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Review Paper

A review of methodologies to estimate river discharge from satellite observations

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Abstract

This paper consists of comprehensive review of different methodologies that are being used by different researchers in the field of estimating river discharge from satellite observations. In this paper five methods Direct equation based method, Quantile function based method, Manning's resistance equation based method, Method using MODIS derived depth and width of flow and Rainfall Runoff models based method are reviewed on the basis of their working principle, ease, accuracy, localized or global application, limitations and future scope. From review we observed that Direct equation based method is pioneer of other methods but having less accuracy as it does not considers any uncertainties, it works on trend concept. Quantile function based method is modification over previous one and very useful in every type of region. Manning's resistance equation based method consist satisfactory parameters and can be used in river discharge time series estimation with promising accuracy. Method using MODIS derived depth and width of flow is second most promising method among these because in this we are getting most important parameter flow depth which has direct relation with discharge, hence it has high accuracy as well. Among all methods most promising method is Rainfall Runoff Models based method. It is developed by integrating river discharge with water surface width and rainfall. This method considers uncertainty with calibrating parameters from Generalized Likelihood Uncertainty Estimation (GLUE) and it has high future potential.

Keywords: Methodologies, River discharge, Satellite, observations.

Introduction

For any hydrologic study or hydrometeorology it is very important to have the prehistoric datasets like rainfall, river discharge, evaporation, evapotranspiration, temperature data etc. In these mentioned parameters river discharge is very crucial parameter for flood routing, climate modeling and management of water resources etc, yet there are a number of basins which are ungauged in the world[1]. Estimation of stream discharge from satellite observation with high accuracy without in situ measurement is very tough task, However as technology is advancing it will be easy with time. Obtaining real time river discharge from satellite observation can lead to increase in ease of data collection, saving manpower and money.

Remote sensing can fill up this gap upto great extent. In this study we have taken some of methodologies that estimates stream discharge from satellite observations as river's water surface width and water surface area. These methodologies are basically subdivided in two parts, one containing water surface width and river discharge relating direct equations derived from regression analysis of prehistoric datasets and second part containing Quantile function based approach, Manning's resistance based method, and by calibrating parameters of Rainfall Runoff (R-R) models.

In this paper above mentioned methods are studied and assessed in order get an idea for suitable method for discharge calculation by remote sensing, without in situ measurement with promising accuracy, However accuracy in these methods are based upon various factors like satellite accuracy, image resolution, environmental condition during image capturing and channel cross sectional properties.

Main idea behind using remote sensing based stream discharge calculation is that stream discharge is related to water surface width, some studies gave power function relation between water surface width and discharge. Power function relations obtained by regression as $w = aQ^b$ (where w – width of water surface (in m), Q – corresponding river discharge (cumec), a and b are numerical constants)[2], on the basis of these relation a number of modifications were in past in order to increase accuracy of these equations and reduce uncertainties. Ashmore P.[3], Bjerklie D. M. et al.[4,5], and Gaurav K.[6] gave promising modifications over Leopold's equation[2].

Elmi et al.[7] gave another statement that rather developing direct relation between width and stream discharge a quantile function is more accurate. After that Birkinshaw S. J. et al.[8] utilized Manning's resistance equation in his approach. Sun W. et al.[9-10] introduced a good method of Rainfall Runoff model based approach by integrating objective function with river width and stream discharge. He utilized HYMOD model with Generalized Likelihood Uncertainty Estimation (GLUE) approach for overcoming uncertainty and for calibration of model parameters[11,12].

Position of problem

River discharge is very important parameter for various studies like flood routing, structural design, flood or draught forecasting and flood frequency analysis. As a number of basin are yet ungauged but their stream discharge is necessary as well as some gauging sites also got damaged or unworkable, to overcome these problems remote sensing based stream discharge estimation can be a good alternative.

Problems regarding remote sensing based stream discharge measurement are uncertainties of at-a-station hydraulic geometry based relation and uncertainties which are associated with river width estimation from remote sensing.

In this paper we have collected from basic method of equation which do not consider neglect these uncertainties and new modified method utilizing these equation with accounting uncertainties. From this paper we will find out some of good methods that can be utilized to estimate stream discharge from satellite observations.

Methods for river discharge calculation from space

Equations based on previous trends of River discharge: In this, equation derived by statistical approach based on historical river discharge trends are developed by different researchers. Leopold et al.[2] derived an equation by regression of river width and corresponding discharge at gaging site power function equation $w = a*Q^b$ (where w is width of water surface (in m), Q is corresponding river discharge (m^3/sec), a and b are numerical constants). This equation was then further modified by various researchers by considering slope of channel bed, particle size of river bed, depth of flow in order to get accuracy[3-6]. They are –

Ashmore et al.[3]

Linear function $Q = aW_e + b$

Power function $Q = aW_e^b$

Polynomial function $Q = aW_e^2 + bW_e + c$

Bjerklie et al. equation[4]

$Q = 7.22\, W^{1.02} Y^{1.74} S^{0.35}$

Gaurav et al. (2018)[6]

$\log_{10}(W/d_{50}) = \alpha_w + \beta_w * \log_{10}(Q)$

Where: W/We= Width/effective width of water surface, Y = depth of flow, S = bed slope, Q = River discharge, d_{50} = average size of particle of river bed. a, b, c, α_w, and β_w are numerical constants depends on channel geometry.

Above equation has some disadvantages as they are based on regional data they can be used for only that region.

Quantile function based approach: This approach was given by Elmi et al.[7] more accurate than previous equation based method, it says no direct relation between river width and discharge can be built but a good relation between quantile function of river water surface width and discharge can be built.

In this work MODIS MOD09Q1 was used that provided imageries in red spectral band and near infrared spectral band with spatial resolution of 250m and with temporal resolution of 8 days. Daily measurements of stream flow in unit of m^3/sec are collected from GRDC data set at specified station. Specified station's measured parameters at site are available from 1970 to 2006.For analysis first unsupervised classification was done then river width was obtained by RivWidth script of ENVI-IDL.

Found quantile function river discharge $Q_{Q(p)}$ and river width $QW(p)$ are defined as followed –

$Q_{Q(p)} = \inf\{X_Q \in R : <= F(X_Q)\}$

$Q_{W(p)} = \inf\{X_W \in R : <= F(X_W)\}$

$X_Q = T(Xw)$

$Q_Q = T(Qw)$

Where F (.) is the CDF function, XQ shows the discharge and, XW shows river width.

This methodology gives 10% of RMSE for discharge quantification during validation.

Method based on Manning's resistance equation: This method was prepared by S J Birkinshaw et al.[8], A methodology to estimate daily stream flow of river was designed for an un-gauged site with the help of satellite observations. Author utilized ENVISAT satellite altimetry and ERS-2 imagery for deriving stream channel stage level's time series and longitudinal slope of channel and Lands at satellite imagery for providing a series of river water surface widths over a 50km river reach. Bjerklie[4] developed an equation to estimate discharge which was utilized and data is substituted into it, this equation is based on Manning's resistance equation and it was developed by utilizing a global database of hydraulic information of channel and discharge measurements.

For validation of this prepared methodology was applied on three different locations on the Mekong river and Ob river and simulated and observed discharge was compared. As a result Nash-Sutcliffe value efficiency for this methodology in study area Nakhon Phanom and Vientiane found to be 0.90 and 0.86 respectively. Similarly in Mekong River and in Kalpashevo of Ob River showed 0.86.

Method using MODIS derived depth and width of flow: A good approach was developed to estimate stream discharge using satellite imagery derived parameters by Sichangi A. W. et al.[13]. In presented study by Shichangi[13], they utilized satellite imagery observed from MODIS and extracted temporal river water surface width for two distant streams segments. Time lag was identified by plotting those segments. With the help of time lag and length of width measuring location, stream velocity was calculated. To estimate river depth an empirical relation is then utilized. Roughness coefficient was obtained from standard table. The slope of channel was estimated from the DEM (digital elevation model) by averaging over a river section approximately of length 516km. At the end with the help of altimetry satellite ENVISAT, stage (depth of flow) of river and by Landsat ETM+ stream width was estimated. This applied methodology showed satisfactory results by providing Nash–Sutcliffe efficiency values more than 0.50 in each case.

From our observation this methodology can be used for the rivers in which stage (river water depth) data is being recorded. As we know there are very less altimetry satellites are available, this may be a big constraint for this methodology. Overall it can be used for discharge estimation worldwide.

Rainfall Runoff Models: This method was developed by Sun W. et al. in 2010 [9,10]. It was also further modified by him in 2012[11] and 2015[12]. River discharge estimation in ungauged (UG) basin is done by Rainfall Runoff (R-R) models. Rainfall runoff model's calibration was done with stream water surface width in place of discharge in ungauged basin.

Water surface width of river is calculated by satellite imageries. In this methodology mainly calibration of parameters of R-R model was discussed in which calibration was done with river water surface width at basin outlet.

Generalized likelihood uncertainty estimation (GLUE) process is that which is utilized for calibration and for uncertainty estimation in hydrological model. In this study there are two major problems resolved – i. Reliable parameterization, ii. Uncertainty of remotely sensed data is large.

This problem is solved by Generalized Likelihood Uncertainty Estimation (GLUE) approach.

Application on HYMOD Model: A parsimonious model HYMOD is being utilized by some authors since long time for rainfall-runoff modelling[14,15]. Sun W. et al.[12] applied this methodology by using HYMOD (Hydrological Model) R-R model, at Pakse place in the Mekong Basin, authorutilized river widths which were obtained from JERS-1 SAR imageries data for calibration. For this region Pakse, 16 imageries of JERS-1 SAR (Level 2.1) captured and extraction of stream widths were done for data from 1995 to 1998, which is having 12.5 m spatial resolution.

Effective width of water surface (We) was then calculated as

$$\mathrm{We} = \frac{a_w}{l} \quad (1)$$

Where a_w= area of water surface within the river reach, l = length of the reach.

The average stream widths that are obtained from the space were plotted against the corresponding per day stream flow data at the Pakse station. The best fit curve in the form of logarithmic function is obtained as $W=1221.3Q^{0.0341}$ and very good correlation of R^2 =0.92 exists between the two variables. Then GLUE method was applied to calibrate HYMOD model parameters, equation parameters a and b were calibrated by, generation of 50000 parameter sets using Latin-Hypercube sampling algorithm, in which parameters are assumed to having uniform distribution[16-19].

After parameter calibration daily step time series of river discharge (simulated) was developed and validated with in situ observed discharge values and its Nash-Sutcliffe efficiency was calculated for each discharge sets.

Results obtained were promising with Nash Sutcliffe efficiency varying 0.45 (for lesser discharge sets) to 0.96 (for most of the discharge sets).

Discussion

Published studies shows that there is a good relationship between river width and discharge which may be used as an alternative for stage discharge relationship. As accurate stage (depth of flow) is tough to obtain from remote sensing (however radar altimetry gives useful results in case of stage) width discharge relation can be established by remote sensing.

From above methods we can say that there is great future with increasing accuracy in remote sensing, one can obtain useful parameters like discharge without in situ measurements. One can increase accuracy of the above methods by utilizing finer resolution imagery, by changing more accurate models, by changing calibration scheme, by utilizing more numbers of previous data for calibration, by considering uncertainty due to water resources structures like dam's effect in stream flow, by considering various losses like evaporation, seepage etc. A good alternative for these methods can be obtained from radar altimetry as it may be helpful to gar stage discharge relationship in stream.

Presently stream discharge in river can obtained by above mentioned technique but in further modification we can adopt this method with conjunction with genetic algorithm for minimizing uncertainty and for heading towards real time stream discharge estimation methods.

Conclusion

From in situ observations Leopold et al.[2] established simple relation as w = aQ^b, which was further modified by Ashmore P. et al.[3] in terms of linear function, power function and polynomial function which was as similar to Leopold equation.

Bjerklie et al.[4,5] by considering flow depth and bed slope of stream which was very successful for braided rivers, This equation has advantage that it not obtained by single basin study but it was established by 108 rivers of different nature and different regions. In some studies modified the equation in terms of river bed particle size and developed log based equation[6]. This equation is accurate but it needs site investigation in order to get particle size. Above methods are only equation based and does not consider uncertainties because they need more than 50% of site investigation.

Quantile function based approach by Elmi et al.[7] was good enough in order to predict river discharge by less than 10% RMSE. It needs previous data for training and after that it can simulate stream discharge. Birkinshaw S J et al.[8] and Sichangi W. et al.[13] both gave the method in which water surface width, bed slope, water depth were obtained by ERS-2, ENVISAT and MODIS in respective study and then Bjerklie[5] equation were used. Both study gives Nash Sutcliffe efficiency > 0.50, it indicates the usefulness of equations by Bjerklie et al.[4]. This method can be utilized in most of regions but numerical constants may vary with different regions and uncertainty of river width calculation by remote sensing it is the disadvantage of this method.

Most versatile method in above study was obtained is by using Rainfall Runoff Models given by Sun W. et al.[12]. This method integrates river water surface width with discharge and it is calibrated by prehistoric rainfall and evaporation time series with uncertainty assessing method GLUE[18,19]. HYMOD model was applied by researcher; it gives quite promising river discharge simulation[14]. This method can be utilized globally and it also considers uncertainties related to estimation but remote sensing accuracy may affect results.

Only lag of this method is that cross section details are required to get high accuracy that means slight field work is required but by GLUE technique cross section parameters are calibrated.

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