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Full Length Research Paper

Reservoir storage variations from hydrological mass balance and satellite radar altimetry

Yunus D. Salami* and Fidelia N. Nnadi

Department of Civil, Environmental and Construction Engineering, University of Central Florida, Orlando, Florida, USA.

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Knowledge of storage variations in reservoirs and lakes is important for water resources planning and use. In developing countries where lakes may be poorly gauged and water quantity data sparse or unavailable, a simple and cost-effective method of estimating storage would be useful for reservoir operation and management. In this study, we showed how to estimate reservoir storage by combining hydrological mass balance and remotely-measured lake levels. Water levels measured by ERS/ENVISAT and Topex/Poseidon satellite altimeters in Kainji reservoir, Nigeria, were first compared with ground-measured levels. The resulting time series plot and high determination coefficient for both data sets (R^2 = 0.93 and 0.95 respectively) showed that altimetric levels can complement gage data for this reservoir. Reservoir storage was then estimated from gage and altimetric lake levels using a storage-level curve generated by performing a simple water balance. The resulting correlation and root-mean-square errors between storage estimated from altimetry and water balance suggest that storage may be directly determined from satellite-measured levels. These results have far-reaching implications for water resources monitoring and quantification in ungaged lakes and the methodology could revolutionize conventional techniques of computing volume changes even in gaged reservoir.

Key words: reservoir storage, satellite altimetry, Africa water resources, Kainji Lake, storage curves, lake volume, reservoir operation.

INTRODUCTION

In order to effectively utilize lakes and reservoirs for such purposes as hydropower generation, irrigation, and flood control, knowledge of water quantity within the reservoir is required. Often, precise values of volume of water available may not be necessary because water surface elevation within the reservoir can be an indication of available storage. This relationship between level and storage, similar to area-volume or level-area relationships makes it possible for engineers to fairly accurately estimate one parameter from the other (Magome et al., 2003). But first, reliable data is required for their computation. In developing countries however, water level and storage data can be difficult to obtain due to financial, maintenance, or administrative issues (Munyaneza et al., 2009). A supplementary solution for water resources management, therefore, would be one that is cost-effective, able to complement conventional technologies, require little human supervision, free of administrative barriers or political interference, and must be demonstrably reliable over long periods and in all kinds of weather. Satellite radar altimeters, devices used for remotely measuring water surface heights from space, hold immense potentials in this area as demonstrated in seminal studies by Birkett (1994, 1995, 2000). A few more recent studies have demonstrated their application in coastal waters and oceans, but they have also seen some successful use in inland waters (Crétaux and Birkett, 2006).

BACKGROUND

This paper demonstrates the potential of combining

*Corresponding author. E-mail: yunussalami@yahoo.com. Tel: 1-407-823-2105.

Table 1. Characteristics of Kainji Reservoir.

Variable	Value
Latitude	9°50' N
Longitude	4°40'E
Maximum capacity (m^3)	15 x 10^9
Minimum capacity (m^3)	3.5 x 10^9
Surface area (km^2)	1270
Maximum length (km)	135
Maximum width (km)	30
Maximum elevation(m, masl)	141.9

validated satellite-measured reservoir level data with ground-measured (gage) hydrological parameters to determine storage variations within reservoirs. Eventually, it shows how reservoir storage may be easily estimated from freely available altimetric water levels measured by satellite altimeters, using a storage-level curve generated from a hydrological mass balance. Many reservoirs in Africa with scarce hydrological data can potentially benefit from this methodology if such reservoirs are amongst the growing global list of reservoirs that are monitored by satellite altimeters. With fairly accurate inflow, outflow, and other hydrological data for a short period only and lake levels from altimeters, storage computations may be performed remotely. In addition, negligible to no changes in the reservoir's geomorphology over time would mean better results, as demonstrated in reservoir storage studies in semi-arid regions like Nigeria (Liebe et al., 2005).

Topex/Poseidon (T/P) Altimeter

Topex/Poseidon altimeter has a 10-day temporal resolution and a spatial resolution of about 580 m, with global coverage stretching to North/South latitude 66°. JASON-1 satellite mission was launched to replace the T/P mission in 2003. At 10 days, T/P has a very good temporal resolution but its main limitation is its comparatively larger spatial resolution, noticeable sometimes in the absence of pass points over some basins (Birkett, 1998). The decadal (1992–2002) hydrological data set derived from T/P based on its original orbit was intended for use with extending Jason-1 coverage data. However, Jason-1 gives much fewer land surface water measurements due to loss of surface contact by the tracker onboard the satellite as well as little accuracy of re-tracking procedures over land surface waters (Leon et al., 2006).

ERS/ENVISAT Altimeter

ENVISAT altimeter measures water surface elevation at a temporal resolution of 35 days and with a spatial resolution of 380 m. The ENVISAT mission replaced the ERS-2 European space missions in mid-2002 which had, in turn, replaced the ERS-1 mission in 1995. ENVISAT and T/P datasets used are relative to WGS84 and GGM02C height systems respectively.

Study area

Lake Kainji was formed in 1968 when the lower Niger River running through Nigeria was impounded for the construction of Kainji hydroelectric dam. The location is between latitudes 9°50' N and 10°35'N and longitudes 4°26'E and 4°40'E. The reservoir measures about 130 km in length and 30 km in width at its widest point. The reservoir surface area is about 1270 km^2 and the maximum volume is 15 x 10^9 m^3 (Table 1). The Niger River, which the Kainji dam impounds, stretches across five African countries, first flowing north then south. With a total length of over 4,000 km, the Niger River is Africa's third largest. The Kainji reservoir depends mainly on inflow from the Niger River for sustenance of the country's electricity demands, some of which is exported to neighboring countries. Its secondary use is flood control (Onemayin, 2008). Sometimes, balancing unexpected changes in water availability patterns with effective management has been difficult in the Kainji reservoir because shortages in the dry months and flooding in the rainy season have frequently occurred within the same year (Emoabino et al., 2007).

METHODOLOGY

Data collection

Altimetric lake level measurements for the Kainji Lake began in 1992/1993 while gage levels and in situ inflow data obtained for this study were available only until 2003. Therefore, only data for the common 10-year period of 1992-2002 was selected for use in this study.

Ground-measured data

In situ inflow and reservoir level data were collected for the 1992-2002 period. Decadal lake evaporation records and precipitation over the reservoir were also obtained for use in computations of storage by water balance from 1992 to 2002.

Altimeter levels

Altimetric water levels measured by ENVISAT and T/P altimeters were collected for the 1992-2002 period. Both sets of altimeter data are freely available online for continental ocean surfaces, and many rivers and reservoir across the earth (Figure 1).

Reservoir level validation

Altimetric water levels were validated with gage measured levels to establish the admissibility of altimetry data for storage estimation.

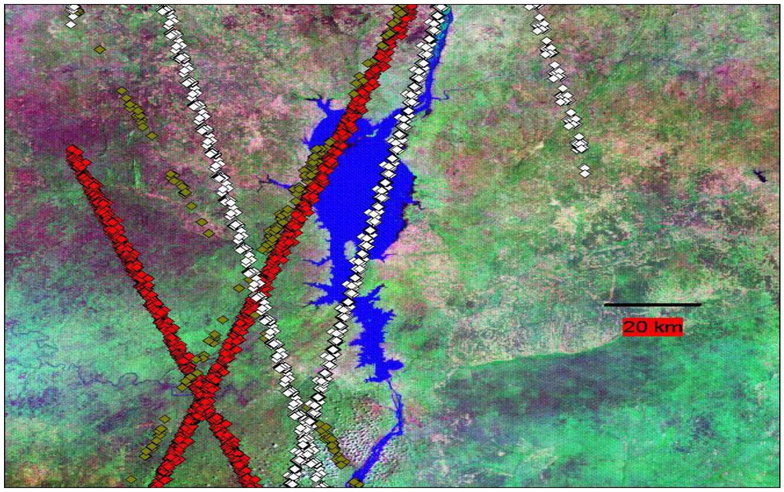

Figure 1. Satellite altimeter pass points over Kainji Reservoir. (White Lines: ERS/ENVISAT, Red Lines: T/P and JASON-1, Olive lines: GFO. These indicate nominal ground tracks. A drift up to +/- 1km is expected in actual operation) Source: 'Surface monitoring by satellite altimetry.

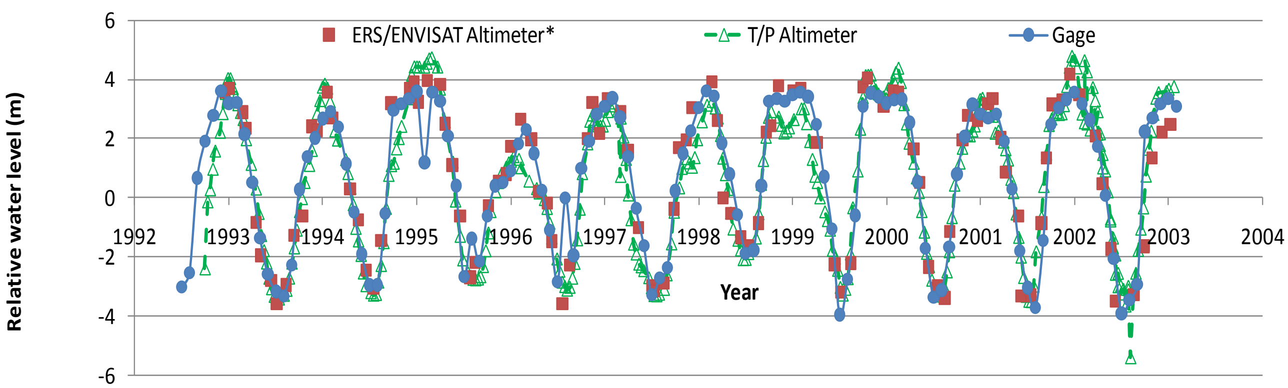

Figure 2. Time Series plot of gage, T/P altimeter and ERS/ENVISAT Altimeter Lake levels. Kainji Reservoir relative water level comparison.

The expectation of this task was that a reliably high correlation between ground-measured and satellite-measured water level data would be obtained, therefore suggesting the possibility of replacing scarce lake level data with easily downloadable altimetric depths for the purpose of directly estimating storage from altimetric lake levels. This validation was done by selecting altimetric lake levels measured on the same day as gage levels, to allow for 'temporal alignment' of data points measured by different methods. These were then plotted, first to compare ENVISAT and gage levels, then T/P and gage levels (Figure 2). Correlation coefficients, standard deviation, and root-mean-square (RMS) errors were calculated for each comparison as shown in Figures 3 and 4, and Table 2.

Where altimetric product are being used to fill in missing water level data, the altimetry reference frame may need to be the same as the gage reference because the mean height for T/P is just an average, and may not correspond to gage datum or mean sea level datum (Birkett,1995). But where climate change or volume change is of interest, the importance of reference frames become negligible and it suffices to compare relative vertical heights or amplitude variations in the different scales of measurement. In effect, different vertical scales of measurement from different altimeters, if necessary, may be slid up and down to check for coincidence so that while absolute heights or water surface elevations may differ because of different reference frames, relative vertical amplitudes would be identical for the same location (Personal communication). In order to homogenize the measurement scales, the original vertical height format of T/P altimetric heights were used directly while both gage and ENVISAT-measured water surface elevations were converted from elevation to relative levels, a scale identical to that used by T/P altimeter. This was done by first plotting T/P altimetric heights against gage water levels and ENVISAT water levels respectively, to obtain a linear plot and equation. The linear regression equation was then used to convert gage and ENVISAT scales to T/P scale. The result of this was a single vertical scale (refered to here as relative water level) by which all three water level data sources were compared.

This preference of a single vertical scale that expresses water levels in a positive and negative scale, as used by T/P altimetric data, also allows for an easy comparison of actual water levels measured using different reference frames.

This validation exercise is discussed more extensively by Salami and Nnadi (2012).

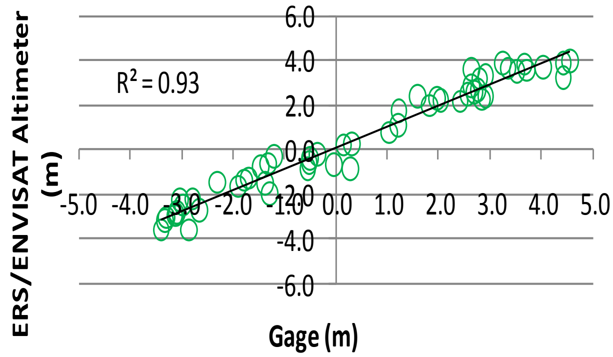

Figure 3. Gage vs. ERS/ENVISAT lake levels.
Note: Kainji reservoir relative water level comparison (ERS/ Envisat vs Gage; 1992-2002).

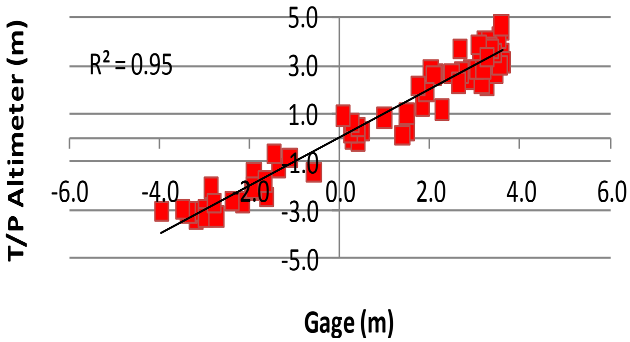

Figure 4. Gage vs. T/P lake levels.
Note: Kainji reservoir relative water level comparison (T/P vs Gage; 1992-2002).

Table 2. Summary of level validation results.

Statistic	Lake level validation results	
	Gage vs. T/P	Gage vs. ENVISAT
R^2	0.95	0.93
RMS error (m)	0.54	0.55
Std. deviation (m)	0.35	0.29

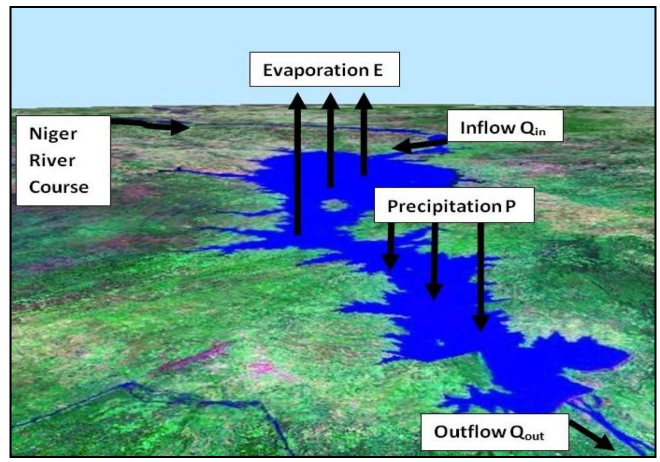

Figure 5. Image of the Kainji reservoir showing main hydrological variables.

Lake storage from hydrological mass balance

After the completion of Kainji Dam, Abiodun (1973) first suggested the possibility that seasonal storage in the reservoir may be estimated using a hydrological mass balance but mentioned that there were hindrances associated with deciding what parameters to include. In our study, the reasons for the inclusion or elimination of each parameter that would normally be involved in a hydrological mass balance for a lake are explained as follows. First, the volume of water lost to irrigation in dry season is minimal because characteristically low Niger River inflows necessitate control of irrigation use. On the other hand, the rainy season naturally creates availability of water for local farmers, removing the need for excessive irrigation uses in those months. While runoff from the reservoir catchment would be an input to consider normally, catchment contribution around the Kainji accounts for less than 10% of inflow (Onemayin, 2008). That there is very minimal contribution from the catchment between both reservoirs is not a phenomenon unheard of for lakes in moderately dry regions of Africa. For instance while Kainji experiences varied precipitation over the lake area yearly (Oyebande, 1995), Yin and Nicholson (1998) have shown that Lake Victoria in Africa experiences 30% more precipitation over the lake than over its catchment, also suggesting that catchment contribution may be lower in such cases. Also, the bed of Lake Kainji is of silty alluvium material and it has been shown that infiltration and seepage losses are negligible in reservoirs over fine-textured soils (Talsma and Leiyj, 1976). Besides, if water balance in the Kainji is examined on a yearly basis, those errors due to infiltration, seepage, and subsequent recharge of surrounding areas become negligible because such lake volumes return to almost the same each year (Sokolov and Chapman, 1974). One exception is that seepage may occur to a limited extent at those parts of the Kainji lake shore where rocks of the Nupe Formation are exposed. However these are in turn surrounded by impermeable rocks of the Basement-Complex preventing any significant seepage (Nedeco, 1961).

This implies that the significant contributors to hydrological input and output in the lake are reduced to inflow, outflow, precipitation, and evaporation only, and brings the hydrological mass balance equation to the form:

$$\Delta V = (Q_i - Q_o)t + (P - E) = V_1 - V_0 \qquad (1)$$

where: t = time interval, $t_1 - t_0$ (in seconds);

If $t_1 - t_0$ is equivalent to one month, then

Q_i = reservoir inflow (m^3/s); Q_o = reservoir outflow (m^3/s); P = monthly precipitation volume over the reservoir (m^3); E = reservoir evaporation (m^3); ΔV = monthly storage change (m^3); V_1 = reservoir storage at time t_1 (m^3); V_0 = reservoir storage at time t_0 (m^3).

Equation 1 fundamentally agrees with that from a study (Obot, 1985) where lake evaporation was the unknown parameter to be determined. By applying Equation (i), reservoir storage was calculated on a mean monthly basis for each year between 1992 and 2002 as revealed in the time series plot in Figure 5. Level-storage curves were then generated using gage levels, ENVISAT

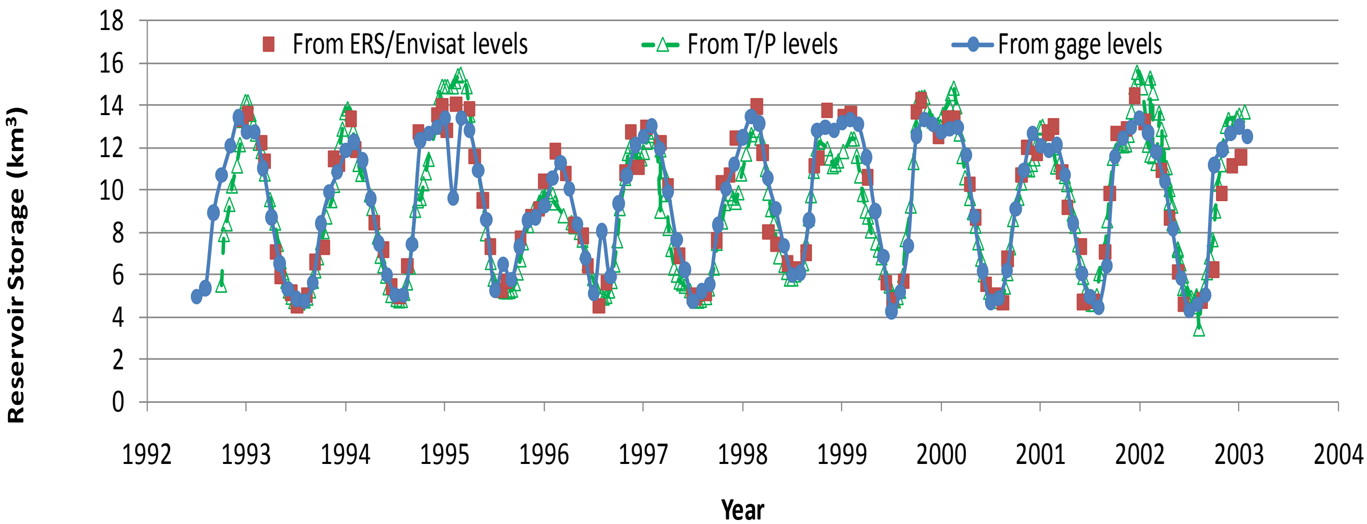

Figure 6. Time series of Kainji reservoir storage derived from in situ, T/P, and ENVISAT levels. Kainji Reservoir storage.

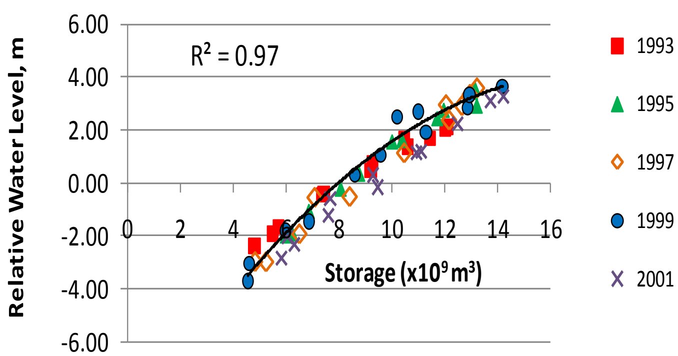

Figure 7. Kainji Reservoir Level-Storage Curve. Kainji reservoir level-storage curve.

levels, and T/P levels respectively. The storage-level curves (Figure 6) were then used to determine actual reservoir storage using historical reservoir level data.

RESULTS

Reservoir level validation results

Gage vs. T/P level comparison gave a RMS error of 0.54 m while gage vs. ENVISAT comparison gave 0.55 m. These results are consistent with values typical for a lake of this size and have also been previously demonstrated specifically for the Kainji lake. (Salami and Nnadi, 2012). It has been shown that the RMS errors vary depending on the size of the lake and the complexity of the contiguous topography (Birkett, 1995). The roughness of the lake surface was also cited as a factor. The RMS values can range from 5 cm for large open lakes to several tens of centimeters (as for Lake Kainji) for more sheltered lakes or those in deep valleys where the instrument only observes a narrow expanse of water (Birkett,1995). The roughness of the lake surface was also cited as a factor. The RMS values can range from 5cm for large open lakes to several tens of centimeters (as for Lake Kainji) for more sheltered lakes or those in deep valleys where the instrument only observes a narrow expanse of water (Cretaux et al., 2011)

Reservoir storage results

In Figure 6, the sudden sharp dip and peak in January 1995 and July 1996 respectively were considered outliers in the datasets but included in our analysis. While equipment malfunction in level reading is ocassionally responsible, such instances of mild to pronounced variations can be due to sudden significant reservoir releases, or sharp increases in inflow or precipitation in those months. Historical reservoir storage through time as shown below is expressed in cubic kilometers.

Between 1992-2002, the geomorphology of the Kanji reservoir did not undergo any major changes (Emaobino et al., 2007) due to natural or anthropogenic factors, suggesting that no significant changes in its level-storage curve is expected. To confirm this, biennial level-storage curves generated showed very close similarities between these curves suggesting that a single level-storage curve may be used for the 1992-2002 period and yearly or biennial curves are not necessary. As shown in Figure 7, the level-storage curves for all five years (1993, 1995, 1997, 1999, and 2001) are identical, except for two outliers in the rainy season of 1999 very likely caused by erroneous hydrological data due to heavy flooding in that year (Olawepo, 2008). Using the level-storage curve

Table 3. Comparison of altimetry-derived storage and *in situ* storage.

Parameter	Results of derived storage	
	***In situ* vs. T/P**	***In situ* vs. ERS/ENVISAT**
Average relative error (%)	6.67	7.94
R^2	0.93	0.92
RMS Error (km^3)	0.81	0.89

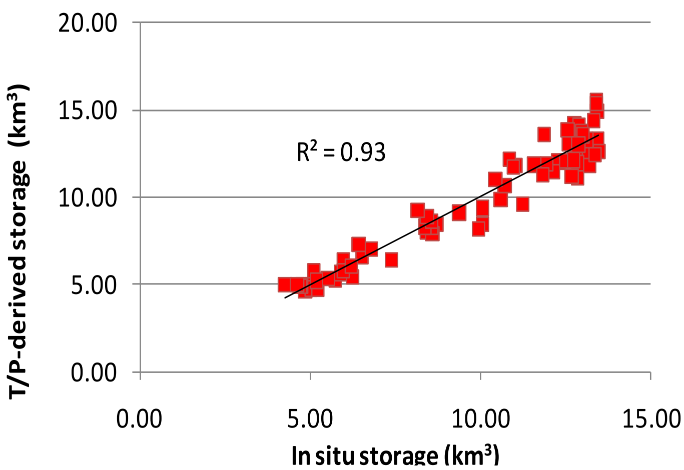

Figure 8. *In situ* storage vs. T/P-derived storage. Comparison of kainji reservoir storage.

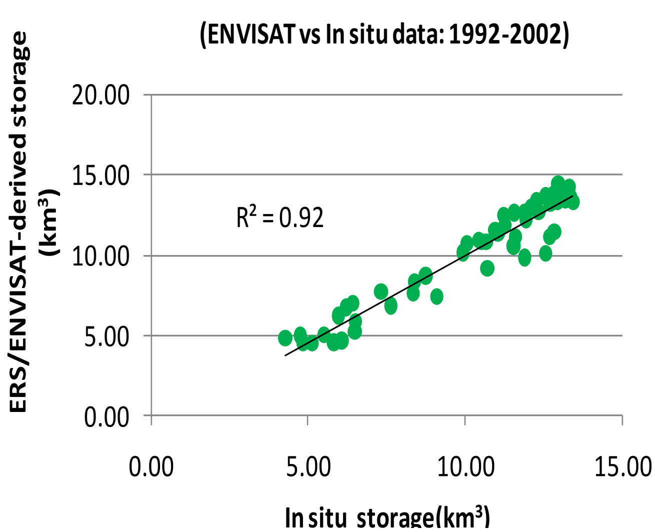

Figure 9. *In situ* vs. ENVISAT-derived storage. Comparison of Kainji Reservoir storage

shown in Figure 7 combined with same-day water level measurements from gage, T/P altimeter, and ENVISAT altimeter, Kainji reservoir storage computed for the 1992-2002 period is shown. Comparisons between these are shown in Figures 8 and 9, and Table 3.

Conclusion

With a RMS error of 0.81 km^3 and relative storage error of ± 6.67%, T/P levels appear to be more useful for Kainji storage estimation, although only marginally. The results of storage derived using both altimetric datasets show that ENVISAT levels are also adequate for storage estimation in the absence of in situ data in the Kainji lake. Overall, the advantage in temporal resolution of T/P over ENVISAT altimeter in Kainji lake level comparison is as marginal as the spatial resolution advantage of ENVISAT over T/P in derived-storage.

The comparison of water level data from both ground-measured and remotely-sensed sources in this study produced results which showed that altimetric level can complement gage levels at the Kainji reservoir. Also, the ease of computing monthly, seasonal, or annual storage variations was sufficiently demonstrated to the extent that as new hydrological or storage data becomes available, satellite altimetry data can be combined with storage data to allow for historic, current, or long-term storage computation. Such information can then be used in effective reservoir operation planning, estimation of hydroelectric energy potential, and overall better water resources management. It is hoped that as the accuracy of altimeters improve, so would the correlation between gage and altimetry levels, and perhaps altimetry-derived storage. In each year, in situ reservoir storage was less than 15 km^3 which is the design maximum capacity of the reservoir. A plausible explanation would be loss of reservoir volume from accumulated effects of sedimentation.

It should be noted however that while the hydrological mass balance method used here for estimating storage is a fairly good approximation, the results are as good as the empirical data received for inflow, outflow, evaporation, and precipitation. Overall, the convenient application of the methods outlined in this study also depends on the consistency of level-storage curves over time, catchment hydrology, internet access, reservoir capacity, and the homogenity of lake level data used.

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