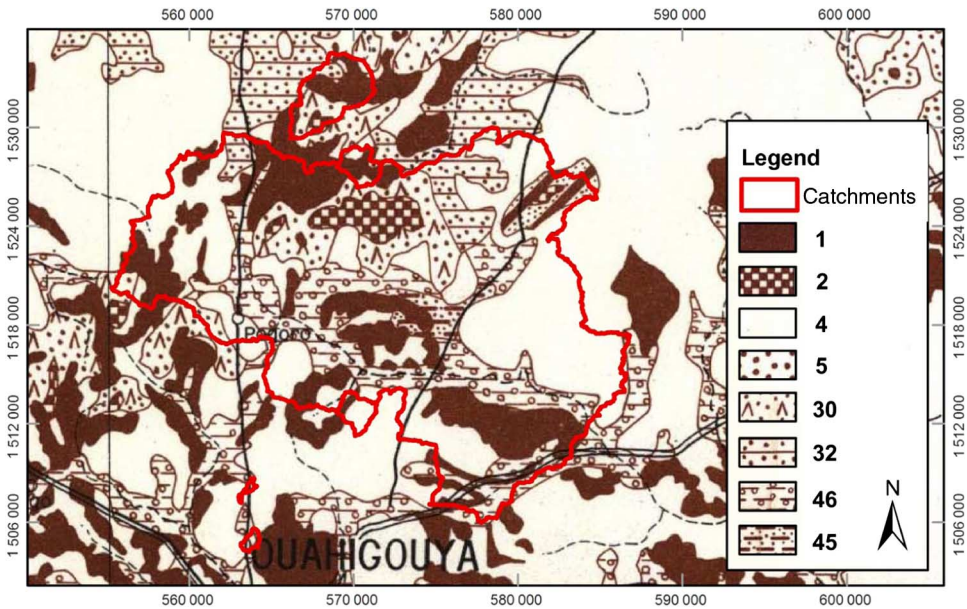

Fig. 12. Pedological map of Haute-Volta (Centre North). 1. Sols minéraux bruts d'érosion sur cuirasse ferrugineuse. 2. Sols minéraux bruts d'érosion sur roches diverses. 4. Sols peu évolués d'érosion régiques sur matériau gravillionnaire. Association lithosols sur cuirasse ferrugineuse. 5. Sols peu évolués d'érosion régiques sur matériau gravillionnaire. Association sols ferrugineux lessivés (ou appauvris) sur matériau argilo-sableux. 30. Sols ferrugineux tropicaux peu lessivés à drainage interne limité en profondeur. Association sols bruns eutrophes sur matériau argileux issu de roches basiques. 32. Sols ferrugineux tropicaux peu lessivés à drainage interne limité en profondeur. Association sols hydromorphes sur matériau argileux issu de schistes argileux (BIRRIMIEN). 45. Sols hydromorphes peu humifères à pseudogley structurés. Association sols bruns eutrophes sur matrieu argileux et sols ferrugineux peu lessivés su sables oliens ou sur sables fins argileux. 46. Sols hydromorphes peu humifères à pseudogley structurés. Association sols ferrugineux peu lessivés sur matériau sablo-argileux peu pais niveau gravillonaire (source [39]).

of the dry season. However, in order to run the model, the estimation of the unknowns E_t, A_{t-1}, and $V_{\max}$ is necessary.

As for the estimation of E_t, since local measurements of net radiation or fractional cloud cover are not available, a temperature-based model has been implemented using the daily temperature measurements at Ouahigouya station in the Hargreaves equation [40]

$$E_t = 0.0023 E_0 \delta_T (T_t + 17.8)(\mathrm{mm/day}) \tag{11}$$

where T_t is the temperature at time t in °C, δ_T is the difference between mean monthly maximum and minimum temperatures, and E_0 is the water equivalent of extraterrestrial radiation in (mm/day) for the location of interest computed as follows:

$$E_0 = 15.392 d_r (\omega_s \sin\phi \sin\delta + \cos\phi \cos\delta \sin\omega_s) \tag{12}$$

in which ϕ is the latitude; δ, the solar declination in radians; ω_s, the sunset hour angle in radians; and d_r, the relative distance between the earth and the sun. These quantities can be computed as follows:

$$\delta = 0.4093 \sin\left(\frac{2\pi}{365} J - 1.405\right) \tag{13}$$

$$\omega_s = \arccos(-\tan\phi \tan\delta) \tag{14}$$

$$d_r = 1 + 0.0033 \cos\left(\frac{2\pi}{365} J\right) \tag{15}$$

where J is the Julian day number.

The water area of reservoirs A_{t-1} is computed depending on the volume at time $t-1$, i.e., V_{t-1}. To this end, an empirical equation is derived, for each basin through linear regression of the volume-surface series obtained from the DEM analysis. The estimation is performed at time step $t-1$ in order to make the procedure explicit.

The maximum reservoir capacity $V_{\max}$ is assumed to be equal to the maximum observed volume. This assumption does not hold if the reservoir does not fill up completely at least once in the observation period. However, it is of course realistic since the small reservoirs under study are usually at their maximum capacity for long periods in the year.

Reservoirs' retention volumes estimated through (10) were compared with those calculated from SAR images (see Fig. 13). Although the extreme simplicity of the model, the absence of calibration and the neglecting of the water withdrawal from the reservoir, the agreement is quite good for almost all the studied catchments. In fact, only the simulation relevant to the Tougou basin is rather disappointing. This is probably due to the bigger dimensions of this watershed with respect to the others and to the presence of other water retention basins in its catchment area, which influence the discharge regime at the outlet.

The model fits quite well the hydrological behavior of the smallest watersheds as Ouahigouya 2 ($0.4\ \mathrm{km}^2$) and Ouahigouya 1 ($0.9\ \mathrm{km}^2$), catches the behaviour of the small ones, i.e., Aoérama ($3.7\ \mathrm{km}^2$) and Derhogo ($4\ \mathrm{km}^2$), while the prediction capability resulted to be worst for the bigger basins of Laaba ($15.5\ \mathrm{km}^2$) and Tougou ($411\ \mathrm{km}^2$). Although the assumptions made and the uncertainties linked to the estimation of some of the input data, the model is able to catch the overall behavior of the system and, therefore, can be used for the simulation of different scenarios of water management. The agreement in the dry season is also quite good; this is probably due to the fact that the amount

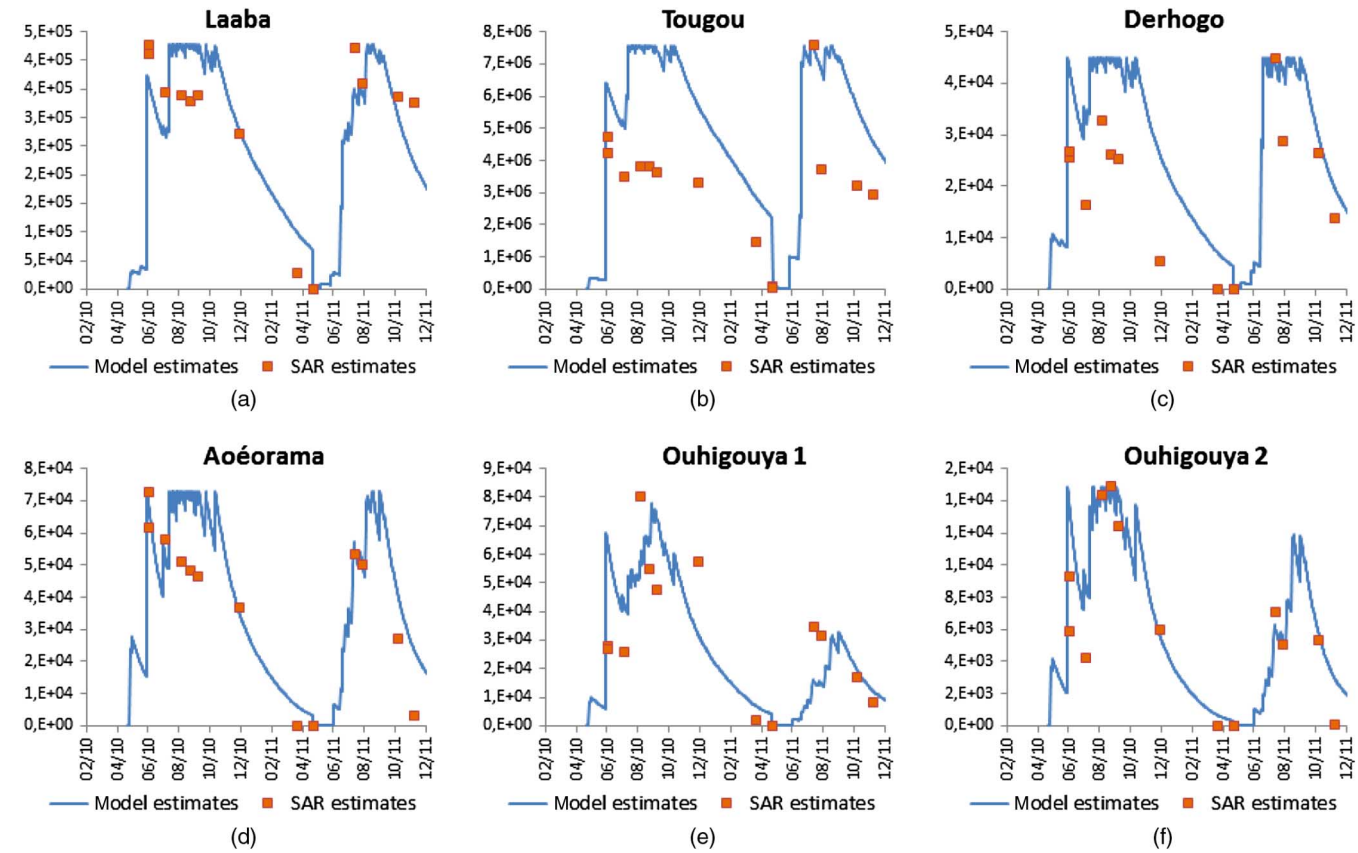

Fig. 13. Simulated retention volumes (m^3) compared to the ones extracted by SAR images.

of extracted water is small compared to the big amount of water lost for evaporation.

In some cases, the water storage simulated in the rainy season is greater than the ones extracted by the SAR data. This discrepancy could be due to the fact that, after the beginning of the rainy season, the vegetation grows at boundaries of the artificial lakes, making it difficult to recognize precisely the shoreline from the SAR images.

TABLE II
LAABA BASIN EFFICIENCY FOR THREE DIFFERENT MANAGEMENT SCENARIOS

	Scenario 1	Scenario 3	Scenario 3
Number of months of irrigation abstraction	6	4	3
Total amount of abstraction (m^3)	321 300	590 400	797 657
Total amount of evaporation (m^3)	684 851	668 097	585 304
c_i	23%	42%	56%
c_e	48%	47%	41%

C. Possible Applications and Benefits of Integrated Modeling

The proposed model can be used to improve the efficiency of the reservoir management. As an example, three different scenarios of water abstraction are simulated for the Laaba basin. In the first scenario, it is assumed that the irrigation abstraction is uniformly distributed in 6 months; in the second scenario, the abstraction is concentrated in 4 months, and in the third, in 3 months. The efficiency of the system is estimated by the ratio c_i between the water volumes used for irrigation and the total water volume which enters into the reservoir as runoff flow in 1 year, i.e., between May 2010 to April 2011. As shown in Table II, the system is more efficient when the abstraction of irrigation water is concentrated in a short period immediately successive to the end of the rainy season. For example, if the abstraction is concentrated in 3 months, it is possible to use the 53% of the total inflow volume into the reservoir, while, if the abstraction is diluted in 6 months, only the 23% can be used. This is due to the fact that the longer the water is retained in the reservoir the bigger the loss of water for evaporation will be. In the simple examples showed, we assessed only the total abstracted volume, but the real variables to maximize are the crop production and the economic benefits for the community. These variables can be computed by the model after introducing agronomic and economic parameters. In this way, it would be possible to use the model for the optimization of the regulation strategy of the reservoirs.

Another important application of the proposed model is the estimation of the impact of small reservoirs on downstream flows. The presence of the reservoirs induces a decrease in the water flow downstream, and this is often the reason of social tension between the beneficiaries of the reservoirs and people living downstream along the same river. It is, therefore, important to estimate the water volumes that are subtracted to the natural flow because of the presence of the reservoirs. This information is also important in order to allow for equitable sharing and utilization of water resources. The model implemented in this paper can be used to perform such estimate, as shown in Table III for the years considered in this study. In the

TABLE III
FRACTION OF THE INCOMING WATER FLOW THAT FLOWED DOWNSTREAM THE DAMS

Basin	2010	2011
Laaba	51%	13%
Tougouu	67%	12%
Derhogo	74%	48%
Aoérama	73%	48%
Ouahigouya 1	17%	0%
Ouahigouya 2	37%	0%

more rainy 2010, all the reservoir overflowed an amount of water between the 17% and 74% of the total incoming flow, while in the drier 2011, the smallest basins did not release volume downstream.

V. CONCLUSION

In semiarid regions small reservoirs form a set of well-distributed and easily accessible water sources that are used for agriculture, domestic use, and livestock. Small reservoirs are widely used to reduce the peoples vulnerability to drought and improve their livelihoods.

In order to optimize the management of these reservoirs, the access to information is a crucial problem that calls for cheap, reliable, and continuous monitoring. In this paper, we propose the use of SAR sensors for extracting meaningful physical parameters and feeding appropriate hydrological models. In particular, the revisit time and the spatial resolution of COSMO-SkyMed data allow a detailed, continuous, and wide observation of the territory that deserves to be exploited in regions where *in situ* measurements are impervious and expensive actions.

We proposed an approach based on the appropriate processing and feature extraction of a set of COSMO-SkyMed stripmap images, devoted to retrieve the presence, extension, and volume of small reservoirs in Burkina Faso. An appropriate combination of SAR and hydrological processing led to the realization of a set of products (digital elevation model, surface and volume of small reservoirs, the drained catchment, and a rainfall–runoff model) that can be used for hydromorphological characterization of the studied area, reservoir monitoring, water management, or prevention and mitigation of conflicts related to water use. The proposed research intends to contribute to facilitate management practices of the diffuse system of small reservoirs and ensure their sustainable use. Further development of the study are in the direction of improving the input data of the hydrological modeling. For example, a better description of the soil and land cover could be obtained by superimposing their classification map over the SAR images or by their estimation from high-resolution SAR data, trying also to catch the seasonal change in land cover and soil humidity. In case of availability of longer series of SAR images, after validating the model, the SAR-derived water storages can be assimilated to the model, thus greatly improving its prediction capability.

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Donato Amitrano was born in Naples, Italy, on December 27, 1985. He received the Bachelor's degree in aerospace engineering and the Master's degree in aerospace and astronautical engineering both from the University of Naples "Federico II," Napoli, Italy, in 2009 and 2012, respectively.

In September 2012, he joined as a Graduate Researcher and is pursuing the Ph.D. degree with the Department of Electrical Engineering and Information Technology, University of Naples "Federico II." His research interests include multitemporal synthetic aperture radar (SAR), remote-sensing techniques for developing countries, SAR images interpretation, and data fusion.

Mr. Amitrano is an invited reviewer for some remote-sensing specialized journals such as IEEE Transactions on Geoscience and Remote Sensing, *International Journal of Remote Sensing*, and *Remote Sensing Letters*.

Fabio Ciervo was born in Salerno, Italy, on May 1, 1979. He received the Laurea degree in civil and environmental engineering in 2008, from the University of Salerno, Salerno, Italy. He is currently pursuing the Ph.D. degree with the Department of Civil Engineering at the same university.

In 2009, he received a grant from the Research Centre on Major Hazards (CUGRI) of Salerno University for research in the field of debris flow initiation and propagation modeling. In 2010, he obtained a research fellowship from the University of Salerno to be spent at the Sediment Transport Research Group (GITS), Department of Hydraulic, Maritime and Environmental Engineering, UPC-BarcelonaTech, Spain, where he came back as a Visiting Scientist in 2013–2014. In 2011, he obtained a research fellowship at the CUGRI for research in analysis and development of measures aimed at reducing risk from flash flood hazard. In 2013, he was a Visiting Scientist at the University Centre for Advanced Studies on Hydrogeological Risk in Mountain Areas (CUDAM), University of Trento, Trento, Italy. His research interests include modeling, flood/flow propagation in urban environment, hydrological and hydraulic analysis in ungauged basins, critical rainfall thresholds and early warning systems, unsaturated soil and bimodal water retention functions, slope stability, and synthetic aperture radar (SAR)-based hydrological and hydraulic analysis for semiarid regions.

Gerardo Di Martino (S'06–M'09) was born in Naples, Italy, on June 22, 1979. He received the Laurea degree (*cum laude*) in telecommunication engineering and the Ph.D. degree in electronic and telecommunication engineering, both from the University of Naples "Federico II," Napoli, Italy, in 2005 and 2009, respectively.

In 2009–2010, he received grants from the University of Naples to be spent at the Department of Biomedical, Electronic and Telecommunication Engineering, for research in the field of indoor electromagnetic propagation and localization of unknown transmitters. In 2010–2012, he worked on a project financed by the Italian Space Agency aimed at the development of techniques for information extraction from high-resolution synthetic aperture radar (SAR) images of urban and natural areas. He is currently a Research Fellow at the Department of Electrical Engineering and Information Technology, University of Naples "Federico II," working on a project regarding maritime surveillance with SAR data. His research interests include microwave remote sensing and electromagnetics, with particular focus on modeling of the electromagnetic scattering from natural surfaces and urban areas, SAR signal processing and simulation, information retrieval from SAR data, and remote-sensing techniques for developing countries.

Maria Nicolina Papa was born in Sant'Agata Militello (ME), Italy. She received the Laurea degree in environmental engineering (*cum laude*) from the Università di Trento, Trento, Italy, and the Ph.D. degree in hydraulic and environmental engineering from the University of Calabria, Cosenza, Italy, in 1997 and 2002, respectively.

Since 2004, she is working as an Assistant Professor in hydraulic engineering with Salerno University. In 2003, she was a Visiting Scientist with the Faculty of Science and Engineering, Ritsumeikan University, Kusatsu, Japan, and in 2010, she collaborated to the research activity of the Hydraulic, Marine and Environmental Engineering Department, Technical University of Catalonia (UPC), Spain. She collaborated with the MERLIN N.G.O post–tsunami relief activity in Indonesia (2005), to the humanitarian project of the GVC (Gruppo di Volontariato Civile) N.G.O. for the improvement of water availability and quality at Gaza Strip, in 2007. Her main research interests include water resources management in semiarid regions, the use of remote sensed data in hydrological modeling, the estimation of constitutive equations in debris flows, and the management of flood risk.

Antonio Iodice (S'97–M'00–SM'04) was born in Naples, Italy, in 1968. He received the Laurea degree (*cum laude*) in electronic engineering and the Ph.D. degree in electronic engineering and computer science, both from the University of Naples "Federico II" (UNINA), Naples, Italy, in 1993 and 1999, respectively.

In 1995, he received a grant from Italian National Council of Research (CNR) to be spent at Istituto di Ricerca per l'Elettromagnetismo e i Componenti Elettronici (IRECE), Naples, Italy, for research in the field of remote sensing. He was with Telespazio S.p.A., Rome, Italy, from 1999 to 2000. From 2000 to 2004, he was a Research Scientist with the Department of Electronic and Telecommunication Engineering, University of Naples "Federico II." He is currently a Professor of Electromagnetics with the Department of Electrical Engineering and Information Technology of the University of Naples "Federico II." He took part in several projects funded by European Union (EU), Agenzia Spaziale Italiana (ASI), Italian Ministry of Education and Research (MIUR), Campania Regional Governament, and private companies. He is currently the UNINA Scientific Responsible of two projects financed by the EU within the Seventh Framework Programme. He is an author or coauthor of over 270 papers, of which over 60 published on refereed journals, and the others on proceedings of international and national conferences. He serves as a reviewer for several international journals. His research interests include microwave remote sensing and electromagnetics: modeling of electromagnetic scattering from natural surfaces and urban areas, simulation and processing of synthetic aperture radar (SAR) signals, SAR interferometry, and electromagnetic propagation in urban areas.

Prof. Iodice received the "Sergei A. Schelkunoff Prize Paper Award" from the IEEE Antennas and Propagation Society, in 2009, for the best paper published in 2008 on the IEEE Transactions on Antennas and Propagation.

Youssouf Koussoube was born on September 30, 1964 in Kiembrara (Burkina Faso). In 1996, he received the Ph.D. in hydrogeology from the University Cheikh Anta Diop Dakar, Senegal, and the Ph.D. degree in hydrogeology from the University of Pierre-and-Marie-Curie (Paris VI), Paris, France, in 2012.

He is currently a Researcher and Lecturer with the department of Earth Sciences, the University of Ouagadougou, Burkina Faso. His research interests include hydrogeology including, in particular, the following aquifers control techniques: remote sensing using optical and synthetic aperture radar (SAR) data, geophysics on the field, and modeling of hydrogeological processes.

Francesco Mitidieri was born on July 1, 1988 in Salerno, Italy. He received the Master's degree (*cum laude*) in civil engineering in 2013 from the University of Salerno, Salerno, Italy, where he is pursuing the Ph.D. degree with the Department of Civil Engineering.

In 2012, he worked as a Trainee with HYDS Hydrometeorological Innovative Solutions (spin off enterprise of Universitat Politecnica de Catalunya of Barcelona, Spain) dealing with the application of Radar technologies to Flood and Debris Flow Risk Management. His research interests include hydrology, water resources management, and remote sensing applications for semiarid regions.

Daniele Riccio (M'91–SM'99–F'14) was born in Napoli, Italy. He received the Laurea degree in electronic engineering (*cum laude*) from the Università di Napoli "Federico II," Naples, Italy, in 1989.

He is a Full Professor of electromagnetic theory and remote sensing with the Department of Electrical Engineering and Information Technology, University of Napoli "Federico II." He was a Research Scientist with the Institute for Research on Electromagnetics and Electronic Components, Italian National Council of Research (CNR) during 1989–2004. He also was a Guest Scientist with the German Aerospace Center (DLR), Munich, Germany (1994 and 1995), and a Visiting Professor with the Universitat Politecnica de Catalunya, Barcelona, Spain (2006). He is a Principal Investigator for the international research projects on exploitation of remote sensing data and design of synthetic aperture radars (SARs), and participates to technical committees of international symposia on electromagnetics and remote sensing. His research interests focuses on microwave remote sensing, electromagnetic scattering, SAR with emphasis on sensor design, data simulation and information retrieval, as well as application of fractal geometry to remote sensing. He has authored three books, including *Scattering, Natural Surfaces and Fractals* (2007), and more than 300 papers. He is the Coordinator of the Ph.D. programme in Information Technology and Electrical Engineering with the University of Napoli "Federico II."

Prof. Riccio is an Associate Editor for few journals on Remote Sensing. He was the recipient of the 2009 Sergei A. Schelkunoff Transactions Prize Paper Award for the best paper published in year 2008 on the IEEE Transactions on Antennas and Propagation. He is a Member of the Cassini Radar Science Team.

Giuseppe Ruello (S'00–M'04) was born on February 12, 1975 in Naples, Italy. He received the Laurea degree (*cum laude*) in telecommunication engineering and the Ph.D. degree in information engineering, in 1999 and 2003, respectively, both from the University of Naples "Federico II," Naples, Italy.

In 2000, he received a grant from the University of Naples to be spent at the Department of Electronic and Telecommunication Engineering for research in the field of remote sensing. In 2000, he won also a grant from the University of Rome "La Sapienza", Rome, Italy. In 2002 as well as in 2004–2005, he was a Visiting Scientist with the Department of Signal Theory and Communications, Universitat Politecnica de Catalunya of Barcelona, Spain. He is currently a Research Scientist with the Department of Electrical and Information Technology Engineering, University of Naples, Italy. His research interests include synthetic aperture radar (SAR) remote sensing, modeling of electromagnetic scattering from natural surfaces, SAR raw signal simulation, modeling of electromagnetic field propagation in urban environment, and remote sensing techniques for low-income semiarid regions.