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Envisat Radar Altimetry Measurements of Water Level in a Semi-Arid River with Complex Morphology: The Lower Save, Southern Africa

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ABSTRACT

Although there are numerous studies on water level changes in large rivers using satellite radar altimetry, there is no altimetry-based published study with specific focus on rivers of semi-arid areas smaller in width and with braided or wandering reaches. Taltimetry to measure water level fluctuations in a river with such characteristics. The lower Save River, a heavily silted river in Southern Africa with a dominant braided pattern, was chosen for this study. The presence of multiple narrow and shallow channels in many sections of the lower Save and the existence of sandbanks, channel bars and small islets represent additional challenges for the processing of altimetry water level measurements. High sampling rate radar altimeter data from the Envisat 35-day exact repeat mission (June 2002 to October 2010) were used in this study. The obtained altimetric water level time series do exhibit a similar variation pattern and show a reasonably good agreement with the nearest river gauge data available, especially when the hydraulic characteristics are similar along the river stretch between both monitoring points and these are not too far apart, and when the return radar signals are not so contaminated by land features. Some of the results are comparable to those from other studies for large rivers, indicating that Envisat radar altimetry can be used to derive water levels for the lower Save, a semi-arid river with relatively small widths and complex channel morphologies.

Key words: Satellite radar altimetry, Envisat, river water level, braided river, Save River, Southern Africa.

1. INTRODUCTION

The East coast region of Southern Africa is periodically affected by extreme hydrological events, such as intense floods in the central wet lowlands of Mozambique (e.g., [1]) and severe droughts in the mountainous and low-lying dry areas. Such events can have significant impacts on the local natural environment and serious and disastrous consequences for the affected populations and communities [2].

In addition, rivers in lowland areas of semi-arid regions are comparatively little studied [3], and although the continuous monitoring of river water levels and discharges is an essential element for the correct management of water resources in transboundary basins, the international river basins in this region of Africa are poorly gauged.

The available hydrological time series from both currently operational and closed hydrological stations are generally short, discontinuous (with gaps ranging from days to years), have quite variable quality (most often low), and are usually difficult to obtain [4]. This emphasizes the advantage of using satellite observations to complement the relatively scarce in situ data available from such areas.

Satellite radar altimetry, despite its evident and important limitations in terms of temporal frequency and spatial coverage of measurements, has shown in other regions (see, e.g., [5]–[7]) to be a valuable complement to river in situ data or even to replace them when no gauge data are available.

On the other hand, although there are a numerous number of studies on water level changes in large rivers using radar altimetry, including satellite altimetry studies of large braided rivers [8, 9], there is no satellite altimetry-based published study with a specific focus on rivers of semi-arid regions with smaller widths and subjected to extensive siltation and unstable flows, which leads to complex morphologies characterized by braided or wandering channel patterns.

In view of that, the main aim of this research is to assess the ability of Envisat radar altimetry for monitoring water level changes in a semi-arid river with highly complex channel morphology and relatively small widths along its course. Having such characteristics, the lower portion of the Save River, located in the East region of Southern Africa, was chosen for this study.

2. STUDY AREA

The Save River rises at an altitude of around 1,450 m in Zimbabwe's Highveld, about 80 km south of Harare, and flows through Zimbabwe and Mozambique to its mouth near the town of Nova Mambone on the Mozambique Channel in the Indian Ocean.

Preliminary and reduced versions of this study were presented at the 3ème Congrès International GIRE3D – Gestion Intégrée des Ressources en Eau et Défis du Développement Durable, cas des Régions Arides, Dakhla, Morocco, and at the 4th International Conference on Ecohydrology, Soil and Climate Change, Tomar, Portugal.

The Save River is approximately 740 km long and its basin (Figure 1) covers an area of around 116,100 km^2, of which about 85,780 km^2 (73.88%) are in Zimbabwe and 30,320 km^2 (26.12%) in Mozambique. The average annual runoff in the Save River basin is around 6,870 million m^3 [10].

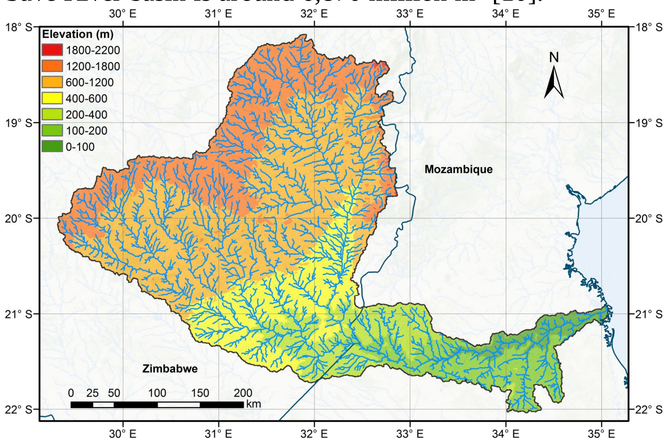

Figure 1: Location map of the Save River basin, showing the basin boundaries, elevation classes and drainage network.

Its major tributary, the Runde River, rises about 60 km east of Bulawayo, in southeastern Zimbabwe, flows through the southeast of Zimbabwe and joins the Save at the country's lowest point, at 197 m above sea level [11], close to the border with Mozambique. The Runde sub-Basin of the Save drains an area of about 41,000 km^2 [12].

The Save River basin is located in a region that is markedly vulnerable to climate change. In the lower part of the basin, the focal area of this study, the climate is predominantly hot semi-arid (BSh type, according to the Köppen climate classification) [13].

Rainfall in the Save basin is unreliable in terms of quantity and duration, and irregular both in space and time, concentrating mainly in the five months of November to March. The mean annual rainfall varies roughly from 400 mm in the south to near 2,000 mm in the mountainous north-east of the basin in Zimbabwe, and between 600 mm in the west to about 1,000 mm in the lowland eastern part of the basin in Mozambique [14]. The high variability and uncertainty of rainfall make this basin subject to wet/dry cycles and recurrent floods and drought events [1, 2].

The flow variability resulting from the high seasonal and inter-annual changes in rainfall is, in itself, a major problem for water management in the Save basin, to which adds the water and environmental degradation resulting from soil erosion, siltation and deforestation, which have been a matter of concern in this transboundary river basin since the 1950s (see, e.g., [15, 16]).

Despite several conservation efforts over the last decades, these problems have been further aggravated as a result of intensive use of water resources for irrigation, mining activities and domestic consumption especially in the upper parts of the river basin, notably from the 1980s, which has contributed to an increase in river siltation and water quality degradation and, coupled with the increasing negative impacts of climate change on water resources, has had a significant effect on the runoff and led to an enormous lowering of the water levels, particularly in the downstream portion of the basin [17], largely situated in Mozambique.

As a result, the Save, which was in the past a relatively large and mighty river, navigable in some sections until the third decade of the twentieth century (see, e.g., [18]), has been gradually transformed into a heavily silted river with a dominant braided channel pattern and wandering reaches, whose flow tends to be reduced to a series of muddy pools and trickles of brown water in its lower portion particularly by the end of the most severe dry seasons [11].

The existence of multiple narrow and shallow channels in many river sections and the presence of mid-channel bars, sandbanks and small islets create additional difficulties for the processing of radar altimetry measurements of water height in the lower Save, which makes it a good choice for this study.

3. DATA AND METHODOLOGY

3.1 Satellite Altimetry Data

In the present study, the reprocessed Envisat radar altimeter (RA-2) GDR data from the first phase of the satellite's mission (Phase A, 35-day repetitive orbit, cycles 6 to 94, June 2002 to October 2010) were used. The RA-2 instrument is a nadir-looking dual-frequency radar altimeter operating simultaneously at 13.575 GHz (Ku band) and 3.2 GHz (S band). The Ku band is employed to obtain very accurate radar altimetry measurements, while the S band is used to estimate the ionospheric propagation delay.

The along-track altimeter data were provided by the Centre for Topographic Studies of the Oceans and Hydrosphere (CTOH), a French observation service dedicated to satellite radar altimetry that distributes the altimeter geophysical data records (GDRs) with up-to-date corrections and additional parameters.

The Envisat RA-2 GDR data contain range values (i.e., the distances from the satellite's centre of mass to the surface of the Earth, as measured by the altimeter) derived from averaged radar echoes at 1/18 sec (18 Hz) interval.

The retracked altimetry measurements, derived from four different retrackers (ICE-1, ICE-2, SEA ICE, and OCEAN), correspond to an along-track ground spacing (resolution) of about 350 m. The spacing between adjacent ground tracks at 21ºS is around 72.5 km (see Figure 2).

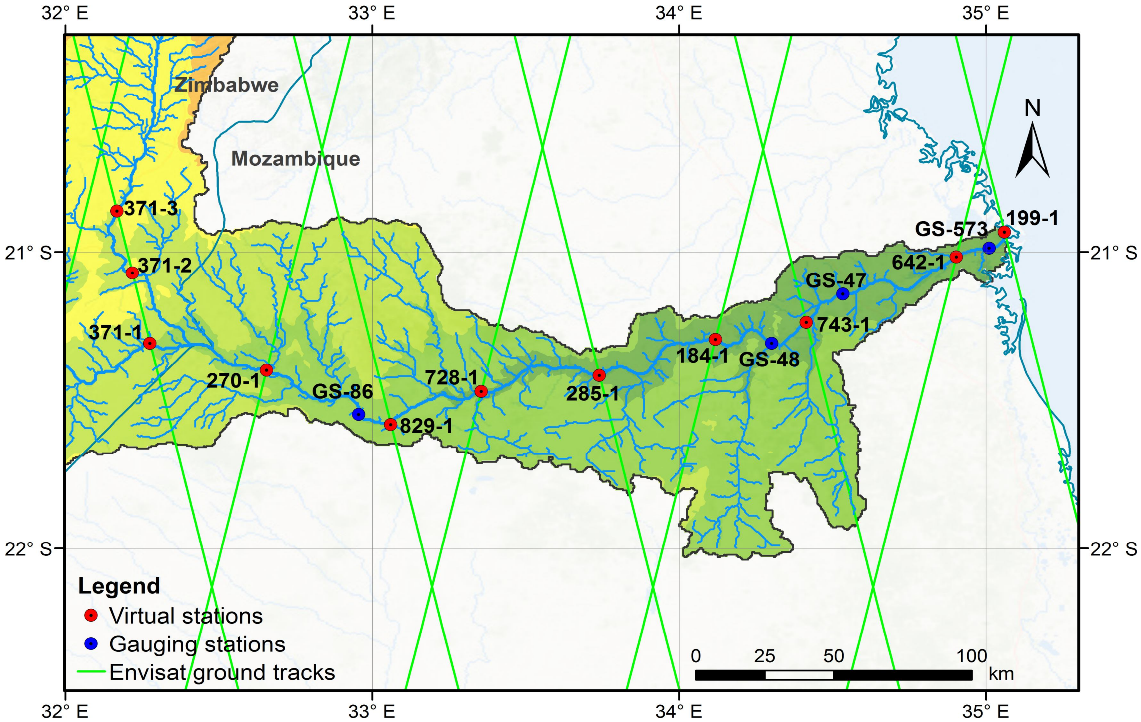

Figure 2: Map of the study area, showing the satellite ground tracks, the virtual stations of the Envisat altimeter over the lower Save River basin, and the location of the hydrometric stations considered in this study.

The Envisat ICE-1 retracker [19], based on the Offset Centre of Gravity (OCOG) empirical retracking algorithm developed by Wingham et al. [20], and the Earth Geopotential Model 2008 (EGM2008) [21] were used in this study.

The Envisat radar altimetry-derived water level time series were produced at "virtual stations" defined at the intersections of the Envisat ground tracks (i.e., the orthogonal projections of the Envisat satellite orbit onto the surface of the Earth) with the Save River and its main tributary, the Runde River.

Figure 2 shows the location of the virtual stations defined at the intersections of the 35-day exact repeat orbit ground tracks with the Save and the Runde rivers. Also shown in Figure 2 are the in situ gauge stations whose data were used for the purpose of comparison with the altimeter-derived time series of water level.

3.2 Hydrometric Data

The hydrological and hydrometric data available for this region of Southern Africa are very limited temporally and spatially.

The hydrometric time series data of water level of the lower Save River used in this study for comparison and validation purposes, provided by the Mozambique's National Water Directorate (DNA), are short and discontinuous, as it is possible to observe in Figure 3.

In Figure 3 (d), it is also possible to observe the tidal influence on the Save River level at Nova Mambone (GS-573) gauging station, situated near the river mouth.

In addition, from the Figure 2, it can be observed that none of the gauging stations is located sufficiently close to the virtual stations (i.e., is within the radar beam footprint), which makes it impossible to correctly validate the altimetry-derived water levels.

3.3 Software Tools

The main computational tools that were used for radar altimetry data processing are indicated below.

The processing and visualization of satellite altimetry data was primarily performed with the help of the VALS (Virtual ALtimetry Station) software tool [22], although an available version of the new Multi-mission Altimetry Processing Software (MAPS) [23], which appeared to need some further improvements, was also initially considered for the radar altimeter data processing.

A MATLAB/Octave routine written by the author was also used to semi-automate and optimize the processing of data from the intermediate files produced by the VALS software.

Finally, Google Earth Pro was used to help in the selection of the altimetry data of each virtual station for use with VALS.

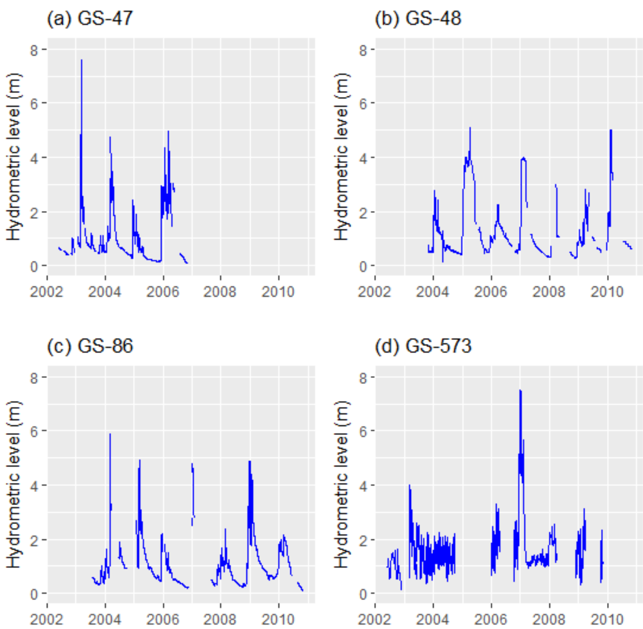

Figure 3: Water level in the lower Save River measured at (a) Jungulo (GS-47), (b) Jofane (GS-48), (c) Massangena (GS-86) and (d) Nova Mambone (GS-573) gauging stations.

3.4 Methodology

The satellite-derived water level time series, determined at virtual stations defined in the intersections of the Envisat ground tracks with the main river and its primary tributary, were constructed by the method described in [6] (see also, e.g., [24, 25]).

The basic altimetry data processing methodology consists of the following steps:

1. Rough selection of the region of interest for data extraction using satellite imagery from Google Earth Pro;
2. Refining of the previous selection in a cross-sectional view using the VALS visualization tool;
3. Computation of the water level height time series (relative to the reference ellipsoid) using all valid satellite radar altimetry measurements selected in the second step;
4. Finally, conversion of the ellipsoidal heights provided by satellite altimetry into altitudes using the EGM2008 geoid model.

The water level h can be estimated as follows (see, e.g., [26]):

$$h = A - H_{alt} - (C_{iono} + C_{dry} + C_{wet}) - (C_{pt} + C_{st}) - N \quad (1)$$

where A is the satellite altitude (i.e., the height above the chosen reference ellipsoid), H_{alt} is the altimeter range (i.e., the distance from the satellite's centre of mass to the Earth's surface), C_{iono} is the ionospheric propagation delay correction, C_{dry} and C_{wet} are, respectively, the corrections for propagation delays introduced by pressure and humidity variations in the atmosphere, C_{pt} and C_{st} are the corrections for crustal vertical motions due to polar and solid earth tides, respectively, and N is the geoid height, a final correction which makes the altitude relative to the geoid datum instead of the reference ellipsoid.

It is important to note that not all the radar altimeter measurements over inland waters are necessarily valid, because they can be affected by several factors, including the extension of the water surface along the satellite ground track, the existence of mid-channel bars (braid bars), islets or sand banks within the river or water body monitored, the complexity of the surrounding terrain relief, and the vegetation cover along the path illuminated by the radar beam [7, 27].

The first two factors pointed out above are particularly relevant for this study, since both the Save and the Runde are braided rivers characterized by a sandy and gravelly substrate and a strongly seasonal flow regime [3] typical of the semi-arid rivers of Southern Africa.

As stated before, the reprocessed Envisat RA-2 GDR data from cycles 6 to 94 (35-day repeat orbit, June 2002 to October 2010), provided by CTOH, were used in this study. Only ICE-1 retracked measurements were employed, since ICE-1 has demonstrated to be the most adequate waveform retracking algorithm for estimating water level heights over rivers and other inland water bodies (see, e.g., [28, 29]).

The Earth Geopotential Model 2008 (EGM2008) [21] was used to convert ellipsoidal heights to orthometric heights (heights above mean sea level, for practical purposes).

When possible, the altimetry-derived water levels were contrasted with in situ data from the Mozambican national hydrometric network for comparison and validation purposes.

The coefficient of determination, R^2, was used as a summary statistic to quantify the goodness of fit between Envisat altimetry-derived and in situ river stage data.

The root mean square error (*RMSE*), an error metric that indicates how far the estimated measures are from the 'truth' values, was also used in the validation of the satellite-based water level estimates. Since the in situ and altimetry datasets have a different datum, anomalies relative to the means rather than actual data values were used in the calculations. The *RMSE* is then given by:

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(x_{i,alt} - x_{i,obs})^2}{n}} \quad (2)$$

where $x_{i,alt}$ is the Envisat water level anomaly, and $x_{i,obs}$ is the in situ measured water level anomaly.

4. RESULTS AND SHORT DISCUSSION

The satellite-derived time series obtained in this study show a reasonable agreement with the nearest gauge observations available, varying from fair to very good according to the degree of non-homogeneity of the hydraulic characteristics along the river stretch between the monitoring points under comparison and the distance between these locations, which in this case is always too large to allow a correct validation of the satellite radar altimetric measurements of water height.

An example of a (relatively long) continuous time series of satellite-derived river water level (with reference to the EGM2008 geoid model) in the lower Save basin, obtained at the VS-0642-1 virtual station (Figure 4), is shown in Figure 5, together with the corresponding water level time series (relative to a different datum) measured at the Jungulo station.

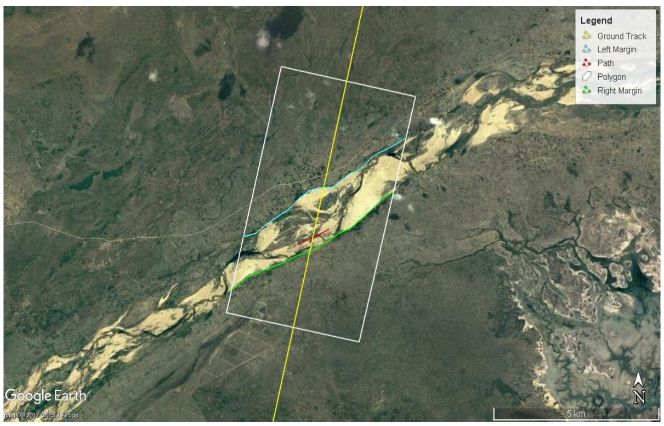

Figure 4: Situation of the river crossing by the Envisat track 0642 (yellow line) and delimitation of the VS-0642-1 virtual station (map data ©Google).

The VS-0642-01 virtual station is situated about 41.5 km downstream from the Jungulo (GS-47) gauging station, in a braided portion of the lower Save River, shown in Figure 4, with hydraulic characteristics somewhat different from those observed upstream in this river. Despite that, the Envisat satellite-derived time series exhibits a water level variation pattern similar to that of the corresponding field observations, as it is possible to observe in Figure 5.

The altimetry-derived water levels (relative to the EGM2008 geoid model) show a good correlation with the corresponding in situ gauge measurements (with respect to a different datum), as can be seen in the scatter plot in Figure 6, corresponding to the continuous part of the altimetric time series. The least squares fit line to these data and the 95% confidence interval for the slope of the regression line are also shown in Figure 6, along with the linear regression equation and the value of the coefficient of determination for these data, $R^2 = 0.89$. However, it is important to highlight that the coefficient of determination rises to 0.92 if all available data from this virtual station are considered.

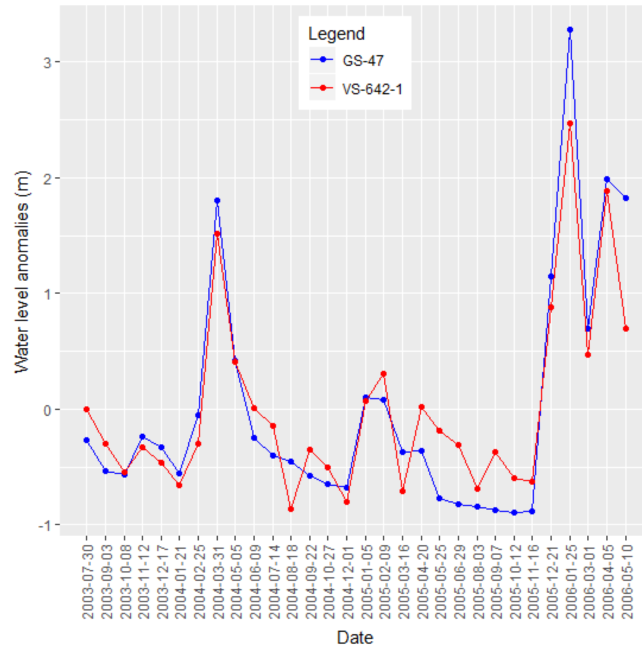

Figure 5: Comparison between water level anomalies derived from satellite altimetry at VS-642-1 virtual station and the corresponding river water level anomalies at Jungulo (GS-47).

As mentioned before, the root mean square error (*RMSE*) was also employed to compare the altimetric and in situ time series and, to make the comparison independent of the datum differences for radar and gauge measurements of water level, the calculations were performed in terms of anomalies relative to the means of the respective water level data sets for the period considered, thus resulting in a *RMSE* of 0.37 m. This result is comparable to the results of the order of 20–40 cm obtained in other studies for large rivers (see, e.g., [28, 30]) and large lakes (e.g., [31]) or even better than those obtained for some small rivers (e.g., [6]).

The results obtained for the VS-270-1 virtual station, situated about 46.5 km upstream from the Massangena (GS-86) gauge station, are equally very good, with a determination coefficient of 0.91 and a *RMSE* of 0.34 m, a value that is even better. However, the results are not so good for some other stations, possibly due to the contamination of the return radar signals by nearby land features and the distinct morphological and hydrological characteristics of the braided river stretches. For example, for the VS-0829-1 virtual station, situated only about 14.5 km downstream the Massangena gauge station, the results are only fair, with a determination coefficient of only 0.50 and a *RMSE* of 0.65 m.

Although the return radar signals are contaminated by the surrounding relief and land cover, because the diameter of the area illuminated by the radar altimeter is much larger than the length of the river sections defined by the satellite ground tracks, the results obtained in this study indicate that Envisat satellite altimetry can be used to derive water level time series for this river, and potentially for other similar poorly gauged semi-arid rivers, in particular in this region of Africa.

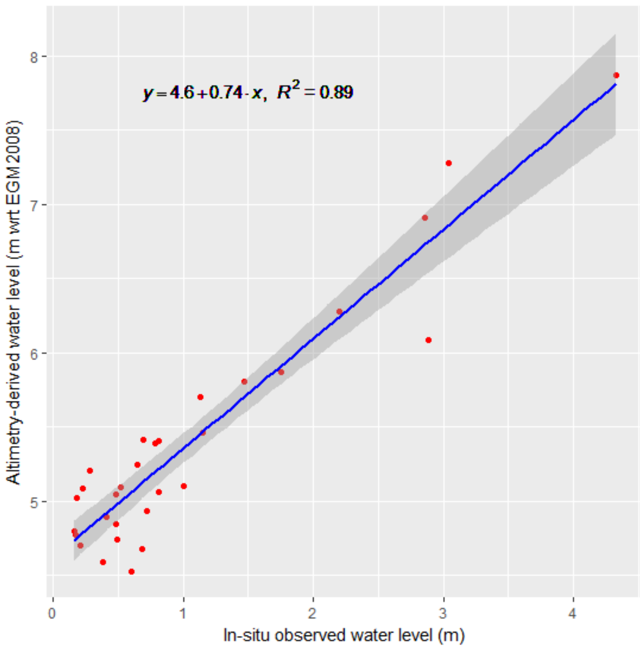

Figure 6: Correlation between Envisat radar altimetry-derived water levels from VS-642-1 virtual station and in situ observations at Jungulo station.

It is important to point out that during the first phase of the Envisat mission, considered in this study, there was no gauge station located within the Envisat altimeter footprint or sufficiently near a virtual station, as it is possible to conclude from the observation of Figure 2, which did not allow the correct validation of the obtained altimetric water level time series. Internal validation at satellite ground track crossovers was also not possible in the studied portion of the Save River.

5. CONCLUSIONS

The available hydrometric data for the Save River and other shared rivers of this region of Southern Africa, in addition to being scarce, are largely incomplete and even inconsistent, due to the lack of a common datum for the gauge stations, which is essential for the accurate estimation and modelling of river discharges.

Although the lack of any gauge station sufficiently close to the altimetric virtual stations have prevented the correct validation of the corresponding altimetry-derived time series of river water level, the results obtained in this study confirm the ability of the Envisat satellite radar altimeter to observe the temporal and spatial water level fluctuations in the lower Save, a semi-arid river of Southern Africa with a predominantly braided morphology.

Envisat radar altimetry, even with its significant limitations in terms of temporal frequency of measurements and spatial coverage (and several other limitations and issues, including inaccurate corrections and, as mentioned before in this paper's methodology subsection, land contamination in the radar footprint that can seriously distort the radar altimeter echo waveforms), can also potentially contribute to the monitoring of water level fluctuations in other semi-arid rivers with complex channel morphologies and relatively small widths (ranging from a few hundred to even only some tens of meters wide), providing thus observations in areas where in situ data are scarce or unavailable.

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