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► **To cite this version:**

C. Pascal, Sylvain Ferrant, A. Selles, J.-C. Marechal, Simon Gascoin, et al.. High-Resolution Mapping of Rainwater Harvesting System Capacity from Satellite Derived Products in South India. 2021 IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2021), Jul 2021, Bruxelles, Belgium. pp.7011-7014, 10.1109/IGARSS47720.2021.9553131 . hal-03385180v1

HAL Id: hal-03385180

<https://hal.science/hal-03385180v1>

Submitted on 4 Jul 2023 (v1), last revised 5 Jul 2023 (v2)

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HIGH-RESOLUTION MAPPING OF RAINWATER HARVESTING SYSTEM CAPACITY FROM SATELLITE DERIVED PRODUCTS IN SOUTH INDIA

C. Pascal¹, S. Ferrant¹, A. Selles², J.-C. Maréchal², S. Gascoin¹, O. Merlin¹

¹Centre d'Etudes Spatiales de la Biosphère/OMP, Université de Toulouse, CNES, CNRS, INRAE, IRD, UPS, UMR5126, 14 Avenue Edouard Belin, 31400 Toulouse, France

²Bureau de Recherches Géologiques et Minières (BRGM), Université de Montpellier, 1039 rue de Pinville, 34000 Montpellier, France

ABSTRACT

Indian Rainwater Harvesting System (RHS) is an essential source of irrigation water in upstream agricultural areas. It is composed of hundreds of thousands of Small Reservoirs (SR) often disconnected from any perennial rivers. This study aims at quantifying the RHS Maximum Water Storage Capacity (MWSC) in the Telangana State, South India. The true bathymetries of 545 dry SR, located from Sentinel-2 (SENT-MWAE) and Landsat Maximal Water Area Extent (GSW-MWAE), are extracted from four Very High Resolution (VHR) Pleiades Digital Elevation Model (DEM). The average water depth at full capacity ranges from 22 cm to 4.6 m (average 1.3 m, std 0.6). The MWSC estimated within the Pleiades ground-coverage, for 62% of the total SR, accounts for 37.2 mm on average. The estimated capacity highly depends on the MWAE data source, varying from 5 to 30%. The Telangana RHS MWSC based on the RHS GSW-MWAE (1.6% of the Telangana area) is estimated at 29.7 mm +/- 9 mm. This capacity seems small compared to the large dam capacity (113mm for 126 registered dams in Telangana), but matters in upstream areas, far from irrigated command areas, to complement local groundwater pumping (from 62 to 295 mm). These preliminary results show the high interest of VHR DEM to evaluate uncertainties derived from MWAE products and medium to high resolution DEM to map water storage in RHS.

Index Terms— Very high-resolution DEM, Pleiades, Sentinel-2, semi-arid agro-hydrology, reservoir bathymetry

1. INTRODUCTION

Many semi-arid countries are facing an increasing need for water, both irrigation water to sustain food production and domestic water for urban areas [1]. To cope with such increasing pressure, big dams have been built. Those infrastructures are inventoried in national and global databases such as the GRanD database [2], complemented by the the more recent inventory GOODD [3] which also includes small reservoirs (SR). SR are much less inventoried and monitored but are

known to have a strong impact on hydrology worldwide [4]. Increasing the number of SR, especially in upstream regions, is a common adaptation to water stressors. In South India, SR have been promoted to catch monsoon runoff to sustain irrigation and to enhance aquifer recharge [5], which is questioned in terms of efficiency given that the loss associated with direct evaporation could be important [6]. This Indian traditional Rainwater Harvesting System (RHS) is composed of hundreds of thousands of SR, spread along a non perennial drainage network. In the Telangana State in Southern India, those SR predominantly consist in flat depressions of few ha to less than one, dammed with an earthen dyke of 2 to 10 m high and 10 to 20 m thick. There is a lack of data to estimate and monitor their water storage, to study their regional hydrological impact. Yet, this hydrological reservoir has been often neglected or roughly approximated in previous hydrological modelling studies [6][7], and never regionalized. Remote sensing data were used to retrieve the volume-area functions using power models for SR of the RHS in South India, Tamil Nadu State, using 12-m Digital Elevation Model (DEM) derived from TanDEM-X data and dynamic surface water mapping [8]. However, the spatial resolution limits the dyke geometry retrieval accuracy, especially for dyke height less than 3 m. In this context, this study aims at building a similar methodology based on true bathymetries computed from Pleiades derived 2-m DEM and Surface water occurrence from Landsat and Sentinel-2 missions, to estimate the Maximal Water Storage Capacity (MWSC) of the Telangana RHS, crucial for local irrigation and livestock.

2. MATERIAL AND METHODS

2.1. Study area

The Telangana State (114,789 km²) is a highly irrigated and populated region in South India, dominated by a semi-arid climate. The monsoon precipitations occur between July and October, ranging from 540 to 1300 mm with an average of 879 mm. The RHS is filled during this season and empties more or less completely during the following dry season. Ac-

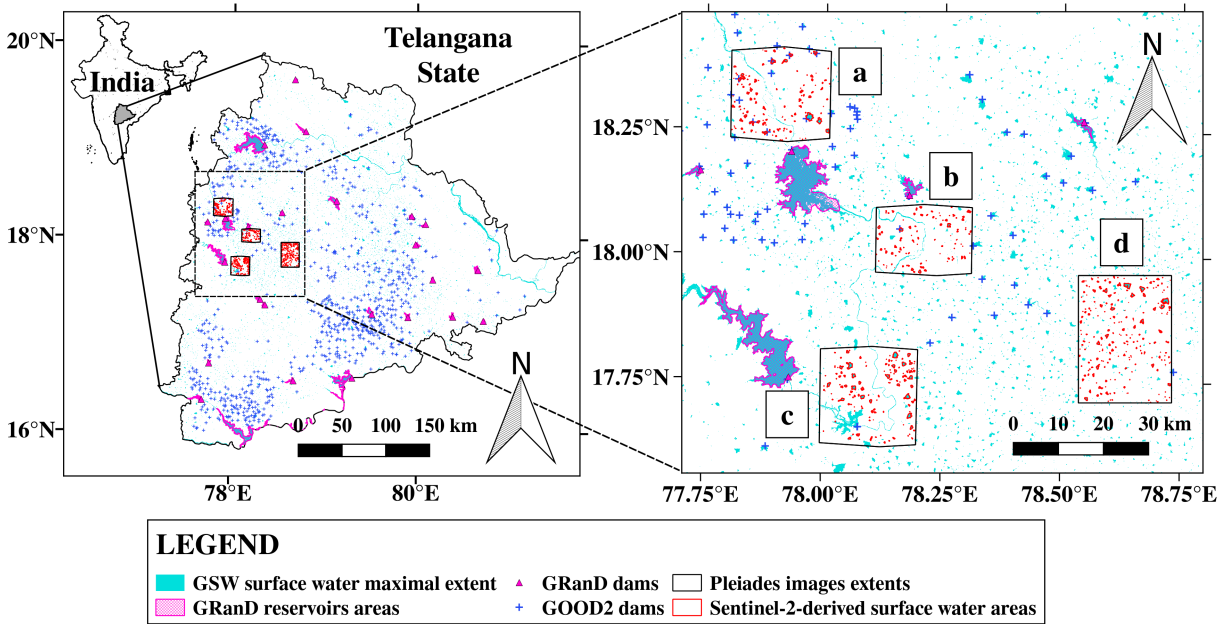


Fig. 1. Location of the study area.

According to the Global Surface Water dataset (GSW, [9]), the SR of the RHS Maximal Water Area Extent (MWAE) and the total MWAE account respectively for 1.6% and 3.4% of the Telangana state area as observed by the Landsat program during the last 30 years.

2.2. Existing datasets of surface water reservoirs

Figure 1 shows an inventory of existing global surface water reservoirs datasets. The GRanD inventory references the 25 biggest reservoirs across the Telangana State [2]. A more recent global dam inventory, GOODD, identifies the dam locations of 887 water reservoirs in the Telangana State [3] of which some are part of the biggest SR of the RHS (MWAE >20ha). Only 126 large dams potential storage capacity located in Telangana are reported in the Indian National Register of Large Dams (NRLD), the cumulative capacity representing 113 mm (<http://cwc.gov.in/sites/default/files/nrld06042019.pdf>). The GSW dataset is to date the most complete RHS geographical database (Figure 1).

2.3. Very High Resolution DEM

The Pleiades stereoscopic images used were acquired during the dry period, with empty SR, through the DINAMIS program (<https://dinamis.teledetection.fr>). They are composed of 4 acquisitions (images a, b, c and d in Figure 1), and cover a total area of 1813.4 km². In those 4 areas, a 2-m resolution DEM was built using the NASA Ames Stereo Pipeline software [10]. Some texture-less areas covered by clouds, water (river bed for example) or bright soils for which signal were

saturated have no elevation estimates, explaining no-data values.

2.4. Sentinel-2 derived RHS MWAE

Time series of surface water maps were computed from 10-m resolution Level 2A Sentinel-2 multispectral data downloaded from <https://www.theia-land.fr/>. The surface water maps were obtained using a pixel-wise random forest algorithm. All maps of the time series were superimposed and merged to obtain a polygon shapefile of the MWAE as observed by Sentinel-2 over a period of 2 years close to the Pleiades acquisition date. The MWAE of the RHS was selected by removing areas corresponding to river bed and dammed river reservoirs. A final selection removed the SR containing more than 5% of no-data in the DEM (Figure 1 in red within the Pleiades ground coverage). A sub sample of 545 SR within the four Pleiades ground coverage is thus selected (around 1 SR per 3 km²), among which only 12 were already identified in the GOODD inventory (blues crosses in Figure 1).

2.5. SR MWSC extraction from DEM and regionalization

Figure 2 shows in red the MWAE as observed by Sentinel-2 at 10 m resolution, that roughly follows the DEM derived contour lines delineated at 2 m resolution (in green). The accuracy of the DEM acquired for dry SR enables to get a true bathymetry. The MWSC for each Pleiades image was obtained by summing the MWSC of each selected SR located

with SENT-MWAE and GSW-MWAE. The RHS MWAE is extracted from the GSW at the Telangana State scale by removing large dammed reservoirs and river bed areas using GRaND dataset [2] and visual inspection.

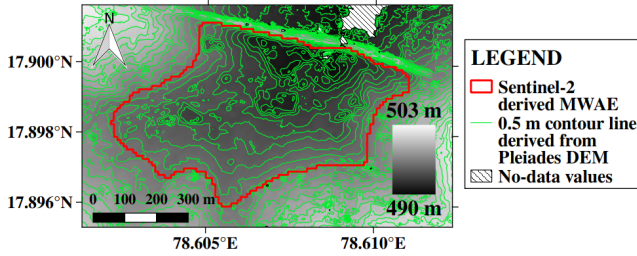


Fig. 2. A Detail of the Pleiades DEM over a SR.

3. RESULTS AND DISCUSSION

3.1. Adequation between Sentinel-2 MWAE and DEM

The 2-m DEM horizontal resolution is small enough to map typical geometries of earthen dykes (<20 m high and large) that dam each SR (as shown in Figure 2). The Sentinel-2 derived MWAE shapefiles allow identifying each SR of the RHS at a 10-m resolution. Among the 670 SR that are part of the RHS identified with this methodology, 545 are selected to compute their volumes. Visual inspection confirms that the MWAE of each SR generally follow the contour lines of the DEM (Figure 2) despite the comparative lower resolution of Sentinel-2 (10 m vs 2 m) and the well known imperfection of water detection methods from multi-spectral data on the shores or caused by vegetation, especially in seasonal shallow temporary lakes [11].

Table 1 presents the proportions of total and selected – by removing DEM no-data – MWAE and their corresponding MWSC derived from GSW database and Sentinel-2 time series for the four Pleiades ground coverage. Half or more of the SR areas were sampled ranging from 1.4 to 2.9% of the total Pleiades ground coverage.

Except for the scene d, acquired in 2019, the GSW-MWAE globally underestimates the SENT-MWAE due to its lower resolution. The SENT-MWAE computed for scene d using 2018-2019 Sentinel-2 time series did not capture the MWAE that occurred in Sept 2016 [7]. The GSW-MWAE aggregated for tiles of 10×10 km² over the Telangana State covers an average of 1.6%, with a standard deviation of 1.15%, much lower than the areas covered by Pleiades, as we tasked Pleiades acquisitions over regions with high SR density. GSW-MWAE underestimates by 14% the SENT-MWAE estimates, leading to MWSC estimates differences ranging from 5 to 36% (Table 1). MWSC derived from SENT accounts for 69% of the MWAE of the RHS covered by the DEM valid data, and reaches 37.2 mm (67.5 MCUM) within

the Pleiades ground-coverage.

3.2. Estimation of Telangana State’s RHS MWSC

Each set of selected SR within the RHS located in the Pleiades ground-coverage (Figure 3, four black crosses) is split in four equal geographical parts to get the cumulative MWAE and corresponding MWSC at a 10-km resolution (plotted in Figure 3, grey points) to compute a predictive linear model of MWSC as a function of MWAE. The linear regression obtained from the 16 points ($R^2=0.96$, $RMSE=8.8$ mm), is a good predictor for small MWAE, with a higher dispersion for the largest values (Figure 3).

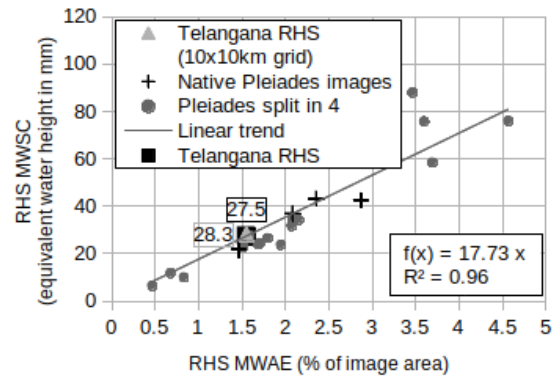


Fig. 3. Empirical relationship between the RHS MWSC (equivalent water height in mm) and the RHS MWAE (percentage of total area).

The linear model is used to estimate Telangana’s RHS MWSC based on (i) the GSW-MWAE averaged for Telangana (black square in Figure 3: 26.9 mm), (ii) the cumulative MWSC estimates from each GSW-MWAE computed within a 10 km grid over the State (grey triangle in Figure 3: 27.5 mm). However, GSW-MWAE is underestimated by 14% compared to SENT-MWAE, leading to underestimate the GSW-MWSC by 10% (table 1). The Telangana MWSC is thus estimated to be 27 mm+2.7 mm (+/- 9 mm, the linear regression model RMSE). This storage capacity is much lower than the potential storage capacity of the 126 referenced dam reservoirs found in the NRLD, estimated at around 113 mm. Yet it matters if compared with the irrigation water demand estimated in previous studies from satellite derived rice mapping and field survey in the Gajwel town watershed, located in the ground-coverage d, that have varied since 2016 from 62 to 295 mm during dry season [7]. This MWSC can be compared to previous estimates of SR volumes derived from TanDEM-X 12m DEM: one over a 5647 km² river basin in Tamil Nadu State in South India, that estimated the MWSC found in 2015 using Sentinel-1 MWAE at 1.5mm on a subset of 274 on the 1503 identified SR [8], and one in the Cuvelai basin (18,370 km²), located between Angola and Namibia, on 190,000 natural SR,

Table 1. Maximum Water Area Extent (MWAE) derived from the Global Surface Water database (GSW) or Sentinel time series (SENT) expressed in km² and percentage. Corresponding Maximum Water Storage Capacity (MWSC) estimates are given in million cubic meters (MCUM) and in mm for each Pleiades ground coverage.

Pleiades names as per fig 1 and acquisition dates	Area covered (km ²)	Total RHS MWAE (km ² / %)		Selected RHS MWAE (km ² / %)		MWSC estimated on the selected MWAE (MCUM / mm)	
		GSW	SENT	GSW	SENT	GSW	SENT
a - 01/06/2016	443.6	12.0 / 2.7	13.1 / 2.9	9.6 / 2.1	10.4 / 2.4	18.3 / 41.2	19.2 / 43.3
b - 14/06/2016	322.3	5.6 / 1.7	7.1 / 2.2	3.6 / 1.1	4.7 / 1.4	5.6 / 17.3	7.0 / 21.8
c - 14/06/2016	463.5	14.2 / 3.1	17.1 / 3.7	9.9 / 2.1	13.3 / 2.9	14.4 / 31.1	19.7 / 42.5
d - 16/06/2019	583.9	19.2 / 3.3	22.5 / 3.8	12.3 / 2.1	12.2 / 2.1	22.7 / 38.9	21.6 / 36.9

estimated at 103mm [12]. The first is clearly underestimating the maximum capacity as it is a single date estimate of MWAE from radar data and for a sub-sample of existing SR. The second, focusing on natural SR in arid area, is maximizing our local estimates ranging from 6 to 88mm (figure 3).

4. CONCLUSIONS AND PERSPECTIVES

The VHR of Pleiades DEM is highly appropriate to detect narrow dykes and flat geometries of the shallow SR of the Indian RHS (<2m), often empty at the end of the cloud-free dry season. This regional hydrological component is limited from the regional perspective (29.7 mm, +/- 9 mm), but becomes non negligible in the local farmer activities. There is great potential in combining those VHR stereoscopy-based DEM and Sentinel-1&2 surface water products in semi-arid area to spatially monitor local water stresses. Upcoming VHR DEM products (comparable to ArticDEM) or future dedicated satellite missions (CO3D [13]) will be an opportunity to monitor, at the continental level, both short term fluctuations of RHS water storage and long term evolutions of MWSC impacted by sedimentation or rejuvenation programs (i.e. Kakatiya project in Telangana).

5. ACKNOWLEDGEMENTS

This work has been supported by the Programme National de Télédétection Spatiale (PNTS, <https://programmes.insu.cnrs.fr/pnts/>), grant n° PNTS-2020-18). The Pleiades images acquisition was supported by the CNES through the DINAMIS program. Those images are commercial data that can be obtained via the website (<https://www.intelligence-airbusds.com/geostore/>).

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