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AN INTEGRATED APPROACH INCORPORATING RIVER CROSS-SECTIONAL GEOMETRY DERIVED FROM HIGH RESOLUTION DSM FOR RIVER DISCHARGE ESTIMATION

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Many kinds of hydraulic information can be obtained from space nowadays, which are potentially useful for river discharge estimation. In this study, river cross-sectional geometry was extracted from high resolution Digital Surface Model (DSM) which was produced from ALOS PRISM images. Then the derived information was combined with Manning Equation to describe relation between discharge and cross-sectional water surface width. By integrating rainfall-runoff model with this relation which is used to describe hydraulic relation at basin outlet, it is possible to calibrate rainfall-runoff model using satellite observations of river width. The methodology is demonstrated through a case study in Mekong River at Pakse. The results show that discharge is estimated with acceptable accuracy and values of parameters for the hydraulic relation obtained from calibration properly reflect hydraulic condition at Pakse region. The proposed method could be an effective approach for discharge estimation in larger ungauged basins.

Key Words: *Large Ungauged Basins, Manning Equation, Cross-sectional Geometry Derived from ALOS PRISM DSM, Satellite Measurement of River Width, Calibration of Rainfall-runoff Model*

1. INTRODUCTION

Without comprehensive measurements of surface water storage and discharge, the availability of freshwater resources cannot be predicted with confidence[1]. River discharge monitoring provides important information which is of great benefit to both society and science. However, gauging stations and access to river discharge information have been decreased since 1980s[2].

River discharge is usually calculated based on continuity equation:

$$Q=A\cdot V=W_e\cdot Y\cdot V \qquad (1)$$

where Q is the volume rate of flow, A is cross-sectional area of the flow which is obtained by multiplication between cross-sectional water surface width W_e and mean water depth Y, and V is mean velocity. Hydrographic data obtained from satellites offer possibility of broad and potentially frequent global coverage of river discharge estimates[3]. As the three variables in Eq.(1) can not be measured from space simultaneously, functions correlate discharge to one or more measurable variables are required[4]. **Table 1** summaries the relations being adopted in researches estimating discharge from space. The parameters in these rating functions are empirical ones that reflect river cross-sectional geometry and balance between gravity and friction. Discharge data is necessary for calibration of these relations, which limits application in ungauged sites.

In these relations, river width or water surface elevation is indispensable, which scales cross-sectional area that water occupies. If information about cross-section shape and slope-resistance relation is also available, using Manning Equation is possible, which eliminates the need of discharge data for calibration. The Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) which is loaded on the Advanced Land Observing Satellite (ALOS) launched by Japan in 2006 is expected to generate worldwide topographic data in respects of its high resolution[9]. The Digital Surface

Table 1 The empirical relations being used for discharge estimation from space in past studies[1]

	Equations
Single variable	$W_e=aQ^b$ [5]
	$Q=c(H-H_0)^d$ [6]
Multiple variables	$Q=k_1 \cdot W_e^e \cdot Y^f \cdot S^g$ [7]
	$Q=k_2 \cdot W_e^h \cdot V^i \cdot S^j$ [7]
	$Q=k_3 \cdot W_e^k \cdot V^l$ [7]
	$Q=k_4 \cdot W^{*m} \cdot Y^{*m} \cdot Y^o \cdot S^p$ [7]
	$Q=qW_e^r \xi^s$ [8]

[1] Q is discharge, W_e is water surface width, H is water surface elevation, H_0 is elevation of zero flow, Y is mean depth, S is channel slope, W^* is bankfull width, Y^* is bankfull mean depth, ξ is channel sinuosity, and a to s are empirical parameters.

Model (DSM) provided by Remote Sensing Technology Center of Japan (RESTEC) has a spatial resolution of 2.5 meter. With this high solution DSM, cross section geometry for large rivers could be obtained, which provide useful information for discharge estimation from remote sensing.

The purpose of this study is to propose a new approach for discharge estimation in ungauged basins, which combines cross-sectional geometry derived from ALOS PRISM DSM with Manning Equation to describe relation between discharge and cross-sectional water surface width (Q-W_e relation). By integrating Rainfall-Runoff model (RR model) with this Q-W_e relation which is adopted to describe hydraulic relation at basin outlet, instead of discharge data, the RR model is calibrated against satellite observations of river width using automatic calibration algorithm. Compared with Sun *et al.*[10] using at-a-station hydraulic geometry to describe Q-W_e relation which also try to calibrating RR model against river with, one advantage is that parameters of this Manning Equation based relation are physically meaningful or can be set according to literature value, which facilitates setting robust ranges of parameters before automatic calibration. And setting proper ranges are important to reduce uncertainty in calibration process.

2. METHODOLOGY

(1) Combining river cross-sectional geometry information derived from PRISM DSM data with Manning Equation

Manning Equation is widely used for discharge estimation in open channel flow condition:

$$Q = \frac{1}{n} \times R^{2/3} \times S^{1/2} \times A \tag{2}$$

where n is the Manning roughness coefficient, S is slope, R is hydraulic radius, and A is river cross-sectional area that flow occupied. River water surface width (W_e) can be observed with wide spatial and temporal coverage from remote sensing. If river cross-sectional shape is known, values of R and A corresponding to specific value of W_e can be obtained. Then if values of n and S are also known, discharge could be calculated. Motivation of using cross-sectional shape derived from PRISM DSM is to make W_e as an index for scaling R and A.

PRISM DSM provides the Earth's surface elevation at a high spatial resolution of 2.5m. The vertical resolution of DSM data is one meter, in other words, the value of elevation is in the form of integer. Water surface are treated as "dead area" and no elevation is provided. To the end of scaling R and A using W_e, several steps are needed:

1. Build relation between river cross-sectional width (W) and corresponding elevation (H) above water surface. As shown in **Fig.1 (a)**, the elevations for the portion of cross section above water surface (blue line) can be obtained in 2.5 meter horizontal interval. Based on this information, the horizontal distance between points with same elevation is derived. From this distance for each elevation above water surface, the W-H relation is built.

2. Extend the W-H relation to the whole cross-section. As shape below water surface (red line in **Fig.1 (a)**) can not be obtained from DSM, we assume the bottom of cross section is flat. By extrapolation from H-W relation derived in Step one and proper estimation about bottom elevation (H_0), the W-H relation for the whole cross-section is built.

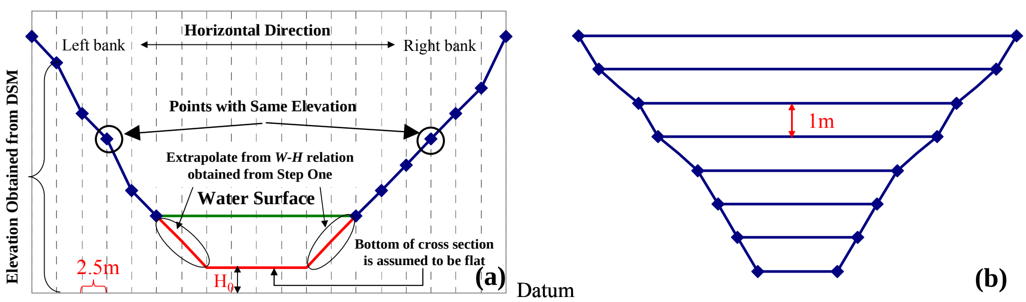

Fig. 1 (a) The schematic description of deriving relation between cross-sectional width and corresponding elevation from DSM data. **(b)** The geometrical model describing cross-section shape which consists of a series of symmetrical trapezoids

3. Build relation between W_e and R, W_e and A. Based on the W-H relation, under assumption that shape between each two adjacent integer elevations is symmetrical trapezoid as shown in **Fig.1 (b)**, quantitive relations between cross-sectional width and other factors describing cross section geometry, such as cross-sectional area, can be obtained. Then R and A corresponding to satellite observations of W_e can be calculated.

Combined with information about cross-sectional geometry derived from PRISM DSM, Eq.(2) is converted into a new form:

$$Q = \frac{1}{n} \times \left[f_1(W_e|H_0) \right]^{2/3} \times S^{1/2} \times f_2(W_e|H_0) \qquad (3)$$

where f_1 and f_2 is the W_e-R and W_e-A relation derived from PRISM DSM respectively, n, S and H_0 are three parameters that values need to be specified.

(2) Integrating RR model with PRISM DSM data based Manning Equation which facilities calibrating RR model against river width measured from satellites

How to get reasonable values for three parameters in Eq.(3) is challenging. n is usually estimated by modeler subjectively, which is one major source of error for discharge estimation using slope-area method [4)]. S and H_0 could be measured from field survey. However, as our target areas are ungauged basins, direct observation are considered to be relatively difficult. To reduce uncertainty associated with estimation for the three parameters, in this study, we didn't use Eq.(3) in straightforward manner as mentioned above.

Rainfall-Runoff model is widely used for river discharge estimation. The reliance on discharge data for calibration limits direct applications in ungauged basins. For RR model, output is simulated discharge at basin outlet. For inverse function of Eq.(3), W_e is expressed as:

$$W_e = f(Q|H_0, n, S) \qquad (4)$$

where Q is input for Eq.(4) , W_e is output, and n, S and H_0 are three parameters. Physical explanation is that variation of discharge is accompanied by change of river width. By integrating RR model with Eq.(4) which is adopted to describe Q-W_e relation at basin outlet, simulated discharge is converted into water surface width, which means output of the integrated model (i.e., RR model combined with Eq.(4)) is river width. For basins discharge gauging is unavailable at basin outlet, but satellite observations of river width, this integrated model can be calibrated directly. And calibration objective is shifted to minimize difference between satellite measurements and simulated values, which is achieved by tuning parameters of RR model and Q-W_e relation simultaneously. And no discharge data are needed under this calibration scheme which is shown in **Fig.2**. After calibration, we consider parameters for RR model being properly identified. Finally, calibrated RR model alone will be utilized for discharge estimation for the same period as calibration.

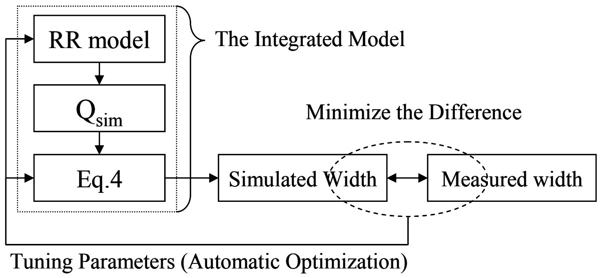

Fig.2 The integrated model and calibration scheme

Under the proposed calibration scheme, the n, S and H_0 are considered to be time-invariant as RR model's parameters. And the cross-sectional geometry derived from DSM for basin outlet is thought to be effective for the whole calibration period. Therefore, to reduce uncertainty associated with incorporating Eq.(4), this method is only applicable to basins for which cross-sectional shape at basin outlet doesn't change dramatically. For measuring river width from remote sensing, to reduce the error associated with spatial resolution of satellite images, large rivers are preferred.

3. APPLICATION EXAMPLE

(1) Study area and calibration data

The study area is Mekong River at Pakse which is located in the southwest part of Laos. Pakse gauging station (15°07'N, 105°48.0'E) is at the confluence of the Xedone and Mekong Rivers. Minimum and maximum discharge for the period of 1923-2005 is 1,060m^3/s and 57,800m^3/s respectively. The whole upstream area for Pakse station (545,000 km^2) is selected as target area for RR model. We obtained 16 scenes of Japanese Earth Resources Satellite-1(JERS-1) Synthetic Aperture Radar (SAR) images over Pakse region which cover the period of 1995-1998. For each image, river width was measured (refer to Sun *et al.*[10)] for detail about extracting river width from JERS-1 SAR images). Totally 16 river width records were obtained as calibration data for the integrated model. A good correlation ($W_e = 1221.3Q^{0.0341}$, $R^2=0.92$) exists between the 16 width records and gauged discharge at Pakse station.

(2) RR model

HYdrological MODel(HYMOD) is a parsimonious daily step model developed by Boyle[11)], based on probability distributed model proposed by Moore[12)]. As shown in **Fig. 3**, it has nonlinear soil moisture

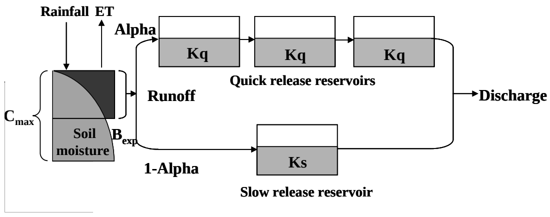

Fig.3 Schematic description of HYMOD's structure

accounting component connected to a linear routing system that consists of a series of three identical quick release reservoirs in parallel with one slow release reservoir. There are five parameters: *Cmax* is maximum soil moisture storage capacity; *Bexp* is degree of spatial variability of the soil moisture capacity; *Alpha* is factor distributing the flow between slow and quick release reservoirs; *Ks* and *Kp* is residence time of the slow release reservoir and quick release reservoirs respectively. To apply HYMOD to large basins, the whole basin was divided into subbasins to more accurately describe spatial variations, and two routing parameters were spatially varied depending on distance between each subbasin and basin outlet. The study area was divided into eight subbasins. Input data are daily rainfall data from 26 gauging stations and Ahn and Tateishi potential evapotranspiration [13].

(3) Extracting river cross-sectional geometry from PRISM DSM

To reduce measurement error and approximate the mean conditions for Pakse region, for measuring river width from JERS-1 SAR images, river width being measured is average width over certain reach length. Based on similar reasons, the *W-H* relations of 30 cross-sections measured from DSM were averaged to reflect regional condition. Locations of the cross-sections are shown in **Fig.4**. The distance between two adjacent cross-sections is around 500 meters.

The DSM was generated from panchromatic images obtained on March 31, 2009, for which it is almost the end of dry season. **Fig.5** shows the *W-H* relations for the 30 cross-sections and the average relation obtained by calculating the average width of each elevation from the 30 cross-sections. The average relation takes on high linear trend. At Pakse region, only in bank flow exists. Single linear function is utilized to describe this regional relation:

$$W = \alpha H + \beta \qquad (5)$$

based on linear regression, value of α and β is 17.606 and 485.68m respectively. And the correlation is high (R^2= 0.95). Under assumption of symmetrical trapezoidal shape, the W_e-A and W_e-R relation is calculated as follow respectively:

$$A = \frac{1}{2\alpha} \times \left[W_e^2 - (\alpha H_0 + \beta)^2 \right] \qquad (6)$$

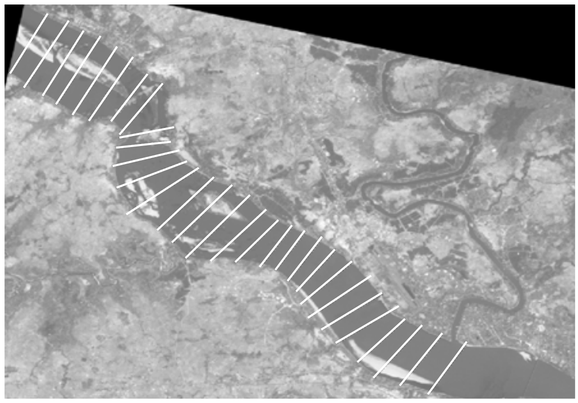
Fig.4 Locations of 30 cross-sections at Pakse for which *W-H* relation is measured from DSM

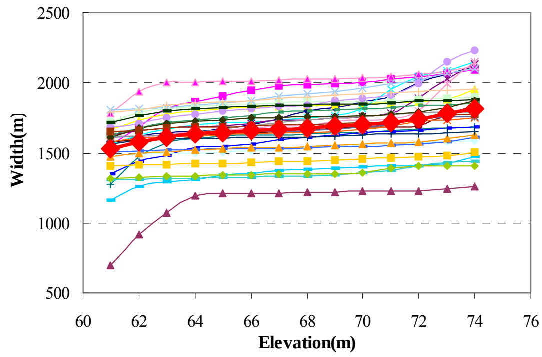

Fig.5 The derived W-H relations for the 30 cross-section and the average relation (thick red one)

$$R = \sqrt{1+\frac{4}{\alpha^2}} \times W_e + \left(1 - \sqrt{1+\frac{4}{\alpha^2}}\right) \times (\alpha H_0 + \beta) \qquad (7)$$

Incorporating Eq.(6) and Eq.(7) with Manning Equation, explicit form of Eq.(3) is obtained. As explicit form of Eq.(4) can not be derived, to calculate W_e corresponding to simulated discharge, Newton-Raphson iteration method was applied to Eq.(3). And values of *n*, *S* and H_0 were generated by automatic calibration algorithm, which were treated as known constants during the process of iteration.

(4) Calibration algorithm

To reduce RR model's parameter uncertainty, multi-criteria method is considered as an effective approach[14]. For the case study, only information from 16 time steps is available for calibration. Visually comparison between observed and simulated hydrograph is impossible. A multi-objective calibration algorithm: the Nondominated Sorting Genetic Algorithm II (NSGAII) was used. Fitness assignment is based on Pareto ranking. And diversity maintenance is based on crowing distance operator. Root Mean Square Error (RMSE) and Coefficient of Determination (R^2) were selected as objective functions. The calibration period for the integrated model is 1995-1998. Then calibrated HYMOD alone was also utilized for discharge estimation for the same period as calibration.

Table 2 Ranges of parameters need calibration

Parameter	Range	Parameter	Range
Cmax	200-400	*Kq*	0.5-2
Bexp	0.4-7	*n*	0.017-0.035
Alpha	0.2-0.99	*S*	0-0.02
Ks	0.01-0.5	H_0	55-63

For application of NSGAII, besides HYMOD's parameters, ranges for parameters in Eq.(4) also need to be specified. For n, S and H_0, robust ranges which must be broad enough to ensure that model behaviors will span the range of observations can be obtained from literatures or estimated from limited local information. Range for n is literature range for alluvial, sand bedded channels with no vegetation[15]. Based on longitudinal variations of average bed elevation in the mainstream of the lower Mekong River[16], river bed slope for Pakse region is very low (2.42×10^{-5}), therefore we set a relative low value for the upper bound of S. The average elevation for the pixels adjacent to water surface in DSM is 61m (σ: 2m). We consider this value as the mean water surface elevation for Pakse region at the moment that the PRISM images being captured. And H_0 should be lower than this value. **Table 2** gives the range for the parameters of HYMOD and Eq.(4).

4. RESULTS AND DISCUSSION

(1) River discharge estimation

With parameter sets lying in the Pareto optimal front, after calibration, HYMOD alone was applied for discharge estimation for the same period as calibration. The average Nash coefficient is 89.98%. **Fig.6** demonstrates the average simulated discharge and observations at Pakse. Most parts of hydrograph are well reproduced by simulation. To quantitively assess the accuracy, the numbers of discharge estimates within different levels of relative error are shown in **Table 3** in the form of percentage.

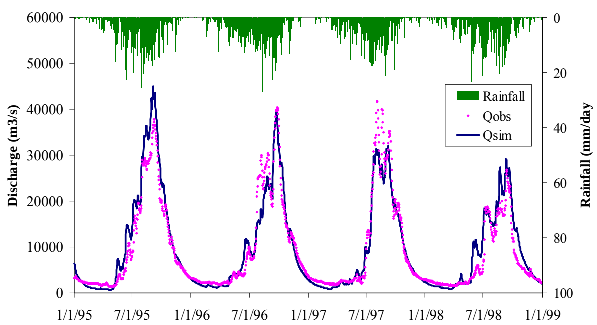

Fig.6 Observed and simulated discharge for 1995-1998

Table 3 Number of estimates within different levels of error

Levels of Relative Error	±0.1	±0.2	±0.5	±1.0
Percentage of Estimates	25%	44%	83%	97%

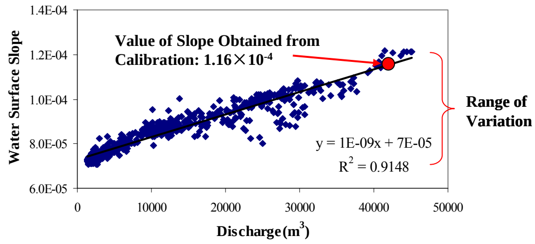

Fig.7 Relation between observed discharge and water surface slope at Pakse region

(2)The *S*, H_0, *n* obtained from calibration

Compared with calibration scheme used by Sun *et al.*[10], one advantage is that S and H_0 describing *Q-W* relation at basin outlet are physically meaningful. From another point of view, effectiveness of the proposed method can be justified by the value of S, H_0, n obtained from calibration, which is 1.16×10^{-4}, 60.93m, 0.0272 respectively. **Fig.7** shows relation between gauged water surface slope and corresponding observed daily discharge at Pakse region for 1999-2000. The calibrated value is within the range of observations. The difference between calibrated H_0 and water surface elevation measured from DSM is 0.07m (61m minus 60.93m). The lowest gauged water stage at Pakse station is 0.46m for 1999-2000. Considering the timing of images producing DSM be captured (end of dry season), low interannual variability of hydrograph and precision of DSM (one meter), we deem that the calibrated value for H_0 is also reasonable.

To validate the value of n, we applied Eq.(3) for discharge estimation directly, based on parameters values obtained from calibration, W_e-R and W_e-A relations extracted from DSM. Discharges corresponding to river width records measured from the 16 JERS-1 SAR images and additional 4 Landsat7 images for 1999-2002 were calculated. As the imaging mechanism for JERS-1 and Landsat7 are different, we consider characteristics of error for width measurements from the two sets of images should be different. However, error of discharge estimates take on similar trends as shown in **Fig.8**: in high flow and low flow range, discharge is under estimated; and it is over estimated in middle flow range. Similar trends for both sets of images illustrate that impact of error in width measurement is minor. Uncertainty associated with using Eq.(3) to describe hydraulic condition for Pakse region is the main reason for error in discharge estimation.

For low flow period, the discharge estimates are sensitive to H_0, which contributes to hydraulic variability that is highest in low flow period because of the effect of bedform and other types of channel irregularity[17]. Variation of water surface slope for the reach at Pakse region is low and calibrated value corresponds to high flow period as shown in **Fig.7**.

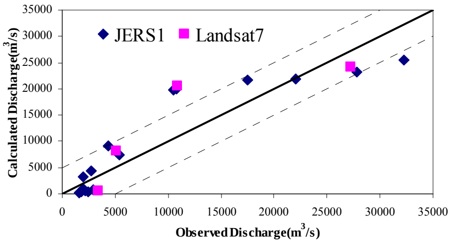

Fig.8 Estimated discharge plotted against observed discharge based on Eq.(3) for width records derived from 16 scenes of JERS-1 images and 4 scenes of Landsat7 images

Dingmans[4] suggests that a characteristic constant channel slope is hydraulic meaningful for certain reach when estimating discharge with a general slope-resistance equation. For Manning coefficient, general understanding is that it decreases as flow increases. The tendency of error in **Fig.8** indicates that the n obtained from calibration is lower than real situation for middle flow and overestimate the resistance for high flow period. Because this value is expected to reflect the average friction characteristic at basin outlet for the whole calibration period, we consider it is reasonable if judged from the view of calibration scheme.

5. CONCLUSIONS

This study is a first attempt to combine river cross-sectional geometry derived from high resolution DSM with Manning Equation to describe Q-W_e relation. It was adopt to describe hydraulic relation at basin outlet, which facilities calibrating RR model in basins that only satellite observations of river width are available at basin outlet. The results of case study show that most parts of hydrograph are well reproduced by the calibrated RR model. And the calibrated values for S, H_0, n properly reflects hydraulic condition for the whole calibration period. In conclusion, the proposed method provide an new approach to apply RR model in ungauged basins, using very limited information for basin outlet derived from remote sensing as a surrogate for discharge data. For further validation of this concept, uncertainty associated with error of DSM need to be analyzed, which requires ground observation of cross-sectional shape for comparison. Under current calibration scheme, n is treated as a time-invariant parameter. To represent hydraulic relation at basin outlet more properly, make n as a dynamic parameter is also desired.

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