Estimation of River discharge using Very High-Resolution Satellite Data in Yangtze River

JIQUN ZHANG, KAIQIN XU, MASATAKA WATANABE

E-mail: zhang.jiqun@nies.go.jp

National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, 305-8506, Japan

CHUNPENG SUN

Hydrology Bureau of Ministry of Water Resources of China, 100053, Beijing, China

Abstract: The measurement of river discharge is among the most fundamental observations and is necessary for understanding many water-related issues, such as flooding hazards, sediment transportation, and nutrient movement. Traditionally river discharge is estimated by measuring the water stage and converting the measurement to discharge using a stage-discharge rating curve. The possibility of monitoring river discharge from satellites has been largely ignored, because it is difficult to measure water surface information from space with sufficient precision. In this paper, an efficient approach to discharge estimation using mainly satellite data is developed and described. The proposed method, which focuses on the measurement of water-surface width coupled with river width-stage and stage-discharge relationships, is applied to the Yangtze River with good results.

Key Words: Yangtze River, River discharge, Water stage, Quickbird-2 satellite, Very high resolution imagery

1. Introduction

Many applications of both water resource management and agriculture management require knowledge of river discharge. Currently, river discharge is estimated by directly measuring flow in the field, and is derived from stage data through the use of a stage-discharge rating curve. Despite the importance of river discharge information, a comprehensive monitoring network faces numerous technological, economic, and institutional obstacles on a global basis. For many rivers, discharge measurements are either nonexistent or not available in a timely manner. This is especially true in underdeveloped countries, for which the cost of establishing and maintaining a dense network of stream gauges is prohibitive. Thus, a method that uses remote data to estimate discharge would be beneficial from an economic perspective and would provide a much larger data network. Up to now, only a few studies have attempted to use satellite data to estimate river discharge. Smith et al. (1995, 1996, 1997) suggested that ERS SAR data may be used to estimate instantaneous discharge in a system of large braided rivers. However, successful application of this technique to braided rivers smaller than the studied one is probably not possible restricted by the 25-meter nominal spatial resolution of ERS SAR data. Just as Schultz(1988) pointed out, satellite sensors do not measure hydrological data directly. In many cases the analysis of remotely sensed data consists only of developing a regression equation between the desired information and the available pixel intensities. For example, if a series of satellite imagery covered the same river control section from dry season to flood season, and if the instantaneous discharge was measured in the ground, then it would be possible to construct the rating curve between satellite-derived section width (or the area of inundation) and discharge. Based on this rating curve, it would be possible to estimate discharge from satellite images. The weakness of this method is that a lot of satellite imagery covering the study site must be acquired; this will be time-consuming and costly. Centimeter scale water level changes have been measured by using satellite radar altimeter data (Birkett, C.M, 1998) or (and) interferometric processing of SAR data (Doug Alsdorf, et al, 2000,2001). As altimetry is a profiling and not an imaging technique, it is applicable only to water bodies great than about two kilometers in width. Interferometric radar measurements of water level changes requires two SAR images acquisitions from identical (or nearly identical) viewing geometries and the two images were coregistered to a sub-pixel accuracy and subtraction of the complex phase and amplitude values at each SAR image pixel.

Recently, some 1-m scale satellite data have become possible for non-military application. This brings the detailed earth observation scope into a feasible and operational stage that other medium/small scale image such as Landsat and SPOT image are not compatible. That potentially enable hydrologists to address the previously unsolved questions, for example, it enable hydrographic information obtained from satellite to be used as the basis for a general method for estimating river discharge.An efficient approach, which focuses on the measurement of water-surface width coupled with river width-stage and stage-discharge relationship, has been developed and validated in Yangtze River.

2. Approach to estimating river discharge from high-resolution satellite data

2.1 Fundamentals of river discharge estimation

Discharge at a river cross section, Q, is the volumetric flow rate through that cross section, and can be given by

$$Q = \int_A V \bullet dA \qquad (1)$$

$$A = WY \qquad (2)$$

Where, V is the average velocity, W is the water-surface width, Y is the average depth, and A is the cross-sectional area perpendicular to the flow direction. Discharge estimation requires the determination and/or estimation of the channel cross-sectional area, including average depth, width, and average stream flow velocity.

Current remote data is restricted to surface features that can be resolved, including information about channel width or water-surface width but not (Y) or (V). However, for almost all medium-sized to large rivers, stage-discharge rating curves have been constructed at the control sections along the river, and the corresponding river channel geometry has been measured and modified every year. This is the foundation for estimating discharge from satellite data. Based on the stage-discharge rating curve as well as channel geometry, satellite-derived water-surface width can be converted to river discharge. The critical problem is how to measure water-surface width with satisfactory accuracy. A remarkable characteristic of QuickBird-2 imagery is that its spatial resolution has reached 0.61 meters (nadir). This means it can be used to determine water-surface width with satisfactory accuracy.

2.2 Discharge estimation procedure

The approach can be summarized as follows:

① Construct stage-discharge rating curve according to hydrologic data from the study site;

② Field survey the channel geometry or construct the relationship between water-surface width and water stage according to hydrologic data in the control cross section;

③ Identify and measure water-surface width in the control cross section from QuickBird-2 imagery;

④ Convert satellite-derived water-surface width to water stage based on step ②;

⑤ Convert water stage to discharge based on step ①.

3. A Case Study at Yichang Section of Yangtze River

3.1 Study area

Yichang (111° 17′ E, 30° 41′ N), located in the upper and middle reaches of the Yangtze River. The Gezhouba Dam, completed at the end of the 1980s, is located here, and the world-renowned Three Gorges Dam is only about 40km to the north of this site (Fig.1).

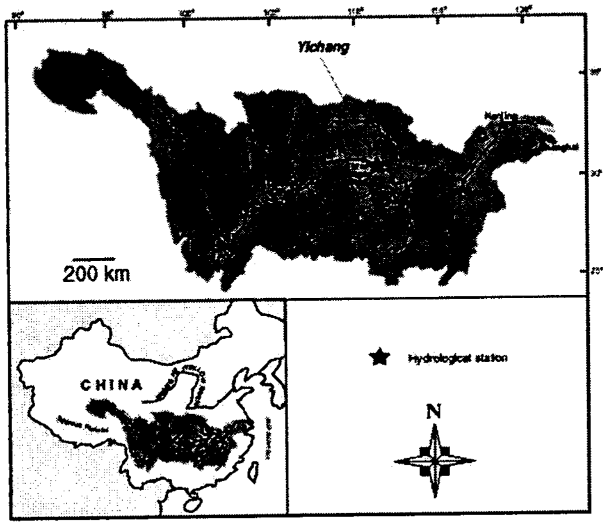


Fig.1 location of study site in Yangtze river

3.2 Relationship between water stage and discharge.

The conversion from river stage to discharge is made according to the stage-discharge rating curve. A total of four years (1998.1.1~2001.12.31) of water stage and discharge data were acquired at the Yichang hydrological gauging station. The correlation between H (water stage) and Q (discharge) is plotted in Fig. 2. It can be seen that the best suitable power function is:

$$H= 14.887Q^{0.1155} \qquad (R^2 =0.9891) \qquad (3)$$

Regression of Log Q on Log H yields Equation (4):

$$Q = (H/14.887)^{8.658} \qquad (R^2 = 0.9891) \qquad (4)$$

Once the relationship has been established, it may be used to convert river water stage to river discharge.

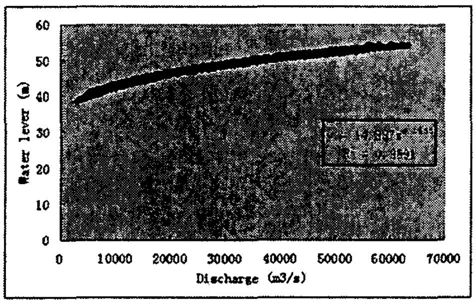


Fig. 2 Stage-discharge rating curve at Yichang section

3.3 River channel geometry in the control cross section

In order to convert satellite measurement data to discharge data, it is essential to measure the geometry of the river channel or to construct the relationship between water-surface width and water stage. From the cross-section geometry, we could construct a width-depth ratio formula in different segments or look-up tables to convert water-surface width to water stage.

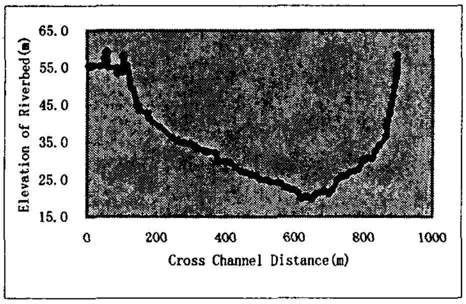


Fig.3 The Yangtze River channel cross-section geometry at the Yichang control cross-section

Based on the water stage (H) and corresponding water-surface width (B), two width-depth ratio formulae were constructed and listed as follows:

When H$\leqslant$ 43.7 or B $\leqslant$ 726

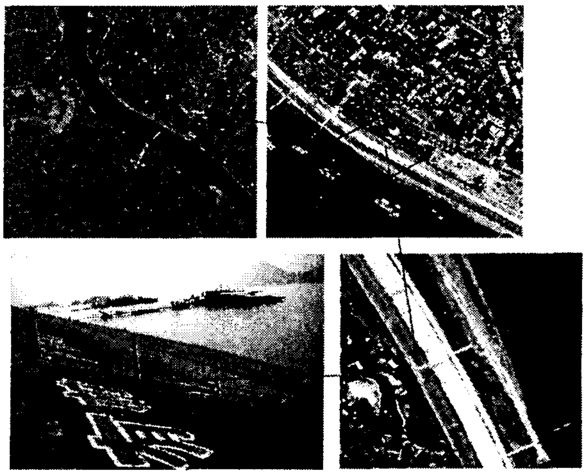
$$H = -1.24683 \times 10^{-6} B^3 + 2.54629 \times 10^{-3} B^2 - 1.6633B + 386.281 \qquad (5)$$

When H > 43.7 or B >726

$$H = 2.39852 \times 10^{-5} B^3 - 5.31617 \times 10^{-2} B^2 + 39.4489B - 9754.36 \qquad (6)$$

3.4 Identification and measurement of water-surface width from satellite imagery

A scene from Quickbird-2 imagery (centered at 111.281° E, 30.688N) was acquired on March 29, 2002 (Fig. 4). The specifications of this scene image are listed in Table 1.



a) The Quickbird-2 image b) Control cross section on the left river bank c) the zoom of the left river bank on the control cross bank d) The photograph of the left riverbank at the Yichang control section

Fig.4 Quickbird-2 Satellite Image of Yichang Section in the Yangtze River (Acquired on Mar. 29, 2002)

Table 1 Specifications of the Quickbird-2 image

Item	Feature	Item	Feature
Acquire Time	2002-03-29 T03:23:27 (GMT)	Satellite Azimuth	342. 14
Col Ground Resolution (m)	0. 7	Satellite Elevation	76. 9507
Row Ground Resolution (m)	0. 7	In Track View Angle	11. 0393
Sun Azimuth	142. 779	Cross Track View Angle	-5. 5146
Sun Elevation	57. 3328	ImageQuality	Excellent

As the study site in which we are interested is a small area with flat terrain, we rectify the satellite imagery by applying polynomial modeling instead of orthorectification. About 10 GCPs were selected to rectify the imagery to the azimuthal equidistant map projection system. The processing described here was realized with the image processing software ERDAS Imagine 8.4. Two GCPs, both located at the control cross section, have been selected and measured. Two intersections, one between the two-GCPs line and another perpendicular to the river water-surface edge, have been identified and located from the Quickbird-2 images. The distance between those two intersections is the water-surface width (B), and it was measured with measurement tools in ERDAS. The water-surface width (B) is 668.86m.

3.5 Estimating river discharge and comparing it with ground-measured discharge

The corresponding water stage (H) was acquired based on the width-depth ratio formula (5):

$$H=-1.24683\times 10^{-6} B^3 +2.54629\times 10^{-3} B^2-1.6633B+386.281 =39.82 \text{ m}$$

Based on Equation 4, the water stage is converted to discharge:

$$Q= (H/14.887)^{8.658} =(39.82/14.887)^{8.658}=5006.2 \text{ (m}^3\text{/s)}$$

From Table 1, we know that the acquired time (Greenwich mean time, GMT) of this scene image is 03:23am, March 29, 2002. Yichang is located 8 time zones east of GMT, so the acquired time can be converted to local time of 11:23am, March 29, 2002. That is to say, in the Yichang section of the Yangtze River, the satellite-derived discharge on 11:23am, March 29, 2002, was 5006.2(m^3/s).

On the other hand, we collected river discharge data from the Yichang Hydrological gauging station. Q=5150(m^3/s), and the observation time was 08:00am, March 29, 2002. On the basis of the ground discharge observation by the hydrological gauging station, we reached a 97.2% discharge estimation accuracy.

4. Conclusions

Traditionally, a river's discharge is monitored by measuring its water depth or surface elevation and then converting these measurements to water discharge using a calibration or stage-discharge rating curve. The possibility of monitoring changes in river flow from satellites has been largely ignored until now. The research described in this paper is the first to focus on the estimation of river discharge from very high resolution satellite data. This approach is based on a series of simple procedures: Water-surface width measurements coupled with river width-stage and stage-discharge rating curve derived from a field survey. The estimation precision of instantaneous river discharge from satellite imagery is influenced mainly by river channel geometry and river discharge-stage rating curve. We believe that this kind of technology is effective for providing hydrographic data suitable for tracking river discharge as an ancillary to the traditional method. Furthermore, because remotely sensed images can be captured more readily with high resolution, efficient methods to convert data obtained from a satellite platform to geographic information like the one proposed here should be very useful for extracting up-to-date and accurate water-related information.

References

Birkett, C.M., 1998, Contribution of the TOPEX NASA radar altimeter to the global monitoring of large rivers and wetlands, *Water Resources Research*, 34, 1223-1239.

Douglas E. Alsdorf, J. M. Melack, T. Dunne, L. A. K. Mertes, L. L. Hess, and L. C. Smith, 2000, Interferometric radar measurements of water level changes on the Amazon flood plain, *Nature*, 404, 174-177.

Douglas E. Alsdorf, Laurence C. Smith, and John M. Melack, 2001, Amazon floodplain water level changes measured with interferometric SIR-C Radar, *IEEE Transactions on Geoscience and Remote Sensing*, 39(2), 423-431.

Schultz GA., 1988, Remote sensing in hydrology, *Journal of Hydrology*, 100(1/3), 239-265.

Smith, L. C., Isacks, B. L., Forster, R. R., Bloom, A. L., and Preuss, I., 1995, Estimation of discharge from braided glacial rivers using ERS-1 SAR: first result, *Water Resources Research*, 31, 1325-1329.

Smith, L. C., Isacks, B. L., Bloom, A. L., and Murray, A. B., 1996, Estimation of discharge from three braided rivers using synthetic aperture radar(SAR) satellite imagery: potential for application to ungauged basins, *Water Resources Research*, 32(7), 2021-2034.

Smith L. C., 1997, Satellite remote sensing of river inundation area, stage, and discharge: a review, *Hydrological Processes*, 11, 1427-1439