USING SATELLITE ALTIMETRY AND IMAGERY FOR THE COMPUTATION OF DAILY RIVER DISCHARGE

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ABSTRACT

Using satellite altimetry retracking schemes with data from ERS-2 and ENVISAT we obtained river stage (or level) along the Mekong. In this study we summarise methodologies to estimate daily discharge from this altimetric stage data, including quality control, in two scenarios. In scenario (1) altimetry measurements at a downstream site are used assuming that in-situ data are available at a site upstream, measured channel cross-sections are available at both sites and a hydrological model can provide lateral inflows between the two sites. The estimated discharge has a Nash-Sutcliffe r2 value of 0.893. In scenario (2) two ungauged sites are assumed. Use is made of satellite altimetry to provide a time series of river channel stage levels and longitudinal channel slope, with Landsat data used to provide a range of channel widths over a 50 km reach of river. The results show Nash-Sutcliffe r2 values of 0.90 and 0.86 at the two locations.

1. INTRODUCTION

There has been considerable interest in the scientific literature in using remote sensing data to estimate discharge in rivers where ground-based measurements are currently not available due to, inter alia, the region being sparsely populated, difficult to access or politically unstable. References [1-3] have reviewed the various satellite data sources and their potential, detailing a number of different techniques that make use of remote sensing to estimate river discharge. Remote sensing data can be used to measure river channel stage (or level), channel width or surface water extent and slope, all of which have potential for use in discharge estimation.

In this study daily discharge is estimated using remote sensing data on the Mekong river. Two scenarios are considered. In scenario (1) daily discharges were estimated at Nakhon Phanom using the following data: ERS-2 and ENVISAT altimetry data to provide river channel stage data at Nakhon Phanom, in-situ daily discharge data at a site 400 km upstream (Vientiane), measured cross-sectional channel data at both sites and the VIC hydrological model [4] to provide lateral inflows between the two sites. The in situ data at Nakhon Phanom was only used in the validation of the discharge estimations. In scenario (2) daily discharges were estimated at Nakhon Phanom and Vientiane using the following data: ERS-2 and ENVISAT altimetry data to provide river channel stage data and channel slope, and Landsat satellite imagery to provide a series of channel widths and hence channel cross-sections. The satellite data are applied to the Bjerklie equation [1] developed using a global database of discharge measurements, which relates channel width, average water depth and slope to the discharge. The in-situ data at Vientiane and Nakhon Phanom was only used in the validation of the discharge estimations

2. DATA

2.1 Mekong River

The Mekong River has a mean discharge of about 16,000 m^3/s, a catchment area of 810,000 km^2 and a length of 4,350 km. The climate of the Mekong basin is dominated by the monsoon between mid-May and early October leading to a seasonal rise in discharge in May and a peak in September or October. The lowest river levels occur in March and April.

A considerable number of measured in-situ stage and discharge data was obtained from the Mekong River Commission (http://www.mrcmekong.org/). With the data from Chian Sean, Vientiane and Nakhon Phanom for the period from 1/1/1996 – 31/12/2005 used here (Fig 1).

2.2 Remote sensing data

Two sources of remote sensing data are used in this work: ERS-2 and ENVISAT satellite altimetry and Landsat satellite imagery.

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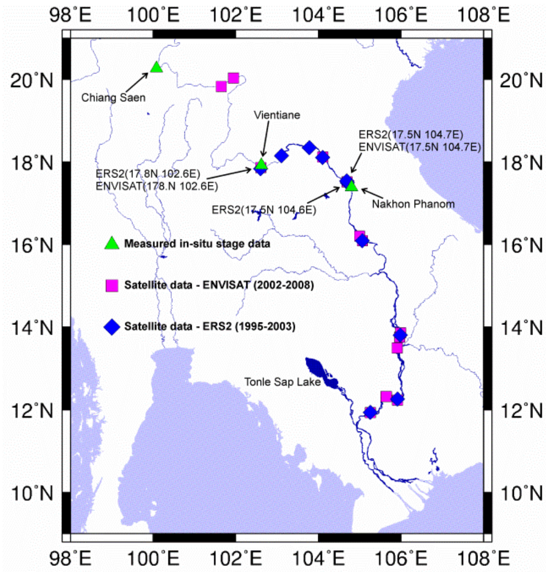

Figure 1. Measured in situ stage and satellite altimetry data on the Mekong River.

Satellite altimetry was utilised to measure both the water level and the slope. The data were derived using the retracking methodology detailed in [5] based on the 20 Hz ERS-2 and 18 Hz ENVISAT altimetric waveforms. The locations of the available altimetry data on the Mekong is provided in Fig. 1 for both ERS-2 (1995-2003) and ENVISAT (2002-2008). The overlap between ERS-2 and ENVISAT allows the data to be adjusted to a common datum to remove the impact of any bias between the two data sources. At each location the stage level is supplied every 35 days, but the crossing day differs for each location. Near Nakhon Phanom, data are supplied from two separate satellite crossing (one on an ascending South-North satellite ground track , the other on a descending N-S ground track) giving values every 17 or 18 days. In total, there are 10 ERS-2 and 12 ENVISAT crossing locations along the Mekong between Chiang Saen in the north and where Tonle Sap discharges into the Mekong in the south. Comparisons against observed stage measurements show that the altimetric measurements have a root mean square error (RMSE) of 0.44–0.65 m for ENVISAT and 0.46–0.76 m for ERS-2 [6].

Landsat images were used to measure the water surface width in river channels. Images were taken from both Landsat 5, which uses the Thematic Mapper (TM), and Landsat 7, which uses the Enhanced Thematic Mapper Plus (ETM+). Visible spectrum bands were used which had a resolution of 30m.

3. QUALITY CONTROL

A number of the altimetry data points are found to be subject to significant error. For example, towards the end of the dry season on 7 May 1999 the stage at Nakhon Phanom is 10.39 m, whereas the measured stage is 0.83 – an error of 9.56 m. In this case, it is possible that the satellite may be sensing irrigated land at the edge of the river. In order to remove these erroneous data points without using measured in-situ data all the contemporaneous altimetry data was considered together. They were scaled so they covered the same range and those points outside set confidence bounds were rejected. Details can be found in [6].

Fig. 2 shows the procedure for ERS-2 with data from ten gauges providing 734 points in total for the whole time period. During the procedure 118 points were rejected leaving 616.

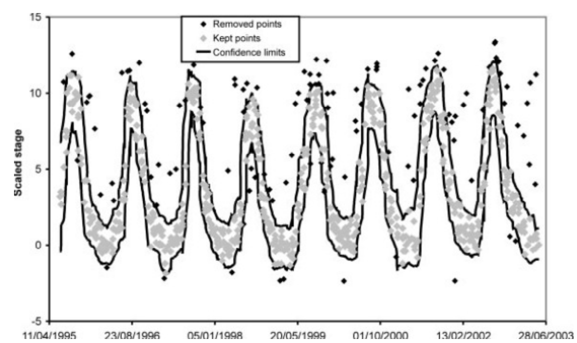

Figure 2. Rejected points, accepted points and confidence bounds for the ERS-2 altimetry data

4. SCENARIO 1

Daily discharge was estimated at a downstream site (Nakhon Phanom) using measured in-situ daily discharge at an upstream site (Vientiane). This also used the measured channel cross-sections at the two sites and the VIC hydrological model [7] to provide lateral inflows between the two sites. Use was made of ERS-2 and ENVISAT satellite altimetry to provide river channel stage levels. Full details of this method can be seen in [6].

An initial estimation of the daily discharge at Nakhon Phanom at time t ($Q^t_{NP\text{-}VIC}$) was taken to be equal to the discharge at Vientiane 3 days earlier (Q^{t-3}_{V}), the travel time is approximately 3 days for the 400km between the two sites, complemented by the VIC lateral inflows between Vientiane and Nakhon Phanom (Q_{VIC}), as shown in Eq. 1.

$$Q^{t}_{NP\text{-}VIC} = Q^{t-3}_{V} + Q_{VIC} \qquad (1)$$

The altimetry data provides stage data every 35 days. Each data point was converted to a discharge ($Q^{t}_{NP\text{-}SAT}$) using the discharge at Vientiane and the channels cross-sectional areas (A) at Nakhon Phanom (NP) and Vientiane (V), see Eq. 2. The areas were calculated by the altimetry measurements and the measured channel cross-sections

$$Q^{t}_{NP\text{-}SAT} = (A^{t}_{NP}/A^{t-3}_{V})\, Q^{t-3}_{V} \qquad (2)$$

This formula is very similar to the one developed by [8].

The updated daily discharge at Nakhon Phanom is then calculated by using the satellite estimated discharge ($Q^{t}_{NP\text{-}SAT}$) where known (every 35 days), but with the daily estimated data ($Q^{t}_{NP\text{-}VIC}$) providing the shape of the curve between these points.

Overall, the comparison between the estimated and measured discharge at Nakhon Phanom gives a Nash-Sutcliffe r2 value of 0.89 for the period from 1996-2005. Figure 3 shows the results for this scenario at Nakhon Phanom for 1996. The shape of the estimated discharge corresponds well with the measured values but the estimated values are lower than the measured values during the wet season. This is because the satellite estimated discharges ($Q^{t}_{NP\text{-}SAT}$), through which the daily estimated discharges curve must pass are too low. One possible explanation is that the ratio of the areas in Eq. 2 is too low, i.e if the area at Nakhon Phanom was larger and/or the area at Vientiane was smaller the value of $Q^{t}_{NP\text{-}SAT}$ would be larger. The areas are based on measured cross-sections and it is possible that a longer reach of river and the techniques used to estimate the channel cross-sections in Scenario 2 would give better results.

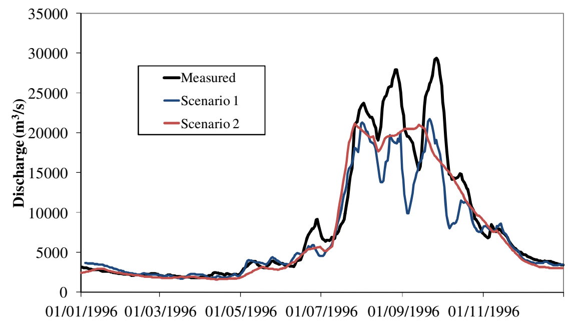

Figure 3. Measured and estimated discharge at Nakhon Phanom for 1996. The measured data was only used for validation

5. SCENARIO 2

Daily discharge was estimated at Nakhon Phanom and Vientiane on the Mekong but no *in situ* data, channel cross-sections or hydrological models were used. Again use was made of ERS-2 and ENVISAT satellite altimetry to provide river channel stage levels, the satellite altimetry also provided the longitudinal channel slope, and Landsat satellite imagery was also used. Full details of this method can be seen in [9].

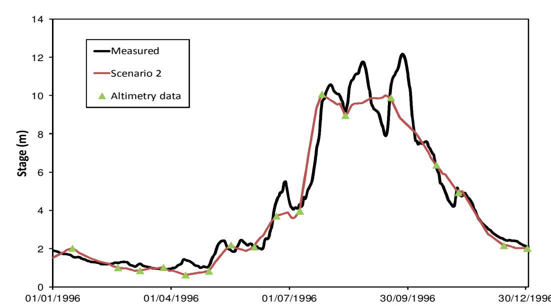

Figure 4. Measured and estimated stage data at Nakhon Phanom for 1996. The measured data was only used for validation

The first step was to use the satellite altimetry to obtain a daily stage time series. This was obtained by using the satellite altimetry data points (values every 35 days) at the desired location but with the shape between points calculated using all the altimetry along the Mekong.

For the 1996-2005 data this gives an RMSE of 0.73m considering only the altimetry points and a RMSE of

0.94m for the daily data. The 1996 data can be seen in detail in Fig. 4 and highlights the main problem, namely, that although, in general, estimated stage values correspond well with the measured values, the short duration high frequency behavior is not captured.

The next step was to obtain a stage-discharge relationship to convert this daily stage data to discharge data. Six Landsat images were used at each location to provide a range of channel widths over a 50 km reach of river (Fig. 5). Following the approach of [10] a long reach of river was used (the reach hydraulic geometry approach) rather than at a specific location. This allows for short-scale variability of natural river morphology as the channel width varies considerably along a reach of river and the average channel width is preferred.

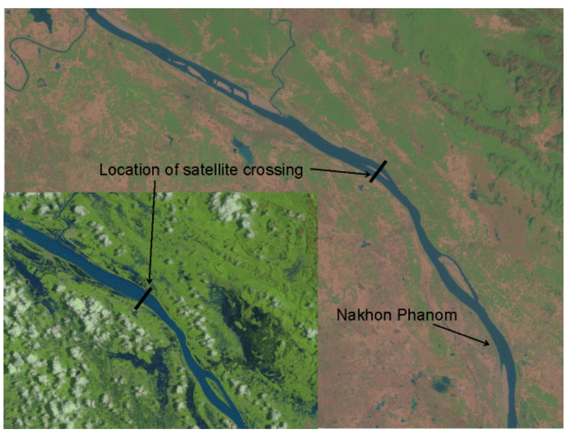

Figure 5. LANDSAT data showing 50km reach near Nakhon Phanom on 15/03/2002 and 30km reach (inset) near Nakhon Phanom on 19/08/2001.

The altimetry stage and width data enabled the channel cross-sections to be estimated (Fig 6). The main source of uncertainty is the unknown bathymetric depth (i.e the water depth below the minimum measured level) which cannot readily be obtained by remote sensing. This has been recognized by other researchers [11] . If measured channel cross-sections are available these could be used directly (although a reach average value would be needed). Alternatively, a single measurement of water level and discharge in a low flow period would be sufficient. In this work a pragmatic solution was to use the Q90 discharge (i.e the discharge exceeded 90% of the time) at another site on the same river. In this case the Q90 value well upstream at Chiang Sean was used

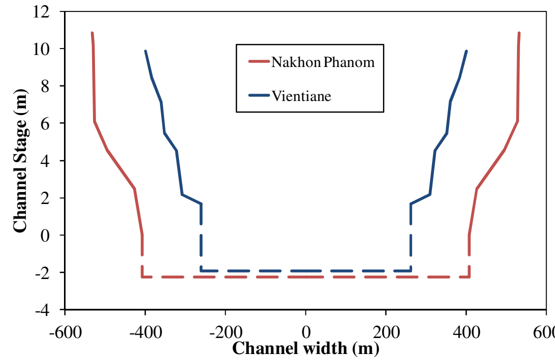

Figure 6. Channel cross-sections (solid lines) and bathymetric depths (dashed lines) for a 50km reach on the Mekong River.

The channel cross-section data was substituted into the Bjerklie *et al.* (2003) equation (Eq. 3), which is based on the Manning's resistance equation, and has been developed using a global database of channel hydraulic information and discharge measurements.

$$Q_B = 7.22\, W^{1.02}\, Y^{1.74}\, S^{0.35} \qquad (3)$$

where Q_B (m^3/s) is the Bjerklie equation estimated discharge, W (m) the water surface width in the river channel, Y (m) the average water depth and S (-) the longitudinal channel slope. The value of 7.22 is a discharge coefficient and it was fitted using only single channels (rather than braided rivers). The equation is based on the resistance equations formulated by Chezy and Manning. In Eq. 3 the width was measured from the Landsat imagery, the average water depth from the channel cross-sections and the longitutidnal slope from the satellite altimetry along that section of river. For each of the 6 Landsat images this equation gave a discharge corresponding to an altimetry estimated stage. Hence an estimated stage-discharge relationship was obtained. This stage-discharge relationship was as used with the daily stage data to give the estimated daily discharge.

For the period from 1996-2005, the comparison between measured and estimated discharge gives Nash Sutcliffe efficiency values of 0.90 for Nakhon Phanom and 0.86 for Vientiane. This can be seen in detail for 1996 in Fig. 3. Particularly encouraging is the timing of the rise and fall of discharge in the wet season, where the estimated discharge corresponds very closely with the measured discharge. The main difference between the measured and estimated results is that, as the short duration high frequency behavior in the stage data (Fig. 4) are not captured in the estimated time series, the corresponding shorter duration high frequency behavior are similarly not captured in the estimated discharge time-series (Fig 3.). This is in contrast to scenario 1 where this behavior was captured. In scenario 1 the daily upstream discharge was available but that is not the case in this scenario.

The better results obtained at Nakhon Phanom compared to Vientiane, are due to two ERS2 satellite crossings close-by at Nakhon Phanom giving data every 17 or 18 days from 1/1/1996 to 31/12/2002, compared to data every 35 days at Vientiane.

6. CONCLUSIONS

Two methodologies have been summarized in which daily discharge is estimated at an ungauged site using altimetric stage data. The estimated discharge is compared against the measured in situ data as a validation test. Both methodologies show promising results and indicate the usefulness of altimetric stage data to estimate daily river discharge at ungauged sites.

In scenario 1 discharge is estimated at Nakhon Phanom assuming in-situ data are available at a site upstream (Vientiane), measured channel cross-sections are available at both sites and a hydrological model can provide lateral inflows between the two sites. The estimated discharge has a Nash-Sutcliffe r2 value of 0.89. In scenario 2 discharge is estimated at both Nakhon Phanom and Vientiane, but less in situ measured data is used. In this case the satellite altimetry is used together with satellite imagery Use is made of satellite altimetry to provide a time series of river channel stage levels and longitudinal channel slope, with Landsat satellite imagery used to provide a range of channel widths over a 50 km reach of river. A simple method is proposed to estimate the unknown river channel bathymetric depth based on the Q90 (the discharge that is exceeded 90% of the time) value at a location on the same river. The results show Nash-Sutcliffe r2 values of 0.90 and 0.86 at the two locations.

The methodologies summarized here are relatively simple to apply and so they have the potential to estimate discharge in rivers where ground-based measurements are currently unavailable. Further work is in progress to test and develop these methodologies on other large rivers.

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