Velocity distribution in natural streams

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Abstract

Velocity profiles were investigated for a natural stream by entropy theory. Flow was measured by Acoustic Doppler Velocimeter (ADV) at different times and periods during seven site visits on the Sarımsaklı stream, which flows through central Anatolia in Turkey. Entropy parameter M was calculated with two different approaches. One of them is linear distribution between mean and maximum velocities at these stations and the entropy parameter was calculated as M=2.9. Second one is the best entropy parameter which can be calculated by using u_{max} and z_{max} for measured verticals and found as M=2.83. Both approaches show good harmony with the measured data along the verticals. Errors between measured (u_m) and calculated (u_c) velocities for the whole depths were calculated. The relative mean errors for the seven measurements and each vertical is determined as 5.65% for the SDE (Sarımsaklı Dam Entrance) station.

Introduction

Distribution of flow velocities in natural streams is an important subject in river hydraulics. It has practical implications for bank protection, navigation and sediment transport-depositional patterns. In natural streams, the velocity in a cross-section varies from point to point, which results from water surface effects and the shear stress at the bed. The velocity distribution in streams is usually three dimensional and quite complex. Velocity distributions in open channels have been investigated through a probabilistic approach based on the entropy concept. Chiu [1,2] proposed a probabilistic two dimensional velocity distribution function based on the principle of maximum entropy, using an isovelline-based coordinate system and entropy parameter M. The M value, which can be derived from the ratio of mean (U_m) and maximum (u_{max}) velocities, is constant for flow in a channel cross section and is invariant with time and flow discharge [3]. Xia [4] investigated the relationship between the mean and maximum velocities using data collected from several river cross sections on the Mississippi River and he found that the relationship was linear for all the considered river sections. Araújo and Chaudhry [5] investigated the velocity distribution with measured longitudinal data and found that entropy model performed better than the logarithmic model, not only in general terms, but also in all flow regions, especially in those near the channel bed. Chiu and Tung [6] studied the location of the maximum velocity as a function of M. Moramarco et al. [7] developed a simple method for reconstructing the velocity profiles at a river section, which was based on the assumption that Chiu's velocity distribution can be applied locally. They showed that the shape of the observed velocity profiles for high flood events can be estimated with reasonable accuracy with their proposed simple approach.

Ardıçlıoğlu et al. [8] investigated the applicability of logarithmic and entropy-based velocity distribution equations for rough-surface open-channel flow and suggested a new entropy parameter M. Their entropy equation leads to better agreement with measured data in all verticals and also near the bottom and free surfaces of the channel.

Ardıçlıoğlu & Özdin [9] were investigated maximum velocity (u_{max}) and its position at four cross-sections. They observed that the maximum velocities were taking place at maximum depth (H_{max}) and (u_{max})/(H_{max}) ratio were constant for each cross section. Using these constant values and measured H_{max} which can be measured easily for any flow conditions, u_{max} and discharge (Q) can be calculated with entropy constant. They found that the results were closed to traditional discharge calculating methods.

Ardıçlıoğlu et al. [10] observed that the entropy parameter M was constant for cross-sections that have the same characteristics. Using this global M value, discharges for all flow conditions can be calculated. They also found that u_{max}/H and z_{max}/H ratios varied very little when y/T was between 0.2 and 0.8. Using these constant ratios, at each station, u_{max} and z_{max} could be determined using water depth. The entropy velocity equation was applied for each vertical and flow condition.

In this study, velocity measurements were taken using Acoustic Doppler Velocimeter (ADV) throughout the entire cross-section in a natural stream in central Turkey at seven different times. Measured velocities were compared with two different entropy based velocity distributions and relative errors were calculated.

Entropy equation

Chiu [1] investigated the flow properties by using probabilistic approaches and proposed an entropy-based two-dimensional velocity distribution function for the simulation of the velocity field in river cross-sections. Chiu and Said [11] indicated that an entropy parameter M reflects the equilibrium state of a channel section and it can be derived from pairs of maximum and mean velocities, u_{max} and U_m, measured at a channel section. The M value is a fundamental measure of information about the characteristics of the channel section. Chiu [1] derived a two-dimensional velocity distribution in the following form:

$$u = \frac{u_{max}}{M} \ln\left[1 + \left(e^M - 1\right)\frac{\xi - \xi_0}{\xi_{max} - \xi_0}\right] \qquad (1)$$

In Equation (1), the term $(\xi - \xi_0)/(\xi_{max} - \xi_0)$ represents the cumulative probability distribution function in which $\xi(y,z)$ is the curvilinear coordinate associated with the isovels; $\xi = \xi_{max}$ at the point where u_{max} occurs; $\xi = \xi_0$ at the channel bed where u = 0; and M is the entropy parameter. On the vertical z-axis, where the maximum velocity u_{max} occurs, ξ may be expressed as a function of z [11]:

$$\xi = \frac{z}{H-h} \exp\left(1 - \frac{z}{H-h}\right) \qquad (2)$$

where z is the distance from the channel bed, H is the water depth and h is the distance from the surface to the point where maximum velocity occurs. The velocity distribution equation is then expressed as

$$u = \frac{u_{max}}{M} \ln\left[1 + \left(e^{M} - 1\right)\frac{z}{H-h}\exp\left(1 - \frac{z}{H-h}\right)\right]$$

(3)

Equation (3) has three parameters M, h and u_{max}. The entropy parameter M is a function of the ratio between the mean, U_m, and maximum velocities, u_{max}, and can be derived using the following relationship:

$$\frac{U_m}{u_{max}} = \frac{e^{M}}{e^{M} - 1} - \frac{1}{M}$$

(4)

Field measurements

The study site was the Sarımsaklı Dam Entrance (SDE) on the Sarımsaklı Stream in central Turkey. Sarımsaklı stream is a tributary of the Kızılırmak River (Figure 1), which is the longest flowing river within the boundaries of the Republic of Turkey. The study region is characterized by a semi-arid climate with some extremities in temperature. Velocity measurements at the SDE station were carried out during ten site visits in 2009-2010 [12]. Water level was below the bank-full stage at each time. The velocity measurements were made with SonTek/YSI FlowTracker Handheld Acoustic Doppler Velocimeter (ADV).

During flow measurements cross-sections were divided into number of slices for each flow condition according to the water surface width. Point velocity measurements were made at different positions in the vertical direction starting 4cm from the streambed for each vertical. It estimates the velocity of a free surface in all verticals by extrapolating the last two measurements of verticals. Using these point velocities discharges (Q) were calculated by velocity-area method and given Table 1. Other flow characteristics are summarized in Table 1 in which H_{max} is the maximum flow depth at the cross-section, U_m is the mean flow velocity, u_{max} is the measured maximum velocity at the cross-section, S_{ws} is the water surface slope, Re (= $4U_m R/\upsilon$) is the Reynolds number, R is the hydraulic radius, υ is the kinematic viscosity, Fr (= $U_m/\sqrt{gH_{max}}$) is the Froude number and g is the gravitational acceleration. As can be seen from the table, flow was turbulent and subcritical during all measurements.

Data analysis and discussion

Chiu's entropy-based velocity Equation (3) is used for vertical velocity distributions along the cross-section at SDE stations. This method requires three parameters for vertical velocity distributions. These are entropy parameter M, maximum velocity u_{max} for each verticals and the depth z_{max} where u_{max} occurs. The challenge here is finding M. For this purpose several velocities and discharge measurements are necessary. This procedure requires much effort and time and it is very hazardous and almost impossible to measure flow during flood events. Another method to determine the entropy parameter is using measured vertical velocities. The best entropy parameter M can be calculated by using u_{max} and z_{max} for measured verticals.

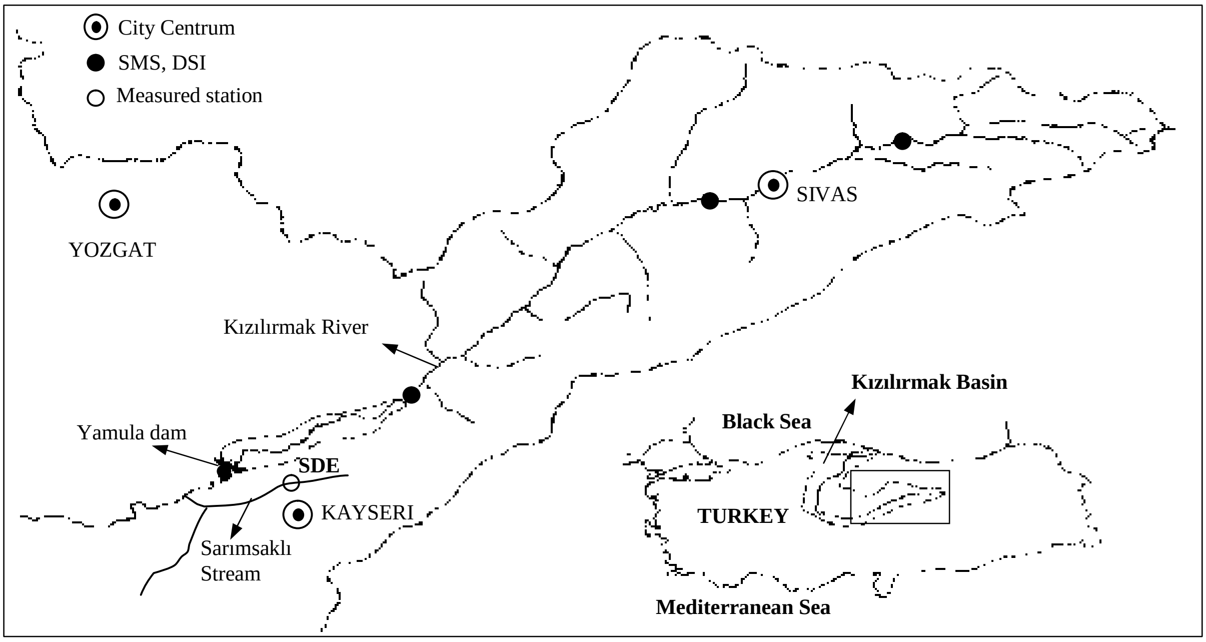

Figure 1 Measurement station at SDE in Kızılırmak basin.

Table 1 Flow characteristics

Measurement	**Dates**	**Q**	**H_{max}**	**U_m**	**u_{max}**	**S_{ws}**	**Re**	**Fr**
	d/m/y	(m^3/s)	(m)	(m/s)	(m/s)	-	-	-
(1)	(2)	(3)	(4)	(6)	(7)	(8)	(9)	(10)
SDE_1	24.06.2009	1.178	0.35	0.987	1.393	0.002	1090452	0.53
SDE_2	02.08.2009	1.021	0.32	0.891	1.192	0.006	803395	0.50
SDE_3	27.09.2009	1.129	0.34	0.954	1.470	0.059	940566	0.52
SDE_4	20.06.2010	1.657	0.41	1.103	1.499	0.011	1265198	0.55
SDE_5	18.07.2010	1.222	0.36	0.960	1.365	0.015	976778	0.51
SDE_6	08.08.2010	1.053	0.32	0.909	1.193	0.016	1026493	0.51

SDE_7	19.09.2010	1.322	0.36	1.017	1.451	0.052	1034764	0.54

For this purpose the entropy parameter, M, was calculated for SDE station. Mean and maximum velocities for seven measurements are plotted and shown in Figure 2. It is observed that there is a linear relationship (R^2=0.81) between the mean and maximum velocities. Using Equation (4), the entropy parameters was calculated and found as M=2.9, for SDE station. Using the value of 2.9 velocity distributions for each vertical were determined using Eq. 3. In this equation, u_{max} and z_{max} values were from measured data. A sample measurement and calculated velocity distribution for SDE_1 is given in Fig. 3. In the figure solid lines show the entropy based velocity distributions obtained with M=2.9. As shown in the figure, calculated velocities for some verticals exceed the measured values.

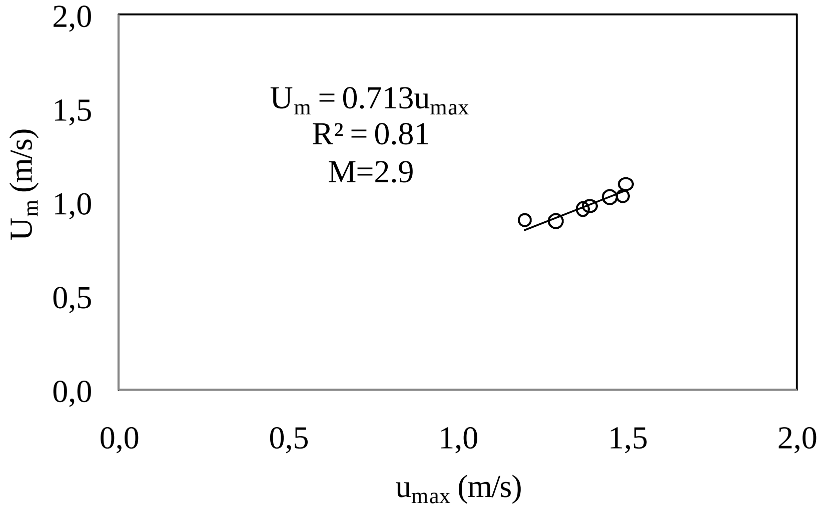

Figure2 Relation between mean and maximum velocities at the SDE station

Second method for the entropy parameter M is using measured vertical velocities. In this method the best entropy parameter M was calculated by using u_{max} and z_{max} for measured verticals. The calculations were done by means of excel program. M value which gives minimum average error was calculated for seven measurements and each vertical, found M as 2.83. This value is also much closed to M=2.9. Using this M=2.83 value velocity distributions were calculated also with Eq.3 given in Figure 3. As shown in this figure, both distributions were much closed for each vertical. That means if we have one measurement for any cross-section entropy parameter it can be calculated with the known u_{max} and z_{max} values.

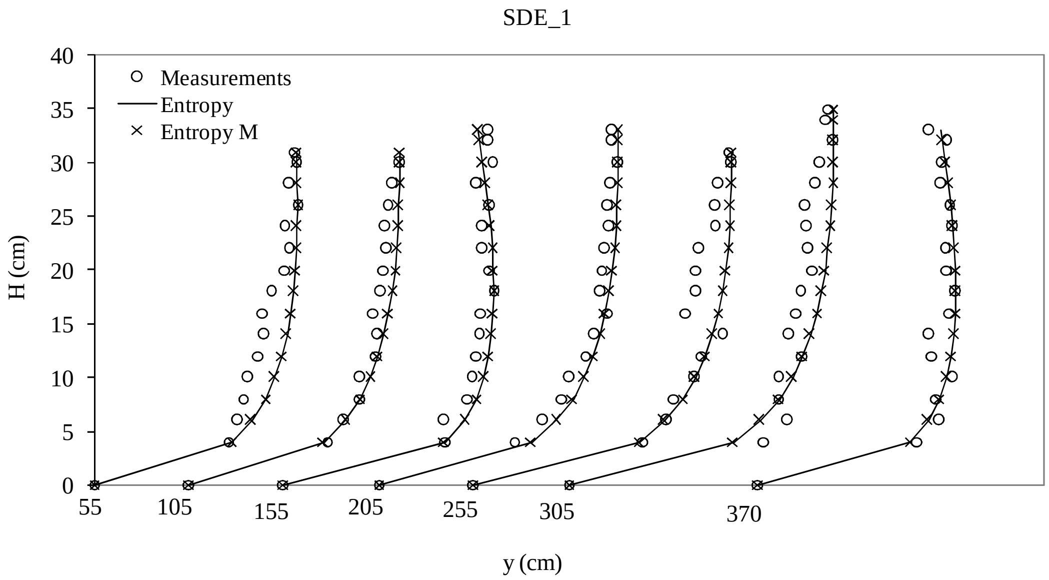

Figure 3 Measured and calculated velocity distributions for SDE_1 measurement

Figure 4 compares measured flow velocities and velocities calculated with the entropy method. The velocities calculated using the entropy principle were generally higher than the measured values along the depth. Errors (calculated as $\varepsilon = \left(100\left|u_m - u_c\right|/u_m\right)*100$) between measured ($u_m$) and calculated ($u_c$) velocities for the whole depths were calculated. The relative mean errors for the seven measurements and each vertical are given in Figure 5. As can be seen in the figure, the entropy distribution models have 10% maximum error near the sidewall. The average error is 5.65% for the SDE station.

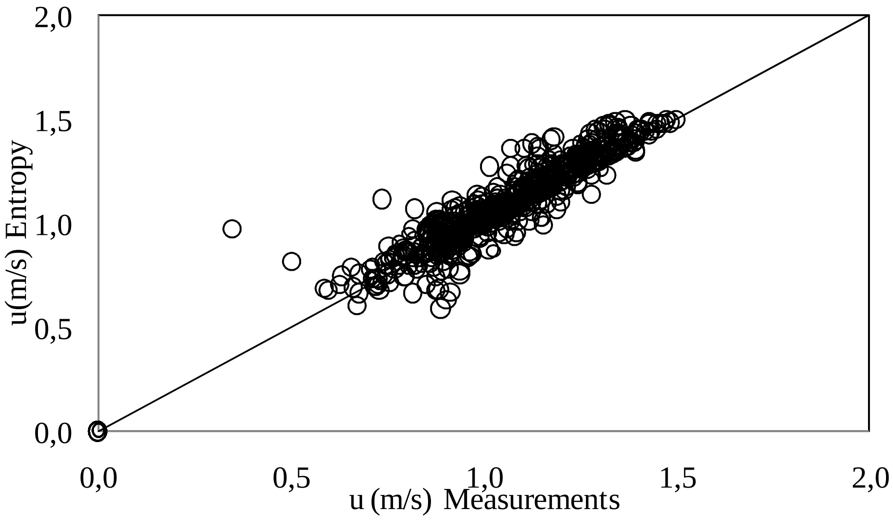

Figure 4 Measured and calculated velocity distributions for SDE station

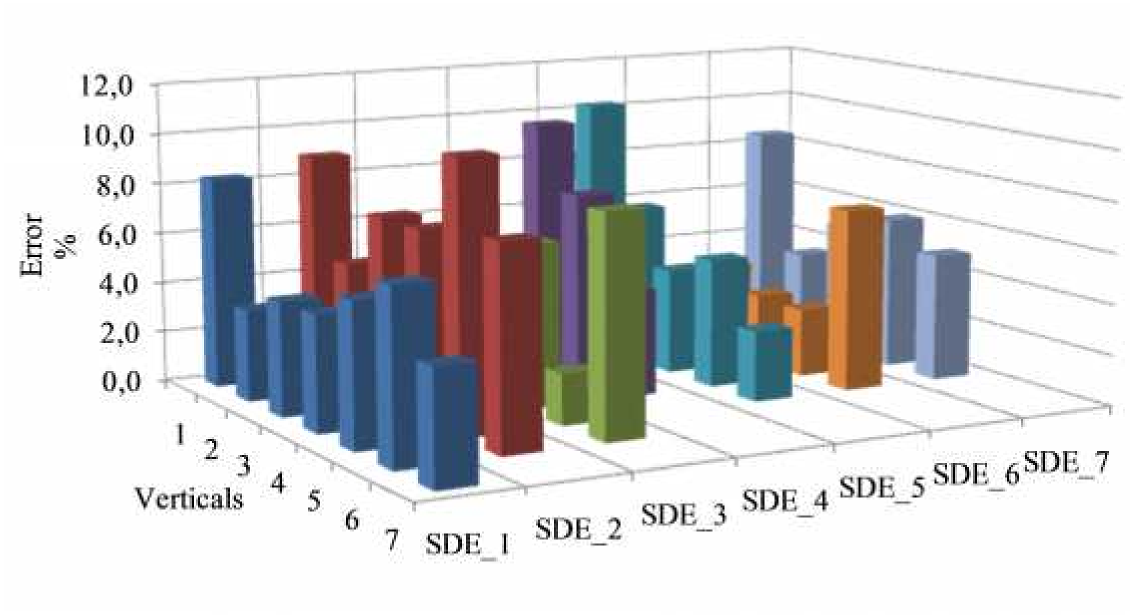

Figure 5 Relative mean errors

Conclusions

The entropy based velocity distribution equation is used for determination of flow properties in natural streams. Main entropy parameter M was determined with two different approaches and found that both values were closed to each other. The entropy parameter for 2-D entropy based velocity distribution equation is found as M=2.9 for the cross-sections of the measured stations. The calculated velocities using the entropy based equation in most cases were slightly higher than the measured velocities. The average error between the measured and calculated velocities using the entropy Equation (3) for all flow conditions were found to be 5.65% for SDE station.

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