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ESTIMATING DISCHARGE BY CALIBRATING HYDROLOGICAL MODEL AGAINST WATER SURFACE WIDTH MEASURED FROM SATELLITES IN LARGE UNGAUGED BASINS

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Conceptual rainfall-runoff models are widely used for river discharge estimation. In the past two decades, as the availability of hydraulic information (e.g., water surface width and water stage) derived from remote sensing has increased, the statistical approach relating the hydraulic information with discharge also has shown promising results. However, in ungauged basins, these approaches are limited by the fact that in situ measured discharge is indispensable for model calibration. In this study, a methodology for estimating discharge in large ungauged basins that utilizes rainfall-runoff model and hydraulic information obtained from remote sensing is proposed. The key is water surface width measured from satellites acts as a substitute of traditionally used measured discharge for the calibration of hydrological models. The applicability of this method is discussed through a case study that involves estimating discharge in the upstream area of the Pakse gauging station in the Mekong River.

Key Words: *Discharge Estimation, Large Ungauged Basins, Water Surface Width, Remote Sensing, Calibration of Hydrological Models*

1. INTRODUCTION

Nowadays frequency of extreme climate events such as floods, hurricanes and droughts is increasing under global warming. In this context, river discharge record which is one key indictor for hydrological cycle is significant to develop countermeasures against these disasters. Unfortunately, monitoring network of river discharge is sparse in a large part of the globe[1)].

The reliable estimation of continuous stream flow in ungauged basins is one of the great challenges. The need for calibration limits direct application of hydrological models in these catchments. Hydrographic data obtained from satellites and other remote sources offer the possibility of broad and potentially frequent global coverage of river discharge estimates[2)]. In the past two decades, with improvements of satellite sensors, possibilities of mapping inundation area, measuring cross-sectional water surface width and water surface elevation from remote sensing have increased, especially for large rivers. Efforts have been made to establish statistical relations between these information with river discharge with the purpose of measuring river discharge from remote sensing (e.g., Smith *et al.*[3)], Zhang *et al.* [4)], Kouraev *et al.* [5)], Coe *et al.* [6)] and Bjerklie *et al*. [7)]).

However, the dependence on observed discharge data restricts applications of this approach in ungauged basins. Another limitation is that the relations derived are only fit for hydraulic condition and cross-sectional geometry of the specific site. Consequently they cannot be applied elsewhere along the same river or to other rivers [8)]. Furthermore, temporal resolution of such method is low due to sampling frequency which is controlled by repeat cycle of the satellite.

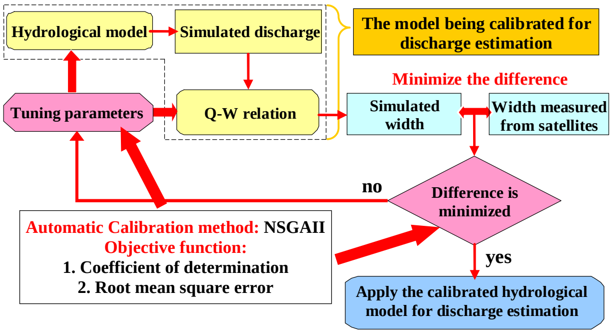

Fig.1 Schematic description of the methodology

In this study, we propose a new method for discharge estimation in large ungauged basins by combining information provided by a rainfall-runoff model and remote sensing. Instead of measured discharge, the hydrological model is calibrated against cross-sectional water surface width measured from satellites. Subsequently the calibrated hydrological model is used for calculating discharge time series. And the proposed method is discussed through a case study.

2. METHODOLOGY

Based on the assumed relationship between discharge (*Q*) and water surface width (*W*), discharge simulated by the hydrological model is converted into water surface width. It means the objective of model calibration shifts from minimizing error in discharge prediction to width prediction. Consequently parameters of the new model which consists of the hydrological model and *Q*-*W* relation are calibrated at the same time for minimizing the difference between simulated width and width measured from satellites. After the difference is minimized, the calibrated hydrological model will be used for discharge estimation. Schematic description of the methodology is shown in **Fig. 1**. And key components of the methodology are explained briefly as follow:

(1) Hydraulic geometry

Leopold and Maddock[9] introduced the concept of hydraulic geometry. It describes how some of the hydraulic factors (e.g., width, depth and velocity) that help to determine the shape of natural stream channels vary with discharge as simple power functions. The *Q*-*W* relation for a given cross section is defined as:

$$W=aQ^b \tag{1}$$

where Q is discharge, W is water surface width, a and b are two parameters.

However, the traditional method of discharge monitoring is based on rating curve converting measured water stage into discharge. It implies that, for the well-known scheme of calibrating hydrological models against discharge, these models are calibrated against measured water stage implicitly. Presently the possible source for measuring water stage from space is radar altimetry. And water stage can only be measured along the satellite orbit.

Compared with water stage, water surface width are easier to be traced by remote sensing, as many choices for extracting river width from space are available, such as multi-spectral image and Synthetic Aperture Radar (SAR). In this study, water surface width measured from satellites is utilized for calibrating hydrological model based on hydraulic geometry. Unlike discharge-stage rating curve which is derived by in situ measurement, parameters of *Q*-*W* relation are treated as two new parameters in addition to the parameters of the hydrological model. In another word, parameters of *Q*-*W* relation and hydrological model are calibrated simultaneously to minimize the difference between simulated cross-sectional water surface width and width measured from space.

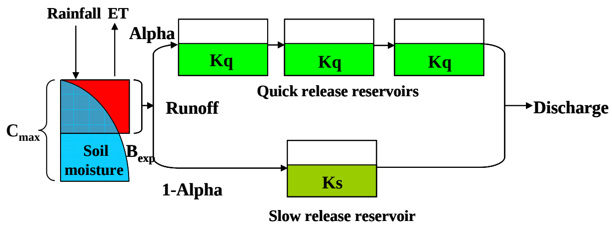

Fig.2 Structure of original HYMOD

Table 1 Description of HYMOD's parameters

Parameter	Description
Cmax	Maximum storage capacity
Bexp	Degree of spatial variability of the soil moisture capacity
Alpha	Factor distributing the flow between slow and quick release reservoirs
Ks	Residence time of the slow release reservoir
Kq	Residence time of the quick release reservoirs

(2) The hydrological model HYMOD

At the stage of estimating applicability of this methodology, a parsimonious hydrological model HYMOD was selected. The HYMOD first proposed by Boyle[10] is a continuous soil moisture accounting hydrological model. The model structure is depicted in **Fig. 2**. HYMOD has five parameters which are shown in **Table 1**. In order to account for spatial variability in large basins, the original HYMOD was revised. The whole basin was divided into subbasins to describe spatial variation. As such modeling makes the number of model parameters increase proportionally with the number of subbasins, a simple parameterization scheme was utilized to reduce the number of parameters. The three runoff production parameters *Cmax*, *Bexp* and *Alpha* were assumed to be constant for all subbasins, but the other two routing parameters *Ks* and *Kq* were spatially varied depending upon the distance between each subbasin and the basin outlet.

(3) Calibration scheme

Model calibration allows reducing parameter uncertainty and finally uncertainty in prediction. As manual calibration is time consuming and subjective to some extent, nowadays, there has been a great deal of demands for the development of automatic optimization algorithm. The automatic calibration procedure typically searches parameter space to find solution points that optimize numerical value of the objective function. Practical experience with model calibrations suggests no single-objective function is adequate to measure the ways in which the model fails to match the important characteristics of the observed data [11]. This leads to the formulation of objective function as a multi-objective problem.

In the present study, model calibration is proposed as an optimization problem that seeks to minimize the difference between simulated width and width measured from satellites. We used a multi-objective global optimization method: the Nondominated Sorting Genetic Algorithm II (NSGAII) for model calibration. NSGAII is characterized as a fast nondominated sorting procedure, an elitist strategy, a parameterless approach and a simple yet efficient constraint-handling method[12], which has been applied to hydrological model calibration[13] and regionalisation of hydrological model parameters[14]. Root Mean Square Error (*RMSE*) and coefficient of determination (R^2) were adopted as objective functions which are computed as:

$$RMSE = \sqrt{\frac{1}{n}\sum (W_{sim,\,i} - W_{obs,\,i})^2} \quad (2)$$

$$R^2 = \left(\frac{\sum (W_{obs,\,i} - \overline{W_{obs,\,i}})(W_{sim,\,i} - \overline{W_{sim,\,i}})}{\sqrt{\sum (W_{obs,\,i} - \overline{W_{obs,\,i}})^2}\sqrt{\sum (W_{sim,\,i} - \overline{W_{sim,\,i}})^2}} \right)^2 \quad (3)$$

where $W_{obs,\,i}$ is the *i*th width record for the selected cross-section measured from satellite, $W_{sim,\,i}$ is the simulated width corresponding to the *i*th measured width record, and *n* is the number of width records. The five parameters for revised HYMOD and two parameters for *Q*-*W* relation are calibrated at the same time by NGSAII. As equifinality for conceptual model like HYMOD is inevitable, the entire set of the plausible value of model parameters lying in the Pareto optimal front were considered to account the uncertainties in the model prediction.

One of the big challenges for the calibration scheme proposed here is low temporal resolution of width measurement which is dependent on repeat cycle of the satellite. In most cases, it is impractical to measure width everyday. In real cases, only several images are available per year for specific site. Therefore it is questionable that the very limited information can capture characteristics of the basin's hydrological behaviors and *Q-W* relation. Perrin *et al.*[15] assessed sensitivity of two rainfall-runoff models with four and six parameters respectively to streamflow data availability. For the 12 basins being studied, only 2.46% daily discharge records randomly selected from all records for the whole calibration period (350 records from 39 years) are able to obtain robust estimates of model parameters. In some cases, only 10 measurements can obtain acceptable results. So we can infer that under the calibration scheme proposed, discharge still can be estimated successfully.

3. CASE STUDY

(1) Study area and data sets

The Mekong River at Pakse (**Fig. 3**) was selected for a case study. The length of Mekong River is about 4800 km, with a drainage area of 795,000 km^2. Pakse gauging station (15°07'N, 105°48.0'E) is located in the southwest part of Laos, at the confluence of the Xedone and Mekong Rivers, with a drainage area of 545,000 km^2 [16]. Minimum and maximum discharge for the period of 1923-1998 is 1,060m^3/s and 57,800m^3/s respectively. The upstream area of Pakse gauging station was divided into eight subbasins for the application of HYMOD as illustrated in **Fig. 3**.

Input data required for HYMOD are rainfall and potential evapotranspiration (PET) for each subbasin. Daily measured rainfall data from 26 gauging station and Ahn and Tateishi monthly PET[17] (representative of 1920-1980) were adopted. Daily measured discharge at Pakse station from Lower Mekong Hydrological Yearbooks is available for validation.

(2) Extract water surface width from SAR image

Japanese Earth Resources Satellite-1(JERS-1) SAR images of level 2.1 (resolution: 12.5m) were used for measuring width. For the period of 1995-1998, 16 images are available for extracting river width at Pakse regions. JERS-1 which carried L-band SAR was an earth observation satellite launched in Feb.1992 and terminated in Oct. 1998. Water surface for which surface roughness is lower than microwave length performs mirror reflection. Low backscattering of water surface makes it take on low brightness on images. As shown in **Fig. 4**, variations of discharge can be traced by the change of water surface area.

Fig.3 Schematic map of the study area and subbasins divided

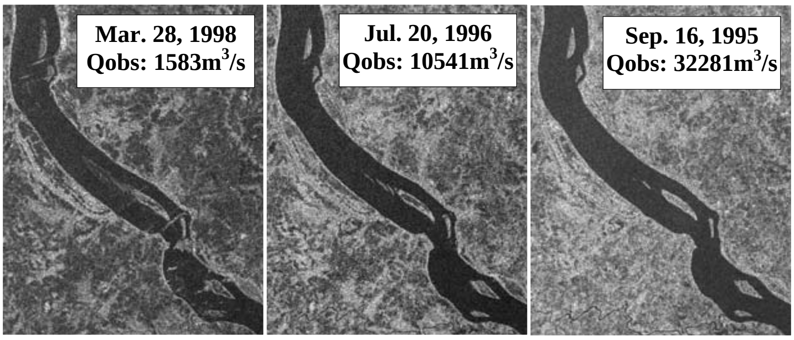

Fig.4 Three SAR images for different flow period at Pakse region and corresponding measured discharge

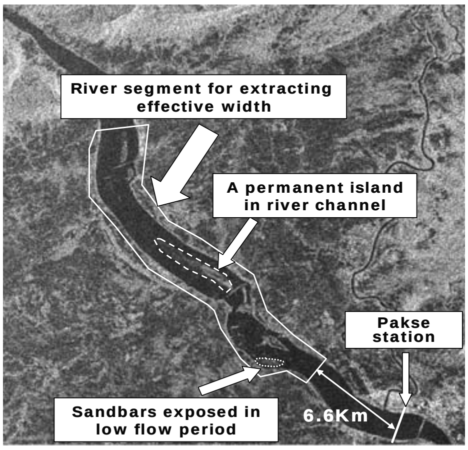

Fig.5 Schematic description of the reach for deriving effective width and elements being measured for width calculation

For measuring water surface width from space, previous studies adopted average width over certain reach (river segment) length that more closely approximate the mean conditions in a channel to minimize localized variability[7]. The reach length typically suggested for calculating averaged width mentioned as "effective width"[3] varies from at least one meander length[18] to a minimum of two meander lengths[19]. In this study, the average width over about two meander lengths was used as effective width.

The reach selected for calculating effective width is shown in **Fig. 5**. The distance between lower cross section of the reach and control section of Pakse station is about 6.6 km. So the measured discharge of the same day when the image was taken can be considered as the discharge corresponding to the measured width. The effective width is calculated as

$$W_e = \frac{a_w}{l} = \frac{a_a - a_i - a_s}{l} \qquad (4)$$

where W_e is effective width, a_w is the actual area that water surface occupies in reach for measuring width, l is reach length, a_a is all the area (include non-water area) within edge of water surface that contacts with river bank of the selected reach, a_i is the area of permanent islands, and a_s is the area of sandbars exposed in low flow period. The l, a_a, a_i and a_s were manually measured from the 16 images.

The width records were utilized for calibration for the period of 1995-1998. After calibration, the revised HYMOD was used for discharge estimation at Pakse station for the same period as calibration.

(3) Results and discussion

a) Calibration of HYMOD against discharge

The revised HYMOD was calibrated against continuous measured discharge at Pakse station to test model applicability in the study area. **Fig. 6** shows the boundary of simulated discharge corresponding to all plausible sets of model parameters that lie in the Pareto optimal front. And average Nash coefficient for these sets is 91.68% for calibration period and 89.09% for validation period. The simulated flow could explain variability in the observed data satisfactorily.

b) Calibration of HYMOD against width

The average *RMSE* and R^2 for calibration against width measured from SAR images is 15.94m and 95.6% respectively for all sets of model parameters that lie in the Pareto optimal front. The performance of HYMOD assessed in term of average Nash coefficient is 88.24% for all these sets. As depicted in **Fig. 7**, the simulated flow explained much of the variability in the observed flow.

Apart from simulated flow, quantification of the uncertainties for the calibration strategy is also essential. We used relative error of mean simulated flow for the entire plausible set of parameters lies in Pareto optimal front to quantify error in prediction. As shown in **Table 2**, compared with calibration against discharge, average relative error is higher for calibration against width, especially for low flow period, which indicates the additional uncertainty associated with width as calibration data.

c) The exponent derived for *Q*-*W* relation

Fig. 8 shows *Q*-*W* relation for the selected reach gained by calibration against width and the relation for the control section of Pakse station based on 134 in situ measured width and discharge records for

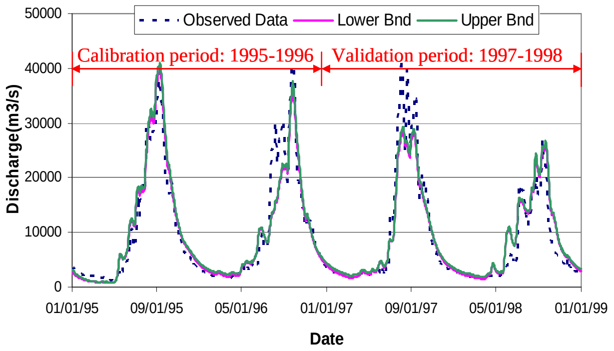

Fig.6 Upper and lower boundary of simulated flow corresponding to model parameters sets derived from calibration against discharge

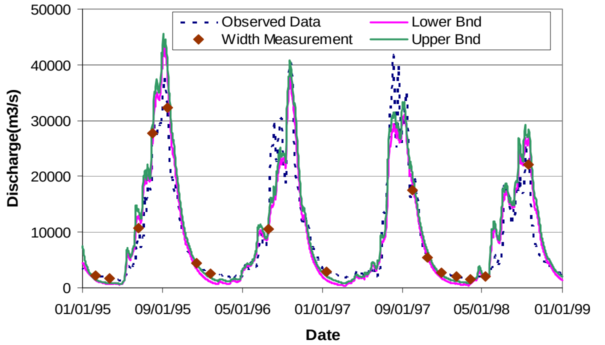

Fig.7 Upper and lower boundary of simulated flow corresponding to model parameters sets derived from calibration against width

Table 2 Average relative error of mean simulated discharge for calibration against discharge and width

Calibration Objective	Flow range	
	Discharge <3000m^3/s	Discharge >3000m^3/s
Discharge	0.053	0.160
Width	-0.333	0.170

the period of 1999-2002. Relative difference among exponent *b* (0.0310/0.0147) is larger than coefficient *a* (1261.5/1459.2). Therefore, the discussion about the two derived *Q-W* relations mainly focused on *b*.

The exponent of the *Q-W* relation is considered as an indictor of the sensitivity of channel's width to changing discharge[3]. Compared with control section of the Pakse station which is located in a single channel reach as shown in **Fig. 5**, the width variation of the selected reach is higher, as area variations of islands and sandbars are included. So it is reasonable that the value of exponent for the reach is higher than the one for Pakse station.

Dingman[20] explored how the exponent varies as functions of hydraulic and geometric factors: the more the cross-sectional shape likes rectangle, the closer the exponent is to 0. The exponents for both *Q-W* relations are close to zero which is consistent with the fact that the cross-sectional shape for river channel in Pakse region is nearly rectangular.

d) Uncertainty in calibration against width

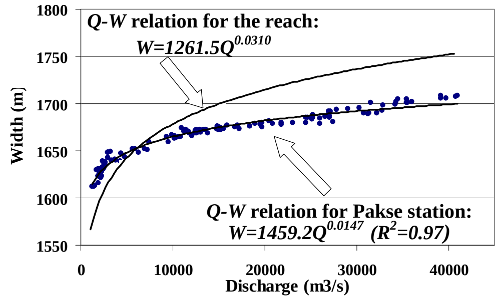

Fig.8 *Q-W* relation for the reach of measuring width obtained from calibration against width and statistical relation for the control section of Pakse station

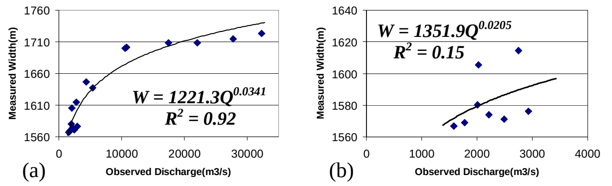

Fig.9 Statistical relations between measured effective width and corresponding measured discharge for (a) whole flow range and (b) discharge lower than 3000m^3/s

As only 16 effective width records measured from remote sensing images were available for calibration, the limited information is one of probable causes for the uncertainty in prediction. Converting discharge into width based on power relation that adds two extra parameters for calibration is another possible source. **Fig. 9** (a) and (b) depicts the relation between width measured from space and in situ measured discharge at Pakse station for full flow range and discharge < 3000 m^3/s. For discharge < 3000 m^3/s, high measurement error associated with SAR images due to difficulty in distinguishing water area from sandbars or inability of power relation or both of them may result in the poor correlation between discharge and width. And this poor correlation is probably one of the reasons that error for prediction in low flow period is higher.

At the same time, it is also justified that the whole method works as performance of HYMOD is influenced by the nature of *Q-W* relationship. Even if cross-section shape of the reach is nearly rectangular (changes of width is not very sensitive to variation of discharge) which is not ideal for building *Q-W* relation, the calibrated HYMOD still could reproduce the hydrograph. However, for the selected reach, a little error in width measurement can lead to higher error in discharge estimation. As show in **Fig. 9** (a), measured flow varies from 1583m^3/s to 32282 m^3/s, but variation of effective width is only about 157m (only about 10% of water surface width in very low flow condition). Bjerklie *et al.* [8] indicated the maximum and minimum uncertainty in width measurement from satellite images is 10 m and 1m, which means it is one important source of error in discharge estimation.

To reduce uncertainty in calibration, the ideal reach for measuring width from space is the one where variation of width is sensitive to changes of discharge, such as the one with parabolic cross-sectional shape or braided form. As effective width measurement depends on the resolution of satellite images, the accuracy of the width measurement would generally be greater for large rivers[7].

4. CONCLUSION

Calibration of hydrological models is essential to reduce uncertainty in discharge prediction. This study explored the prospect of utilizing water surface width measured from satellites for calibration of hydrological models in large ungauged basins. From results of the case study, conclusions can be drawn as follow:

- The flow simulated by the parameters obtained through calibration against effective width measured from SAR images can explain majority of variations in the observed flow.
- The exponent value of *Q-W* relation obtained from calibration against width is reasonable which also justifies the calibration scheme is effective.
- Performance of model prediction is influenced by the nature of *Q-W* power relation. For certain discharge range, poor *Q-W* relation leads to high uncertainty in prediction.

In conclusion, though model performance is poor compared with the calibration against measured discharge, this method still shows great potential, as calibration of hydrological model doesn't need measured discharge data. And it is possible that discharge of river segment in ungauged basins for which only several satellite images are available can be estimated. Future works should be focused on automatic algorithm for detecting water surface area from satellite image and selection of a more distributed hydrological model to describe spatial variability in large basins. A comprehensive evaluation is also needed to explore the interaction between the hydrological model and *Q-W* relation.

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