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Full Length Research Paper

Determining agricultural water demand from natural streams using the entropy concept

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Determining water flow discharge in open channels is a very important task for agricultural water management, but current methods are labor-intensive and difficult. The entropy method suggested by Chiu and Said (1995) promises to simplfy the task of measuring water flow rates. This paper offers a further simplification of ongoing discharge measurements by showing that the u_{max} and H_{max} values form a constant in a specific water channel cross section. Once the u_{max}/H_{max} constant is determined, u_{max}, and therefore discharge, can easily be calculated from H_{max} measurements. This method, which we call Q_{umax} method in this paper, was compared against the integrated discharge method for accuracy and was found to have an accuracy similar to that of two other common methods, the integrated $Q_{0.2\ to\ 0.8}$ and the entropy methods (Q_{Mi}). Comparisons were carried out at four sites along the tributaries of the Kizilirmak river in central Anatolia, Turkey.

Key words: Agricultural water, discharge, natural stream, entropy.

INTRODUCTION

Water management becomes more difficult day by day because of the increasing competition between power, irrigation, municipal, industrial and other uses. Public concepts of how to share and manage the finite supplies of water are changing depending on economic and social requirements. The steadily increasing demand for water and the increasing needs for better river management require special efforts in order to better understand the phenomenology of water courses. Best management, measures and practices without exception depend upon conservation of water. Good water management and conservation require accurate water measurement techniques. Agriculture is the dominant user of fresh water compared to the other categories of users, especially in arid and semi-arid regions of the world. Lacking adequate precipitation during the growing season, agriculture in these areas is dependent on a large amount of surface water and groundwater storage. The cheapest source for irrigational usage is surface water. For this purpose, water from rivers, streams or reservoirs can be used directly. Good water management requires accurate water measurement.

There are many benefits of upgrading water measurement programs and systems. Although some of the benefits are intangible, they should be considered during system design or when planning water system upgrade. Some benefits of water measurement for agricultural purposes include: (U.S. Bureau of Reclamation, 2001):

i) Equitable shares of water for different users,
ii) Accurate and equitable distribution of water within a district or farm,
iii) Minimizing negative environmental impacts,
iv) Determining seepage losses during water flow,
v) Future planning for agricultural purposes,
vi) Preventing ground water pollution with chemicals and pesticides and
vii) Preventing redundant water usage.

Discharge is the volume of water flowing through a cross-section of a stream in a given amount of time and it drives various hydrological processes. Many discharge prediction methods have been developed for open channels. The velocity-area method for discharge determination is commonly used at stream gaging stations in rivers. Measurements of stream discharge require information about the mean velocity and geometry of the river cross-section at the measuring

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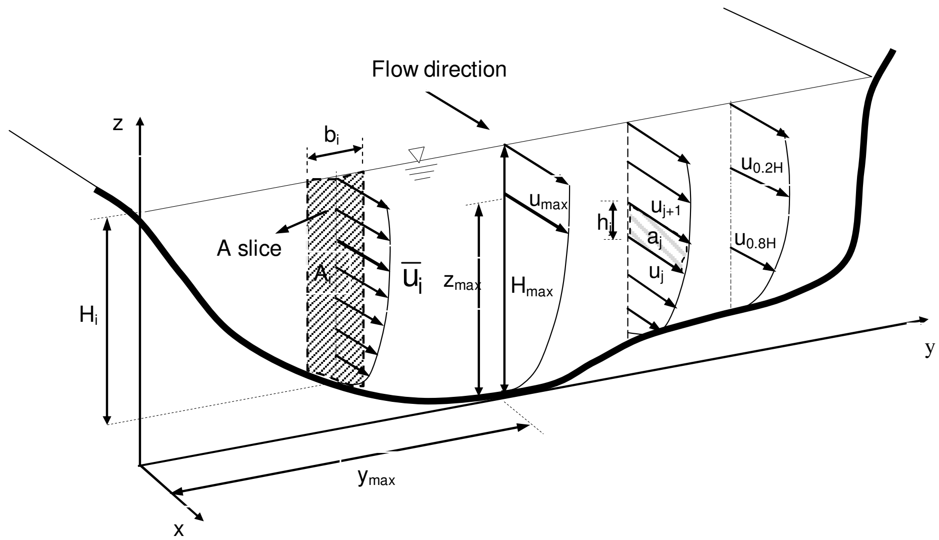

Figure 1. Velocity distribution in measuring cross-section.

station. Multiple depth and velocity measurements are taken by a current meter across the channel and the discharge. These sub-areas are summed to calculate the total stream discharge at a given moment.

Weirs are one of the oldest structures used in measuring flow of water in open channels. As water flows over the weir, the depth or "head" of the water is measured. The water head is entered into a discharge formula specific to the geometry of the weir. Several rating equations were developed for different types of weirs (Ackers et al., 1978; Kaya, 2010). The introduction of the entropy concept in hydraulics by Chiu (1989, 1991) provided an opportunity for developing a simple method to estimate discharges in natural streams. Considering the probabilistic formulation, the mean velocity (U_m) can be expressed as a linear function of the maximum velocity (u_{max}), through a dimensionless entropy parameter M, (Chiu and Said, 1995). The M value of a channel section contains information about its overall hydraulic characteristics. These analyses allow an easy employment in the field of applied hydraulic engineering due to the use of simply-derivable parameters instead of difficult and hardly measurable ones. In this study, velocity measurements were taken using acoustic doppler velocimeter (ADV) at four different stations on the Kizilirmak river tributaries and their branches in central Anatolia, Turkey. Each site was visited six times for velocity and discharge measurements. Velocity area and entropy methods were used for discharge calculations.

The region where maximum velocity occurs on cross-section was determined and u_{max}/H_{max} relations were investigated for each station.

DISCHARGE CALCULATION

The discharge of a stream usually is calculated from a series of measurements of width, depth and velocity along a cross section of the stream. Theoretically, the true discharge would be an integration of the velocity and area throughout the cross section. Discharge is expressed in volume of water per unit of time, usually liter per second or cubic meters per second in the metric system. Discharge measurements may be conducted by several methods given in the literature (Rantz et al., 1982a, b). However, the conventional integrated method is most commonly used in natural streams. In this method cross section is divided into slices according to the width of the section as shown in Figure 1. Mean velocity $\overline{u}_i$, in a vertical obtained from velocity observations at many points in that vertical, but it can be approximated by making a few velocity observations and using a known relationship between those velocities and the mean velocity in that vertical. The more commonly used approaches for determining mean vertical velocity are the vertical velocity curve, the two-point, the six-tenths-depth and the average of these measurements methods. 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 Figure 1.

The mean velocity in the vertical is obtained by measuring the area between the curve and the ordinate axis and dividing the area by the flow depth in this vertical by using Equation 1. In this equation a_j is the area between two successive velocity measurements, u_j and u_{j+1} are velocities measured at two points on the same vertical separated by the distance h_j. H_i is mean flow depth for slice i:

$$\overline{u}_i = \frac{\sum a_j}{H_i} = \frac{\sum \frac{(u_j + u_{j+1})}{2} h_j}{H_i} \qquad (1)$$

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. This method is based on many studies involving actual observation (Ardiçlioğlu et al., 2007, 2010) and mathematical theory (Gupta, 1989; Chapra and Canale, 1988). Similarly, 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

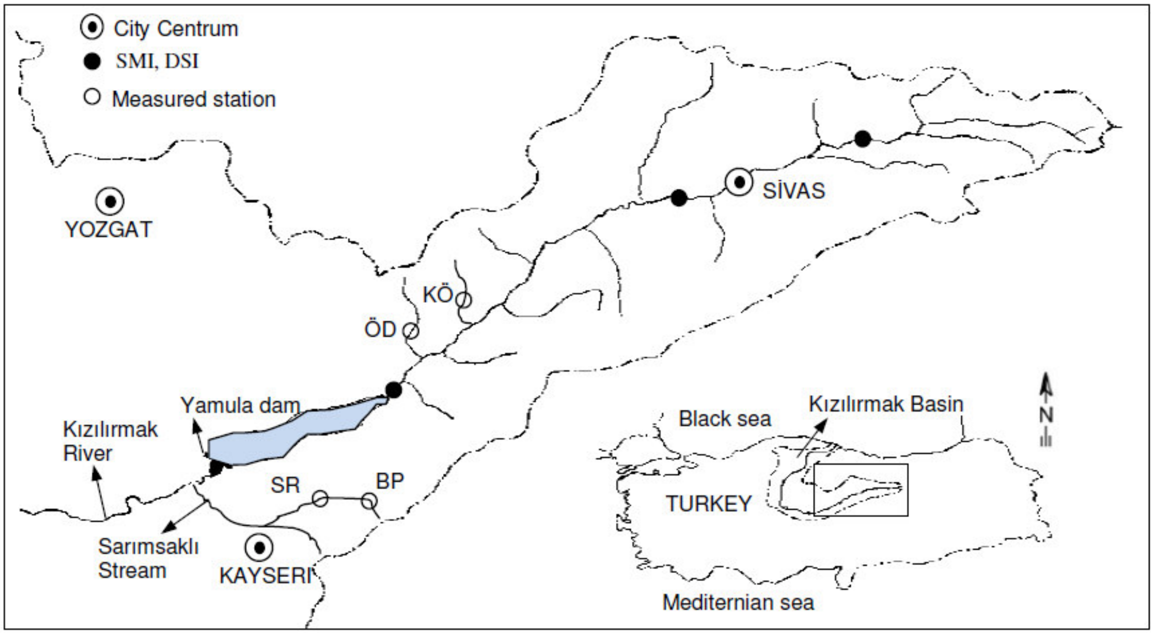

Figure 2. Kızılırmak River Basin with location of measuring stations.

the mean velocity in the vertical. This method is usually applied when the stage in a stream is changing rapidly and a measurement must be made quickly. From a practical standpoint, however, when it is necessary to measure velocities where water depths are as shallow as 10 cm, the 0.6-depth method is used.

The discharge (q_i) through the slice can be calculated by Equation 2, which is simply the slice area (A_i) multiplied by mean velocity ($\overline{u}_i$). Flow discharge (Q) for the cross-section can be determined by Equation 3. In this equation "n" is the number of slices:

$$q_i = A_i \ \overline{u}_i \qquad (2)$$

$$Q_{int} = \sum_{i=1}^{n} q_i = \sum_{i=1}^{n} A_i \overline{u}_i = \qquad (3)$$

Chiu (1989, 1991) proposed an entropy-based two dimensional probabilistic velocity distribution function for simulation of velocity distributions in river cross-sections. Considering the probabilistic formulation, the mean velocity U_m can be expressed as a linear function of the maximum velocity u_{max}, through a dimensionless entropy parameter M (Chiu and Said, 1995) as:

$$\phi(M) = \frac{U_m}{u_{max}} = \frac{e^M}{e^M - 1} - \frac{1}{M} \qquad (4)$$

Equation 4 shows that, if a sample of pairs (U_m, u_{max}) is given, first $\phi(M)$ can be calculated to estimate the entropy parameter, M. Chiu and Tung (2002) developed a relationship between M and the location of maximum velocity when the maximum velocity occurs below water surface. This relationship provided a more efficient procedure for estimating discharge. Ammari and Remini (2009) showed that when the M parameter is known for a stream cross-section, mean velocity U_m can be determined from u_{max}, which can be measured directly. They showed that for more than 90% of the cases maximum velocity appears at the deepest vertical, at the same place and in the vicinity of the water surface.

For determination of velocity distribution and discharge in streams, many theoretical and experimental studies have been carried out based on the entropy concept (Moramarco et al. 2002, 2004; Ardiçlioğlu et al., 2008, 2009, 2010).

FIELD MEASUREMENTS

Field measurements were undertaken in the Kizilirmak basin, which is in central Anatolia, Turkey (Figure 2). The study region is characterized by semi-arid climate with some extremities in temperature. Central Anatolia has a Steppe climate with low annual precipitation. Most precipitation occurs in spring and winter months. Ambient air temperature show strong diurnal and seasonal variations. Kizilirmak is the longest flowing river within the boundaries of the Republic of Turkey. Several dams were constructed over the Kizilirmak river for electricity, irrigation and domestic water supply, and flood control purposes. There are also many diversion weirs for irrigation purposes on the tributaries of the Kizilirmak River and their branches. Four different stations which are on three different tributaries of the Kizilirmak River were identifed for discharge determination: Bünyan Pinarbasi (BP), Sarimsakli (SR), Kiriközu (KÖ) and Özdere (ÖD). Velocity measurements were carried out during six site visits to each site, between 2009 and 2010. The water level was below the bank (below full stage) at each time. The velocity measurements were made with SonTek/YSI FlowTracker Handheld acoustic doppler velocimeter (ADV). ADV measures three-dimensional flow velocities (u, v and w) in a sampling volume. The ADV sampling volume is located 10 cm in front of the probe head. Therefore, the probe head itself has a minimal impact on the flow field surrounding the measurement volume. The velocity range that ADV can accurately measure is 0.001 to 4.5 m/s with ±1% accuracy (SonTek, 2002).

Flow characteristics at each site are summarized in Table 1. In

Table 1. Flow characteristics and discharges.

	Dates	Q_{int}	H_{max}	U_m	u_{max}	T/R	$Q_{0.2\_0.8}$	Q_{Mi}	Q_{umax}
	m/d/y	(m^3/s)	(m)	(m/s)	(m/s)	-	(m^3/s)	(m^3/s)	(m^3/s)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
BP_1	06.24.2009	0.788	0.72	0.354	0.595	7.0	0.803	0.755	0.713
BP_2	08.02.2009	0.434	0.65	0.214	0.412	7.5	0.444	0.477	0.587
BP_3	09.27.2009	0.636	0.72	0.301	0.593	8.2	0.660	0.713	0.676
BP_4	04.04.2010	1.082	0.80	0.405	0.687	7.3	1.114	1.046	0.950
BP_5	05.16.2010	1.188	0.84	0.426	0.671	7.0	1.190	1.068	1.044
BP_6	06.20.2010	0.708	0.75	0.286	0.557	7.3	0.726	0.786	0.826
SR_1	06.24.2009	1.178	0.35	0.987	1.393	13.3	1.231	1.186	1.152
SR_2	08.02.2009	1.021	0.32	0.891	1.192	16.7	1.090	0.974	1.011
SR_3	09.27.2009	1.129	0.34	0.954	1.470	14.2	1.306	1.241	1.110
SR_4	06.20.2010	1.657	0.41	1.103	1.499	13.1	1.756	1.606	1.699
SR_5	07.18.2010	1.222	0.36	0.960	1.365	14.5	1.275	1.239	1.264
SR_6	08.08.2010	1.053	0.32	0.909	1.193	13.0	1.113	0.986	1.023
KÖ_1	07.05.2009	0.132	0.26	0.306	0.536	11.3	0.130	0.134	0.138
KÖ_2	08.16.2009	0.041	0.21	0.150	0.295	12.6	0.043	0.045	0.048
KÖ_3	10.18.2009	0.036	0.17	0.197	0.418	14.7	0.035	0.040	0.038
KÖ_4	04.25.2010	1.019	0.38	0.616	0.894	9.2	1.086	0.916	0.863
KÖ_5	05.23.2010	0.351	0.40	0.512	0.835	13.3	0.422	0.332	0.336
KO_6	06.27.2010	0.235	0.34	0.427	0.872	16.3	0.229	0.262	0.229
ÖD_1	05.07.2009	0.072	0.29	0.119	0.263	11.9	0.071	0.072	0.067
ÖD_2	08.16.2009	0.029	0.24	0.064	0.111	13.6	0.031	0.031	0.031
ÖD_3	10.18.2009	0.055	0.31	0.097	0.236	12.0	0.058	0.060	0.051
ÖD_4	04.25.2010	0.720	0.73	0.450	0.826	10.3	0.783	0.684	0.612
ÖD_5	05.23.2010	0.330	0.63	0.252	0.570	7.5	0.363	0.336	0.315
ÖD_6	06.27.2010	0.163	0.58	0.137	0.364	7.7	0.176	0.182	0.187

See text for definition of terms.

this table, first column shows measurement dates, Q_{int} is the integrated discharge, H_{max} is the maximum flow depth at a given cross-section, U_m (= Q_{int}/A) is the mean velocity, A is the wetted area of the cross-section and u_{max} is the measured maximum velocity at the cross-section. T/R is the aspect ratio with T being the surface water width and R is the hydraulic radius. Flow measurements were made under turbulent flow conditions ($3.95 \times 10^3 \leq Re = 4U_mR/\upsilon \leq 1.27 \times 10^6$), where Re is the Reynolds number, υ is the kinematic viscosity, under sub-critical flow conditions ($0.04 \leq Fr = U_m / \sqrt{gH_{max}} \leq 0.55$), where Fr is the Froude number and g is the gravitational acceleration.

RESULTS AND DISCUSSION

The cross-section was divided into slices for each flow condition according to the water surface width. Point velocity measurements were made at different positions in the vertical direction starting 4 cm from the bed for each vertical. Free surface velocity was then estimated by extrapolating the upper two measurements. Mean vertical velocities, $\overline{u}_i$, were calculated using Equation 1 for each verticals. Then slice discharges (q_i) were calculated by Equation 2. Stream flows (Q_{int}) for each measurement were calculated by Equation 3 and are given in Table 1 on 2th column. Mean velocities (U_m) were calculated using the integrated discharge and cross-sectional area ($U_m = Q_{int}/A$) for each flow condition. A simple procedure using two point velocities, at 0.2 and 0.8 times the flow depth from the water surface was used to calculate the vertical mean velocity at each vertical. Point velocities at 0.2 and 0.8 H were interpolated with closed measured depth velocities. Using these velocities total flow rates were determined using the same procedure aforementioned and given in the 7th column of Table 1.

Relative errors (ε) between the two methods were calculated for each measurements and stations using Equation 5. Average absolute relative errors (ε) between the two methods were calculated as 2.3, 8.2, 6.4 and 6.7% for BP, SR, KÖ and ÖD stations respectively:

$$\varepsilon = \left| \frac{Q_{int} - Q_{0.2\_0.8}}{Q_{int}} \right| x100 \quad (5)$$

As shown in these values, relative errors are very small

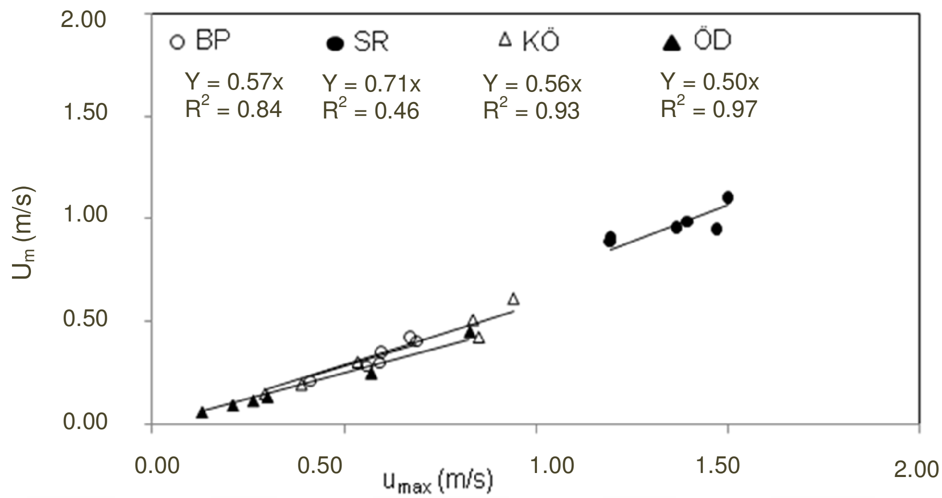

Figure 3. Relation between U_m and u_{max} based on measured data for four station.

for all stations and this procedure is applicable for discharge calculation. For this reason two point velocity method is commonly used in practices for discharge calculation by General Directorate of State Hydraulic Works of Turkey. Chiu and Said (1995) suggested a technique for determining discharge from the entropy parameter M of a river cross-section. The value of M being constant for a river cross-section can greatly simplify discharge determination. For this purpose, equation (4), the entropy parameters, M_i (I = 1,.., 4) were calculated for each measurement station. Figure 3 shows the relationship between the maximum velocities (u_{max}) versus the cross-sectional mean velocity (U_m) for six different flow conditions at four different stations. As shown in the figure u_{max} and U_m present a linear relationship and the M_i values for four station were calculated by Equation 4.

The entropy parameters, M_i, were determined to be 0.85, 2.9, 0.73 and 0.1 for BP, SR, KÖ and ÖD stations, respectively. Since M is known, the cross-sectional mean velocity (U_m) can be estimated using the maximum cross-sectional velocity (u_{max}) with Equation 4. As the maximum velocities occur at or near the surface, their measurement is much easier. This is a big advantage during high flows, where getting in the water could be dangerous. Using the constant proportion of measured cross-section and u_{max} values for each measurements, mean velocities and also discharges (Q_{Mi}) were calculated and were given in Table 1, column (8). Relative errors (ε) between the integrated (Q_{int}) and entropy discharges (Q_{Mi}) were calculated for each measurements and stations using Equation 5. Average absolute relative errors (ε) between the these two methods were calculated as 8.4, 4.6, 9.6 and 8.7% for BP, SR, KÖ and ÖD stations respectively. Application of entropy methods is very easy for known entropy parameter M and this concept gives discharge results that are closer to integrated ones. This method needs measurement of only one parameter u_{max} and its position can be estimated easily. Maximum velocity must be known in order to calculate the discharge in natural streams using the entropy concept. Maximum velocity usually occurs in the center of the cross-section at a uniform depth and below the water surface. Its exact location is defined by the free surface and side wall effects.

The region where maximum velocity occurs on cross-section were investigated for 24 measurements. Maximum velocities, u_{max}, were observed at deepest vertical for 17 measurements and others, it was observed at second deepest depth of cross-section. Similar result was observed at Ammari and Remini‘s (2009) study. Determination of the deepest depth of a cross-section is easy with a gauge stick. Therefore maximum velocity can be found at or near the deepest vertical along the cross-section. The challenge here is finding u_{max}. It is not easy to measure the maximum velocity which is observed in the vicinity of the deepest place, especially during flood periods. Finding u_{max} requires time and effort. Hence, a simple relation was sought for u_{max} at each station. In Figure 4, distribution of u_{max}/H_{max} with respect to aspect ratio (T/R) were given for four stations. As shown in this figure u_{max}/H_{max} ratios are almost constant for each stations and average $c=u_{max}/H_{max}$ values were found as c_{BP} = 0.78, c_{SR} = 3.83, $c_{KÖ}$ = 2.15 and $c_{ÖD}$ = 0.79 for BP, SR, KÖ and ÖD stations respectively. Using these constant values and measured H_{max} which can be measured easily for any flow conditions, u_{max} can be calculated. With known u_{max} value discharge can be calculated by Equation 4 with entropy concept. Using the constant proportion of measured cross-section and u_{max} values for each measurement’s, mean velocity and also discharge (Q_{umax}) were calculated and are given in Table 1, column (9).

Relative errors (ε) between the integrated (Q_{int}) and

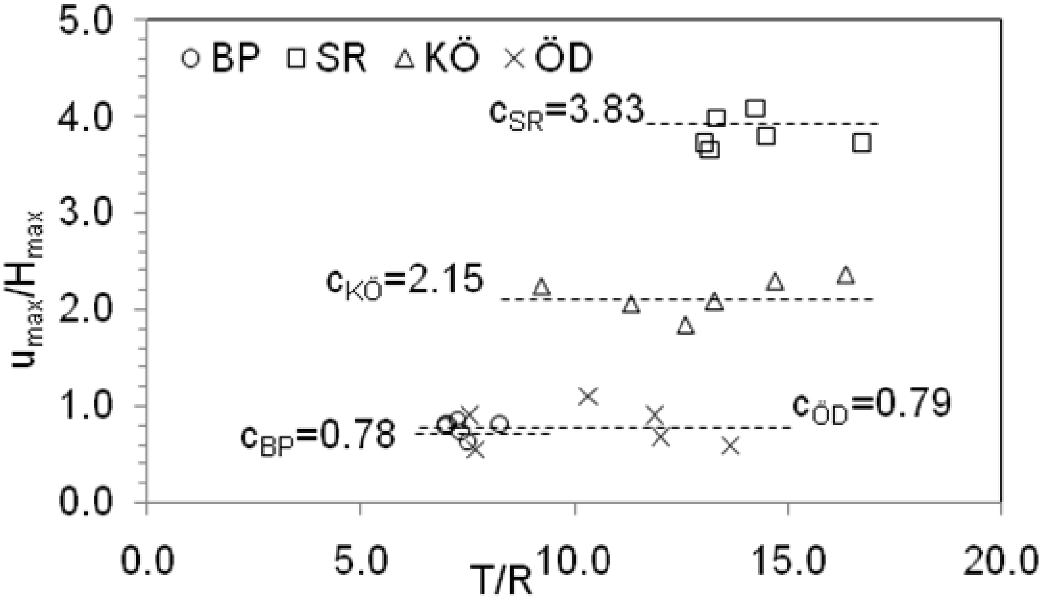

Figure 4. u_{max}/H_{max} ratio depends on aspect ratio (T/R).

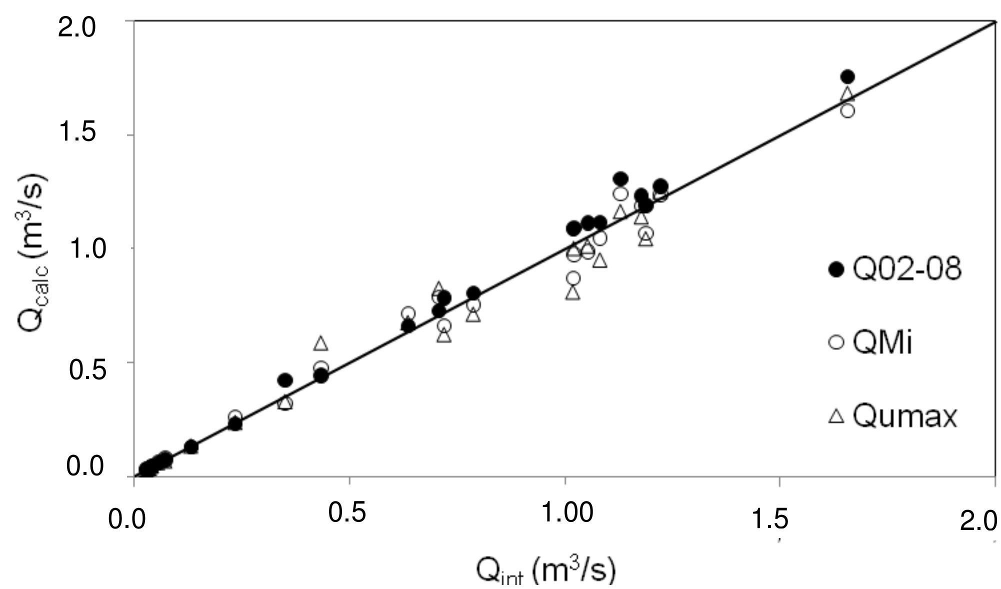

Figure 5. Integrated and calculated discharges.

Q_{umax} discharges were calculated for each measurements and stations using equation (5). Average absolute relative errors (ε) between these two methods were calculated as 9.6, 2.4, 8.5 and 9.0% for BP, SR, KÖ and ÖD stations respectively. The application of the entropy method with suggested u_{max}, which can be calculated from the constant u_{max}/H_{max} ratio for each station, is very easy for known entropy parameter M. This method gives closer discharge results compared to integrated ones. It needs measurement of only one parameter H_{max} along the cross-section for different flow conditions. In Figure 5, the relationships between integrated discharges (Q_{int}) and calculated discharges as predicted by three different methods were given. As shown in the figure, the integrated and calculated discharges show good agreement. $Q_{02\ to\ 08}$ discharges showed overestimation for Q >1.0 m^3/s. In Figure 5, Q_{Mi} discharges showed the best agreements with integrated discharges.

When suggested, u_{max} are used with entropy concept for discharge calculation no relevant trend was observed, except for a slight trend of underestimation for discharge between 0.7 and 1.2 m^3/s.

Conclusion

In this study different methods that can be used for estimating flow discharge in natural streams are investigated. For the velocity-area method, discharge (Q_{int}) could be calculated with integration of the velocity and area throughout the cross section but this method requires a great amount of time and effort. The simple procedure that uses two point velocities, at 0.2 and 0.8 times the flow depth from the water surface was used to calculate the vertical mean velocity for each vertical. Using these velocities total flow rates were determined ($Q_{02 \text{ to } 08}$) and relative errors (ε) between the Q_{int} and the $Q_{0.2 \text{ to } 0.8}$ discharges were calculated for each measurement and station. Average absolute relative errors (ε) between the two methods were calculated as 2.3, 8.2, 6.4 and 6.7% for BP, SR, KÖ and ÖD stations respectively. Two point velocity method gives very accurate results in comparison with integrated discharges. Mean and maximum velocities at the four stations exhibited linear distribution and the entropy parameters M_i were calculated. Using these values, discharges for all flow conditions were calculated (Q_{Mi}) as a function of the measured maximum velocities' u_{max}. Average absolute relative errors (ε) between this two methods (Q_{int} and Q_{Mi}) were calculated as 8.4, 4.6, 9.6 and 8.7% for BP, SR, KÖ and ÖD stations respectively.

Application of the entropy method is very easy for each known entropy parameter M and this concept gives discharge results that are close to the integrated results. It needs the measurement of only one parameter, u_{max}, and its position can be estimated easily. Maximum velocities, u_{max}, were observed mostly at the deepest vertical and u_{max}/H_{max} ratios are almost constant for each station. Once these constant proportions are determined for each station, the u_{max} value can easily be calculated based on a simple reading of the H_{max} value. Discharges using the suggested u_{max} Q_{umax} were calculated and these values are reasonably close to the integrated dischrage values. Average absolute relative errors (ε) between these two methods were calculated as 9.6, 2.4, 8.5 and 9.0% for BP, SR, KÖ and ÖD stations respectively. The Q_{umax} method is the simplest method to implement in agricultural water management because once the u_{max}/H_{max} constant is determined for a specific cross-section in any artificial or natural channel, u_{max} can easily be calculated from H_{max} measurements.

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