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Full Length Research Paper

Seasonal and interannual validation of satellite-measured reservoir levels at the Kainji dam

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Although several studies have demonstrated the potential for inland water monitoring using satellite radar altimeters, the technology still carries with it certain limitations. Therefore, the direct application of altimetry data to reservoir management is often preceded by validation of satellite altimetry data with reliable ground-measured data. Kainji reservoir in Nigeria was selected for this study due to its remote geographical location, hydrological behavior, operational requirements and morphometry. Validation of Kainji reservoir altimetric levels would highlight the applicability of the technology for monitoring one of Africa's largest reservoirs with a surface area of 1270 km^2. We performed and improved the validation exercise by separating each lake level dataset into two separate seasons: dry and wet, to investigate the effect of different seasons on the relationship between ground-measured and satellite-measured data sets. Lake level data from Topex/Poseidon and ERS/ENVISAT satellite altimeters were compared with gage data from 1992 to 2002. The results suggested a significantly higher relationship between gage and satellite data for the wet season (R^2=0.93) than for the dry season (R^2=0.77). For interannual validation, the trend was the same for both satellite altimeters but the relationship was generally higher for the T/P altimeter (R^2=0.95). Root-mean-square errors in water levels ranged between 0.50 to 0.83 m for both altimeters and seasons, agreeing with values expected for lakes of identical physical characteristics.

Key words: Satellite altimetry, remote sensing water, reservoir level variation, Kainji dam, African lakes.

INTRODUCTION

The balance between availability of water and effective water management can become strained as is the case with the Kainji reservoir in Nigeria, where low water levels in the dry months and flooding in the rainy season have frequently occurred within the same year (Emoabino et al., 2007). Because this reservoir is relied upon for flood control, hydropower, and irrigation, there is the need to develop a simple and reliable method of monitoring and quantifying available water in the reservoir. Direct measurements of storage may be difficult but storage-level curves, where available for a given reservoir, are extremely useful estimation tools (Magome et al., 2003). However, reservoir level data must be easily obtainable and reliable. In parts of Africa and other developing countries where level and storage monitoring technologies and policies may already exist, these are hampered by poor maintenance and implementation. Therefore a supplementary solution is desired which must be cost-effective, able to replace conventional technologies, require little human supervision, not subject to administrative barriers or political interference, and 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 the key. Their applications have been demonstrated

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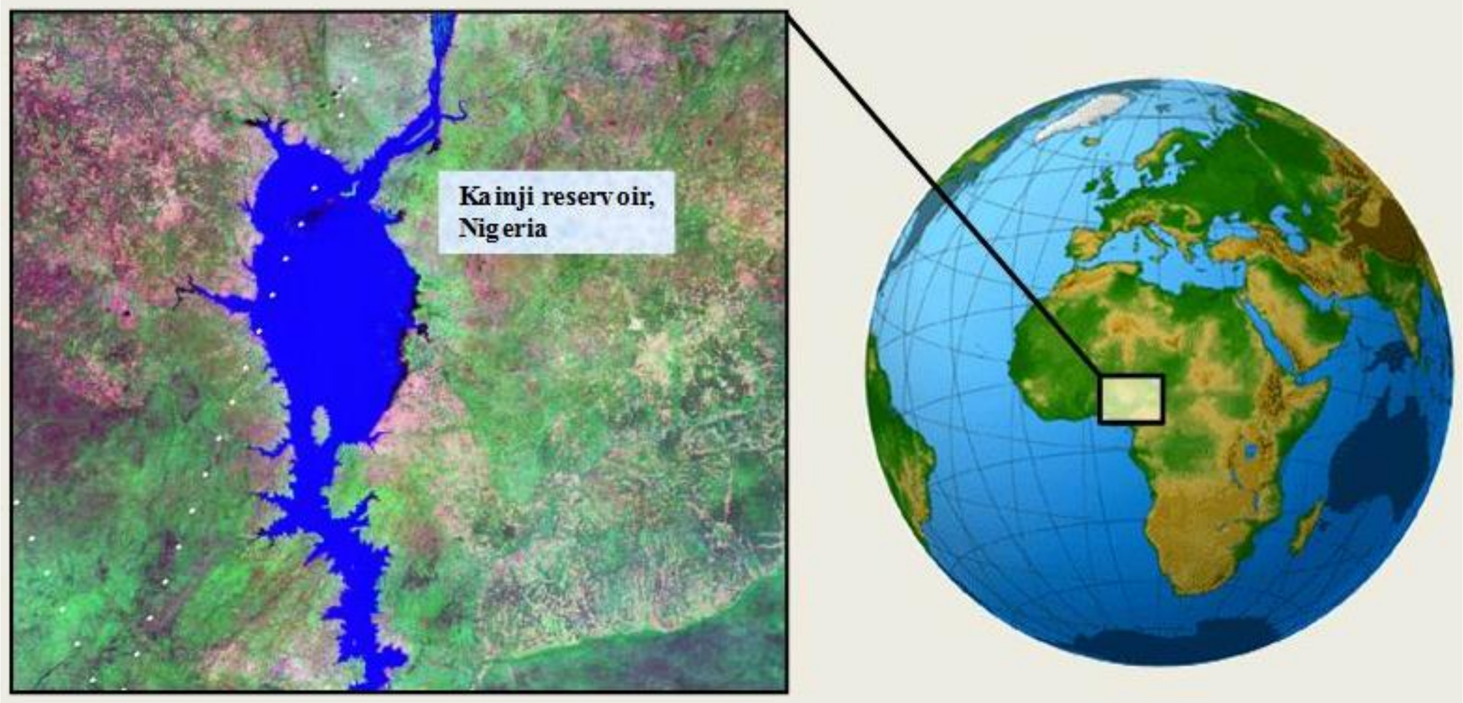

Figure 1. Location of Kainji Lake (White dotted lines indicate altimeter pass-points).

in coastal waters and oceans, but they have also been successfully used for inland waters (Cretaux and Birkett, 2006).

Background

Unlike imaging instruments, altimeters only collect elevations along a narrow path determined by the instrument's characteristics (Birkett, 1998). The actual 'footprint diameter' depends on the nature of the target, and can range from several hundred meters to many kilometers. While originally conceived of for use in larger water bodies like oceans and seas, satellite radar altimeters have been frequently and extensively used in inland waters (Crétaux and Birkett, 2006). Previous validation exercises have been mostly year-long comparisons, like studies on Lake Dongting, China (Zhang et al., 2006) and Lake Kivu, Rwanda (Munyaneza et al., 2009).

Our study took the validation task a step further by conducting temporally-sensitive seasonal comparisons between gage and satellite data. While year-long comparisons may be sufficient in some cases, they may not reveal the possibility that hydrological and operational factors in dammed lakes may affect the outcome and reliability of validation.

In summary, our study was aimed at:

1. Investigating the applicability of altimetry data to continuous lake level monitoring.
2. Investigating the applicability of altimetry data (for different seasons of the year) to understanding Kainji lake seasonal behavior.
3. Identifying which satellite altimeter data gives the best correlation determination coefficients and root-mean-square errors (RMSE) and therefore can substitute gage data for reservoir level monitoring.

Study area

The Kainji Lake (Figure 1) was created by impounding the Niger River in the late 1960s during the construction of Kainji hydroelectric dam. A summary of the characteristics of the lake is given in Table 1.

Data collection

Gage data and satellite altimeter data

Daily and monthly averages of water level within the Kainji reservoir were obtained for the 1992-2002 period.

Water height data were acquired from Topex/Poseidon

Table 1. Characteristics of Kainji reservoir.

Latitude	9°50' N
Longitude	4°40'E
Maximum Capacity (m^3)	15×10^9
Minimum Capacity (m^3)	3.5×10^9
Surface Area (km^2)	1270
Length (km)	135
Maximum Width (km)	30
Maximum elevation (m.a.s.l)	141.9 m

(T/P) and ERS/ENVISAT altimeters for the 1992 to 2002 period. Both sets of altimeter data are freely available online for continental ocean surfaces, and many rivers and reservoirs across the earth's surface. Gage level data were measured relative to a datum. Although not the same datum as the altimeter datasets, the relative heights are comparable since both measurements (altimeter and gage) represent relative changes in elevation. Different vertical axes were adopted for each separate series for coincident time frames.

T/P altimeters have a 10-day temporal resolution and a spatial resolution of 580 m, with global coverage stretching to North/South latitude 66°. JASON-1 satellite mission replaced the T/P mission in 2003 after the latter had its orbit altered. ERS/ENVISAT altimeters measure water surface elevation at a temporal resolution of 35 days and at intervals of 380 m. The ENVISAT mission replaced the ERS-1 and ERS-2 European space missions in 2002 but they are still so referred to. Additional information on the principle of altimeters and an extensive discussion of each satellite mission is presented by Birkett (1995, 2000).

METHODOLOGY

Temporal correction and alignment

Two main types of comparisons were made between gage levels and altimeter levels. First, a time series plot of gage level and altimeter levels was performed (Figures 3 and 4). A second set of comparisons were then made to validate altimeter levels, first interannually, then seasonally. The RMSE and standard deviation of the mean offset were then determined and reported as an indication of the overall altimetric error.

Time series plots

To allow for a fair and concurrent comparison, the measurement dates of the gage data and both altimetry data sets were expressed in the form of 'year plus fraction of year' in which each was measured. For example, water surface elevation data measured by a gage on January 31, 1994 was converted to $1994 + \left(\frac{31}{365}\right)$ or 1994.0849. This expresses both sets of altimeter data and gage data in a homogenous time format where dates within any year are expressed in decimals.

Data validation technique

For seasonal validation, each datasets was separated into: (i) high stage (or 'dry' season) (ii) low stage (or 'wet' season).

High stage period ('Dry' season)

This occurs from October to March/April. Average precipitation and reservoir inflow are relatively low during these months. Given the increased demand for water in the dry season, managers ensure that operational and hydrological parameters of the reservoir are balanced in order to achieve high water levels in these months.

Low stage period ('Wet' season)

This occurs from April/May to September. Precipitation and inflow to the reservoir are relatively high in these months. The need to accommodate both these hydrological input parameters leads managers to operate the reservoir with medium to low stage most of the wet season.

Spatial correction

Figure 2 shows the pass-points of T/P altimeter and ERS/ENVISAT altimeter. Altimetry data were obtained for the same location as the gage levels. These were then compared and plotted. Microsoft Excel was used for all data preparation.

RESULTS AND DISCUSSION

Time series plots of lake levels

For the gage vs. ERS/ENVISAT altimeter time series (Figure 3), there is a slight but consistent vertical offset arising from differences in the respective reference points of the gage and altimeter instruments. However, the amplitude variations or water height variations were identical. Since only actual water height variations are more important in this study, the gage and altimeter datasets were plotted as relative water levels or lake height variations as shown in Figure 4 to reveal any differences or similarities in amplitude variation. In addition to homogenizing all three measurement scales (gage, T/P and ERS/ENVISAT altimeters), Figure 4 demonstrates the similarities in relative water heights and their preference over water surface elevations for such studies involving water level or volume monitoring.

Alternatively, simply sliding gage and altimetry levels

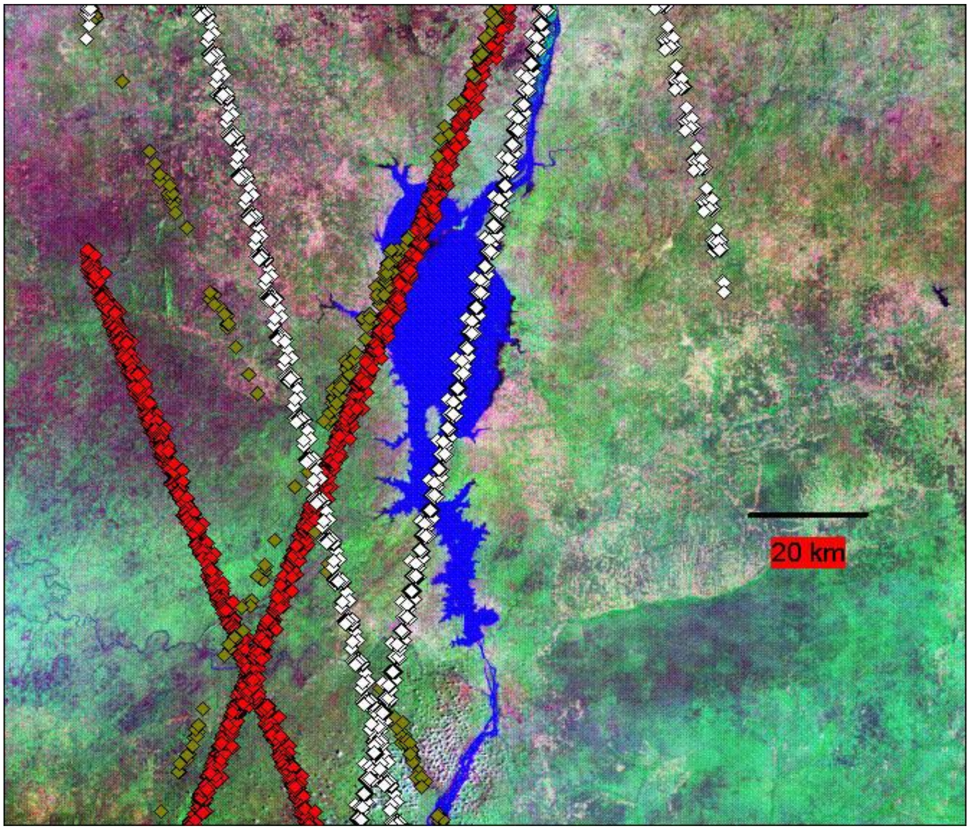

Figure 2. Satellite Altimeter tracks over Kainji reservoir. (White Lines: ERS/ENVISAT, Red Lines: T/P and JASON-1, Olive lines: GFO) Source: “Surface monitoring by satellite altimetry”

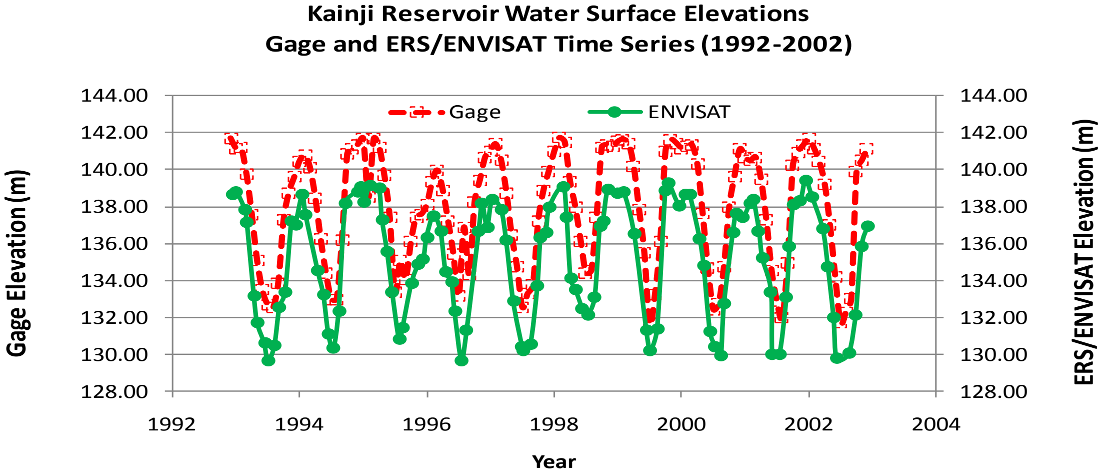

Figure 3. Time series plot of gage and ERS/ENVISAT altimeter lake surface elevation.

along the same vertical scale should also reveal any similarities in relative heights, in spite of different reference frames. As with the gage vs. altimeter plots in Figure 4, the amplitude variations are identical.

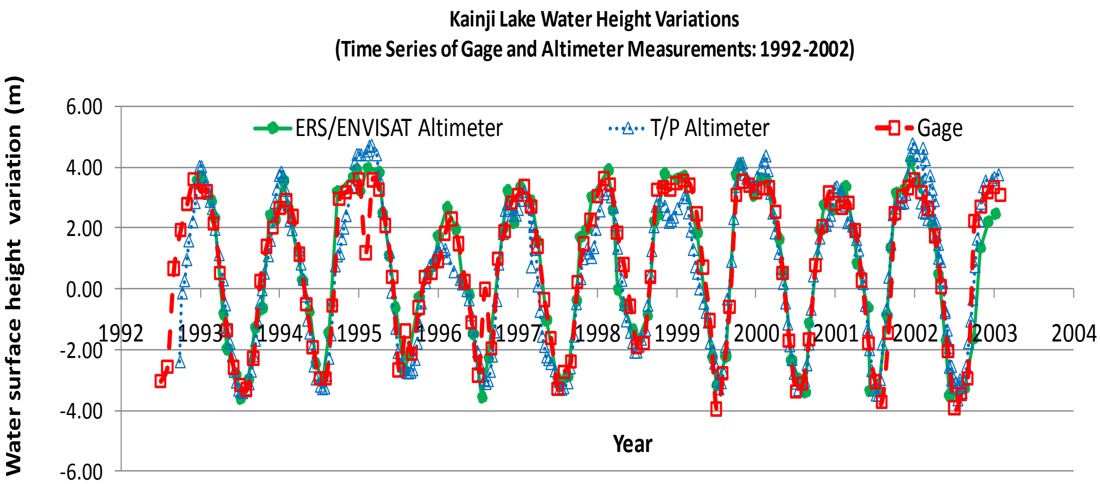

Figure 4. Time series plot of gage and altimeter lake water heights.

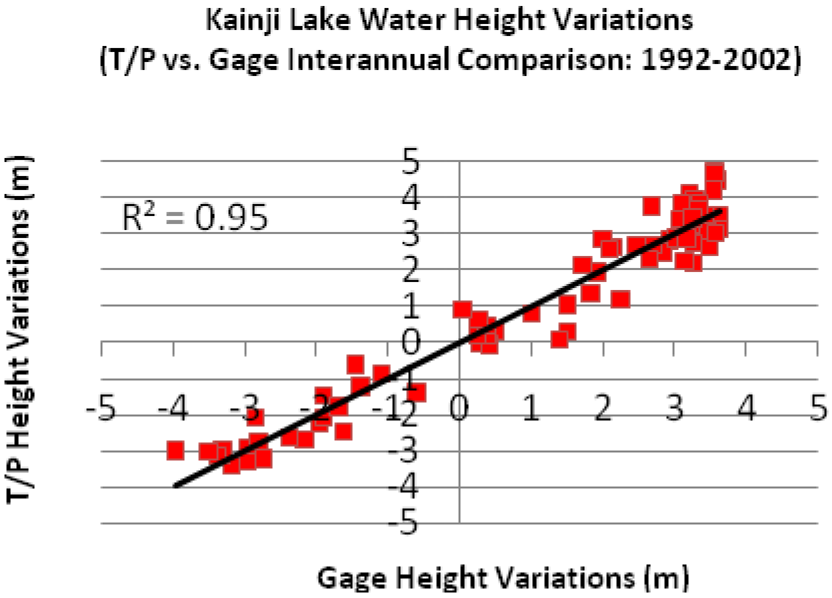

Figure 5. Interannual comparison of Kainji lake height variations: T/P altimeter vs. gage.

Interannual validation results

As shown in Figure 5, the interannual comparison between T/P altimeter levels and gage levels, suggested a coefficient of determination of 0.95, a RMSE of 0.54 m, and a standard deviation of 0.35 m. In Figure 6, ERS/ENVISAT vs. gage comparison gave a coefficient of determination, RMSE, and standard deviation of 0.93, 0.55 and 0.29 m respectively.

Seasonal validation results

Figure 7 shows T/P vs. gage height variations comparison for the dry seasons. This produced a determination coefficient, RMSE, and standard deviation of 0.77, 0.77 and 0.70 m respectively. The dry season comparison of ERS/ENVISAT and gage height variations (Figure 9) yielded 0.76, 0.83 and 0.80 m respectively for the same tests. For the wet season, the comparison of

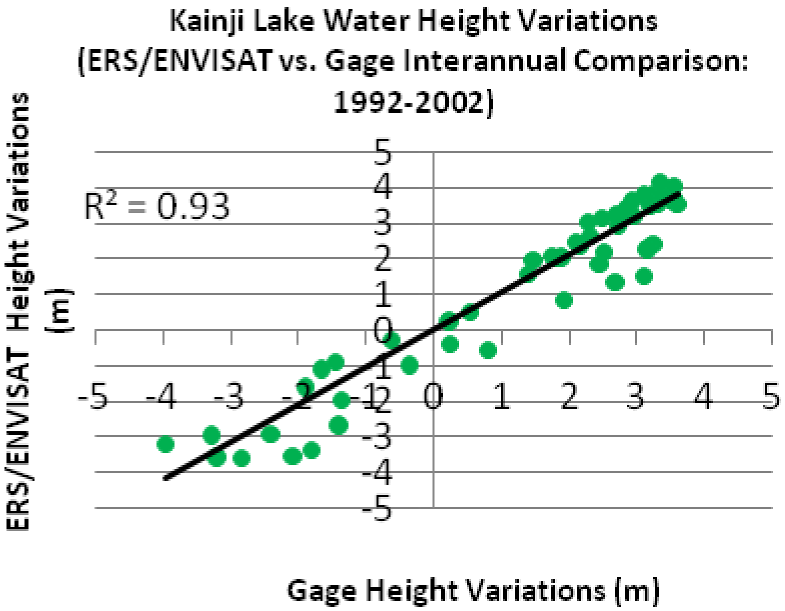

Figure 6. Interannual comparison of Kainji lake height variations: ERS/ENVISAT altimeter vs. gage.

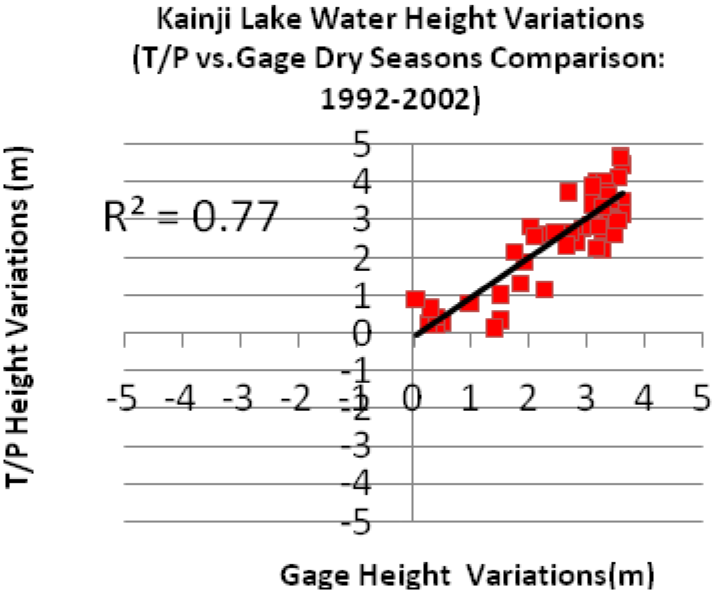

Figure 7. Kainji lake height variations in dry season: T/P vs. gage.

T/P vs. gage height variations (Figure 8) produced a determination coefficient, RMSE and standard deviation of 0.90, 0.50 and 0.24 m respectively, while in Figure 10, ERS/ENVISAT vs. gage comparison for the wet season gave 0.80, 0.59 and 0.47 m respectively. All validation results for both interannual and seasonal comparisons are given in Table 2.

As shown in Table 2, RMSE varied between 0.50 and 0.83 m, demonstrating some consistency with previous studies. For instance, Birkett (1998) found that RMSE varied depending on the size of the lake and the complexity of the contiguous topography and that RMSE values range from 5 cm for large open lakes to many tens of centimeters for lakes that are smaller and shielded to

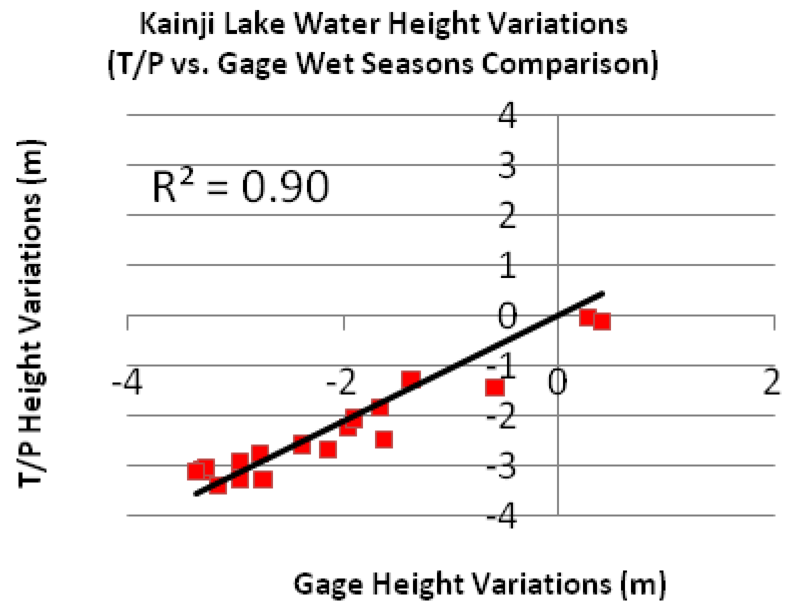

Figure 8. Kainji lake height variations in wet season: T/P vs. gage.

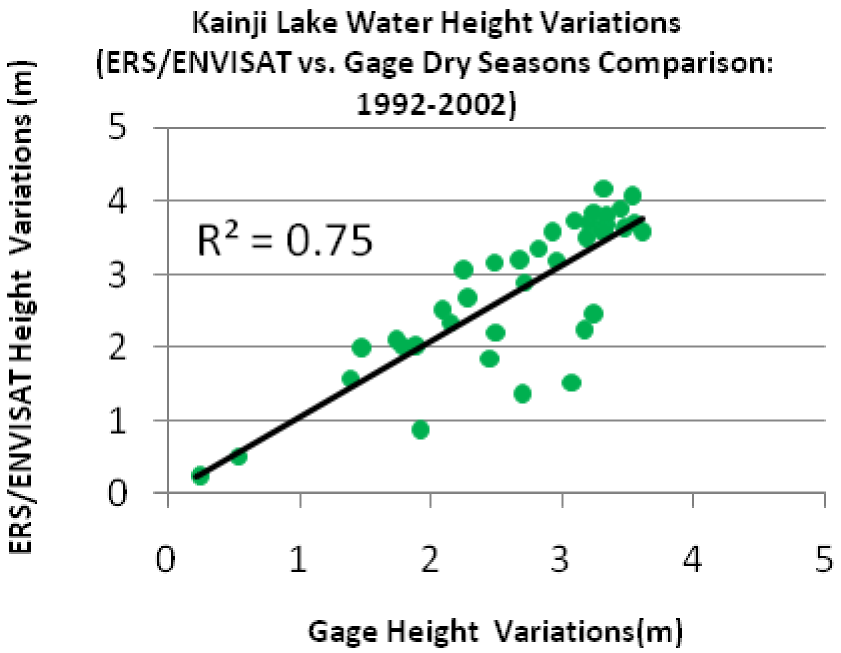

Figure 9. Kainji lake height variations in dry season: ERS/ENVISAT vs. gage.

those in deep valleys where the instrument only observes a narrow expanse of water. Also, the location of Kainji reservoir which is south of the Sahel (a semi-arid region) suggests it is affected by very dry, dusty harmattan winds typical of dry season as well as other windstorm events, possibly reducing the reliability of dry season altimeter-stage validation. The trend was the same for both satellite altimeters. The improved validation results observed in wet season may be attributed to the relatively lower operational stage of the reservoir which is

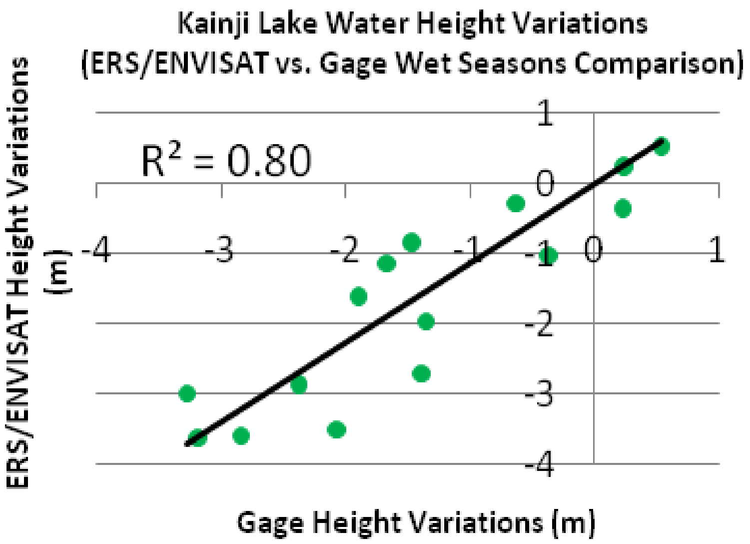

Figure 10. Kainji lake height variations in wet season: ERS/ENVISAT vs. gage.

Table 2. Summary of validation results.

Parameter	Interannual		Seasonal			
			Wet Season		Dry Season	
	Gage vs. T/P	Gage vs. ERS/ENVISAT	Gage vs. T/P	Gage vs. ERS/ENVISAT	Gage vs. T/P	Gage vs. ERS/ENVISAT
R^2 (%)	95	93	90	80	77	76
RMSE (m)	0.54	0.55	0.50	0.59	0.77	0.83
Std. Deviation (m)	0.35	0.29	0.24	0.47	0.70	0.80

accompanied by calmer flow regimes within the reservoir. At such low stages and without precipitation events, backwater effects from the dam site and flood waves within the reservoir (Peng et al., 2006) are lower at these times of the year, further improving the validation results.

Conclusions

This study shows that altimeter data offer great potential for Kainji Lake level monitoring in wet seasons. For dry seasons, altimetric data are still admissible but must be used selectively, alongside gage data. Perhaps until the technology improves greatly, wet season gage measurements in the Kainji Lake seem more reliable than dry season lake level measurements. As a result, additional research is required to improve understanding of the application of altimetry data to stage-derived parameters like reservoir storage based on level data for specific altimeters and seasons. This will increase the overall reliability of altimetry data for reservoir operation and management in the Kainji reservoir.

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