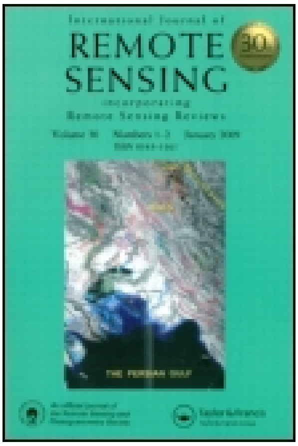

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Effectiveness of high-resolution SAR for water resource management in low-income semi-arid countries

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This article presents an efficient framework and a sustainable pilot project on the effective use of spaceborne synthetic aperture radar (SAR) in low-income countries and semi-arid climatic contexts. The technical efficiency was pursued by integrating SAR models and hydrological assessment methods; the socio-economical sustainability was guaranteed by the joint work of scientists, technicians, and volunteers. The pilot project was developed in the Yatenga region, a Sahelian area in northern Burkina Faso. In particular, an original development of SAR interferometry algorithms was tailored to the peculiar climate, the soil characteristics, and the land cover of the semi-arid regions. A digital elevation model (DEM) was derived, and an original approach based on the use of SAR amplitude images is proposed for its validation. The achieved resolution (9 m) is significantly better than that of the previously available DEMs in the study area (30 m). Based on the DEM, the soil sedimentation rate of small reservoirs was estimated together with the average soil loss in the contributing catchments due to the erosion process. A multi-temporal filter was implemented on the SAR images for monitoring of water intake volume in small reservoirs, and its seasonal evolution. The developed tools provide an innovative contribution for the improvement of water resource management in the study area. This approach is repeatable and scalable to suit situations with similar economic and climatic conditions.

1. Introduction

More than 2.5 billion people in the world live on under 2.5 dollars per day and depend on subsistence agriculture (UNDP 2011). Their existence is rendered even more fragile and unsafe by major environmental events, occurring more and more frequently due to climate change. Hence, management of the physical environment is essential for ordinary needs as well as for the prevention and mitigation of, and response to, crisis events. For these purposes, hydrological modelling can provide a crucial support but it requires a huge amount of information distributed both geographically and temporally (Bates et al. 2008; Perry et al. 2009). This information could be obtained by deploying a distributed, hydrological monitoring network. In low-income countries, this costly deployment is inapplicable for economic, social, and technological reasons.

Remote-sensing instruments can be a powerful support for hydrological model developers. They provide the capability to estimate several governing variables of the hydrological cycle for

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*Corresponding author. Email: ruello@unina.it wide regions, with spatial resolution and revisit time compatible with many hydrological applications. Key projects have been reported in the literature. The TIGER project (ESA 2012, Fernandez et al. 2009), launched by the European Space Agency in 2002, supported African institutions to access Earth observation data for water-related projects. Significant results were obtained also by the GLOWA Volta project, which provided an analysis of the physical and socio-economic determinants of the hydrological cycle within the Volta Basin (van de Giesen et al. 2002).

Nevertheless, in low-income countries, where a synoptic view would be extremely useful for resource identification and management, satellite data are scarcely used. Despite the fact that orbital laws oblige satellites to cover almost the entire Earth, in many low-income regions, satellite data are rare or not acquired at all. Data acquisition is not requested mainly because of the (logical) prejudice that remote sensing could never support the political and scientific communities of low-income countries without extra (costly) side activities.

One of the goals of this article is the overturning of this paradigm, demonstrating that the joint work of scientists, technicians, and volunteers can provide useful, zero-cost products for these countries. Space agencies can promote the data and explore a new business sector. Researchers and technicians can gain both technical and cultural benefits, along with the young students involved in the project. Beneficiaries can be advantaged in the short term by the exploitation of the products, and in the long term by the creation of a research system that is expected to produce socio-economic results.

Remote-sensing approaches, methods, and technologies need to be customized to each specific context. In particular, in this article we focus on semi-arid regions, defined as areas where the annual potential evapo-transpiration rate is higher than that of precipitation (Peel, Finlayson, and McMahon 2007). These areas are characterized by variable hydrological regimes, with the alternation of intense rainy and long dry seasons. In this context, farmers and decision-makers face extreme constraints often exacerbated by both seasonal droughts and floods that threaten regional food security. Groundwater is limited, and must be shared between agriculture, farming, and human consumption.

In this article, we present the pilot project ‘water resource management in semi-arid regions’ (WARM-SAR) developed in Burkina Faso, providing a support to decision-makers in the fields of hydrology and land management and based on the use of high-resolution synthetic aperture radar (SAR) sensors. The philosophy and methodology of the project are presented in Section 2.

During the project, we used a set of SAR images provided at zero cost by the Italian Space Agency under the aegis of AO2007 (Di Martino, Iodice, Natale, et al. 2012; Di Martino, Iodice, Riccio, et al. 2012).

The images relate to the Yatenga region, a Sahelian area of northern Burkina Faso. This area, whose description is presented in Section 3, is characterized by a two-season climate with the alternation of extreme weather conditions. Floods occur in the June–September rainy season, and droughts are frequent at the end of the October–May dry season (Sienou and Karduck 2012).

In Burkina, the farmers mainly accumulate the wet-season rain in small-capacity reservoirs. The location of the dams and the use of water are often left to the farmers’ experience and they are neither planned nor optimized. The exact number, location, and capacity of small reservoirs are not recorded. Such a situation is both a scientific and technical challenge and, from the remote-sensing viewpoint, an opportunity for developing *ad hoc* algorithms.

The analysis of this context led to a definition of the appropriate technical actions necessary in order to exploit the available data. The implemented standard and innovative remote-sensing techniques exploit the specific climate for extracting the required physical parameters. In particular, in Section 4, we present the interferometric SAR (InSAR) algorithm adopted to extract the digital elevation model (DEM). This was then used to measure reservoir capacity and its reduction with time due to the deposition of water-transported sediments. In Section 5, we present how the COSMO-SkyMed data facilitated the estimation of water intake in small reservoirs.

2. Project rationale

The adoption of a new technology can be effective only with the participation of all of the stakeholders. The pilot project (Di Martino, Iodice, Natale, et al. 2012) presented in this article involved local communities, university researchers from Italy (Napoli and Salerno) and Burkina Faso (Ouagadougou), and volunteers from the non-profit humanitarian association Engineering Without Borders. All participants contributed with their cultural skills, and achieved satisfactory results and progress.

The first step of such a holistic approach is the analysis of the working environment. An accurate analysis of the case study (see Section 3), from both physical and social perspectives, allows the definition of the user needs and the development of techniques appropriate to the context.

Once the case study has been analysed, the next step is to outline the activities needed to provide the necessary solutions to the beneficiaries. In water management problems, a huge amount of data with high spatial and temporal resolution is often needed and usually not available in low-income countries. In this article, some data were provided by the remote-sensing instruments. For instance, most of the hydrological modelling requires an accurate DEM, which is not easy to obtain in low-income countries. In Section 4, we present the InSAR technique used for the DEM generation and the end product.

Value-added products were then obtained by integrating complementary remote-sensing and hydrology skills. The hydrological models were fed by remote-sensing data, whose interpretation benefits from interaction with hydrologists (Di Martino et al. 2011). Such an approach is detailed in Sections 4 and 5, where the proposed algorithms are tailored to the specifics of the semi-arid climate.

3. Case study

This article presents the first implementation of the philosophy and methodology described above. A set of 16 strip-map and seven spotlight images with coverage of almost 18 months, including two rainy seasons, was acquired for the project. The SAR images cover a rectangular area of almost 1600 km^2 in the Yatenga district (see Figure 1) in the north of Burkina Faso, a small country (240,000 km^2) in West Africa.

From the social viewpoint, nearly 80% of the 14 million inhabitants (INSD 2006) live in rural areas, and the main activity consists of subsistence farming and ranching. The country is underdeveloped: according to the human development index, it is classified amongst the bottom seven from a total of 187 countries (UNDP 2011). More than two million people are in food insecurity and about 34% of the population is subject to chronic malnutrition (FAO 2012). Export items mainly consist of cotton, cattle, and gold. In recent decades the country has witnessed the development of both illegal and authorized mining activities.

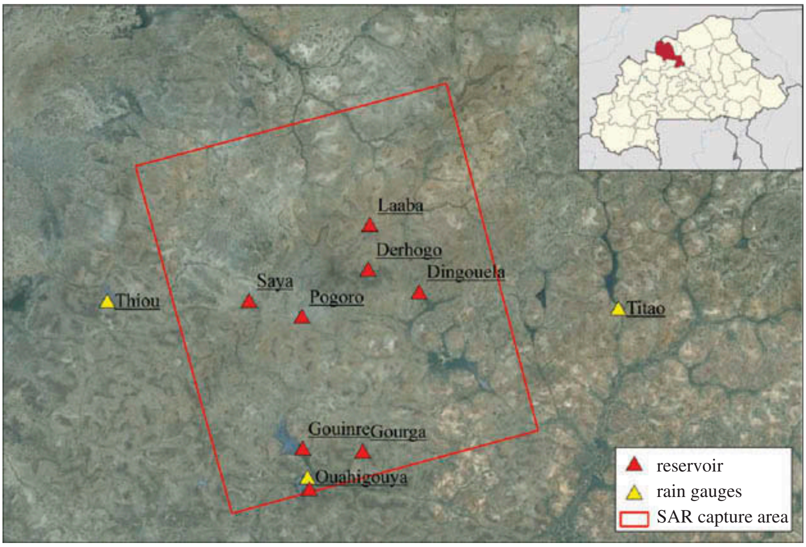

Figure 1. Google Earth view (1:1,000,000) of the Yatenga region, Burkina Faso.

From the geological viewpoint, the basement of Burkina Faso is characterized by two geographically well-distributed features of different ages.

- The Palaeoproterozoic crystalline basement, covering 82% of the country, composed of volcano-sedimentary and volcanic rocks and granitoids (Castaing et al. 2003).
- The Neoproterozoic sedimentary basin, covering the northern (including the Yatenga region), western, and eastern borders, rests on crystalline formations. Among sedimentary rocks, there is a variety of sandstone and limestone (Koussoubé 2010).

From the climatic viewpoint, Burkina Faso experiences a wet season, from May to October, characterized by short, intense storms, and a dry season, from November to April. Total seasonal rainfall ranges from 100 to 650 mm in the north, and from 650 mm to over 1100 mm in the south of the country. The non-uniform spatial distribution and the seasonal inter-annual variations have a strong impact on vegetation. Therefore, there is a Sahelian zone in the north, and a Sudan–Sahelian zone in the centre and south of the country (Peel, Finlayson, and McMahon 2007). The area covered by SAR images (see the red rectangle in Figure 1) is located in the Sahelian zone; the three rainfall gauge stations close to the study area (see Figure 1) are Ouahigouya (13° 35′ N, 2° 26′ W, elevation: 329 m 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.). In Figure 2, annual rainfall over the last 40 years is illustrated. Historical records are not available for the period 2004–2010 for all three stations, and are also missing for some other years. Despite the area being almost flat, average annual rainfall over the last 40 years differs significantly between neighbouring villages: 483 mm at Titao, 527 mm at Thiou, and 610 mm at Ouahigouya. Annual rainfall in the region is characterized by large variation; for example, in Thiou, it has ranged from 309 to 775 mm, and this variation has had a major impact on crop production. For

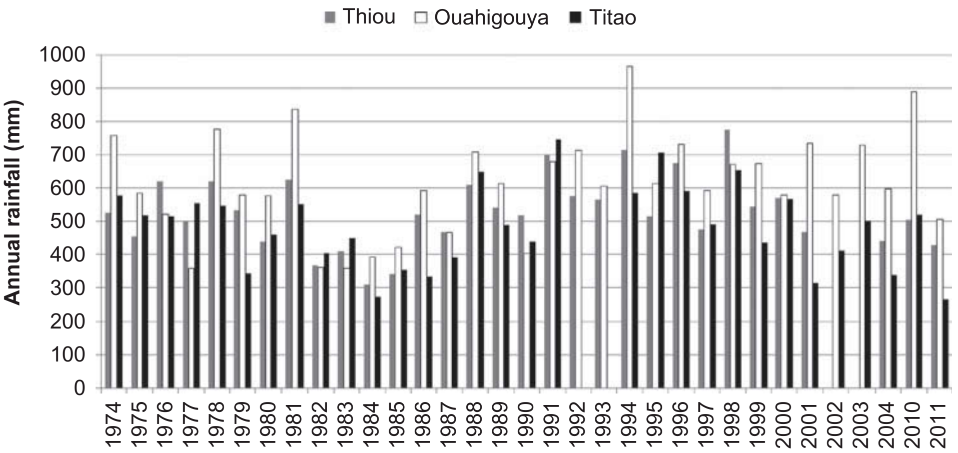

Figure 2. Cumulated annual rainfall (mm) measured at Ouahigouya (13° 35′ N, 2° 26′ W, elevation: 329 m a.s.l.), Thiou (13° 49′ N, 2° 40′ W, elevation: 303 m a.s.l.), and Titao (13° 46′ N, 2° 04′ W, elevation: 329 m a.s.l.).

example, millet, one of the most widely grown crops in the area, has a vegetative life of 90 days and cannot develop without irrigation when the annual rainfall is less than 350 mm.

Over the past 40 years, West Africa has experienced a long dry period. At Ouahigouya, the average annual rainfall in the period 1922–1969 was 716 mm (Albergel and Lamachère 1993), while for 1974–2011 it was 610 mm (see Figure 2).

Figure 3 shows the average monthly rainfall for the three stations. About 75% of the rain falls during the months of July, August, and September, while from November to April monthly rainfall is lower than 20 mm.

From the agricultural viewpoint, Burkina Faso has arid soils. In the Yatenga district, the main crops are sorghum, millet, and cotton. Livestock also plays an important role in the economy of the area. The erratic and scarce rainfall severely impacts agro-pastoral production. Moreover, the decline in rainfall over the last 40 years, combined with the progress of desertification, has led to an increased vulnerability of agro-pastoral systems.

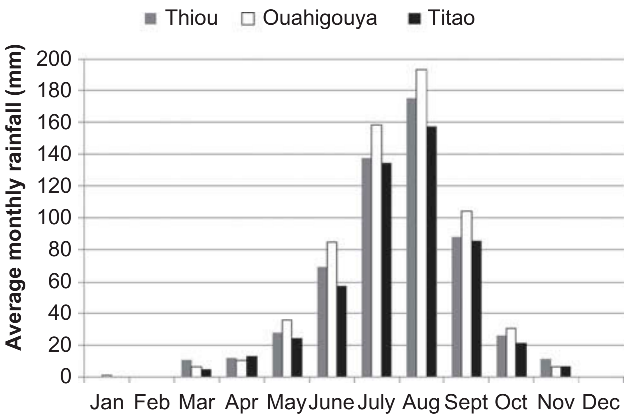

Figure 3. Average monthly rainfall (mm) computed for the period 1974–2011.

Since 2000, repeated crises have occurred in the Sahel. In 2011 the inadequate, erratic, and late rainfall led to a reduced harvest and consequently 60% of rural villages were officially declared to be at risk of food insufficiency (FAO 2012). FAO estimated that more than 17 million USD would be required to deal with the 2011 crisis – for Burkina Faso alone.

Soils suffer from water and wind erosion and degradation. In order to bolster the resilience of farmers and herders to climatic variability, it is necessary to increase the amount of stored water and improve irrigation structures and aqueducts. Traditional water-harvesting systems have demonstrated their efficacy in reducing water erosion and increasing crop production in drought periods (Barry, Olaleye, and Fatondji 2008).

In such a context, there are two clear outcomes.

(1) Water storage is a critical factor for coping with seasonal rain shortage and improving the chances of successful cultivation in the dry season.
(2) Accurate and wide-ranging knowledge of the physical environment is crucial for planning and verifying appropriate actions for improvement in the standard of living.

4. Topographic analysis

Topographic information is a prerequisite for any activity aiming at natural resource conservation and management. Particularly in the fields of soil conservation and water management, highly detailed topographic data (mapping scale larger than 1:25,000 or raster resolution less than 10 m) are needed.

In humanitarian projects, the use of appropriate topographic information is often limited by the scarce availability of low-cost products and by the prohibitive cost of *ad hoc* products. Topographic maps are often freely available, but the mapping scale is inadequate for many applications, and the maps are not up to date. For example, the West Africa Topographic Maps Series N504 of the US Army Map Service (PCLMC n.d.) has a map scale of 1:250,000 and was produced in 1955. Some more detailed topographic maps are produced locally, but they cover very limited areas. In the case of Burkina Faso, only 36% of the country is covered by a topographic map at a scale of 1:50,000, while for the entire country only the 1:200,000 map is available. Moreover, these products are relatively expensive.

The derivation of DEMs from remotely sensed data has partly filled the gap. DEMs are now freely available with a global coverage (e.g. SRTM at 90 m resolution and ASTER at 30 m resolution) (Coltelli et al. 1996; Farr et al. 2007; Tachikawa et al. 2011). However, the resolution of these DEMs is still too coarse for many applications relevant to the success of humanitarian projects.

In this section, we describe the interferometric chain implemented in this project for the derivation of a detailed (9 m resolution) DEM from SAR images.

4.1. *Digital elevation model extraction*

SAR interferometry is a well-established and powerful instrument for topographic mapping (Rosen et al. 2000). In our work, we implemented an interferometric processing chain, whose rationale is outlined in Figure 4. In the following, we provide basic details on the blocks reported in Figure 4.

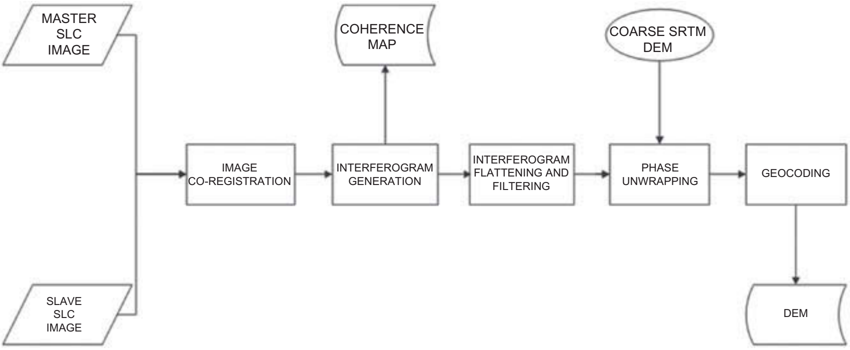

Figure 4. Block scheme of the interferometric chain.

4.1.1. *Image co-registration*

The first step in the processing chain is the co-registration of two interferometric images acquired on 28 and 29 April 2011, at the end of the dry season via a three-step procedure (Li and Bethel 2008). In particular, a first image alignment is obtained using orbital information and solving the Range–Doppler equations (Franceschetti and Lanari 1999); then, a coarse co-registration is performed maximizing the intensity cross-correlation on 256 × 512 windows; finally, a fine sub-pixel shift is evaluated maximizing the over-sampled (by a factor of 2) coherence within 32 × 32 sliding windows.

4.1.2. *Interferogram generation*

Once the two images are co-registered, the interferogram and coherence map can be evaluated (Rosen et al. 2000). The coherence map thus obtained is shown in Figure 5(*a*).

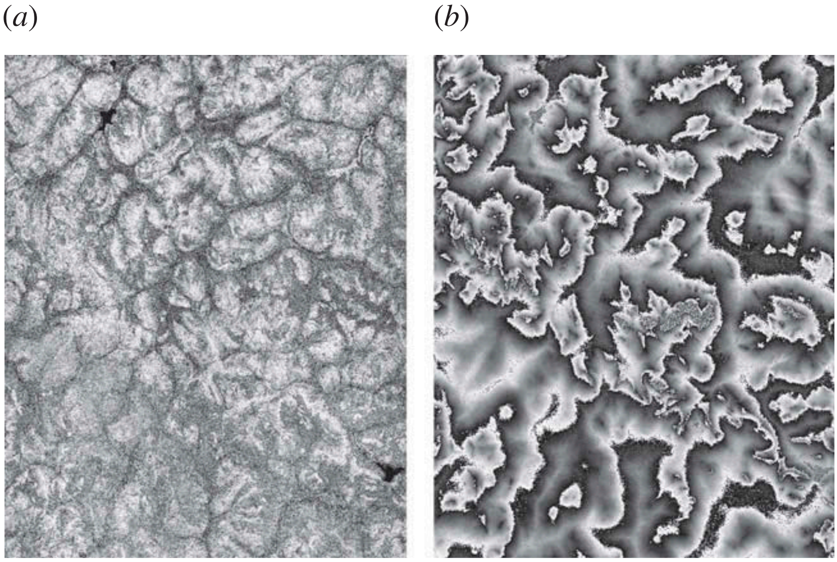

Figure 5. (*a*) Coherence map and (*b*) flattened filtered interferogram phase.

Due to the scarcity of water and vegetation at the end of the dry season, the interferometric coherence obtained is high over the entire area. More than 67% of the pixels have a coherence value over 0.5. The low-coherence pixels refer to areas located close to the largest water reservoirs – a key prerequisite for obtaining high-quality DEMs. As is well known, the expected standard deviation of the height σ_Z and the interferometric phase σ_ϕ are related as:

$$\sigma_z = \frac{\lambda r \sin\theta}{4\pi B_\perp}\sigma_\varphi, \tag{1}$$

where σ_ϕ is a function of the coherence coefficient (see Lee et al. [1998] for details). For the geometry of our pair, the wavelength is λ = 3.125 cm, r at centre scene is about 767 km, $B_\perp$ is 280.1 m, and look angle θ is 37°. With these values, for a coherence value of 0.5 that corresponds to a σ_φ of 0.5 radians with the applied number of looks, the expected σ_Z is about 2 m.

A complex 3 × 3 multilook is applied at this step, in order to mitigate detrimental speckle effects corrupting the interferogram phase. This implies a decrease in spatial resolution from 3 m (original COSMO-SkyMed single-look product resolution) to 9 m (final DEM resolution).

4.1.3. Interferogram flattening and filtering

The interferometric phase obtained is a combination of the topographic, flat Earth, and noise phases; the latter two must be reduced before phase unwrapping. Interferogram flattening is performed with the aid of a radar-coded synthetic DEM, obtained from a standard SRTM DEM of the area (Monti Guarnieri et al. 2003). The residual speckle is mitigated through the application of the adaptive Lee phase filter with a negligible loss in resolution (Lee et al. 1998). The interferometric phase obtained after the filtering step is shown in Figure 5(*b*).

4.1.4. Phase unwrapping and geocoding

The phase obtained is then unwrapped with the SNAPHU algorithm, which is based on a statistical minimum-cost flow network method (Chen and Zebker 2001). After conversion from phase to height, the final DEM is geocoded and ready to be displayed in a geographic cartographic reference system.

The DEM obtained is shown in Figure 6, and that particularly relevant to the area of the Laaba basin in Figure 7.

The DEM obtained was compared with the coarser-resolution DEMs available (SRTM and ASTER), as shown in Figure 8, and with GPS ground truth acquired during an on-site measurement campaign, as shown in Table 1.

The agreement of the DEM obtained with *in situ* measurements is approximately in the order of GPS accuracy, demonstrating the effectiveness of the proposed framework.

DEM reliability has also been tested in a different and original way. The borderline of the water retention basins located in the study area can be observed in SAR images at different time steps, in both wet and dry seasons. Due to the marked climate seasonality, the perimeters of the small reservoirs range from zero in the dry season to values corresponding to maximum water intake in the wet season. Because reservoir borders constitute topographic contour lines, DEM reliability can be estimated through the comparison of water borders and contour lines computed on the basis of DEM. In Figures 9 and 10, two examples of such a comparison are shown, corresponding to the

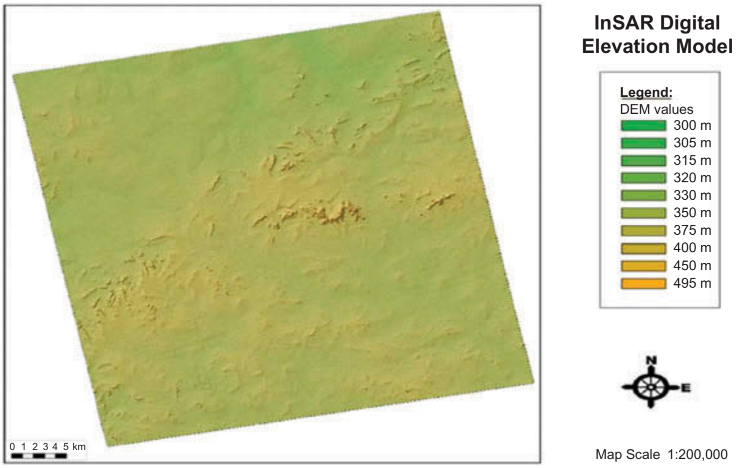

Figure 6. Georeferenced DEM covering an area of 40 × 40 km^2 at spatial resolution of 9 m. The centre scene geographical coordinates are 13° 47′ 50″ N, 2° 23′ 31″ W.

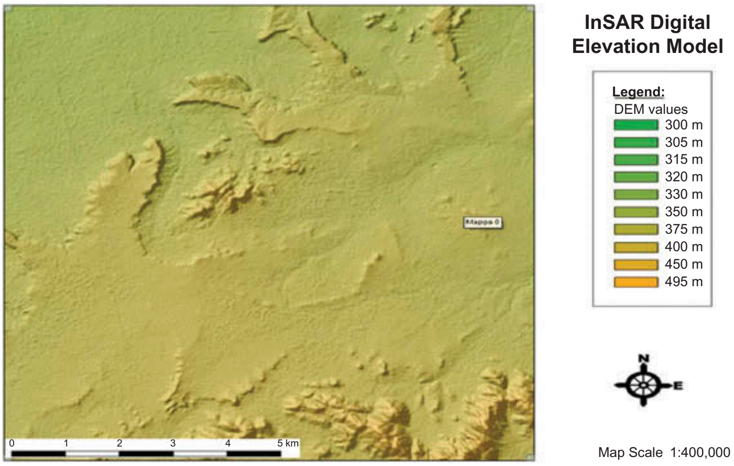

Figure 7. Particulars of DEM relevant to the Laaba basin area. The centre scene geographical coordinates are 13° 51′ 26″ N, 2° 22′ 31″ W.

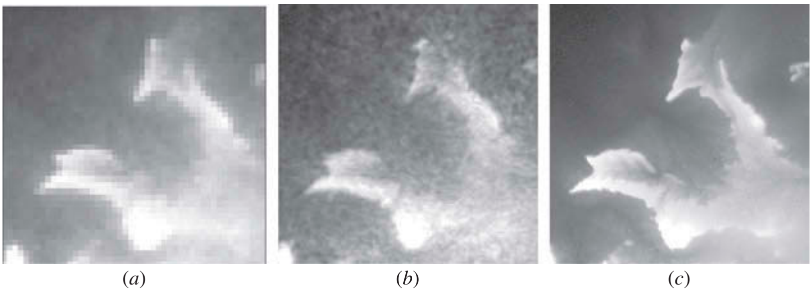
(*a*) (*b*) (*c*)

Figure 8. Comparison of DEM obtained under the aegis of the WARM project to previously available DEMs. The centre scene geographical coordinates are 13° 53′ 30″ N, 2° 22′ 52″ W. (*a*) SRTM: resolution 90 m; (*b*) ASTER: resolution 30 m; (*c*) WARM: resolution 9 m.

Table 1. Comparison between WARM-SAR DEM and four GPS points assumed as ground truth.

Corner id	Position (GPS)	ASTER (m)	SRTM (m)	WARM DEM (m)
1	13° 55′ 03.6″ N, 2° 29′ 40.1″ W, 309 m	307 (–2)	312 (3)	312 (3)
2	13° 53′ 38.8″ N, 2° 29′ 49.6″ W, 312 m	306 (–6)	316 (4)	314 (2)
3	13° 50′ 04.9″ N, 2° 24′ 38.8″ W, 358 m	354 (–4)	359 (1)	356 (–2)
4	13° 41′ 45.8″ N, 2° 11′ 57.5″ W, 333 m	327 (–6)	335 (2)	332 (–1)

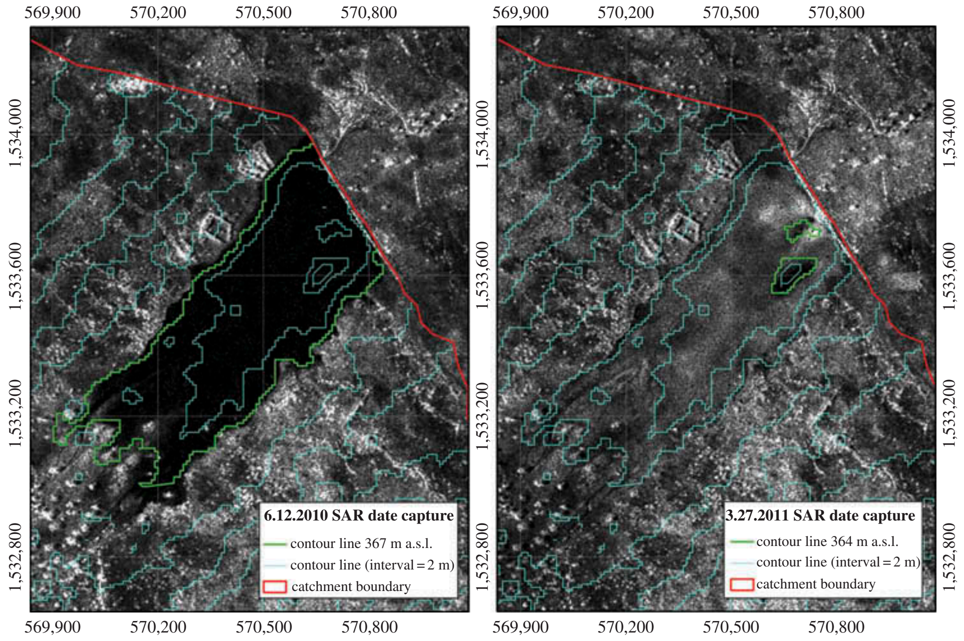

Figure 9. Comparison between DEM-derived contour lines and reservoir borders at Laaba.

Laaba and Derhogo reservoirs, respectively. In the Laaba reservoir, DEM accurately reproduced a hole that was dug to free the inlet of the irrigation canal buried by deposited sediments (see Figure 9).

It is worth noting that the method for DEM validation given here may be exported to other similar contexts, provided that climatic conditions and reservoir size determine an almost complete drying up of the reservoirs at least once per year. In regard to northern Burkina Faso, the procedure can be employed for small reservoirs (depth <2.5 m) but not to those below a minimum size, as dictated by DEM resolution. In the analysis presented here, the smallest reservoir considered has a capacity of about 15,000 m^3.

4.2. DEM-based monitoring of reservoir sedimentation and soil erosion

DEM is the basis for the planning of development policies, the protection (and management) of natural resources, and the design of engineering works. In this article, a sample application is presented in which the estimations of reservoir sedimentation and average water erosion rate are based on DEM analysis. Soil erosion due to water, and consequent sedimentation of reservoirs, are major problems in West Africa (Lal 1993; Pimentel et al.

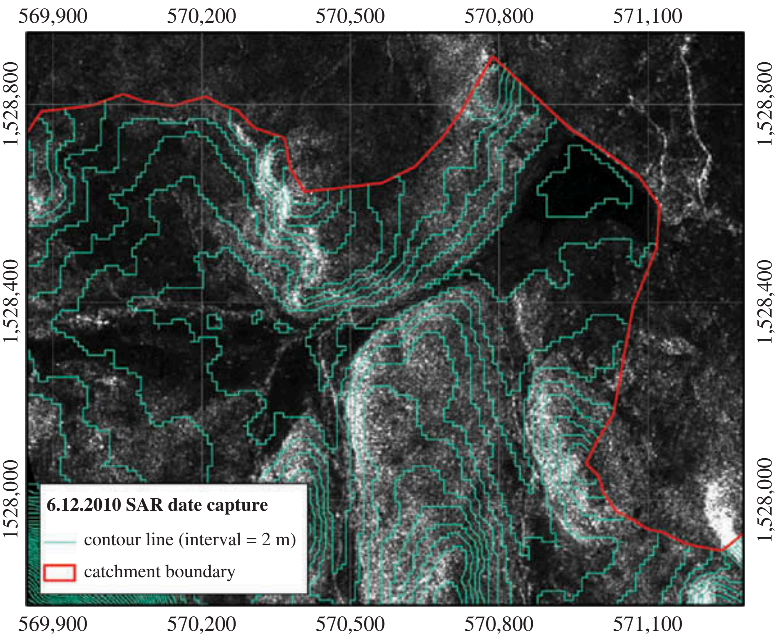

Figure 10. Comparison between DEM-derived contour lines and reservoir borders at Derhogo.

1995; Warren, Batterbury, and Osbahr 2001). Soil erosion leads to a decline in soil productivity and is one of the causes of low levels of crop yield in the area. The life span of reservoirs and the amount of water available for agriculture are severely affected by reservoir sedimentation (Grimaldi et al. 2013).

Data on the original capacity (V_0) and year of construction (t_0) of the reservoirs were derived from the database 'Base de données sur les ressources en eau' (DGH 1996), written in 1996 by the Direction Générale de l'Hydraulique (DGH) of Burkina Faso. In this database, we identified eight reservoirs located within the study area (Table 2).

The residual reservoir capacity in the year 2011 (V) was obtained from DEM. All DEM operations described here were performed in a geographic information system (GIS) environment. An open-source GIS dedicated to hydrological and geomorphological analyses was used – the Java Geographic Resources Analysis Support System (JGrass). A

Table 2. Reservoir database.

Reservoir	Year of construction	Original capacity (1000 m^3)	Capacity in 2011 (1000 m^3)	Reservoirs sedimentation (m^3/year)	Drained catchment (km^2)	Average catchment erosion (10^3 kg/(ha*year))
Pogoro	1987	330	0	13,750	55,9	3,7
Saya	1981	20	0,02	666	0,3	31,6
Gouinre	1967	1988	–	–	141,5	–
Gourga	1988	24	0,06	1041	43,0	0,4
Ouahigouya	1977	2700	–	–	–	–
Dinguela	1985	22	5,9	732	5,5	2,0
Derhogo	1987	14	3,8	425	4,2	1,5
Laaba	1989	602	572	1364	15,5	1,3

simple routine for evaluating V for any of the eight reservoirs was compiled by implementing the following formula:

$$V = \sum_{i=1}^{n} (z_w - Z_i)\delta^2, \tag{2}$$

where z_w is the maximum water level in the reservoir, Z_i is the elevation of the pixel i, δ is DEM resolution, and n is the total number of pixels of the reservoir.

The two largest reservoirs could not be monitored using the technique developed because these also hold a large amount of water in the dry season. As it is not possible to derive DEM for areas covered by water, we could not estimate the reservoir capacity for these basins.

The average annual loss in reservoir capacity (S), due to sedimentation of solid material transported by the tributary river, was estimated using the following equation:

$$S = \frac{V - V_0}{t - t_0}, \tag{3}$$

where V is the residual reservoir capacity evaluated in the year t, V_0 is the original capacity, and t_0 is the year of dam construction. The resulting S is expressed in m^3/year.

Because of the high rate of soil erosion in the area (Warren, Batterbury, and Osbahr 2001), over about 25 years most of the reservoirs lost 50–100% of their original capacity.

When catchments drained by dams are included in the SAR images, it is possible to extract the catchment area by elaborating DEM. The boundaries of the drained catchments were derived using JGrass tools. Neglecting the sediment volume that may overflow the dam, and the possible loss of sediment due to reservoir dredging, it is possible to provide a rough estimation of average soil erosion, E:

$$E = \frac{S}{A}, \tag{4}$$

where A is the area of the catchment drained by the dam.

The values reported in Table 2 were obtained assuming a sediment apparent density of 1500 kg/m^3 (Lamachere 1998), and are within the same range estimated for the area (Lamachere 1998; Warren, Batterbury, and Osbahr 2001). The catchment drained by the Saya dam shows an average soil loss one order of magnitude greater than for the others. This peculiarity determined a change of use for the reservoir and it is thus no longer used for collecting water, but is exploited for the extraction of silt for brickmaking.

The technique described here may be employed for monitoring reservoir sedimentation, and consequently soil erosion at the catchment scale, on an annual basis. To accomplish this, a couple of interferometric SAR images should be regularly acquired each year at the end of the dry season (i.e. in April), in order to obtain DEM.

5. Monitoring of water intake in small reservoirs

In the Sahel, as well as in other parts of the world where climatic conditions lead to severe seasonal water shortages, water reservoirs are essential for livestock, irrigation, groundwater recharging, human consumption, and other purposes. In Burkina Faso, there are 1450 registered reservoirs (Cecchi et al. 2009), half of which were built between 1974 and

1987 during a dramatic drought that affected all of West Africa. Almost 900 of these reservoirs are small, with a capacity of less than 10^6 m^3, but they constitute an essential local water resource. In many areas, the creation of small reservoirs has resulted in increased household income through productive agricultural activities upstream and downstream of the reservoir (Liebe, van de Giesen, and Andreini 2005). Despite that, there is a pernicious lack of information about the number, size, location, and functioning of these reservoirs, often preventing efficient water management and reservoir maintenance.

Moreover, the information on water volume collected by dams may be used as a surrogate of run-off gauge measurements (Liebe et al., "Determining Watershed Response in Data Poor Environments," 2009). Given the chronic lack of hydrological data, especially in developing countries, acquiring this information could be crucial for developing hydrological models.

Analysis of the hydrology of an area needs sufficient historical information, and this is of such importance that the International Association for Hydrological Sciences (IAHS) has promoted the initiative 'Prediction in Ungauged Basins' (PUB), a scientific mission aimed at reducing uncertainty in hydrological forecasting and promoting new reference models for the management of land and water (Sivapalan 2003).

Monitoring of small reservoirs may be derived by optical imagery (Frazier and Page 2000; Liebe, van de Giesen, and Andreini 2005), but only in the absence of cloud cover, and therefore it is not possible to observe the reservoirs in the rainy season when they are completely full. Another drawback of optical images is that they may provide only the water surface area, and thus expensive bathymetric surveys are needed to derive the corresponding water volume.

In the approach described here, the bathymetry of the reservoirs is derived from DEM as explained above, and water surface area is estimated at different time points from SAR images. The extraction of water surface from SAR data is possible because water acts as a mirror, reflecting most of the incident field in the specular direction. Therefore, the SAR sensor measures a weak backscattered signal that corresponds to a dark area in the image. The extraction procedure performances are limited by the presence of speckle (Ulaby, Moore, and Fung 1986). In this article, we employ multi-time de Grandi filtering for reducing speckle and preserving the original spatial resolution (de Grandi et al. 1997). An example of the effects of the filtering process is shown in Figure 11, where we compare the SAR image of the Laaba dam before and after the filtering procedure.

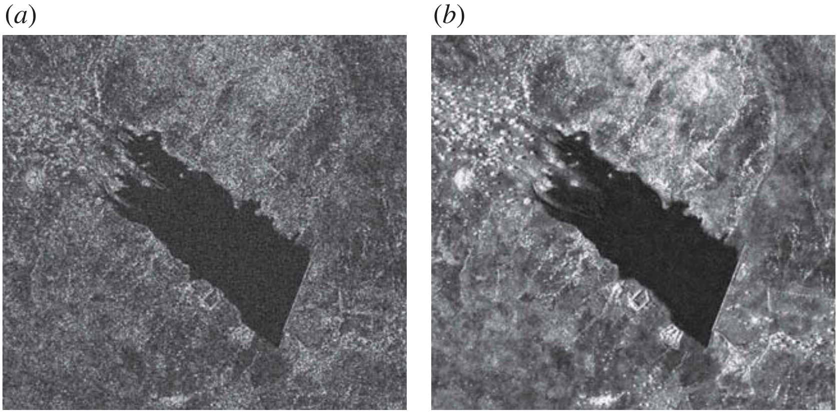

Figure 11. (*a*) Strip-map single-look and (*b*) de Grandi-filtered SAR images of the Laaba dam, acquired 12 June 2010.

In Figure 11(*b*), one can observe that the significant reduction in speckle did not compromise the spatial border, allowing a more reliable extraction of water surface boundaries. In addition, the contrast between open water and the surrounding environment is increased. In Figure 12, comparison between pre- and post-filtering histograms of the SAR image shows that the procedure employed allows separation of open water and the surrounding soil, leading to a reliable automatic segmentation procedure.

The water surfaces extracted from SAR images were overlapped to DEM in a GIS environment, and the corresponding water volume (W_t) at time t was computed by the following equation:

$$W_t = \sum_{i=1}^{m_t} (Z_t - Z_i)\delta^2, \tag{5}$$

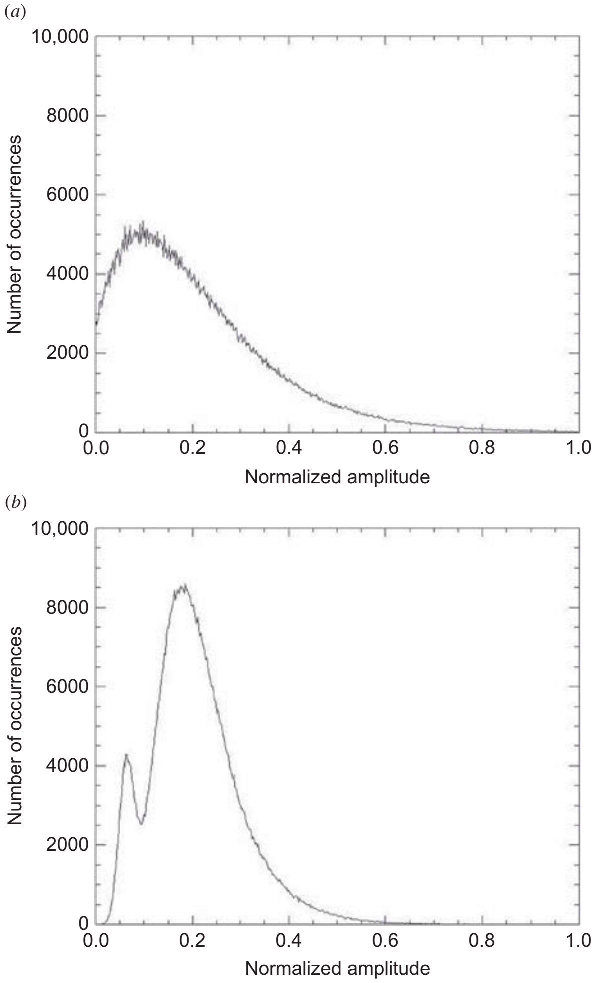

Figure 12. (*a*) Histogram relative to single-look and (*b*) filtered SAR images of the Laaba dam, acquired 12 June 2010.

where m_t is the number of pixels covered by water at time t, and Z_t is the elevation of the water surface at time t. Z_t is set to the elevation of the contour line that fits the boundary of the water surface at time t. Z_i is the elevation of the pixel derived from DEM. The annual depth of sediment deposited is assumed negligible, and therefore Z_i is presumed static over the year.

Figure 13 provides an example of the application of the proposed technique to the Laaba reservoir. For comparison, temperature and daily rainfall measured at Ouahigouya station are reported. The Ouahigouya station is located 329 m a.s.l. and is about 35 km from Laaba reservoir (365 m a.s.l.). As will be seen from the graph, a few rainy days at the beginning of the rainy season are enough to fill up the small reservoir. During the rainy season, emergent vegetation may grow in the tail part of the reservoir and this is probably the reason why we observed an apparent decrease in water surface. In fact, in SAR images, the presence of emerging vegetation at the boundaries of water basins can determine the occurrence of volume and multiple scattering phenomena, which can limit the possibility of accurate extraction of the reservoir extent. This phenomenon is described in the literature (Annor et al. 2009; Horritt et al. 2003; Liebe et al., "Suitability and Limitations of ENVISAT," 2009; Wang et al. 1995), and different techniques have been developed to correct it (Mason et al. 2012). However, these techniques are based on *a priori* knowledge about the vegetation (type, average height, etc.), which is currently not available in sufficient detail for the area of interest (Annor et al. 2009; Liebe et al., "Suitability and Limitations of ENVISAT," 2009). Further studies will be necessary in order to correct these kinds of effect and improve reservoir water extent evaluation for the rainy season. These errors are not relevant to the estimation of water surface areas for the beginning of the rainy season, as vegetation is almost absent at that time.

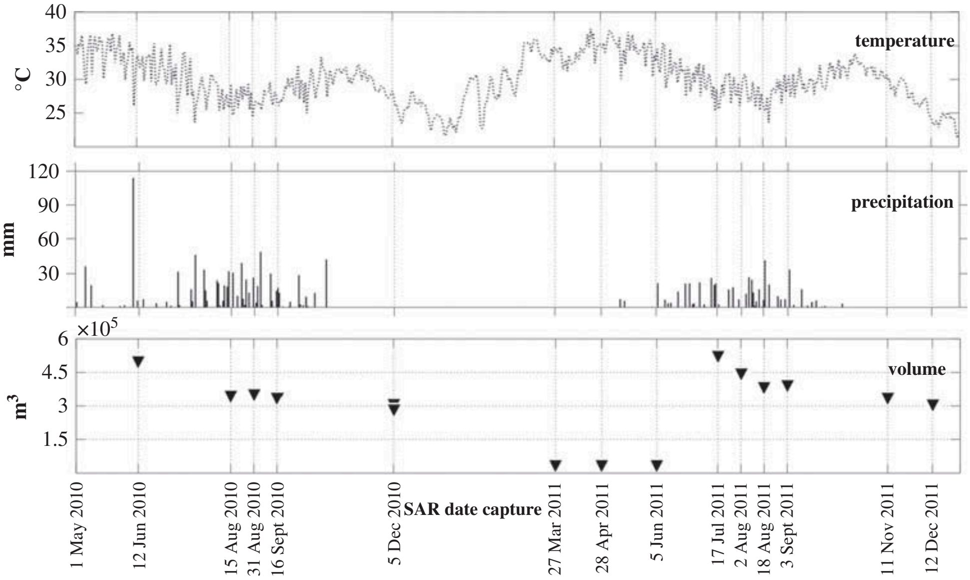

Figure 13. Time series of temperature (°C) and daily rainfall (mm) at Ouahigouya meteo station and water volume (m^3) at Laaba reservoir.

In conclusion, water surface area may be estimated for reservoirs of any size, but the possibility of extracting bathymetry, and therefore water volume, is only possible for basins that are completely dry at least once per year.

6. Conclusion

In this article, an innovative approach is presented for the effective use of high-resolution SAR data for water-related applications in low-income, semi-arid regions. In particular, from COSMO-SkyMed SAR images we retrieved appropriate information to support decisions on water resource management. The approach was implemented in a pilot project in the Yatenga district of northern Burkina Faso, a low-income country in the West African Sahel. The project was based on the integration of complementary skills in the fields of remote sensing and hydrology, and adapted to the needs of local stakeholders and to the social, economic, and physical details of the study area.

The SAR images were acquired under the two extreme climatic conditions (rainy and dry) that characterize the area. DEM of the study area was obtained via standard interferometry processing of the images taken in the dry season. Due to the stable climatic conditions and the almost complete absence of vegetation cover in the scene of interest, the dry season images have high interferometric coherence (67% of the area investigated has a coherence map >0.5). Dedicated GPS acquisitions demonstrated that DEM accuracy is comparable to GPS precision. An innovative method of verification of DEM quality is also presented, with the combined use of phase and amplitude data. In fact, the contour lines obtained by DEM were compared with reservoir boundaries in order to estimate DEM precision. The great advantage of the proposed method is that it allows the possibility of verifying a SAR product by means of another SAR product, without the need for expensive field campaigns. Due to the high resolution of COSMO-SkyMed, we obtained an increase in resolution of one order of magnitude with respect to the previously available SRTM DEM.

To the best of the authors' knowledge, this is the highest-resolution DEM available for the area of interest. Such an outcome is particularly important for low-income countries, where the absence of reliable and high-resolution topographic data is a major problem in engineering applications. The DEM obtained is not only important *per se* but also for the various applications that it can support. In areas experiencing a sufficiently long dry and hot season, such as that investigated here, smaller artificial water intakes dry up completely every year. Since evaporation rates in the study area are over 2.0 m/year, water intakes of depth less than 2.5 m are completely empty in the dry season. For these basins, because DEM produced from SAR images acquired in the dry season yields reservoir shape, its maximum capacity may be estimated. Reservoir capacity decreases rapidly in the study area because of reservoir sedimentation, and therefore for the effective management of water resources and forecasting of water-related crises, it is crucial to survey actual reservoir capacity in sensitive areas.

Estimation of the sedimentation rate of reservoirs was also performed. This parameter, in combination with DEM-based identification of the drained catchments, allowed the estimation of average soil erosion at the basin scale. The tool developed constitutes an innovative and low-cost SAR-based technique for the estimation of soil erosion in semi-arid areas.

The integration of DEM obtained with SAR amplitude images allowed the development of innovative algorithms for the monitoring of water intake in reservoirs, and its evolution over time. With this technique, a synoptic view of the total water volume available in the reservoirs of an entire region can be provided. This information, often lacking in low-income countries, is crucial for both the appropriate management of water use and the prevention and mitigation of water crises.

Our results show that remote sensing in general, and SAR images in particular, hold enormous potentialities, mainly in the poorest areas of the Earth, and that their use can provide significant advantages to all stakeholders.

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