

Application of spatiotemporal velocity method in concrete canals with vegetation patch

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Abstract: Understanding the interaction of flow and vegetation in open canals has a great impact on better implementation of environmental projects and hydraulic engineering. The purpose of this research is to apply spatiotemporal (spatial and temporal) averaging method in concrete canals in the presence of vegetation patches. Therefore, in this research, four reaches of irrigation canals with vegetation patches were investigated in Iran. The measured data includes flow velocity and reaches surveying. The results of spatiotemporal velocity profiles showed that the log-law fits nicely the measured velocity data near the bed with vegetation patches. The local values of velocity and shear velocity were compared with the unit value extracted from the double-averaged velocity profile. The results of this comparison showed that the percentage difference between the local values resulting from each flow velocity profile and the unit value of the spatiotemporal velocity is not significant in most cases. Thus, the spatiotemporal velocity method is able to reflect the characteristics of the entire flow conditions in concrete canals in the presence of vegetation patches.

Keywords: Irrigation canals; Logarithmic law; Shear velocity; Spatiotemporal velocity method.

1 INTRODUCTION

One of the most common questions in hydraulic engineering is to report a unit value for hydraulic parameters such as flow velocity, shear velocity, and bed shear stress for a reach. The spatiotemporal velocity method is a suitable answer to this question. The concept of DAM has been discussed extensively in literature by many researchers including Dey (2024). However, the spatiotemporal method suggested in this study may be considered an experimental method for engineers in natural channels and rivers. In fact, the significant challenge of engineers in the field and laboratory studies is to present a representative parameter for a reach. This reduces the number of calculations for shear stress and roughness coefficient in a reach and increases the accuracy of estimated hydraulic parameters.

The equilibrium boundary layer cannot be reached in natural channels due to very different factors influencing the velocity and turbulences features along a reach.

Also, the equilibrium boundary layer requires self-similarity of velocity, Reynolds stress and turbulence intensities distribution along the reach. In natural reach due to vegetation and different size of sediment, it is not possible to reach the equilibrium condition. In addition, the equilibrium boundary layer does not depend on its upstream conditions, it has no memory. For this reason, it is better to apply the spatiotemporal method along a reach to present key hydraulic parameters in practice. Non-uniform flow has many challenges in practice, however, late professor Graf and his colleagues studied in details accelerating and decelerating flows in laboratory for gravel-bed streams without the presence of vegetation. The main consideration in non-uniform flows is the location of the maximum velocity, for accelerating flow, it occurs under the water surface and for decelerating flows at the water surface.

The flow is non-uniform in many open canals. This non-uniformity is due to the flow depth or roughness size changes. These changes affect the roughness coefficient estimation and may present an unrealistic evaluation of flow resistance in open channels. One method which may reduce the effect of variation of roughness and flow depth is spatiotemporal method of velocity estimation which can extend to shear stress estimation, applying spatial and temporal measurements of velocity along a reach or channel. There are of course some spatiotemporal methods in literature based on theoretical considerations. For example, the double-averaging method (DAM) was first used in geophysics to investigate the atmospheric boundary layer flows on the earth's surface vegetation, and then river engineers used this method to analyze the flow in open channels (e.g., Dey and Das, 2012; Manes et al., 2007; Nikora et al., 2001). The DAM by averaging the velocity data in time and space for the length of the desired reaches provides a single profile. By examining this profile, it can be shown whether it can represent the whole velocity field along the selected reach or not. This method is a special method for assimilation in time and space (Franca et al., 2010). The time average is the average of the velocity values recorded (e.g., by a current-meter) at each point during a certain time interval, e.g., 50 s. To determine the spatial average, an average of the velocity data having an equilibrium distance from the bed is considered. In this way, only one velocity value is obtained for each level. Figure 1 shows four levels with the same distance from the bed in the flow direction.

Smith and McLean, (1977) used the DAM along a triangle-shaped dune where the flow depth was variable along the triangle. Nikora et al., (2001) by studying the flow on a rough bed showed that the shape of the double-averaging velocity profile changes linearly in the area under the rough layer. Fazlollahi and Afzalimehr, (2013) used the double-averaging velocity method in a laboratory study and showed that by using

this method, in addition to following the data from the logarithmic distribution of the flow velocity in the inner region of the boundary layer, the random irregularities, which occur due to the bed roughness in the temporal profiles, are adjusted. This makes possible to better estimate hydraulic parameters, such as velocity and shear velocity. In order to overcome the spatial flow heterogeneity on the bed, the DAM was applied also in the case of a water-worked bed flow (e.g., Cooper and Tait, 2010; Padhi et al., 2018 and 2020; Penna et al., 2020; Penna et al., 2022a).

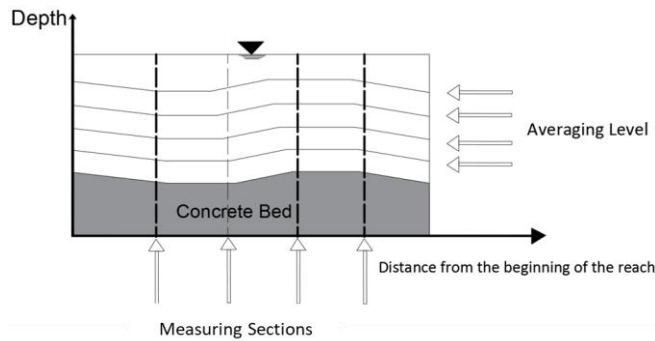


Fig. 1. Balanced levels for the spatiotemporal velocity estimate

Water transport is an important part of an irrigation system. Usually, the feed source and the irrigated fields are far from each other, and, for this reason, it is necessary to determine the hydraulic parameters of the flow properly. Vegetation growth in the bed and margins of agricultural canals is an almost unavoidable thing that induces several effects: it increases the roughness of the path, reduces the shear stress and average flow velocity, preserves the channel bed, reduces water energy and changes the velocity distribution. In other words, vegetation changes the flow velocity profile in the cross-section of the river (Coscarella et al., 2021). From the hydraulic viewpoint, the slowness of the flow caused by vegetation in natural channels is an important factor in the flood design of the plain and the management of natural rivers and canals.

It should be noted that, the detailed investigation of the effect of vegetation on the hydraulic characteristics of the flow is necessary for the design of agricultural canals. Indeed, in agricultural rivers and canals, velocity profiles usually have significant changes in different places, which makes the traditional method (time averaging) not useful for providing suitable results (e.g., Li et al., 2024). Therefore, the double-averaging velocity method (temporal and spatial averaging) mostly eliminates these significant changes.

Many researchers have used this method in rivers and their results are satisfactory (White and Nepf, 2007; Shahiri Tabarestani et al., 2021; Raupach et al., 1986). Since this method has not been used in concrete canals with vegetation which have different roughness and effects on the flow, this research tries to evaluate the application of spatiotemporal method in velocity and shear stress in irrigation channels.

There are many studies conducted to investigate the interaction of flow and vegetation in laboratory channels and coarse-grained rivers (Coscarella et al., 2021; Liu et al., 2019; Nosrati et al., 2022; Xu et al., 2022; Wang et al., 2024; Sediqi et al., 2024a, b). In fact, the role of vegetation in the protection and stabilization of river walls and banks has been widely studied by researchers in all parts of the world (e.g., De Serio et al., 2018; Penna et al., 2022b; Barahimi and Sui, 2023; Barahimi and Sui, 2024a and 2024b; Cai et al., 2024). However, the field study on agricultural canals with concrete bed with vegetation is limited. Therefore, the objectives of this research are the application of

the spatiotemporal velocity method, the validation of the logarithmic law method, and the investigation of the occurrence or non-occurrence of the dip phenomenon in concrete channels with vegetation.

2 MATERIALS AND METHODS

In this study, it is assumed that the effects of lateral and vertical velocities are neglected in comparison to the main flow that is why 1D study is reasonable. No significant obstacle is prevalent in the flow direction. The flow is steady and gradually varied flow with no spatial changes in flow discharge. There is no sediment transport in the selected channel.

2.1 Study area

In this research, four reaches of irrigation canals with vegetation patches were investigated in Fars province (southern Iran). These reaches are made of concrete and have a trapezoidal cross-section with different depth, width of the bed and slope of the side walls. The selected reaches are named as letters A, B, C, D based on the order of data measurement time. Data collection started on February 15, 2021 and ended on May 28, 2021. Figure 2 shows the selected reaches and the measured sections, where black arrows show the flow direction.



Fig. 2. Pictures of the selected reaches and measured sections

2.2 Vegetation patch in selected reaches

Reaches with vegetation patches having different arrangements were considered to investigate the effect of vegetation cover on hydraulic parameters. In reaches A and B, there were 5 and 6 submerged and scattered vegetation patches, respectively. Reach C had one vegetation patch with a long length (about 16 meters) showing emergent and continuous vegetation on the right bank of the channel. Finally, reach D had 4 patches with emergent vegetation on the right bank. Figure 3 shows an example of vegetation patches in these four reaches.

2.3 Velocity data

In general, the measurement data set in this research includes velocity and surveying geometric data. After dredging the

channels and preparing the selected reaches for data measurement, velocity measurements were carried out using a Butterfly Current Meter (BCM).



Fig. 3. An example of vegetation patches in the four selected reaches.

This device is a propeller type with a horizontal axis (Wallpert Company, England). To reduce the measurements error, the BCM was calibrated before data collection. In each reach, 6 to 10 cross-sections and, in each cross-section, 2 or 3 velocity profiles (including 18 points in each profile) were measured in the central axis. Moreover, in 4 different locations at the left and right banks of the channel, two velocity measurements were performed at the elevations $0.2h$ and $0.8h$. This two-point approach was used for a more accurate estimation of the flow rate in the section. The measurement time in each point was 50 s with two or three repetitions. Many river studies use current-meter to measure velocity in the main direction of flow, including the authors' papers in field and rivers. Our results have shown no difference in the averaged velocity values between samples captured for 50s and those for 300s, even when measurements were repeated three times. Since working in the field including rivers or natural open channels, is time consuming process and needs significant risk and cost, the authors fixed the measuring time for each point at 50s. BMC method was developed by Afzalimehr and Anctil (2000) and it was subsequently tested by the authors for different projects, including Afzalimehr and Rennie, (2009), Afzalimehr et al. (2010), and Afzalimehr et al. (2011), showing very near agreement with ADV (Acoustic Doppler velocimeter) for average values.

Table 1. A summary of the velocity measurement data in the selected reaches.

Reach name	Length of each reach	Number of sections	Number of 18-point profiles	Number of 2-point profiles
A	23	10	26	40
B	24	9	27	36
C	21	9	26	36
D	23	6	18	24
Sum	91	34	97	140

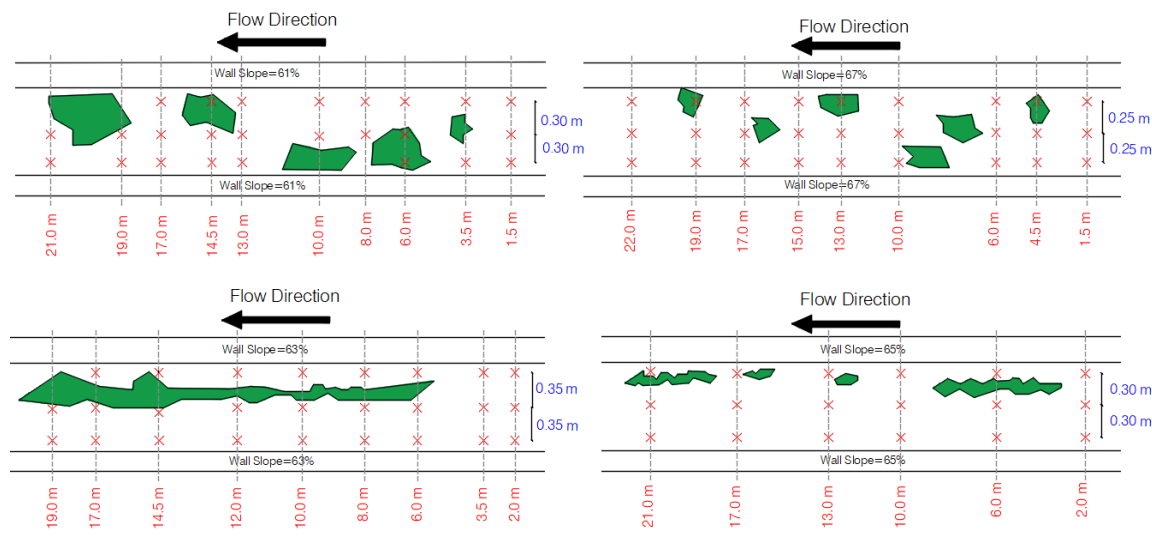


Fig. 4. Plan view of the studied reaches and vegetation patches along with the locations of the measured velocity profiles.

Table 1 shows a summary of the velocity measurement data. Accordingly, a total number of 34 sections, 97 18-point profiles and 140 2-point profiles were investigated, indicating a large amount of data measured in the selected reaches.

Using a 1D current-meter in field has shown that this instrument plays a major role in velocity measurements in engineering projects to determine the key parameters including shear velocity reasonably. In addition, estimating the average values of hydraulic parameters in 1D is not only easy and

available method but also is interesting for engineers in field studies because all required information about the flow conditions can be estimated by streamwise velocity including Reynolds number and the Froude number, shear stress.

Figure 4 shows the plan view and the vegetation patches in each investigated reach along with the location of the measured velocity profiles. It should be noted that for a better display of the figure, the scale of the vegetation masses shown in this figure has been slightly changed. In Figure 4 the red numbers show the distance of the velocity distributions from the beginning of the reach in the flow direction, and the blue numbers show across the flow direction.

2.4 Surveying data

To calculate the area, the wetted perimeter of the cross-sections, the longitudinal slope and the dimensions of the vegetation patches in the studied reaches, a Leica Total Station camera model TS02 was used. In addition, reflectors, tripods, ropes, hammers, rods and meters were used to survey the studied areas. Surveying in irrigation channels includes the bed and side walls of the channels as well as vegetation patches. The vegetation dimensions and submergence ratio of each reach are given in Table 2.

Table 2. The dimensions of vegetation patches in the selected reaches of agricultural canal.

Reach name	Vegetation cover number	Average height (m)	Area (m ²)	Perimeter (m)	Volume (m ³)	Submergence ratio
A	1	0.10	0.07	1.21	0.007	0.29
	2	0.16	1.07	6.60	0.171	0.46
	3	0.18	1.02	4.84	0.183	0.49
	4	0.13	0.55	3.62	0.072	0.32
	5	0.11	0.90	4.67	0.100	0.29
B	1	0.06	0.09	1.22	0.005	0.15
	2	0.16	0.67	3.55	0.107	0.42
	3	0.15	1.34	5.17	0.201	0.41
	4	0.21	0.34	2.64	0.550	0.55
	5	0.40	0.06	0.99	0.002	0.97
	6	0.20	0.22	2.02	0.044	0.50
C	1	0.46	8.23	32.84	1.997	1.00
D	1	0.27	2.60	11.29	0.546	1.00
	2	0.26	0.03	0.69	0.002	1.00
	3	0.32	0.06	0.99	0.005	1.00
	4	0.30	0.66	4.66	0.072	1.00

To survey the channel bed, 5 points were taken at each section, 2 of which were on the side walls of the channel and 3 on the bottom. The distance of the investigated sections in the longitudinal direction was 1 m to determine the longitudinal slope of the channel.

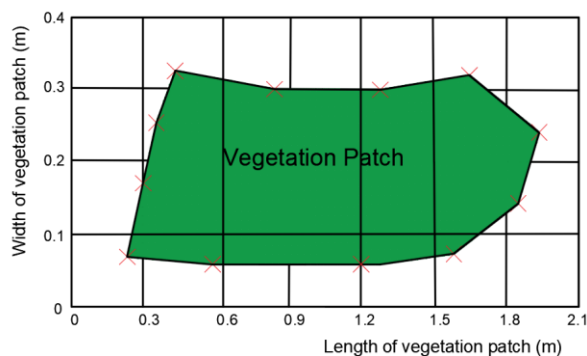


Fig. 5. The dimensions and surveyed points (red symbols) for one of the patches of reach A.

In order to collect the sizes of the vegetation patches in the studied reaches, the number of surveyed points was considered more in the length of the patch where there were many changes, and on average, a 0.3×0.1 m² grid was used for collecting data around the vegetation patch. As an example, Figure 5 shows the dimensions and the surveyed points for one of the patches of reach A. It should be mentioned that in order to determine the height and volume of the vegetation patch, a number of points have been surveyed over the patch, which are not shown in this figure. The characteristics of the patches in the selected reaches are summarized in Table 2.

2.5 Equilibrium boundary layer

An equilibrium boundary layer does not depend on upstream conditions and does not change in the flow direction is called an equilibrium flow. In this case, the dimensionless representation of the velocity and turbulent components are self-similar irrespective of the position along the main flow direction. Equilibrium flow does not occur only in uniform flows or zero

pressure gradient, but also in non-uniform flows (Kironoto et al., 1995). Considering the equilibrium flow makes it possible that in the non-uniform flow where the flow depth changes from one section to another, only the characteristics of one flow section can be used to study the non-uniform flow in an interval. Since the presence of vegetation in the flow path changes the structure of the flow, as a result, an equilibrium boundary layer is not usually formed in flows with vegetation, which makes it necessary to use the double-averaging (spatiotemporal) velocity method and provide a single profile. Various methods have been presented to check the flow equilibrium state in literature. One of these methods is the use of the shape parameter, H , which is defined by equation (1):

$$H = \frac{\delta_*}{\theta} \quad (1)$$

where δ^* and θ are the thickness of the boundary layer displacement and that of the momentum, respectively, and are calculated through equations (2) and (3) (Afzalimehr and Ancil, 2000):

$$\delta_* = \int_0^h \left(1 - \frac{u}{u_{max}}\right) dz \quad (2)$$

$$\theta = \int_0^h \frac{u}{u_{max}} \left(1 - \frac{u}{u_{max}}\right) dz \quad (3)$$

In the above relationships, h is the total flow depth, u is the velocity at depth y , and u_{max} is the maximum velocity in the velocity profile. If the value of the shape parameter is constant along a section, it means that an equilibrium boundary layer is formed.

2.6 Bed Shear stress estimation

The velocity profile in the area near the bed, where viscosity is dominant, follows the logarithmic law and is in the form of equation (4) (Clauser, 1954):

$$u = \frac{u_*}{k} \ln\left(\frac{z}{k_s}\right) + u_* Br \quad (4)$$

where z is the distance of each mean point velocity from the bed, k_s is the equivalent roughness height, k is Von Kármán constant, u_* is the shear velocity, and Br is the integration constant. The Von Kármán constant is less than 0.4 in the condition of sediment transport and more than 0.4 in the presence of bedforms, and it is considered equal to 0.4 in the absence of these items. In this research, the value of 0.4 is assumed (Emadzadeh et al., 2010; Fazlollahi and Afzalimehr, 2013). After taking the regression between the values of u and $\ln(z/k_s)$ for data near the bed and calculating the slope and the intercept from

origin in the horizontal direction, it is possible to calculate the shear velocity and the constant of integration. One of the existing methods in calculating the shear velocity and bed shear stress is the logarithmic law method (Afzalimehr et al., 2019); however, its application needs the data near the bed fits well to this law and the assumption of using $k = 0.4$ rest valid for flow through the vegetation cover.

Instead, in the outer region, the log-law deviates from the experimental data near the free surface. This is because such a law cannot be able to capture the velocity-dip-phenomenon, which causes the maximum velocity to occur below the water surface.

Shear velocity and local bed shear stress can be calculated using the boundary layer characteristics method as (Afzalimehr and Ancil, 2000):

$$u_* = \frac{(\delta_* - \theta)u_{max}}{C\delta_*} \quad (5)$$

$$\tau_0 = \rho u_*^2 \quad (6)$$

where δ_* and θ are the thickness of the boundary layer displacement and the thickness of the momentum, and are calculated using equations (2) and (3), respectively, u_{max} is the maximum velocity in a velocity profile, ρ is the density of water, and C is a constant value obtained in natural streams without bed irregularity and with uniform grain size distribution equal to 4.4 (Afzalimehr and Ancil, 2000). Considering natural deposition of material for the flow in the selected channels during this study, it was assumed the value $C = 4.4$ rests valid in this study.

3 RESULTS

3.1 Geometrical parameters of channels

The irrigation channels in this study have a trapezoidal cross-section (Figure 6). Table 3 shows the summary of measured and calculated data based on the survey.

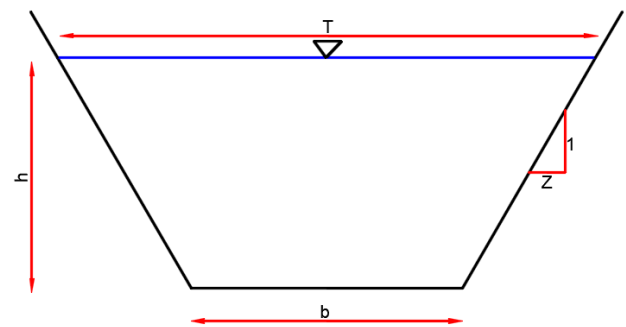


Fig. 6. Cross-section shape in the selected reaches of irrigation channels.

Table 3. Average geometric parameters of the cross-sections for each reach.

Reach name	b (m)	h (m)	Z	A (m ²)	T (m)	P (m)	D (m)	R (m)	S_r
A	0.77	0.34	1.64	0.451	1.89	2.07	0.24	0.22	0.0026
B	0.61	0.42	1.49	0.519	1.86	2.12	0.28	0.24	0.0011
C	0.85	0.36	1.59	0.512	1.99	2.20	0.26	0.25	0.0029
D	0.75	0.27	1.55	0.315	1.59	1.75	0.20	0.18	0.0039

According to Table 4, the highest and lowest flow rates belong to reaches C and B, respectively. The values of the Froude number in all the four reaches are less than 1, which means that the flow is subcritical. Also, the values of the Reynolds number indicate that the flow is always turbulent. The aspect ratio is smaller than 5 in all the reaches, indicating the presence of narrow open-channel flow and secondary currents of Prandtl's second kind.

3.2 Velocity profile

3.2.1 Assessing the state of flow equilibrium

Figure 7 shows that the shape factor changes along the flow path in the central axis of the channel, therefore the flow in a concrete channel in the presence of irregular vegetation is not in equilibrium. Therefore, one profile without spatial considerations cannot be representative and it is required to use spatiotemporal method to present a representative velocity to calculate shear velocity and bed shear stress.

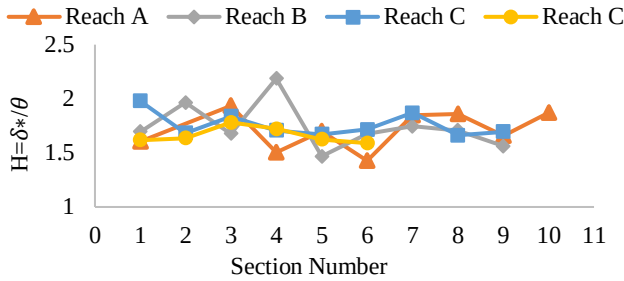


Fig. 7. Shape parameter changes along the central axis in the four studied reaches.

From the analysis of Figure 7, the following points arise:

- 1) In section no. 2 reach A, due to the presence of vegetation with a high height in the central axis and the physical limitation of the BCM in measuring the velocity at 2.5 cm near the bed, it was not possible to perform velocity measurements.
- 2) The shape parameter was not constant along the flow path in any of the reaches, indicating the absence of an equivalent boundary layer in all the four selected reaches. This is due to the presence of vegetation in the flow path that causes a change in the flow structures.
- 3) The range of changes in the shape parameter in reaches C and D, where vegetation was regularly located on the right bank, is less compared to reaches A and B with scattered vegetation along the flow path; however, the formation of an equilibrium boundary layer in these streams with vegetation on the banks cannot be confirmed.

3.2.2 Investigating the location of the maximum velocity in the velocity profiles

Gibson, (1909) showed that, at low aspect ratio, the maximum velocity occurs under the water surface, which is due to the high influence of secondary currents. This effect is reduced in high aspect ratios. In relation to the location of the maximum velocity, the parameter *Dip* is defined, which shows the decrease in the maximum velocity of the flow and is defined in the form of Equation (7).

$$Dip = 1 - \left(\frac{z}{h}\right)_{u_{max}} \quad (7)$$

In the above relationship $\left(\frac{z}{h}\right)_{u_{max}}$ is the dimensionless depth for which the velocity is maximum. If the maximum velocity occurs at the water surface, the value of the *Dip* parameter is equal to zero, and the closer the maximum velocity is to the bed, the closer this parameter gets to one. In this research, to determine the location of the maximum velocity in the velocity profile, the values u/u_{max} were plotted against z/h . In the four selected reaches, a total of 97 velocity profiles were measured. Figure 8 shows some of the profiles where the maximum velocity occurred below the water surface. Table 5 (see appendices) shows the value of the *Dip* parameter and the depth at which the maximum velocity occurred. It should be noted that for naming the velocity profiles, the following aspects were considered:

- 1) name of the studied reaches: A, B, C, and D.
- 2) section number: the order of section numbering is from upstream to downstream and starts from 1.
- 3) velocity measurement location in the cross-section: in each cross-section, 2 or 3 velocity profiles were measured denoted by letters R (right bank), M (central axis) and L (left bank).

For example, A_3_L represents the velocity profile in reach A, in section no. 3, and on the left bank.

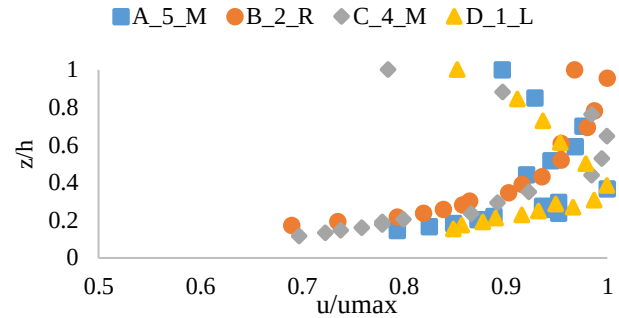


Fig. 8. An example of profiles with a drop in the flow velocity close to the water surface in the four selected reaches.

In table 5, some profiles have a lower height than the others (for example, profiles A_3_M, A_3_L, B_2_R) in which the velocity profiles were measured on the vegetation patch, leading to higher velocity based on continuity equation.

In reaches C and D, in all the measured profiles, the maximum velocity occurred under the water surface, which can be due to the regular presence of vegetation on the right bank, compared to reaches A and B, which have scattered vegetation patches.

In 68 profiles (about 70%) the maximum velocity occurred under the water surface and the average value of the *Dip* parameter is equal to 0.45. Naderi et al., (2022) by investigating vegetated rivers showed that in the 39% of the profiles, the dip phenomenon occurred with an average value of the *Dip* parameter equal to 0.23. The reason of the difference between the present work and that of Naderi et al., (2022) is the much lower aspect ratio value, which causes secondary currents to intensify.

In the profiles that were measured very close to the vegetation patches (C_1_R, A_6_M, and C_7_R), the maximum flow velocity is closer to the bed and the dip parameter value is higher, because vegetation patches intensify the turbulence heterogeneity, causing the development of secondary currents (Naderi et al., 2022).

Based on the results of this research and previous works, the factors affecting the location of the maximum velocity causing the dip phenomenon can be named as follows (Hu et al., 2018; Liu et al., 2018; Parvizi et al., 2023): the aspect ratio, the flow

non-uniformity, the presence of vegetated flow, the vegetation type.

3.2.3 Evaluation of the spatiotemporal method of velocity

The spatiotemporal velocity method leads to summarize the results and to present easier data analysis. There are two ways to plot the double-averaged velocity profiles. The first method is averaging from points that have the same distance from the bed, and the second method is to use the dimensionless velocity profile. In this research, the first method was used, because for the application of the second method to derive the averaged velocity profile requires the use of the maximum or the minimum water depths. The first option may cause irregularities close to the water surface, whereas the use of the minimum depth leads to the removal of many data (especially those close to the water surface).

In Figure 9, the spatiotemporal velocity profiles corresponding to each cross-section is drawn. The graphs presented with a triangle mark show the time-averaged velocity

profiles measured at the centerline of each cross-section belonging to the four different reaches, and the lines with square marks show the profile of double-averaged velocity (temporal and spatial). The analysis of Figure (9) shows that in three out of four reaches the maximum velocity occurred below the water surface and in only one reach the velocity profile is S-shaped. As was demonstrated before, this is due to the small aspect ratio in these reaches, which causes secondary flow. In addition, the maximum velocity occurs at $z/h=0.41$ in the channel, while the *Dip* parameter value is equal to 0.059. Chow, (1959) stated that for an aspect ratio smaller than 5, the maximum velocity occurs under the water surface. Many researchers have stated that the width-to-depth ratio or the aspect ratio can be used to determine whether the flow is two-dimensional or three-dimensional. For example, Kironoto and Graf, (1995) stated that for an aspect ratio less than 5, the flow is three-dimensional, and the walls affect the flow structure, and for an aspect ratio greater than 5, the flow is two-dimensional. In this research, the aspect ratio in the four selected reaches is smaller than 5.

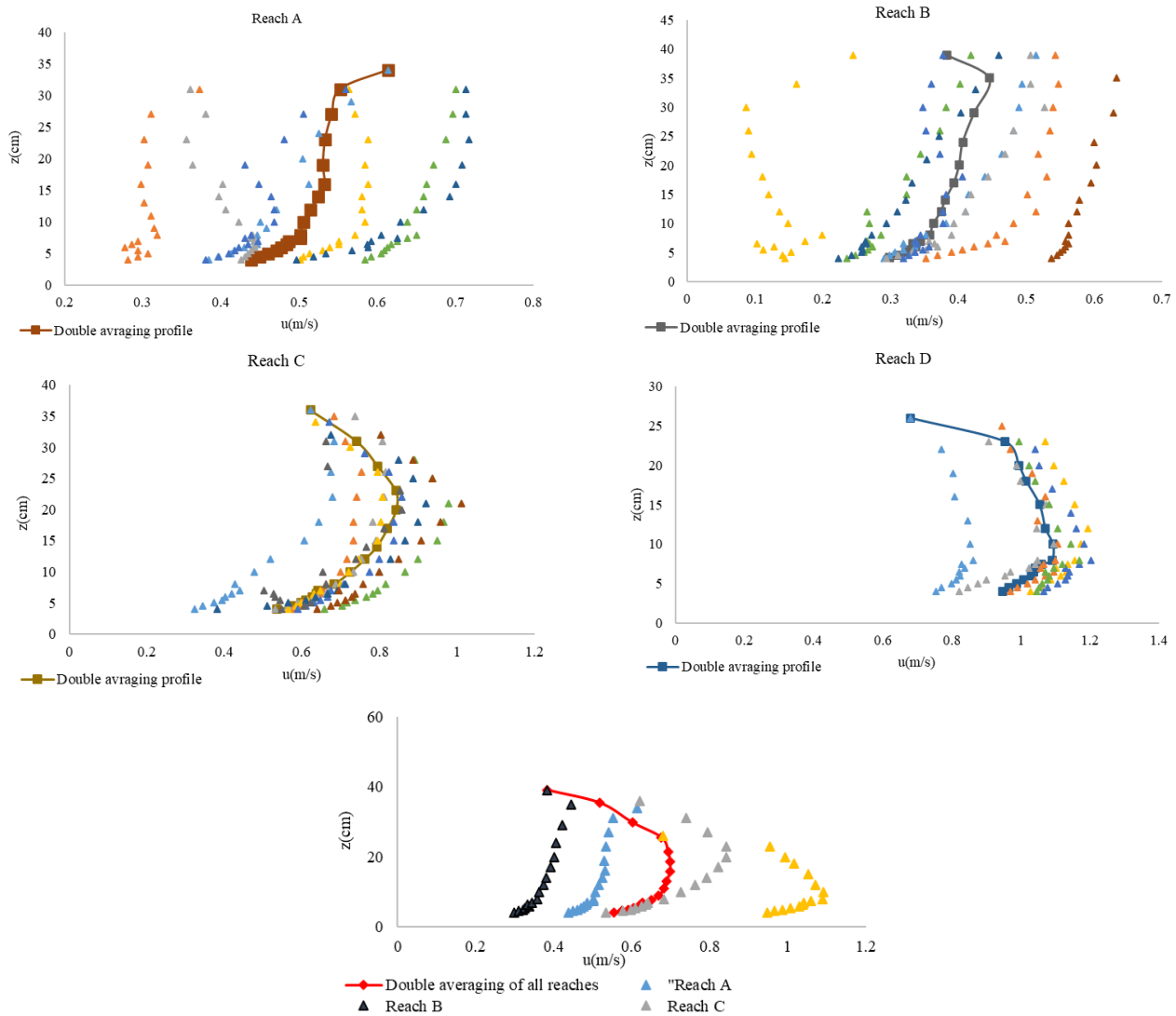


Fig. 9. Double-averaged velocity profiles in the four selected reaches.

After having extracted the spatiotemporal (double-averaged) velocity profiles related to each reach, the validity of the logarithmic law was investigated. Figure 10 and Table 6 show the results of this investigation referring to Equation (4). The

value of k_s was considered equal to 0.0015 m as suggested by Ackers, (1958). In Figure 10, the points with blue color follow the logarithmic law (inner layer) and the orange points indicate the points that deviate from the logarithmic law (outer layer).

According to this figure, the value of the coefficient of determination (R^2) in all the reaches is greater than 0.94, which indicates that the logarithmic law is valid in the profiles obtained by the double-averaging velocity method. Also, in all the reaches, except for reach C, the deviation of the data of the outer layer is towards the bottom of the regression line, which indicates the predominance of the favorable pressure gradient ($\partial p/\partial x < 0$) (Barahimi and Afzalimehr, 2019). Based on the values in Table 6 the upper limit of validity of the logarithmic law for the profile averaged from the four selected reaches is 0.21, which is consistent with the results obtained from laboratory studies by Afzalimehr and Ancil, (2000), Song and Graf, (1996), and Kironoto and Graf, (1995). However, this value is different from the studies of Keulegan (1938) which believed that this logarithmic law is valid for the total flow depth and is not limited to a region near the bed. The value of logarithmic constant (Br) was determined positive for three reaches and negative for one

of reach. A negative value may show very complex interaction of vegetation with flow and concrete roughness. The double-averaged velocity profile for the four selected reaches gives $Br = 1.88$.

Kummu, (2002) shows that the velocity distribution above the vegetated bed follows the logarithmic law only its middle part of velocity profile. The log law deviates from the measured data due to invalidity of constant shear stress in whole of flow depth and invalidation of mixing length approximation. It should emphasize that many researchers including Barenblatt, (1982) reports that the log law is an experimental law and may be only fitted with the velocity data in some conditions. Afzalimehr and Dey, (2009) applied vegetation on the vertical wall and gravel over the flume bed and found when the ratio of flume width to flow depth decreases to 4 the logarithmic law can only be applied to the range $0.3 < y/h < 0.8$.

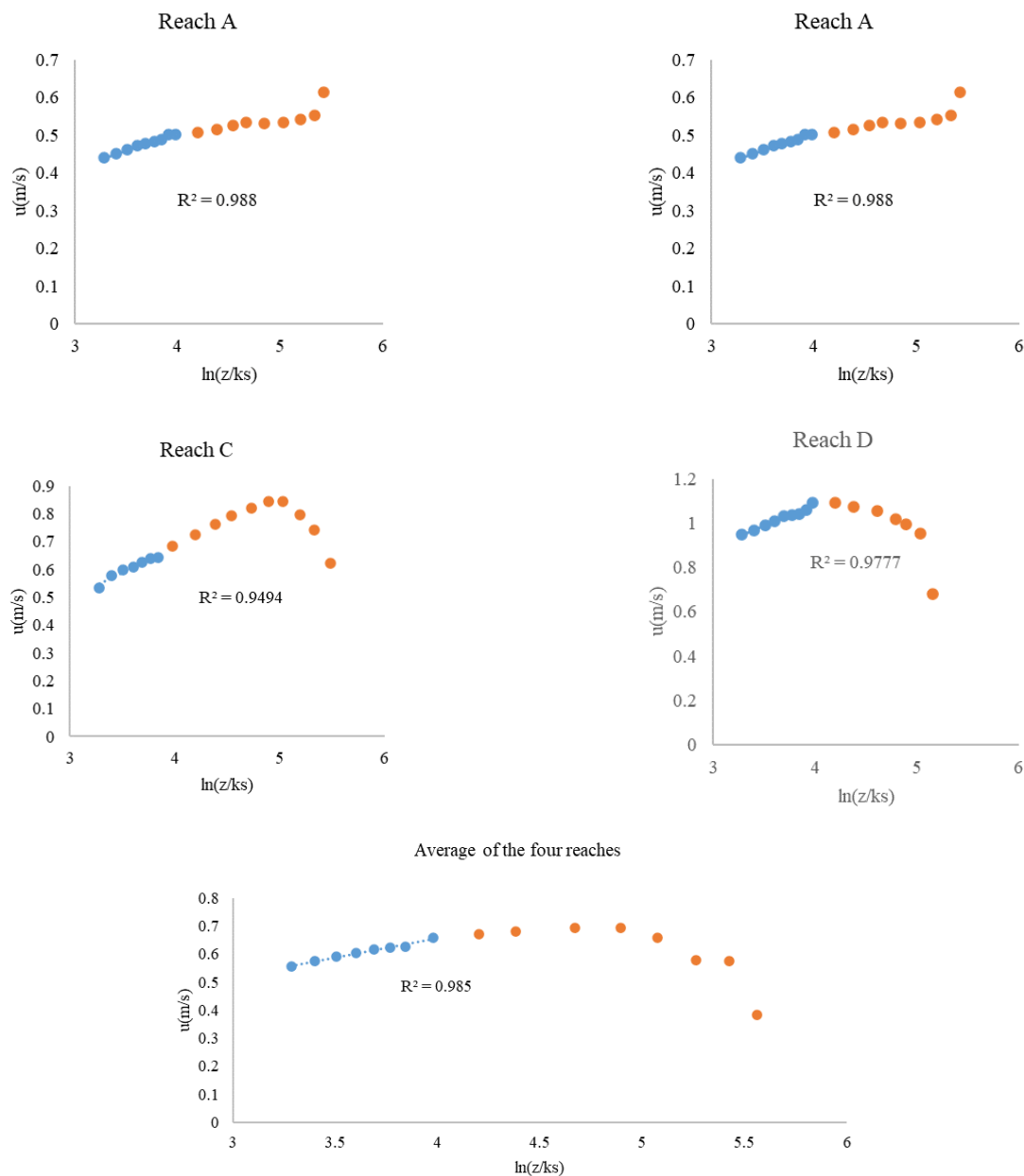


Fig. 10. Validity of the logarithmic law for the double-averaged velocity profiles in the four selected reaches.

Table 6. The upper limit and the integration parameter of the logarithmic law resulting from the spatiotemporal (double-averaged) velocity profiles.

Reach name	The regression equation of the inner layer	$\frac{z}{h}$	Br
A	$u = 0.0921 \ln\left(\frac{z}{k_s}\right) + 0.1372$	0.22	3.72
B	$u = 0.0784 \ln\left(\frac{z}{k_s}\right) + 0.0438$	0.21	1.40
C	$u = 0.1844 \ln\left(\frac{z}{k_s}\right) - 0.0578$	0.19	-0.78
D	$u = 0.1915 \ln\left(\frac{z}{k_s}\right) + 0.3167$	0.31	4.13
Four selected reaches	$u = 0.1383 \ln\left(\frac{z}{k_s}\right) + 0.1039$	0.21	1.88

Table 7 shows the values of velocity, shear velocity and bed shear stress using the spatiotemporal (double-averaged) velocity method and the normal averaging method. In this table, the parameters calculated using the spatiotemporal and the normal averaging methods are indicated by the index spatiotemporal and an upper bar, respectively. Also, F represents the percentage of difference between the hydraulic parameters calculated by double-averaging and the normal averaging methods. For example, F_{u*} represents the percentage of difference between the shear velocity calculated using the double averaging and the normal averaging method.

Based on this table, the percentage of difference between the two methods in all the four selected reaches and for all the investigated parameters is less than 15% and even in some cases the difference is negligible, indicating that the double-averaging velocity method is able to present the characteristics of the entire reaches.

It should emphasize that different velocimeters have been applied to measure the velocity field within the vegetation, however, due to very dense vegetation in these sections, the velocity-meters could not measure any data. For this reason, the velocity measurements were conducted upstream, downstream and from top of submerged vegetation, in reaches A, B and D. For reach C where the vegetation is emergent the current meter does not work inside the vegetation patch due to high noise generated by around vegetation. It should emphasize that for dense vegetation, the velocity is very slow and may not affect the main flow in natural streams. In fact, when vegetation is dense, it acts such as solid obstacle such as pier or pile in which the flow velocity cannot pass the obstacle, therefore, the flow conditions are influenced by around the patch not inside the patch

(Li et al., 2024). This may be considered as a limitation in the present field study, however, for practical purposes, the results give reasonable information to engineers for better decisions. Unfortunately, no instrument was available to take a side view of measurements. The length of each studied interval, along with the distance of the measured velocity profiles from the beginning of the interval, are presented in Tables 1 and 5, respectively. Also, the location of the measured profiles was selected in such a way that one of the profiles was located exactly in the middle of the cross-section and the other two profiles were located on the left and right banks, a short distance from the intersection of the sloping wall and the channel bed.

Kironoto and Graf, 1995 stated that for an aspect ratio (width/flow depth ratio) of less than 5, the flow is three-dimensional and the maximum velocity occurs below the water surface, while for values of greater than 5, the flow is two-dimensional and the maximum velocity occurs on the surface of the water. The presence of vegetation causes the dip phenomenon gets stronger in which the location of the maximum velocity takes far from the water surface. This change of location for the maximum velocity at the presence of vegetation is due to activation of secondary currents which influence the flow structures and turbulence characteristics. Turbulence inhomogeneity is the main factor in the development of secondary currents, which is manifested immediately in the occurrence of the dip phenomenon. Turbulence inhomogeneity and the observation of the dip phenomenon depend on the size of vorticity and normal and shear stresses in the flow. However, the dip occurring in accelerating non-uniform currents and rarely occurs in uniform and decelerating currents.

Table 7. Comparison of the values of hydraulic parameters obtained from the spatiotemporal (double-averaging) velocity and the normal averaging methods.

Reach name	U_{DAM} (m/s)	$\bar{U}$ (m/s)	F_U %	u_{*DAM} (m/s)	$\bar{u}_*$ ($\frac{m}{s}$)	F_{u*} %	τ_{0DAM} ($\frac{N}{m^2}$)	$\bar{\tau}_0$ ($\frac{N}{m^2}$)	F_{τ_0} %
A	0.491	0.561	12.4	0.025	0.026	-3.9	0.64	0.70	-8.6
B	0.370	0.378	2.1	0.019	0.019	0	0.351	0.41	14.4
C	0.700	0.674	-3.7	0.036	0.036	0	1.29	1.35	-4.4
D	0.923	0.852	-7.7	0.049	0.051	-3.9	2.43	2.59	-6.2

4 CONCLUSIONS

One of the most common challenges in natural and artificial streams is the accuracy in the determination of the key hydraulic parameters, including velocity, shear velocity and resistance to flow in the presence of vegetation as an extra roughness. Since these parameters change along a stream, it is necessary to find the representative values to use in equations and models for a reach. The spatiotemporal is a suitable tool to be applied in this case. Accordingly, in this research, this method was investigated in four reaches of concrete canals in the presence of vegetated patches. Using spatiotemporal for velocity, a unique value was obtained for each reach. Using this averaging velocity profile, shear velocity and bed shear stress were obtained as representative values of a reach to use in hydraulic models. Comparison of the local values in each section with that extracted by spatiotemporal showed that the percentage of difference is not significant in most cases, revealing that the spatiotemporal is able to reflect the characteristics of the entire flow conditions of a reach in the presence of vegetation patches.

By fitting the logarithmic law on the data of the inner layer obtained from the spatiotemporal (double-averaged) velocity profile, it was found that the logarithmic law fits well to the unit profile, indicating the values 1.88 and 0.21, as the constant value of the log-law (Br) and the upper limit of validity of the logarithmic law, respectively.

In the four selected reaches, 68 out of 97 profiles (70%) show the presence of the dip phenomenon, indicating that the aspect ratio is not the only factor affecting the dip phenomenon. In reaches C and D, in all the measured profiles, the maximum velocity occurred below the water surface, which can be attributed to the regular presence of vegetation on the right bank of these reaches compared to reaches A and B that had scattered vegetation.

In addition, the investigation of the equilibrium boundary layer in the selected reaches showed that its occurrence in the presence of vegetated patches in concrete channels is not confirmed.

The results of this research can be used in concrete canals with vegetation patches for a more accurate prediction of the velocity profile, leading to more accurate estimation of flow discharge, shear velocity and flow resistance, and as a result, a better justification of the cost of hydraulic engineering projects

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Appendices

Table 5. *Dip* parameter value in the profiles where the velocity drop occurs.

Profile name	h (m)	z (m)	$\left(\frac{z}{h}\right)_{u_{max}}$	<i>Dip</i>	Profile name	h (m)	z (m)	$\left(\frac{z}{h}\right)_{u_{max}}$	<i>Dip</i>
A_1_L	0.34	0.29	0.85	0.15	A_3_L	0.28	0.24	0.86	0.16
A_3_M	0.13	0.11	0.85	0.15	A_4_R	0.30	0.14	0.47	0.53
A_5_M	0.27	0.10	0.37	0.63	A_5_R	0.31	0.16	0.52	0.48
A_6_L	0.31	0.19	0.61	0.39	A_6_M	0.31	0.07	0.23	0.77
A_7_L	0.31	0.14	0.45	0.55	A_7_R	0.19	0.10	0.53	0.48
A_8_L	0.31	0.19	0.61	0.39	A_8_M	0.31	0.19	0.61	0.39
A_9_L	0.31	0.23	0.74	0.26	A_10_M	0.31	0.23	0.74	0.26
B_2_L	0.39	0.26	0.67	0.33	B_2_M	0.39	0.34	0.87	0.13
B_2_R	0.23	0.22	0.96	0.04	B_3_L	0.39	0.30	0.77	0.23
B_4_L	0.39	0.04	0.10	0.90	B_4_R	0.39	0.13	0.33	0.67
B_5_L	0.39	0.08	0.21	0.79	B_5_M	0.39	0.18	0.46	0.54
B_5_R	0.22	0.20	0.91	0.09	B_8_R	0.17	0.05	0.29	0.71
C_1_L	0.36	0.26	0.72	0.28	C_1_M	0.36	0.31	0.86	0.14
C_1_R	0.36	0.14	0.39	0.61	C_2_L	0.35	0.31	0.89	0.11
C_2_M	0.35	0.26	0.74	0.26	C_2_R	0.35	0.18	0.51	0.49
C_3_L	0.35	0.26	0.74	0.26	C_3_M	0.35	0.26	0.74	0.26
C_3_R	0.35	0.22	0.63	0.37	C_4_L	0.34	0.22	0.65	0.35
C_4_M	0.34	0.22	0.65	0.35	C_4_R	0.34	0.18	0.53	0.47
C_5_L	0.34	0.22	0.65	0.35	C_5_M	0.34	0.22	0.65	0.35
C_5_M	0.34	0.22	0.65	0.35	C_6_L	0.32	0.18	0.56	0.44
C_6_M	0.32	0.21	0.66	0.34	C_6_R	0.32	0.15	0.47	0.54
C_7_L	0.32	0.21	0.66	0.44	C_7_M	0.32	0.21	0.66	0.44
C_7_R	0.32	0.055	0.18	0.82	C_8_L	0.32	0.21	0.66	0.44
C_8_M	0.32	0.21	0.66	0.44	C_8_R	0.32	0.21	0.66	0.44
C_9_L	0.31	0.20	0.65	0.35	C_9_M	0.31	0.20	0.65	0.35
D_1_L	0.26	0.10	0.38	0.62	D_1_M	0.26	0.08	0.31	0.69

D_1_R	0.26	0.16	0.62	0.38	D_2_L	0.25	0.10	0.40	0.60
D_2_M	0.25	0.10	0.40	0.60	D_2_R	0.25	0.13	0.52	0.48
D_3_L	0.23	0.15	0.65	0.35	D_3_M	0.23	0.10	0.43	0.57
D_3_R	0.23	0.10	0.43	0.57	D_4_L	0.23	0.10	0.43	0.57
D_4_M	0.23	0.15	0.65	0.35	D_4_R	0.23	0.08	0.35	0.75
D_5_L	0.22	0.08	0.36	0.64	D_5_M	0.22	0.08	0.36	0.64
D_5_R	0.22	0.12	0.55	0.45	D_6_L	0.23	0.065	0.28	0.72
D_6_M	0.23	0.08	0.35	0.65	D_6_R	0.23	0.055	0.24	0.76
