Calibration of a propagation model in large river using satellite altimetry

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ABSTRACT: Satellite altimetry may be used for monitoring large rivers, such as Niger River. Since data samples are sparse in time and accuracy of measurements is limited, an interpolation method is developed in order to get water levels at any time and to adjust observed values, taking account of their limited accuracy. The method uses a flood propagation model dedicated to flood propagation in large African rivers calibrated from one gauge station, used as a reference, and satellite altimetric data provided by Topex or Envisat. It allows capturing the water level behavior at the flood peak even though no measurement was available at that time.

1 INTRODUCTION

In sub-saharian Africa, large floodplains may be widely affected by hydrological changes, as observed in the past 30 years, whether these changes may be due to climate change, land use or water management strategies. This is particularly the case for the central part of Niger River, the Inner Delta, in Mali, which is the main focus of this study. In this area (see Fig. 1), the flood, which inundates a vast floodplain, is generated by precipitations during the months of June to September, mainly in the upper basin of the Niger, while rainfall depths vary from 150 to 400 mm per year within the Inner Delta. Due to propagation lag-times, the flood arrives in the Delta in August-September (Seiler et al. 2009), while the flow starts to decrease only in January in the downstream part of the delta.

Gauge stations are necessary to monitor the flood propagation in order to schedule water activities linked to the flood (such as seeding dates or gate operations at dikes) and identify long term hydrological changes. Ground measurement of water levels is only done on the river itself, at stations that may be distant more than 100km from each other. Establishing more stations would strengthen the hydrological monitoring, but the issues of cost and reliability may become a problem, especially at remote locations.

Satellite altimetric data, primarily used for ocean surface monitoring, have provided consistent observations of continental water bodies (Alsdorf 2007), including large rivers such as the Amazon (Birkett 2002; Roux et al. 2008). Such measurements are sparse in time, due to return period of satellites, and have a limited accuracy due to atmospheric conditions, sensor and satellite characteristics, and reflectance conditions. One challenge is to obtain continuous estimations of water levels based on sparse measurements. A second challenge is to quantify the accuracy of the estimates so that they can be used to monitor the water level variations with a known confidence.

This communication presents an interpolation method of the satellite altimetric measurements. The method uses a flood propagation model which is calibrated using the satellite observations and one gauge station, yielding continuous water levels.

2 METHOD

2.1 *Study area*

The studied portion is 1200 kilometers long between Bamako and Ansongo in the Malian part of Niger River (Figure 1). Reference measurements are provided at 15 stations on Niger River monitored daily by the National Hydraulic Department (DNH) thanks to gauge readers or automatic sensors. Elevations are given in the local geoid model NGAO (*Nivellement general d'Afrique de l'Ouest*). Field observations are costly, as they need maintenance (like replacing iron gauges displaced by boats) and require good communications, which is difficult in remote areas. That is why many gauge hydrographs are incomplete.

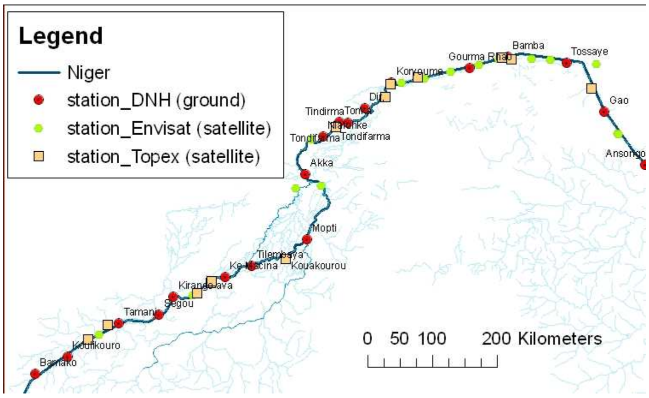

Figure 1: study area, and satellite altimetric stations

Satellite altimetric observations may solve some of the aforementioned problems, and above all provide supplementary datasets to monitor the river flow. The satellite altimetric data are provided by Topex/Poseidon (T/P), Envisat and Jason-2 satellites; approximately 50 orbites crossed the studied portion of the river during the period 1993-2002 (T/P), 2002-2007 (Envisat) and 2008-2009 (Jason-2). The data are available from the Hydroweb database (LEGOS 2009). Nine altimetric stations are available for T/P (plus two on lakes) and 16 for Envisat (Fig. 1). Elevations were transformed into the NGAO geodetic system so that water levels can be compared between satellite and gauge stations. The accuracy of each measurement may vary from a few tens of centimeters with the most recent sensors to 1 meter and more with T/P (Bercher, 2008). Due to the return period of satellites (10 to 35 days), these measurements have a low frequency compared to field observations, complicated by the fact that many measurements may be invalid. Roux et al. (2008) developed an interpolation procedure using daily data provided at ground stations on Rio Negro (Amazon Basin), yielding daily estimates of the satellite altimetric stations. Table 1 gives the list of the altimetric stations (ground or satellite) used in the results section. In the following, we propose to improve the water level estimates by adding some knowledge about propagation dynamics in the river, calibrated between ground stations.

Table 1: list of limnimetric station: ground stations (maintained by DNH), Envisat and Topex satellite altimetric stations

Altimetric station	Longitude (dec. degrees)	Latitude (dec. degrees)	PK (distance to sea in km)	Type
Kirango aval	-6.07	13.70	3227.3	DNH
TP_085c	-5.54	13.92	3152.3	Topex/Poseidon (T/P)
Ke Macina	-5.35	13.97	3055.3	DNH
Mopti	-4.20	14.50	2964	DNH
Env545_02	-4.00	15.25	2861	Envisat
Akka	-4.23	15.40	2826.3	DNH
Diré	-3.40	16.32	2640.5	DNH
Koryoume	-3.03	16.67	2562.9	DNH
Env917_01	-2.20	16.83	2440	Envisat
Gourma Rhaous	-1.93	16.88	2410	DNH
Bamba	-1.40	17.03	2339.3	DNH
Tossaye	-0.58	16.95	2236.6	DNH

2.2 *Flood propagation model*

Flood recession cropping is largely developed along large African large rivers. In Mali, for instance, it represents more than half of the area controlled for irrigation. It is applied on floodplains, which play a key role in the flood propagation, as they store large volumes of water, delay and damp the flood peak. Physically-based models require taking account of these floodplains, and then the physical structures that control the flow between the river and the floodplain (dikes, gates, feeding channels, etc.). As all this information is difficult to collect, Lamagat et al. (1993) developed a flood propagation model adapted to large rivers with overflow. Their model has been calibrated successfully on Niger River (Lamagat et al. 1993; Morel-Seytoux et al. 1993), and it is used to define management rules for reservoirs in Senegal basin (Bader et al. 2003). The model is based on the determination of propagation times, defined as functions of the observed level, and correspondence functions between measured water levels:

$$Z_2(t) = f\left(Z_1(t-T)\right) \tag{1}$$

$$T = g\left(Z_1\right) \tag{2}$$

where t is the time, Z_i is the water level at station i (i=1, 2), T is the delay time, f and g are functions of the water level at station 1 (Fig. 2a). The calibration of the propagation model consists in determining the functions f and g. The idea is that, for an observed value of level Z_1 at a time t and at station 1, one will observe a corresponding value Z_2 at a time T later at station 2. The correspondence includes flood propagation in the river bed, in its floodplain and possible other inflows/outflows. Several years are required to calibrate properly the functions. This is done by dividing the range of values of Z_1 in N elementary intervals (typically, N=15 to 20), so that there are enough points in each interval to get meaningful statistics. For each interval j, the mean value of the interval is calculated (Z_{1j}) and the propagation time is the value of T that maximizes the correlation between Z_{1j} and Z_2. The procedure is particularly efficient when a large number of floods are available.

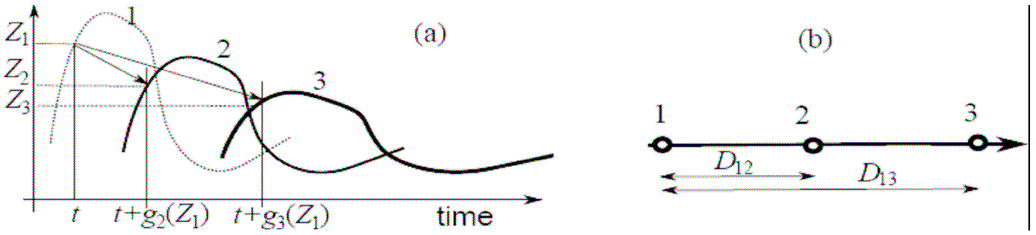

Figure 2: propagation model between stations 1 and 2. (a): variation of water levels at stations 1, 2 and 3. At time t, if the elevation at 1 is Z_1, elevations in 2 and 3 are $Z_2=f_2(Z_1)$ and $Z_3=f_3(Z_1)$ at times $t+g_2(Z_1)$ and $t+g_3(Z_1)$ respectively. (b): station 2 is between stations 1 and 3, D_{ij} is the distance between stations i and j.

In this paper, we propose to use the propagation model to interpolate the values between the satellite observations, station 1 being a daily-observed gauge station, station 2 being the satellite altimetric station. Compared to previous calibrations of Lamagat et al.'s model, values of Z_2 are sparse, and with limited accuracy. Therefore, in order to get enough points (15) in each interval, these ones are defined based on the satellite data series.

In option, the following adaptations may be done too:

- If station 2 is situated between 2 daily-observed stations (1 and 3, see Fig. 2b), the propagation celerity can be assumed to be constant between 1 and 3; therefore, the propagation function g_2 between 1 and 2 is obtained by multiplying g_3 (propagation between 1 and 3) by the ratio of distance between 1 and 2 (D_{12}) to the distance between 1 and 3 (D_{13}).
- Function f may have a predetermined shape. Experiments on several couples of field stations have shown that polynomial functions (second to fourth order) may give satisfying results. In this case, the calibration of the propagation model consists in calibrating a set of the five parameters that define the function f.

For calibration, the following quadratic error function is used:

$$E = \sqrt{\sum_{k=1...n} \frac{1}{n} (Z_{2,k}{}^{(s)} - Z_{2,k}{}^{(m)})^2} \tag{3}$$

where n is the number of measurements, superscripts (s) and (m) denote the simulated and measured values respectively.

3 RESULTS AND DISCUSSION

3.1 *Calibration of the propagation model using satellite data*

The calibration of the propagation model can be performed using any ground station (monitored daily) as input station (labeled 1 in the previous section) and satellite station as output. To illustrate the results, we use input stations located immediately upstream from the output station that needs to be interpolated.

Figures 3 and 4 show the results between Mopti gauge station and Envisat satellite station Env_545_02, and Diré and Env_917_01 respectively. The standard errors (error bars) are provided by the Hydroweb database. They represent the dispersion of the different measurements of the water level for each day. Although Koryoume station is closer to Env_917_01, it is preferable to use Diré station which is almost complete. Functions *f* and *g* are obtained by an interpolation (polynomial or linear by interval) of the calculated points (Fig. 5).

One can note that the flood dynamics is well represented by the interpolated model. Unlike what can be observed on the raw Topex data (see Fig. 6, early 1995), the simulated water levels have generally a smooth behavior. For instance, it can be observed at the ground stations that the water level seldom decreases during the flood rise, and seldom increases during the flood recession. Due to the accuracy of the altimetric data, this may not be verified on the raw data. On the contrary, the flood propagation model imposes that the output station behaves similarly to the input station (here, a gauge station). The method allows also capturing the maximum level during the flood (which is key information for the river knowledge and management). Since function *f* is monotonous (with a positive derivative), the intensity of the flood peak at the output station is consistent with the flood peak at the input station. This may be not the case for the satellite stations, due to accuracy (mainly Topex data) and to limited frequency of observations (mainly Envisat observations). One can note also that the dispersion of the satellite measurements are consistent with the simulated values. The root mean square error E is between 20 and 50 cm for all results, with Nash coefficients between 0.65 (poor results for one Envisat station) and 0.94, most values being between 0.85 and 0.90.

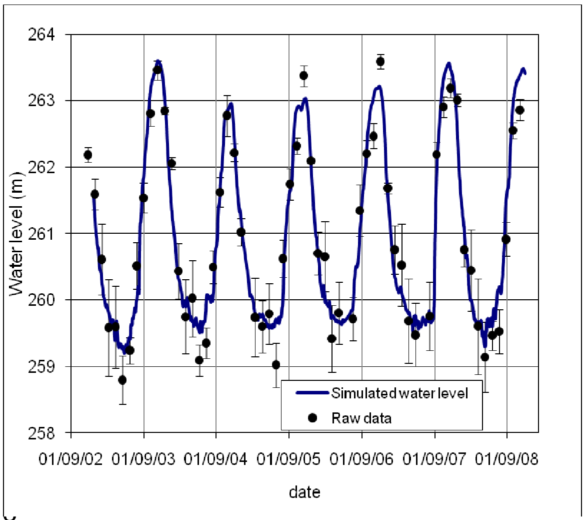

Figure 3: simulated level at satellite station Env_545_02, using gauge levels at Mopti. E=36cm, Nash coefficient=0.93

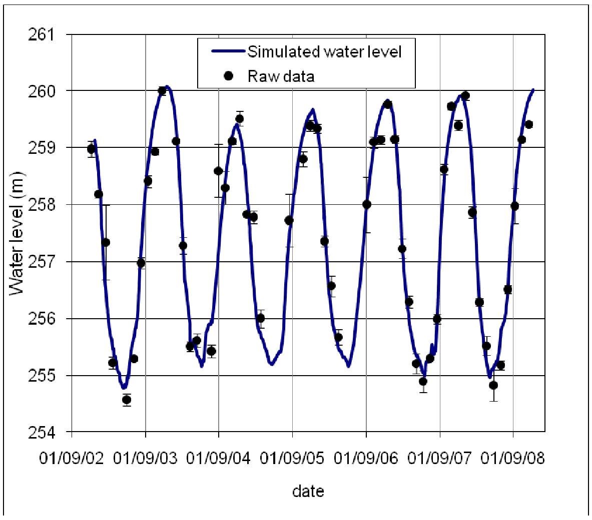

Figure 4: simulated level at satellite station Env_917_01, using gauge levels at Diré. E=41cm, Nash coefficient=0.90

The functions *f* and *g* are given in Figure 5. Each point corresponds to the optimal value obtained within the elementary interval of calibration. One can notice that *f* may be represented by two lines, which correspond to two distinct behaviors without overflow (level at Mopti lower than 262.5m) and with overflow. At low flow, the flood celerity tends to increase with water depth, whereas overflow tends to make it decrease due to water storage in the floodplain. Compared to calibrations obtained between gauge stations, there is much more noise on the propagation time with water level (see discrepancy of values around the polynomial fitting). This is explained by the much lower number of data used in each calibration interval and to reduced accuracy.

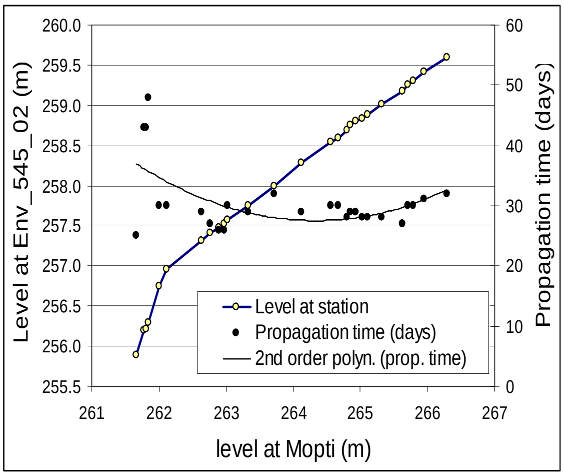

Figure 5: Calibrated functions *f* (level at station Env_545_02 as a function of level at Mopti) and *g* (propagation time as a function of level at Mopti).

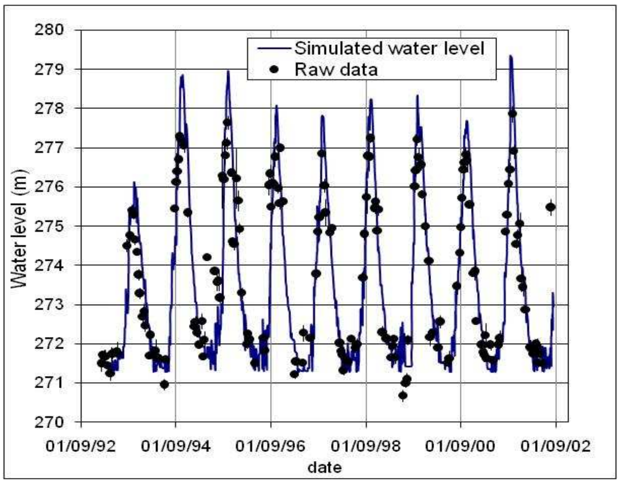

Figure 6: Simulated level at satellite station Topex_085c, using gauge levels at Kirango.

3.2 *Using propagation model between gauge stations to constrain the model*

The flood propagation model has been calibrated for each couple of ground stations, yielding functions *f* and *g* between ground stations (see examples on Figs. 7 and 8). Since data are much more numerous (daily data for more than 30 years for some stations), RMSE can drop down to a few centimeters, which proves that the model is efficient to simulate the flood dynamics. Under the assumption that propagation time is proportional to the distance (constant propagation celerity), one can predetermine the propagation time at the satellite stations, using the functions *g* calibrated between ground stations. The advantage is to have propagation times consistent with gauge observations and to minimize the number of calibrated parameters. As the degrees of freedom are reduced, the accuracy is slightly decreased, but a more robust calibration is expected, for example in the context of prediction. Typical functions *f* may also be obtained from empirical observations (Fig. 8) or physically-based models.

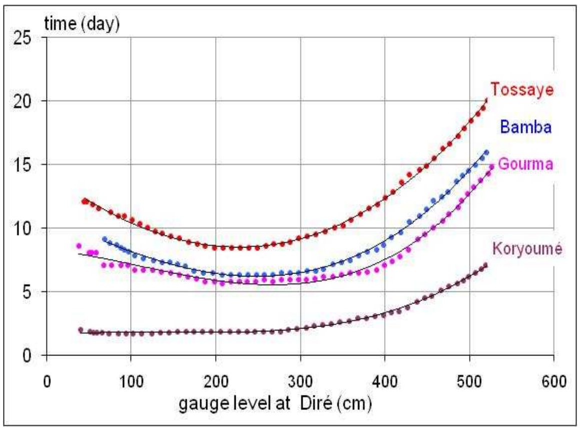

Figure 7: Propagation time between Diré and downstream stations

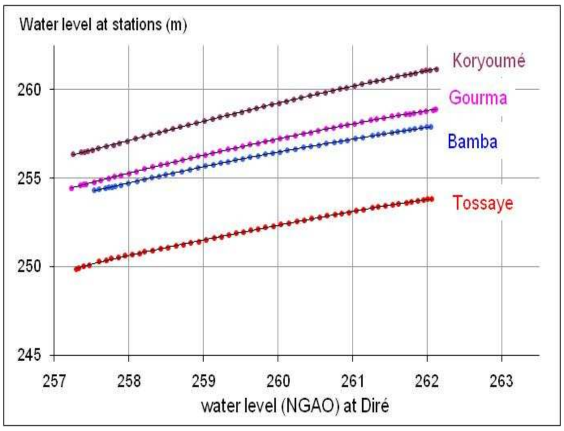

Figure 8: Level correspondence between Diré and downstream stations

3.3 *Taking account of measurement accuracy*

For gauge stations, the accuracy of each measurement is centimetric. For satellite observations, one may consider the relative accuracy of each measurement by weighing the contribution of each measurement inversely to its standard deviation. The new error function would be defined as follows:

$$E' = \sqrt{\sum_{k=1..n} \frac{1}{\sigma_k^2 / n} ({Z_{2,k}}^{(s)} - {Z_{2,k}}^{(s)})^2} \tag{4}$$

where σ_n is the standard deviation of measurement *n*. Actually, the correlation parameters are searched independently for different intervals of water levels. The error on the satellite measurements (and the dispersion of the values) are mainly linked to side effects on the river banks, and then correlated to the water level (Bercher 2008). This can be observed on Figure 3, where the dispersion is clearly the highest at low flow and minimum at high level (where side effects are minimized). Therefore, the relative weight of each measurement doesn't change much by the use of Equation 4 instead of Equation 3. However, it is possible to calculate confidence intervals for each simulated value. A better accuracy is expected at high flow than at low flow.

4 CONCLUSION

Satellite altimetry may be used for river monitoring, as shown here for Niger River and previously on other basins. One main challenge is to develop the hydrologic observation network with available measurements from space. Since data samples are sparse in time and accuracy of measurements is limited, an interpolation method is required to get information between measurements, and to adjust observed values to take into account their limited accuracy. The proposed method uses a hydrodynamic transfer function that has been designed to predict water level variations in large African rivers. It allows for interpolation of satellite observations at any time and captures the flood peak even though no measurement was available during this peak. The main advantage of the method developed here is to link the observed satellite level with reliable measurements and a reliable model. Improved accuracy may be obtained by improved accuracy of each single altimetric measurement, but also by improving propagation models, keeping them simple enough to use them in a data assimilation framework.

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