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Calculation of mean velocity and discharge using water surface velocity in small streams

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ABSTRACT

Calculation of mean velocity and discharge are very important for demands such as water management, water supply, irrigation and flood control. This paper presents to determine the mean velocity and discharge in small streams using based water surface velocity. For this purpose, flow measurements were carried out at four different cross-sections at eighteen field measurements in central Turkey. The mean velocities (U_m) were calculated using velocity–area method. (U_m) and water surface velocities (u_{ws}) at these stations exhibited a linear distribution as $U_m = 0.552u_{ws}$ which has $R^2 = 0.99$ determination coefficient. It was observed that this constant was smaller than the literature value 0.85. The advantage of this ratio is that it does not change in T/R (T; width of cross-section, R; hydraulic radius) and Froude numbers for the small streams. Using this constant, mean velocities (U_{mcal}) and discharges (Q_{mcal}) for all measurements can be calculated. The average relative error between measured and calculated discharges ($Q - Q_{mcal}$) was found to be 4.08%. The results presented that this method can be utilized to determine the mean velocity and discharge in small streams successfully.

1. Introduction

One of the most influential problems in water resources and hydraulic engineering is to determine the discharge. Investigation of the flow properties such as discharge by the conventional methods becomes difficult, hazardous for the researchers in rivers and streams during unsteady high flowsand sometimes impossible to perform because of the significant floods. The difficulties encountered during the measurement of flow discharges in rivers especially in periods of floods have prompted to researchers to explore the simpler method.

Researchers who study on an open channel flow would like to describe one of the most important magnitudes in an open channel flows, discharge. Discharge measurements involve velocity samplings in order to determine the cross-sectional mean velocity. The discharge in an open channel is expressed in units of volume per time. Common units are liters per second (l/s), or cubic meters per second (m^3/s). In stream flow measurement, discharge is often estimated by determining the mean velocity at which water flows through a measured cross-sectional area. Furthermore, the stream flow can be measured through a measuring device and direct methods or it may be determined indirectly methods such as empirical equations and mathematical models.

In recent years, the importance of water has been increasing due to rising water demands which is related to higher population, industrialization, and agricultural developments. However, the changes in the relation between rain fall and run off along with climatic and environmental parameters complicate the control and usage of water resources. For this reason, the flow properties must be investigated in order to carry out wisely sustainable usage of water resources in terms of both quantity and quality. Assessment of small streams has become more important for countries at nowadays. Small streams are substantial water resources for natural life. They are important as conduits in the water cycle, instruments in groundwater recharge, and corridors for fish and wildlife migration.

The velocity measurement, which is the best correct method to calculate discharge in an open channel flow, is a duty requiring high effort and expense. Measurement of discharge is important in situations where water management is a priority concern. Chow [13] informed that empirical equations such as Chezy, Darcy–Weisbach and Manning's equations, which are called slope-area methods, were not very effective. However, Rantz et al. [17,18] stressed that discharge measurements may be realized by these empirical equations. Which method is preferred depends on the characteristics of the stream and the application. The most commonly used method in discharge measurement is the

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velocity–area method. Its utilization needs the mean slice velocity and also the cross-sectional area for measured cross-sections [21]. The conventional methods to determine the mean velocity and discharge from measured velocity samples require a great amount of time and effort for the measurements and the resultant computations [11].

In recent studies, the entropy concept has been presented to water resources and hydraulic engineering by Chiu [9,10]. It has given the possibility to develop a new method to measure discharges in natural streams.

Yorke and Oberg [25] studied on velocity and discharge of river using acoustic Doppler profilers (ADCP). In this research, discharge measurements have been confirmed by comparison with measurements made with traditional velocity–area techniques.

Sahu et al. [19] investigated discharge in straight compound open channel flow. In this study, an artificial neural network model is proposed for accurate estimation of discharge in compound channel flume. He expressed that ANN model is a convincing model.

Ardiclioglu et al. [6] presented a new approach to entropy method to determination of discharge and velocity distribution in streams. In this approach, they showed that maximum velocity, u_{max} and its position, z_{max} could be obtained just as a function of the water depth H.

Comina et al. [14] stressed that discharge measurements by means of the salt dilution method is a traditional and well-documented technique. However, this methodology can be strongly influenced by the natural streaming characteristics of the canal.

Al Khatib and Gogus [2] studied on determination of discharge in rectangular compound broad-crested weirs. They developed prediction models to estimate the discharge.

Al Khatib et al. [1] studied to predict mean velocities in asymmetric compound channels. They stressed that the mean velocity measurements are related to a dimensionless parameter called the relative depth defined as the ratio of the depth above the flood plain bed to the depth above the main channel bed.

As mentioned above, empirical equations, conventional methods, and current methods are not very effective and they are all extremely sensitive to roughness parameters and are not easy to determine.

For this reason, the main objective of this study is to develop an easy discharge and mean velocity calculation that provides suitable results based on water surface velocity that are simple to measure or derive. In this study, the relationship between water surface and mean velocity was investigated to determine discharge of small streams. Applicability of calculated discharge (Q_{mcal}) based on water surface velocity wasinvestigated for small streams.

2. Mean velocity and discharge calculation

The discharge of stream is an important environmental variable to measure for several key reasons such as flood forecasting, water resources management, hydrologic analysis and water quality monitoring in river engineering. The mean velocity (U_m) of flow and the cross-sectional area (A) of the measured cross-section must be calculated to determination of discharge (Q). Flow is the product of the cross-sectional area multiplied by the mean velocity as given in the following equation:

$$Q = U_m A \tag{1}$$

It should be considered that the velocity distribution of flow varies both across a stream channel and from the bottom to the surface of the verticalsbecause of friction and irregularities in cross-section. The biggest velocities in stream are usually near the center of the channel and near the surface. Because of friction, the velocities of near the bottom and sides of a channel are slower than velocities of near the center of the channel and near the surface.

Some studies were carried outto calculate the variability in stream velocity within any cross-sectional area. As a result of these studies, several general practically rules were presented as below [24].

1. Mean velocity in a vertical profile is approximately estimated by the velocity at 0.6 depth in small depths.
2. Mean velocity in a vertical profile is more properly determined by the average of the velocities at 0.2 and 0.8 depth.
3. The mean velocity in a vertical profile is 80–90% of the water surface velocity.
4. In shallow waters, it is stated that this coefficient calculated to be around 0.67.

A lot of studies were performed by many researchers and similar results were obtained. Ardiclioglu et al. [3] investigated mean velocity and discharge using ADV in natural streams. Ardiclioglu et al. [7] presented relationship between water surface velocity and mean velocity as 0.45 in small streams.

Manning equation, shown below, is used as indirect method.

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

where Q=discharge, A=cross-sectional area, n=roughness coefficient, R=hydraulic radius, S=friction slope. Application of Manning equation in an unsteady nonuniform flow is difficult, because both the energy slope and Manning's n tend to vary with time and water depth from section to section along the flow direction [15].

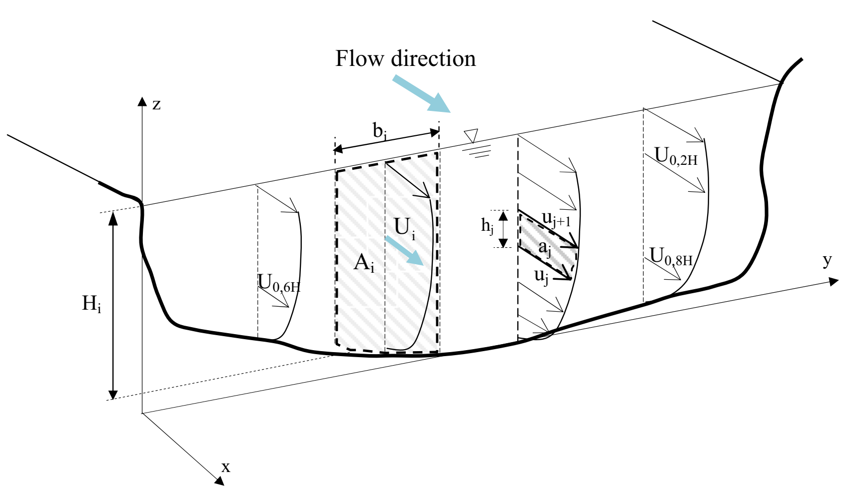

Fig. 1. Calculation of mean velocity and discharge in measuring cross-section [7].

The method most commonly used for determination of discharge is the velocity area method. In this method, cross section was divided into slices according to the width of the section as shown in Fig. 1. The verticals should be so spaced that any subsection has no more than 10% of the total discharge [5].

As shown in Fig. 1, vertical velocity curve, two-point and six-tenths-depth methods are the most commonly used methods for determining mean vertical velocity. In the two-point method of measuring velocities, observations are made in each vertical at 0.2 and 0.8 of the depth below the surface. The average of those two observations is taken as the mean velocity in the vertical. In the six-tenths-depth method, an observation of velocity made in the vertical at 0.6 of the depth below the surface is used as the mean velocity in the vertical. This method is usually applied when the stage in a small stream is changing rapidly and a measurement must be made quickly. In the vertical-velocity curve method, a series of velocity observations at points well distributed between the water surface and the streambed are made at each of the verticals as shown in Fig. 1 [4].

While discharge is determined by the velocity area method, mean vertical velocity is needed. The mean velocity in the vertical in measured cross-section is obtained by measuring the area (a_j) between the curve and the ordinate axis and dividing the area by the flow depth (H_i) in this vertical by using Eq. (3). In this equation, a_j is the area of the between two different consecutive velocities u_j and u_{j+1} and h_j shows distance between consecutive velocities measurements points. H_j is mean flow depth for this slice.

$$U_i = \frac{\sum a_j}{H_i} = \frac{\sum \left((u_j + u_{j+1})/2 \right) h_j}{H_i} \tag{3}$$

A_i is the slice area and it can be calculated using Eq. (4). Eq. (5) is used for slice discharge where A_i is slice area and the total flow rate of the stream is determined as the sum of the flows through all the subsections using Eq. (6). In this equation n shows the slice number.

$$A_i = b_i H_i \tag{4}$$

$$q_i = U_i A_i \tag{5}$$

$$Q = \sum_{i=1}^{n} q_i = \sum_{i=1}^{n} U_i A_i \tag{6}$$

3. Field measurements

Field measurements were undertaken on Kızılırmak and Seyhan basins where their locations are in the central of Turkey. Turkey has a semi-arid climate with some extremities in temperature. Winters are long and cold in Central and Eastern Anatolia, while mild and short in coastal regions. Field measurements were performed on Kızılırmak and Zamantı Rivers and shown in Fig. 2. Three stations are within the Kızılırmak basin: Bünyan, Şahsenem and Barsama on the Sarımsaklı Stream, which is a tributary of the Kızılırmak River. It drains into the Black Sea in northern Turkey. Sosun station is on the Sosun stream, which is a tributary of the Zamantı River in the Seyhan basin. Zamantı River drains to the Mediterranean Sea in southern Turkey. All of four stations have similar geographical features.

Bünyan, Şahsenem and Barsama stations were visited different times between 2005 and 2010 (Table 1, column 2). Velocity measurements at the Sosun station were carried out during three site visits from 2009 to 2010. The water level was below the bankfull stage at each time point. The velocity measurements were undertaken using by acoustic Doppler velocimeter (ADV). ADV is designed to record instantaneous velocity components at a single-point with a relatively high frequency. Measurements are performed by measuring the velocity of particles in a remote sampling volume based upon the Doppler shift effect. The probe head includes one transmitter and between two to four receivers [23,16]. ADV measures three-dimensional flow velocities (u, v, w) for x, y, z dimensions in a sampling volume using the Doppler shift principle. In measurements, the ADV records one second velocity data for the specified averaging time, location and water depth parameters, and a variety of statistical and quality control data. The remote sampling volume is located typically 5 or 10 cm from the tip of the transmitter, but some studies showed that the distance might change slightly [12]. In this study, the ADV sampling volume is located 10 cm in front of the probe head. Therefore the probe head itself has least impact on the flow field surrounding the

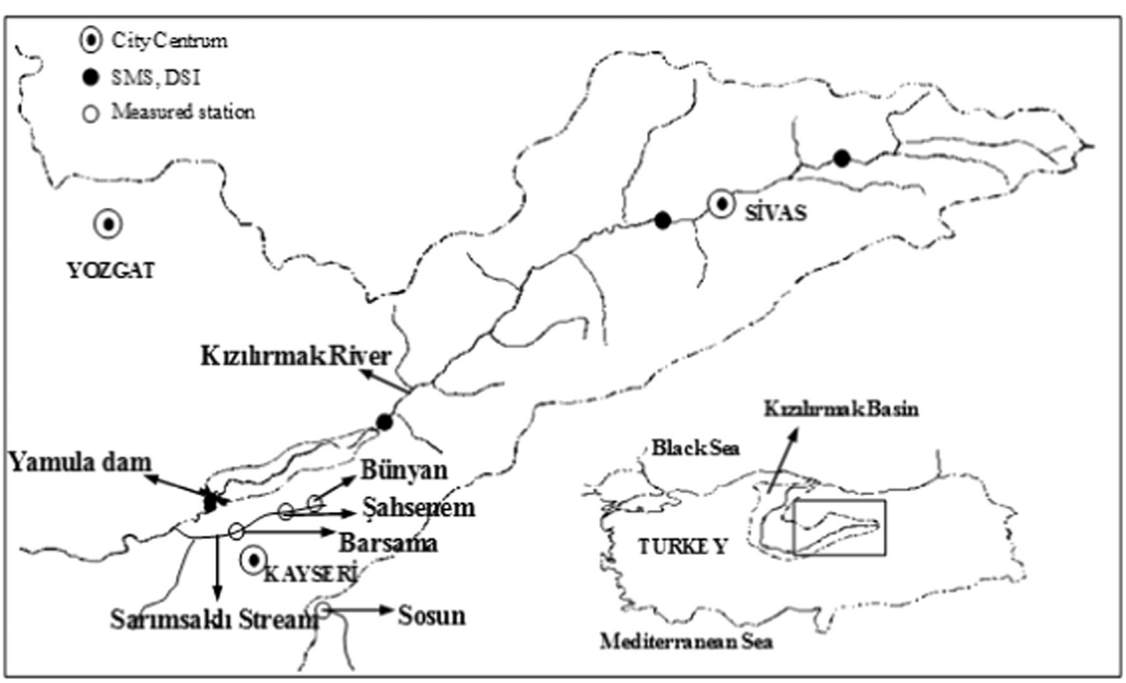

Fig. 2. Location of the study area and measurement stations [6].

Table 1
Flow characteristics for all stations.

Stations 1	Dates (d/m/y) 2	H_{max} (m) 3	A (m^2) 4	T (m) 5	T/R 6	S_{ws} 7	Re ($\times 10^6$) 8	Fr 9
Barsama_1	28/05/2005	39.0	2.04	8.3	34.00	0.0091	0.76	0.481
Barsama_2	19/05/2006	40.0	2.32	9.0	35.20	0.0036	0.94	0.531
Barsama_3	19/05/2009	45.0	3.24	9.0	29.70	0.0094	1.47	0.578
Barsama_4	31/05/2009	26.0	1.64	8.4	45.40	0.0092	0.40	0.333
Barsama_5	24/03/2010	38.0	1.87	8.6	34.40	0.0097	0.61	0.417
Barsama_6	18/04/2010	38.2	2.48	8.8	22.10	0.0120	0.85	0.421
Bünyan_1	24/06/2009	72.0	2.23	4.0	7.00	0.0020	0.71	0.133
Bünyan_2	08/02/2009	66.0	2.03	4.0	7.50	0.0030	0.40	0.084
Bünyan_3	27/09/2009	72.0	2.11	3.9	8.20	0.0022	0.50	0.113
Bünyan_4	04/04/2010	85.0	2.67	4.0	7.30	0.0018	0.78	0.140
Bünyan_5	20/06/2010	79.0	2.48	3.9	7.30	0.0010	0.53	0.103
Şahsenem_1	29/03/2006	28.0	1.40	6.0	26.80	0.0059	0.47	0.350
Şahsenem_2	03/05/2008	32.0	1.18	5.4	25.10	0.0045	0.39	0.307
Şahsenem_3	11/10/2008	32.0	1.24	5.5	22.00	0.0046	0.44	0.303
Şahsenem_4	08/11/2008	34.0	1.40	5.6	19.60	0.0064	0.51	0.282
Sosun_1	19/05/2009	62.0	1.58	3.2	7.49	0.0032	0.84	0.227
Sosun_2	24/03/2010	45.0	1.03	2.9	8.85	0.0026	0.37	0.156
Sosun_3	18/04/2010	54.0	0.98	2.3	6.53	0.0034	0.67	0.235

measurement volume. Velocity range is ± 0.001 m/s to 4.5 m/s, resolution 0.0001 m/s, accuracy $\pm 1\%$ of measured velocity [20].

The flow characteristics are presented in Table 1. As shown in Table 1, H_{max} is the maximum flow depth at a given cross-section, A is the cross-section area, T is the surface width, T/R is the aspect ratio, R is the hydraulic radius, S_{ws} is the water surface slope, Re ($=4\,U_m R/\upsilon$) is the Reynolds number, with R ($=A/P$) being the hydraulic radius, P being the wetted perimeter and υ being the kinematic viscosity, and Fr ($=U_m/(gH_{max})^{1/2}$) is the Froude number, where g is the gravitational acceleration. Froude and Reynolds numbers which given in Table 1 shows that all the flow measurements were made under subcritical and turbulent flow conditions.

During flow measurements, according to the water surface width, cross-sections were splitted into number of slices for each flow condition. Point velocities were measured in the vertical direction starting 4 cm from the streambed for each vertical. The velocities of free water surface in all verticals were estimated using extrapolating the last two measurements of verticals.

These stations are relatively small and shallow stream, where the maximum water depths, H_{max} change between 0.26 and 0.85 m in measured cross sections. And also the water surface width, T vary between values 2.3 and 9.0 m.

4. Data analysis and results

4.1. Water surface velocity measurements

Determining the velocity of the free water surface is much easier than that of mean and maximum velocities in open channels [22]. Measurement of water surface flow is an important component such as water quality monitoring projects and determination of mean and maximum velocities in open channel flows. Surface velocity measurements are often the best available measurements in extreme floods. The relationship between surface water and mean velocitiesis used in both the planning and assessment phases of open channel flows. Water surface velocity can be easily determined with an object that is movable on water surface and not too heavy such as leaves, twigs and so on. The other methods such as acoustics, optics, or floats are used to estimate the surface velocity. The cheapest and easiest way to determine water surface velocity is to simply float something down the stream and see how fast it goes. In this study, in how many seconds a tree branch passed distance of 10 m was measured using a chronometer. In this study, we used the water surface velocity

Table 2
Calculation of water surface velocity for Barsama_2 measurement.

Test no	T (s)	u_{ws} (m/s)
1	5.52	1.81
2	5.25	1.91
3	5.34	1.87
4	5.34	1.87
5	5.15	1.94
6	5.50	1.82
7	5.46	1.83
8	5.49	1.82
9	5.50	1.82
10	5.64	1.77
$u_{ws}=$		**1.85**

measured in the middle of the river. This procedure was repeated 10–15 times, and shown in Table 2 for Barsama_2 measurement. In this way, average water surface velocities (u_{ws}) were determined for all stations and shown in Table 3.

4.2. Mean velocity and discharge

Discharge and mean velocity are important because of their impacts on water quality and on the living organisms and habitats in the stream. Calculating stream flow involves solving an equation that examines the relationship among several variables such as stream cross-sectional area, stream slope, and water velocity etc. This procedure requires considerable effort and time. However, especially in floods, flow properties must be determined by researchers as soon as possible. Floods are natural events which often result in loss of life and property damage. Therefore, a simple method needs to calculate the discharge and velocity of the stream. The method of water surface velocity seems to be best adapted in the case of the Central Anatolian's rivers, for a fast discharge and mean velocity measurement with a maximum precision. In this study, a simple and an easy method were presented to determinedischarge and mean velocity.

Cross-sections were divided into number of slices for each flow measurements according to the water surface width (T) as shown in Fig. 1. Mean vertical velocities U_i, were calculated using Eq. (3). Total discharges (Q) were calculated using Eq. (6) and given in Table 3. Then mean velocities (U_m,) can be calculated using Eq. (1) and given in same table. In this study, a relationship between water surface and mean velocities was tried to obtain.

Table 3
Measured and calculated discharges and velocities in stations.

Stations 1	Q (m^3/s) 2	U_m (m/s) 3	u_{ws} (m/s) 4	U_{mcal} (m/s) 5	Q_{mcal} (m^3/s) 6	ε (%) 7
Barsama_1	1.816	0.890	1.60	0.883	1.801	0.77
Barsama_2	2.438	1.051	1.85	1.021	2.368	2.83
Barsama_3	3.933	1.214	2.08	1.148	3.718	5.43
Barsama_4	0.968	0.590	1.14	0.629	1.031	6.64
Barsama_5	1.507	0.806	1.55	0.856	1.599	6.14
Barsama_6	2.145	0.865	1.63	0.900	2.230	4.01
Bünyan_1	0.788	0.354	0.65	0.359	0.798	4.45
Bünyan_2	0.434	0.214	0.40	0.221	0.448	6.54
Bünyan_3	0.635	0.301	0.54	0.298	0.629	4.10
Bünyan_4	1.081	0.405	0.74	0.408	1.090	6.83
Bünyan_5	0.708	0.286	0.53	0.293	0.724	1.36
Şahsenem_1	0.840	0.600	1.04	0.574	0.803	3.18
Şahsenem_2	0.611	0.518	1.00	0.552	0.651	0.97
Şahsenem_3	0.665	0.536	1.01	0.558	0.692	0.86
Şahsenem_4	0.722	0.516	1.00	0.552	0.772	2.29
Sosun_1	0.886	0.561	0.96	0.530	0.837	5.54
Sosun_2	0.337	0.327	0.63	0.348	0.358	6.33
Sosun_3	0.530	0.541	0.93	0.513	0.503	5.12

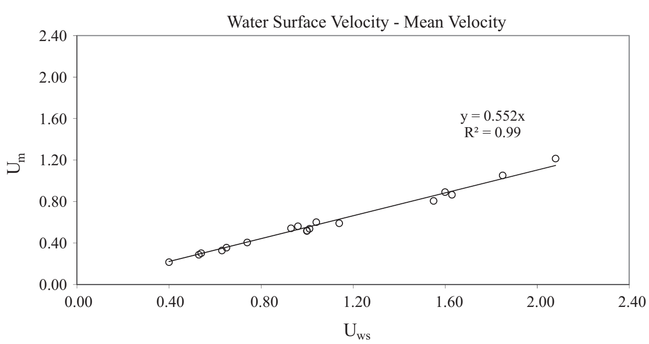

Fig. 3. Relation between U_m and u_{ws} for four stations.

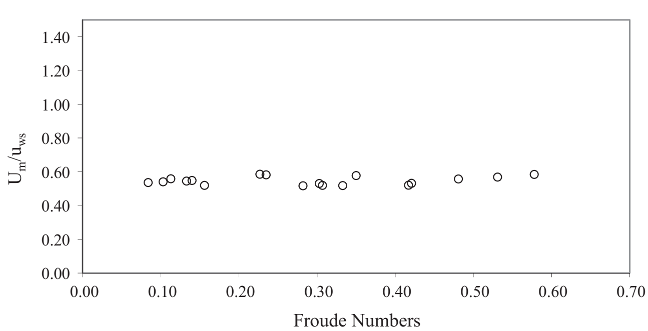

Fig. 4. Relation between U_m/u_{ws} and Froude numbers for four stations.

When mean and water surface velocities for all four stations are plotted on the same graph, it is observed that there is a very strong linear relationship ($R^2=0.99$) between the mean and the water surface velocities (Fig. 3). The slope of this linear regression line is 0.552 which correspond to U_m/u_{ws}. Calculated mean velocities U_{mcal} were determined using this value, and shown in Table 3. Since U_{mcal} is known, the cross-sectional discharge could be calculated using Eq. (1). Calculated discharges (Q_{mcal}) were given in Table 3. Average relative error between measured and calculated discharges was found using Eq. (7) and presented in Table 3.

$$\varepsilon\ (\%) = \left|\frac{Q_m - Q_{mcal}}{Q_m}\right| \times 100 \qquad (7)$$

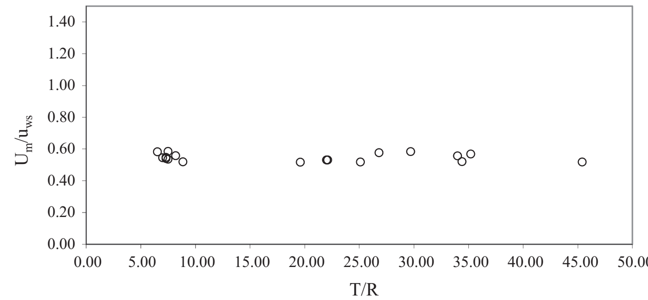

Fig. 5. Relation between U_m/u_{ws} and T/R for four stations.

For all measurements average error was found as 4.08%. Given the simplicity of this method, it can be stated that surface water flow measurement method can be used as a cheap and easy technique for estimating the flow discharge in small streams.

Aspect ratios (T/R) vary between 6.53 and 45.40 and Froude numbers are between 0.084 and 0.578 in these measurements. The advantage of this approach is that U_m/u_{ws} constant does not change in T/R and Froude numbers for the streams as shown in Figs. 4 and 5.

5. Conclusions

Determination of discharge in small stream flow is important research area for many purposes such as flood forecasting, water resources management, hydrologic analysis and water quality monitoring. In this study, the linear relationship between the mean and the water surface velocities is found to be accurate at four different cross-sections as $U_m=0.552\,u_{ws}$. It was observed that this constant was smaller than the literature value 0.85. The advantage of this ratio is that it does not change in T/R and Froude number for the measured small streams. Using this ratio, discharges (Q_{mcal}) for all flow conditions were calculated. The average relative error between Q and Q_{mcal} was found to be 4.08%. The results provide proof that this efficient method can present successful performance in measuring discharge in small streams. This method significantly reduces the time and cost of discharge measurement with righteousness in small streams. Considering the convenience of the application, this method could serve as a cheap, quick and practical alternative for the determination of mean velocity and discharge. The utilization of the method can be investigated for small streams and river in subsequent studies.

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