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River Discharge Estimation Using Maximum Depth-Averaged Velocity: The Case Study of The Godavari River Basin

Jitendra Kumar Vyas, Sitaram Saini, Akash Johari, Pooja Jain, Pawan Patidar
Department of Civil Engineering, Swami Keshvanand Institute of Technology, Management & Gramothan, Jaipur-302017 (INDIA)
Email: **jitendra.vyas@skit.ac.in, sitaram.saini@skit.ac.in, akash.johari@skit.ac.in, pooja.jaincivil@skit.ac.in, pawan.patidar@skit.ac.in**
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Abstract- The mean (average) flow velocity is an important hydraulic parameter for river engineers. It is calculated by using the stream flow rate (discharge) and the sectional flow area. Several techniques are available to estimate the sectional average or mean flow velocity. The recently introduced entropy theory technique is a reliable and quick approach compared to traditional techniques like the velocity-area method. The entropy theory technique can estimate the discharge by measuring the single point velocity measurement only. The estimated parameters are well compared with the observed ones. The results were compared in terms of correlation coefficient (more then the 0.99) and error percentage. The error percentage is well within the acceptable limits (varies from 8 % to 15%).

Keywords– Mean flow velocity, Maximum point flow velocity, discharge, entropy theory.

1. INTRODUCTION

The sectional mean (average) flow velocity is considered an important hydraulic parameter which directly or indirectly related to numerous aspects of the river flow system like geomorphological study, peak discharge, mean discharge, and flood forecasting etc [1].

The sectional mean (average) flow velocity is the ratio of the volume flow rate (discharge) passing through the section to the cross-sectional flow area. Several techniques are available for the computation of the sectional average flow velocity, passing through the section like traditional techniques, non-conventional techniques, etc.

The velocity-area method [1] is regarded as the most popular conventional method for the computation of discharge. The depth-averaged velocity ($u_{0.6D}$) [2] of the selected verticals (flow depth) across the section is required for the computation of the average stream flow velocity. The number of verticals shares a linear relationship with the width of the section. And hence more time is required for the measurement of the $u_{0.6D}$ especially for the larger river sections like the Godavari River of Southern India [3]. The flow measurement can be performed by the current meter. The current meter can only be used during the day time measurements. Hence the measurement of depth-averaged velocity is not possible during the night time flood events. It's a biggest drawback of the current meter [3].

Considering the limitations of the traditional method, Chiu [4] applied the entropy theory [5] for the stream flow computations, which needed the singular point velocity. In deterministic hydraulics, maximum flow is not considered as important as average flow velocity [1]. Usually, the maximum-point flow velocity is not measured for the gauging sites where traditional methods are employed [2,3].

The observation of the maximum-point (Single point velocity) flow velocity (u_{max}) is always a less time-consuming process than the measurement of depth-averaged velocity ($u_{0.6D}$) [3]. Maximum-point velocity of flow always lies at the top part of the sectional area [6]. For most of the flow conditions, it happened at the free or top surface of the section (For wider river sections) [6]. Sometimes, it may occur below the top surface of water [3] due to the presence of transverse components (secondary currents, for narrow river sections).

The depth-averaged flow velocity can only be measured by contact-based flow measuring instruments like the current meter because it occurs at *0.6d* from the free surface. Whereas maximum flow velocity can be measured either by contact-based flow measurement like current meter or non-contact-based flow measurement like surface velocity radar (SVR) [2, 7]. Hence, the measurement of maximum flow velocity is much easier than the measurement of depth-averaged velocity. Non-contact flow measuring instruments like SVR can measure the flow velocity during night time flood events which is unexpected from contact-based flow measuring instruments like current meters [7-9].

Upto this stage one can conclude that entropy theory is the more practical approach than the traditional methods because it is quicker as well as discharge can be obtained for nighttime flood events [9, 10].

As far as the Indian scenario is concerned, the traditional method (velocity-area method) is used as the hydrometric practice [9]. It has already been discussed that the velocity-area method is time-consuming, especially for large river sections like the Godavari River and unable to measure the night time flood events [10]. For the Indian conditions, biggest limitation is the availability of measured maximum flow velocity [2]. Because it is not required in the case of the conventional method. Hence one can not employ the entropy theory for the discharge computation for the Indian Rivers or the gauging stations where traditional methods are used [2, 11].

This case study accepts the relation between the entropy theory and the velocity-area method [3]. In other words, it accepts the relation between the depth-averaged velocity ($u_{0.6D}$) and the maximum point flow velocity (u_{max}).

2. METHOD

The article describes a methodology of the discharge computation using historical stream flow data and the entropy theory. The relationship between the maximum depth-averaged velocity and the maximum flow velocity is expressed as [3]:

$$u_{\max\_c} = \frac{M\, u_{0.6D,max}}{\ln\left[1+(e^{M}-1)\frac{y_{0.4D}}{D(x)}\exp\left(1-\frac{y_{0.4D}}{D(x)}\right)\right]} \quad \text{..... (1)}$$

Where $u_{\max\_c}$ is the calculated maximum flow velocity, $u_{0.6D,max}$ is the maximum depth-averaged velocity (usually occurs at the or near the maximum flow depth vertical), M is known as an entropic constant, $D(x)$ is the flow depth of the deepest vertical, and $y_{0.4D}$ is location of $u_{0.6D,max}$ measured from the bottom of the river section. The entropic parameter (M) or state equlibiruim constant Ω (M) can be obtained by the measured pairs of the mean flow velocity (u_m) and the maximum flow velocity (u_{max}).

$$\frac{u_m}{u_{max}} = \left(\frac{e^M}{e^M-1}\right) - \frac{1}{M} = \Omega\,(M) \quad \text{.... (2)}$$

Where u_m is the sectional mean flow velocity of the river section, u_{max} is the maximum (highest) point flow velocity of the river section, and Ω (M) is the state equilibrium constant. The value of M or Ω (M) can be obtained either by Eq. (1) or Eq. (2). If the pairs of the sectional mean flow velocity and the maximum point flow velocity are available then one can directly obtain the value of M or Ω (M) by Eq. (2) [2].

For all the gauging stations across the globe, where traditional methods, like the velocity-area method, are employed, the maximum flow velocity is unavailable because it is not required for the computation of sectional average flow velocity [3]. In the case of the Indian situations, the traditional method is used for all the gauging stations, hence maximum point flow velocity is unavailable or one can not use the Eq. (2) for the computation of M or Ω (M) [3]. Although one can estimate the M value using Eq. (1) [4].

To compute the cross-sectional average (mean) flow velocity and the volume flow rate (discharge) passing through the sectional area, using the measured maximum depth-averaged velocity ($u_{0.6D,max}$) following steps were used:

1. Select the vertical location of the *y-axis* (location where u_{max}, and $u_{0.6D,\,max}$).
2. Obtain the value of M or Ω (M) either using Eq. (1) or Eq. (2). (if pairs of u_{max} and u_m are available then use Eq. (2), if the pairs are not available then use Eq. (1)).
3. Measure the maximum depth-averaged velocity ($u_{0.6D,max}$) at a *y-axis*.
4. Compute the $u_{\max\_c}$ from Eq. (1) and $u_{0.6D,max}$ (from step 3).
5. Compute the sectional mean flow velocity (u_{m_c}) from Eq. (2) using $u_{\max\_c}$ (from step 4).
6. Estimate the discharge using flow area and the estimated average flow velocity, u_{m_c} (from step 5).
7. Compare the observed and estimated discharge.

3. STUDY AREA

To test the accuracy of this case study the Bhadrachalam gauging station of the Godavri River was used. Total 13 events were used in this study to test the acceptability of the method. The range (variation) of discharge is 13000 m^3/s to 43101m^3/s. It is well known to us that the entropic parameter (M) or state eequilibrium constant Ω (M) remains constant along the river reach or in other words Ω (M) of one gauging can be used for all the gauging stations of the river basin [3]. The Godavari River basin is equipped with the total 48 gauging stations so using the Ω (M) of any one gauging station one can directly estimates the cross sectional mean flow velocity by knowing the maximum flow velocity only from Eq. (2). In this case steady Ω (M) = 0.683 amd M = 2.4 of the Perur gauging site of the Godavari River were used [3]. So, the Eq. (2) can be written for the Bhardachalam gauging site of the Godavri River using the Ω (M) value of the Perur gauging station.

$$u_m = 0.683\, u_{max} \quad \text{....... (3)}$$

From Eq. (3) one can conclude that only the measurement of maximum point flow velocity is needed to estimate the discharge of any river flow event. The measurement of maximum point flow velocity is much easier than the measurement of maximum depth-averaged velocity (required for the velocity-area method).

4. RESULT AND DISSCUSION

$u_{\max\_c}$ was obtained from Eq. (1) using *M = 2.4* [4] and the measured value of maximum depth-averaged velocity ($u_{0.6D,max}$). Once the $u_{\max\_c}$ value is obtained, one can estimate the cross-sectional mean velocity from Eq. (2) by using $u_{\max\_c}$ (estimated from Eq. (1)) and $\Omega(M) = 0.683$. Figure (1) compares the estimated mean flow velocity with the observed mean flow velocity. The high value of the coefficient of correlation ($R^2 = 0.99$) shows the accuracy of Eq. (1). Accuracy of the estimated mean flow velocity (by Eq. (2)) will result in the accurate measurement of discharge. Figure (2) compares the estimated mean flow velocity with the corresponding observed mean flow velocity for individual flow events. For all the events the estimated mean flow velocity is very close to the observed mean flow velocity, as shown in Figure (2).

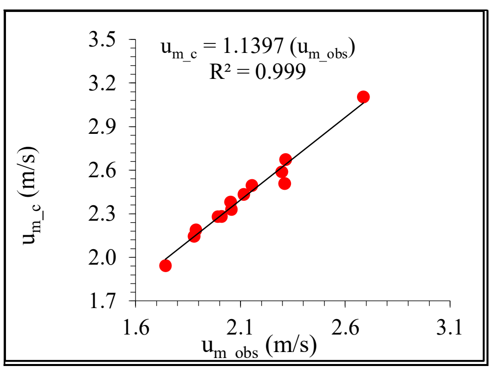

Figure 1: Comparison of the observed and the estimated mean flow velocity (13 events).

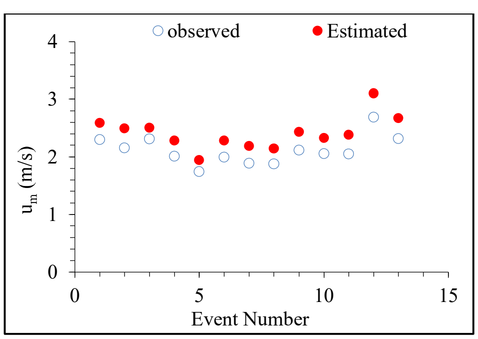

Figure 2: Comparison of the observed and the estimated mean flow velocity for each flow event (13 events).

Once the cross-sectional mean flow velocity is obtained (from Eq. (2)), then the stream flow rate of the river section is obtained as the product of mean flow velocity and the sectional flow area (A).

Figure 3 shows the comparison of the estimated discharge with the observed discharge. In this situation, the coefficient of correlation (R^2) value is more than 0.99. Figure 4 shows the comparison of the estimated discharge with the corresponding observed discharge for each flow event. Figure 3 and Figure 4 show the closeness of the estimated discharge with the observed discharge.

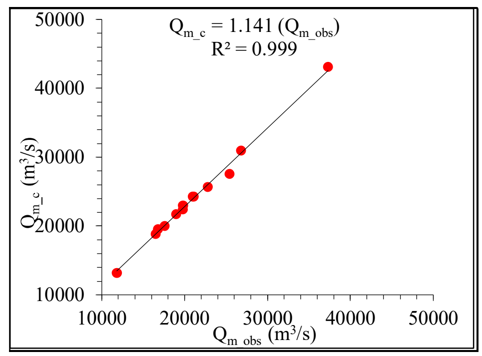

Figure 3: Comparison of the observed and the estimated discharge (13 events).

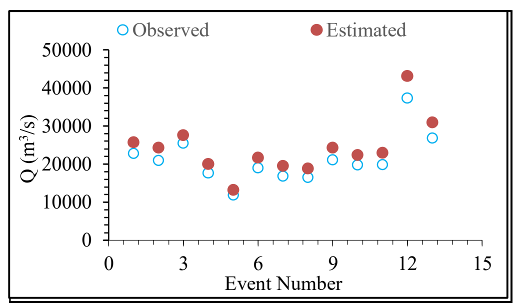

Figure 4: Comparison of the observed and the estimated discharge for each flow event (13 events).

Figure 1 and Figure 3 shows the accuracy of the Eq. (1). all the results were obtained by using the measured maximum depth-averaged velocity (single point velocity) only. This result shows that the entropy theory requires the single point velocity (either u_{max} or $u_{0.6D,\ max}$) to compute the discharge whereas the traditional method (velocity-area) requires the multi measurements across the section. Hence the entroy theory is the quick as well reliable approach compared to the velocity-area method.

Percentage error (ε %) is the one of the criteria to evaluate the accuracy of the method. It can be expressed as

$$\varepsilon\,\% = \frac{Q_c - Q_{obs}}{Q_{obs}} * 100 \qquad \text{..... (3)}$$

where ε % is the error percentage, Q_c is the estimated discharge and Q_{obs} is the observed discharge.

The variation of the range of percentage error is 8.4 to 15.9. The ε % is well within the acceptable range. Figure 5 shows the ε % for each flow event. Figure 6 shows the varation of ε % with the observed discharge. Figure 6 shows that this approach is equally efficient irrespective of the range of discharge. Hence one point measurement is enough to compute the discharge of any flood event and whatever may be the width of the river section. It is a well-established fact that the location of maximum depth-averaged velocity ($u_{0.6D,\ max}$) remains to fix like the location of the maxiumum flow velocity (u_{max}) [3]. The location of u_{max} and $u_{0.6D,\ max}$ always occurs in the same portion of flow area (*y-axis*).

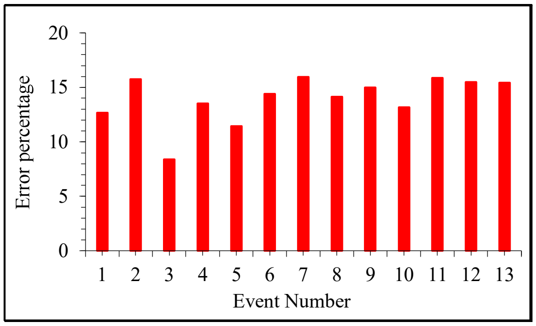

Figure 5: Error percentage for the each flow event (13 events).

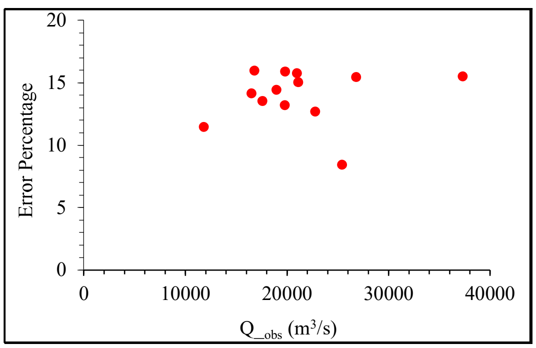

Figure 6: Variation of the error percentage wrt the observed discharge (13 events).

5. CONCLSION

The case study represents that the entropy theory is the well acceptable an alternative method to the traditional method (velovity-area). Figure 1 to Figure 6 shows the accuracy of the entropy theory. These results were obtained using the measured maximum depth-averaged velocity ($u_{0.6D,\ max}$). A high value of the coefficient of correlation shows the reliability of Eq. (2). The error percentage for all the 13 events are well within the acceptable limits as shown in Figure 5 and Figure 6. Thus, this study is a quick as well as reliable approach compared with the existing traditional method. This study further strength the following facts:

1. M or Ω (M) value remains constant.
2. Location of u_{max} and $u_{0.6D,\ max}$ always occurs in the same portion of flow area (*y-axis*).
3. Historical records of the velocity-area method can be used to for the estimation of M or Ω (M).
4. For future events mean flow velocity can directely by maximum flow velocity and using Eq. (2).

6. ACKNOWLEDGEMENT

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