Introduction

The reliable streamflow data are of great importance for the water balance analysis and decisions regarding water management (Hershey, 1995). This paper describes the practical implementation of various streamflow measurement methods, the data processing procedure and interpretation of the obtained results. The uncertainty related to each method will be annotated and the recommendations for the flow estimation improving will be given.

The streamflow measurements were carried out at Denham Country Park, Uxbridge (Figure 1).

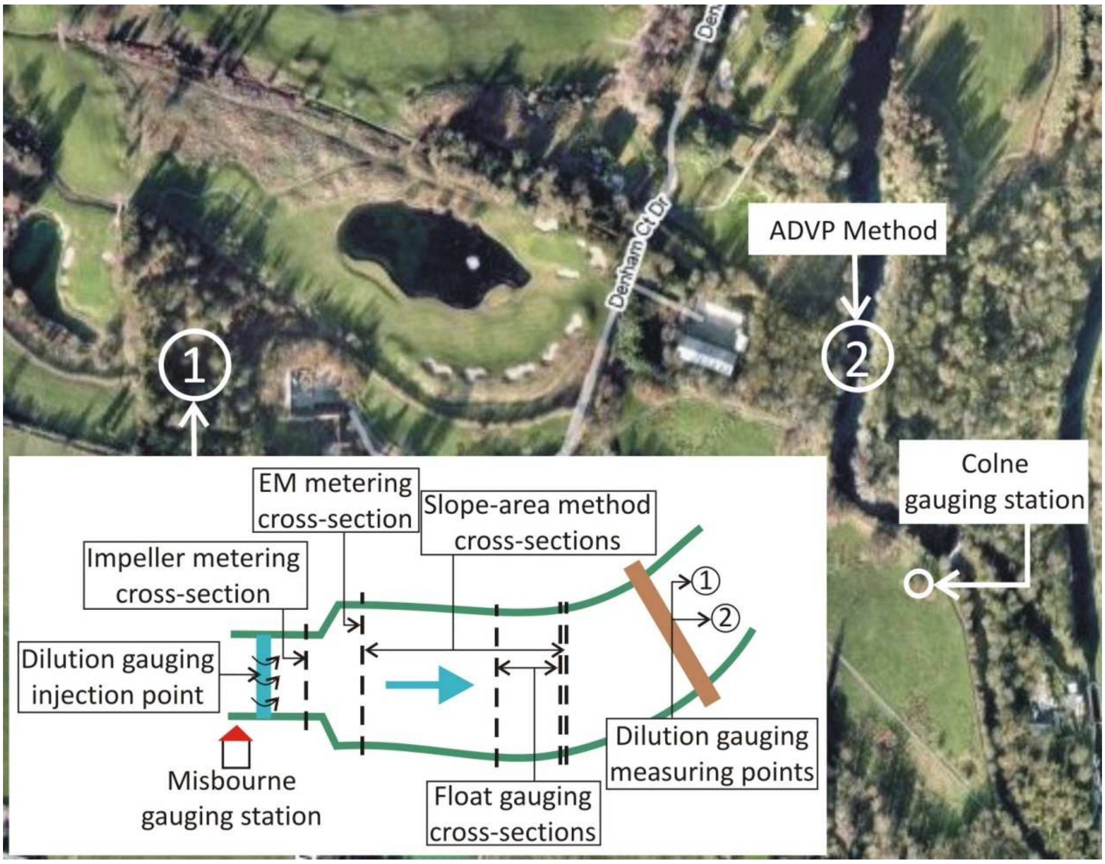

Figure 1. Denham Country Park map and measurement locations

Two measurement locations have been selected as follows:

1. The river Misbourne, where electromagnetic (EM) and impeller metering, dilution and float gauging and the collection of data for the slope-area method were carried out.

2. The river Colne, where the acoustic Doppler velocity profiler (ADVP) was used.

All data from the location 1 have been taken downstream of the Misbourne gauging station (Figure 1), whereas the ADVP measurements were carried out at the cross-section upstream of the Colne gauging station. The stations' sample hydrographs (UK National Environment Research Council, 2008) show the mean daily flow at the time when the measurements were taken (end of November) of approximately 0.22 m^3/s and 4.6 m^3/s, respectively.

Methods

Electromagnetic and impeller metering

The measurements of flow using EM and impeller current meters were performed by wading the river and using the velocity-area method. The selected cross-sections are presented in Figure 1. The implementation of both methods has been done following the procedure given by Hershey (1995). The measuring tape was stretched across the river at approximately right angles to the direction of flow. The number of verticals has been determined and their positions used for the depth and velocity readings were located by measuring the horizontal distances from the bank.

Both meters were attached to the top-setting rod (Hershey, 1995) which was used for the measurement of depths. As the depths at both cross-sections were lower than 0.75 m, velocity observations were made at a single point at 0.6 of the depth from the water surface. Obtained values were treated as the average velocity at a vertical. The flow was calculated using the mean-section method (Mcintyre, 2008). Processed data for EM and impeller gauging are shown in the Appendix, Tables 1 and 2, respectively.

Slope-Area Method

For the application of the slope-area method two cross-sections were selected as presented in Figure 1. The upstream cross-section was same as the one used for EM metering. The downstream cross-section area was determined by measuring the horizontal distances and correspondent depths using measuring tape and rod, respectively. The water elevation in both locations was read with a rod and level.

The flow was calculated using the slope-area method for the non-uniform flow (Mcintyre, 2008). The Manning's roughness coefficient *n* was estimated as recommended by Hauer & Lamberti (2006) and the calculation is shown in the Appendix, Table 3. The velocity head adjustment factor β equal to 0.5 (Hershey, 1995; Mcintyre, 2008) was used for the total energy lost calculations. Application of the slope-area method is presented in the Appendix, Tables 4-6.

Dilution gauging

For the direct measurement of flow, 754 g of salt was dissolved in 20 L of water using two buckets. The gulp injection approach was used (Mcintyre, 2008) and the tracer was instantly added to the river. The conductivity was recorded at two downstream points (Figure 1) and the obtained values were related to concentration applying the calibration curve provided by Mcintyre (2008). The flow was calculated using the section-average concentration value (Appendix, Tables 7 & 8). The dilution gauging tracer profiles are shown in the Appendix, Figure 1.

Float gauging

The measurements of horizontal distances by measuring tape and depths by rod were used to determine the start and end cross-sections for the float gauging method (Figure 1). Six oranges were used as floats and their positions at upstream and downstream sections were recorded. Two time records were concurrently taken and the average value was used in calculations. The sampling data are presented in the Appendix, Table 10.

The flow was calculated using the procedure recommended by Mcintyre (2008). The reduction coefficient k for the calculation of the average velocity at a vertical was found approximately from the Manning and Chezy equations (Hershey, 1995) using the value of n estimated for the slope-area method. The obtained velocity values were assumed to be representative for verticals at average positions of floats (Appendix, Figure 2 and Table 11) and the mean-section method was used for the calculation of the flow. The calculation procedure is shown in the Appendix, Table 12.

Acoustic Doppler Velocity Profiler metering

The ADVP was used for the measurement of the river Colne flow (Figure 1). The meter and corresponding software settings have been done by the expert for the UK Environment Agency. The current meter was boat-mounted and the rope was used to move the device across the river section. The measured data were transmitted to the portable computer which included data processing software.

Before the beginning of measurements the river depth and flow regime have been estimated. The moving bed test has been done by positing the ADVP at the middle of the cross-section. Analysis of the recorded data showed stability of the river bed. The measurements were carried out using three different modes (for the low, medium and flood flow) during eight channel crossings. The flow was calculated for each sampling of velocity distribution across the river and the average value was used as the estimation.

Results and discussion

The estimation of flow using each method is presented in Table 1.

Table 1. The estimation of flow using various measurement methods

Location	Time of day	Method	Q_{est} (m^3/s)	Classification of methods			
				Direct	Indirect	Cross-section	River reach
River Misbourne	Morning	Impeller gauging	0.2243		x	x	
		EM gauging	0.2297		x	x	
	Afternoon	Slope-area method	0.2387		x		x
		Dilution gauging	0.2546	x			x
		*Float gauging**	0.2466		x	x	x
River Colne		ADVP	4.4000		x	x	

* a*lthough measurements are carried out within a river reach, the calculation of flow is done at a cross-section*

In order to discuss the uncertainty of measured values the classification of methods shown in Table 1 has been done. The unsteady flow conditions in natural streamflows have the influence on the uncertainty in all methods. The selection of measuring location is important since it can eliminate the negative influences related to the channel geometry and flow conditions.

All indirect procedures, excluding the slope-area computation apply the velocity-area method for the calculation of the flow. The highest contribution to the uncertainty of this method is the number of verticals across a cross-section and number of points for the determination of the average velocity at a vertical (Hershey, 1995). The methods where measurements are taken within the river reach usually cannot meet requirements for a straight section without lateral flows (Mcintyre, 2008). These methods also use the estimation of various coefficients, such as n, β and k which have a significant influence on the final result. More precise depth measurements can decrease the uncertainty of all the indirect methods. This can be achieved by using an electric-tape gauge or steel tape (Hershey, 1995).

The direct method of dilution gauging can suffer from high noise in the signal and sometimes the long observation time is required for the solution to pass the measuring cross-section (Mcintyre, 2008). Finally, errors in current and conductivity meters' calibration curves can have a significant influence on uncertainty, especially in low flow conditions.

The Table 1 shows dispersion of flow values in river Misbourne within the range of approximately 15% which indicates that all results have to be taken into consideration for flow estimation. The difference in obtained flow values can be due to unsteady flow conditions, especially if the data are divided into two groups as follows:

- Morning samplings which include EM and impeller metering data and
- Afternoon samplings which include slope-area method and dilution and float gauging data.

Tables 1 and 2 in the Appendix show that number of verticals for EM and impeller gauging was properly estimated. All segments contain approximately ten or less percents of the total flow. The improvement in application of these methods can be achieved by increasing the number of points for the estimation of average velocity at a vertical.

The result of the slope-area method is highly sensitive to the change of the value of Manning's roughness coefficient *n*. Hence observation of all factors listed in Table 3 of the Appendix, which have the influence on the value of *n,* should be performed.

The float gauging method includes lots of approximations and as such is liable to high uncertainty in the final result. The change of channel width within the reach (Appendix, Table 9) is causing the underestimation of the flow value. The difference between actual and estimated flow paths (Appendix, Figure 2) also yields the erroneous result. The flow estimation also depends on the value of the reduction coefficient *k*. The table 12 in the Appendix shows that some segments used for the mean-section method contain more than 20% of a total flow. This indicates that the improvement in this method can be achieved by using more floats, especially near the right bank.

The dilution gauging profiles (Appendix, Figure 1) show adequate response to the applied concentration of the tracer. Negative concentration values are due to the applied calibration curve (Appendix, Table 7). The samplings from the measuring point 2 show high stability while other set of data includes lots of noise in the signal which implies the uncertainty in the estimation of the background concentration. But since both set of data are correlated in respect of the arrival and passing time of the tracer, they were used for the calculation of the section-average concentration. The noise in the signal is probably due to problems in conductivity measuring device functioning which should be inspected.

Although ADVP method is the most advanced one, the device performance and data processing should be carefully studied in order to decide if the recorded data are physically realistic and can be further applied.

Conclusion

All applied methods of streamflow measurement give physically realistic values that correspond with the mean daily flows from stations' sample hydrographs. The obtained results have been analysed with respect of sampling time and location. The difference in the Misbourne flow values between morning and afternoon samplings is assumed to be due to unsteady flow conditions on a daily basis.

Both EM and impeller metering have low uncertainty of the flow estimation. The advantage is given to the impeller metering flow value of 0.2243 m^3/s due to the selection of the measurement location. The recorded depth was uniform across the rectangular cross-section which decreases the uncertainty of estimated flow.

Among three methods applied in the afternoon, the dilution gauging gives the best flow estimation of 0.2546 m^3/s due to lowest uncertainty related to its application. The slope-area method and float gauging should be limited to flood conditions when other methods are not applicable. Hence the mean daily flow for the river Misbourne can be estimated as the average value of impeller metering and dilution gauging results and is equal to 0.2395 m^3/s.

The estimation of all methods can be improved by taking into consideration the components that have the influence on the result uncertainty such as selection of measuring location and number of verticals and velocity measuring points. The performance of measuring devices should be controlled in advance and the elements that determine the values of applied coefficients should be observed.

References

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Appendix

Electromagnetic and impeller metering

Table 1. The EM metering calculation of the flow

N	Distance (m)	Depth (m)	V (m/s)	q (m^3/s)	q_{rel} (%)
1	0.00	0.00	0.000		
2	0.15	0.04	0.008	0.0000	0.0
3	0.55	0.09	0.059	0.0009	0.4
4	0.95	0.10	0.109	0.0032	1.4
5	1.35	0.11	0.290	0.0084	3.6
6	1.75	0.13	0.324	0.0147	6.4
7	2.15	0.14	0.267	0.0160	6.9
8	2.55	0.16	0.286	0.0166	7.2
9	2.95	0.16	0.329	0.0197	8.6
10	3.35	0.18	0.318	0.0217	9.4
11	3.75	0.17	0.387	0.0243	10.6
12	4.15	0.13	0.433	0.0246	10.7
13	4.55	0.16	0.363	0.0231	10.1
14	4.95	0.16	0.313	0.0216	9.4
15	5.35	0.17	0.291	0.0199	8.7
16	5.75	0.13	0.165	0.0137	6.0
17	6.00	0.00	0.000	0.0013	0.6
			Q=	**0.2297**	**m^3/s**

Table 2. The Impeller metering calculation of the flow

N	Distance (m)	Depth (m)	n (1/min)	V (m/s)	q (m^3/s)	q_{rel} (%)
1	0.0	0.23	0	0.000		
2	0.1	0.23	39	0.338	0.0039	1.73
3	0.4	0.23	34	0.297	0.0219	9.76
4	0.7	0.23	33	0.289	0.0202	9.00
5	1.0	0.23	34	0.297	0.0202	9.00
6	1.3	0.23	36	0.313	0.0210	9.38
7	1.6	0.23	33	0.289	0.0208	9.26
8	1.9	0.23	35	0.305	0.0205	9.13
9	2.2	0.23	33	0.289	0.0205	9.13
10	2.5	0.23	29	0.256	0.0188	8.37
11	2.8	0.23	30	0.264	0.0179	7.99
12	3.1	0.23	30	0.264	0.0182	8.12
13	3.4	0.23	28	0.247	0.0176	7.86
14	3.5	0.23	0	0.000	0.0028	1.27
				Q=	**0.2243**	**m^3/s**

Slope-area method

Table 3. Calculation of Manning's roughness coefficient

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)m$$

Aditive Factors		n ($m^{-1/3}s$)
Material Involved	Coarse Gravel	0.028
Degree of Irregularity	Minor	0.005
Variation in Channel Cross-Section	Gradual	0.000
Effect of Obstructions	Negligible	0.000
Riparian Vegetation	Low (grass/weeds)	0.008
Multiplicative Factor		m (-)
Degree of Meandering	Minor	1.000
	n=	**0.041**

Table 4. The slope-area method cross-sections

(a) Upstream cross-section

N	Distance (m)	Depth (m)	A_i (m^2)	P_i (m)
1	0.00	0.00		
2	0.15	0.04	0.003	0.16
3	0.55	0.09	0.026	0.40
4	0.95	0.10	0.038	0.40
5	1.35	0.11	0.042	0.40
6	1.75	0.13	0.048	0.40
7	2.15	0.14	0.054	0.40
8	2.55	0.16	0.060	0.40
9	2.95	0.16	0.064	0.40
10	3.35	0.18	0.067	0.40
11	3.75	0.17	0.069	0.40
12	4.15	0.13	0.060	0.40
13	4.55	0.16	0.058	0.40
14	4.95	0.16	0.064	0.40
15	5.35	0.17	0.066	0.40
16	5.75	0.13	0.060	0.40
17	6.00	0.00	0.016	0.28

(b) Downstream cross-section

N	Distance (m)	Depth (m)	A_i (m^2)	P_i (m)
1	0.00	0.00		
2	0.50	0.08	0.020	0.51
3	1.00	0.15	0.058	0.50
4	1.50	0.19	0.084	0.50
5	2.00	0.19	0.094	0.50
6	2.50	0.21	0.100	0.50
7	3.00	0.19	0.100	0.50
8	3.50	0.21	0.100	0.50
9	4.00	0.21	0.105	0.50
10	4.50	0.20	0.103	0.50
11	5.00	0.12	0.080	0.51
12	5.15	0.00	0.009	0.19

Table 5. The slope-area method's parameters

	Cross-section	
	Upstream	Downstream
$A (m^2)$	0.795	0.852
P (m)	6.05	5.21
R (m)	0.132	0.163
$K (m^3/s)$	5.016	6.206
Water level (m)	1.94	1.985

Table 6. The slope-area method calculation of the flow

			Iteration	
			1	2
L (m)	24.74	$Q (m^3/s)$	0.2380	0.2387
$n (m^{-1/3}s)$	0.041	V_1 (m/s)	0.2992	0.3002
β (-)	0.5	V_2 (m/s)	0.2795	0.2804
$S_{f,uni}$ (%)	0.182	$S_{f,non-uni}$	0.0018	0.0018
$K (m^3/s)$	5.58	$Q (m^3/s)$	0.2387	0.2387
		Q=	**0.2387**	**m^3/s**

Dilution gauging

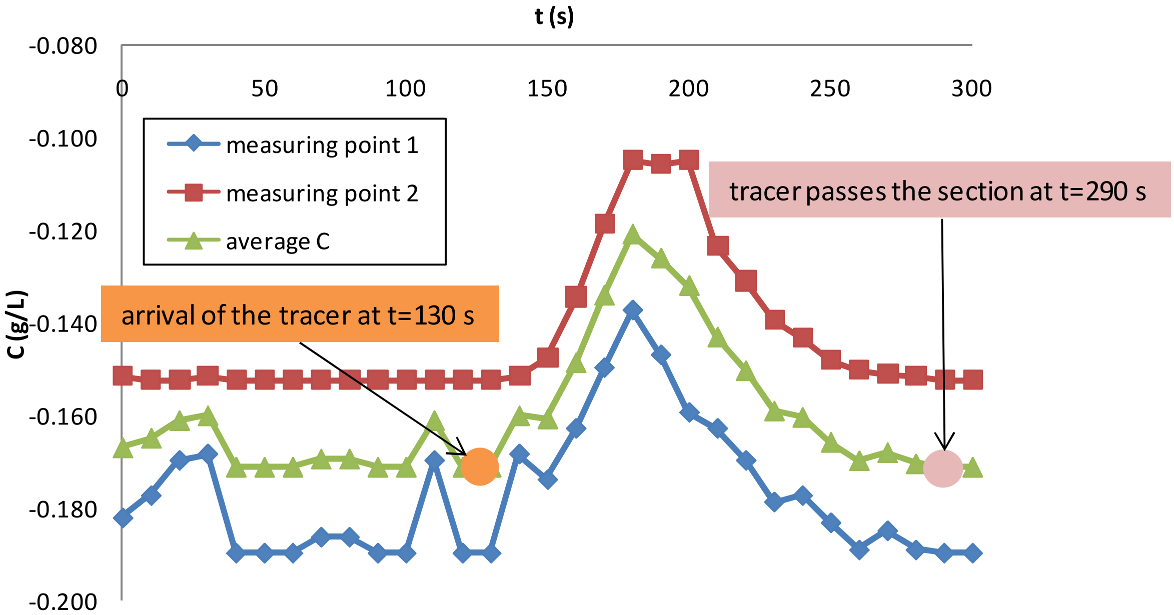

Figure 1. Dilution gauging tracer profile

Table 7. Dilution gauging sampling data processing

$$C(g/L) = [Cond(\mu S) - 634.18]/1451.1$$

	Measuring point 1		Measuring point 2				
Time (s)	Cond (mS)	C (g/L)	Cond (mS)	C (g/L)	C_{av} (g/L)	$(C-C_0)_{av}$ (g/L)	A_i (gs/L)
0	0.370	-0.182	0.414	-0.152	-0.167	0.004	
10	0.377	-0.177	0.413	-0.152	-0.165	0.006	
20	0.388	-0.170	0.413	-0.152	-0.161	0.010	
30	0.390	-0.168	0.414	-0.152	-0.160	0.011	
40	0.359	-0.190	0.413	-0.152	-0.171	0.000	
50	0.359	-0.190	0.413	-0.152	-0.171	0.000	
60	0.359	-0.190	0.413	-0.152	-0.171	0.000	
70	0.364	-0.186	0.413	-0.152	-0.169	0.002	
80	0.364	-0.186	0.413	-0.152	-0.169	0.002	
90	0.359	-0.190	0.413	-0.152	-0.171	0.000	
100	0.359	-0.190	0.413	-0.152	-0.171	0.000	
110	0.388	-0.170	0.413	-0.152	-0.161	0.010	
120	0.359	-0.190	0.413	-0.152	-0.171	0.000	
130	0.359	-0.190	0.413	-0.152	-0.171	0.000	
140	0.390	-0.168	0.414	-0.152	-0.160	0.011	0.055
150	0.382	-0.174	0.420	-0.148	-0.161	0.010	0.107
160	0.398	-0.163	0.439	-0.135	-0.149	0.022	0.164
170	0.417	-0.150	0.462	-0.119	-0.134	0.037	0.296
180	0.435	-0.137	0.482	-0.105	-0.121	0.050	0.434
190	0.421	-0.147	0.481	-0.106	-0.126	0.045	0.474
200	0.403	-0.159	0.482	-0.105	-0.132	0.039	0.419
210	0.398	-0.163	0.455	-0.123	-0.143	0.028	0.334
220	0.388	-0.170	0.444	-0.131	-0.150	0.021	0.243
230	0.375	-0.179	0.432	-0.139	-0.159	0.012	0.164
240	0.377	-0.177	0.426	-0.143	-0.160	0.011	0.114
250	***0.369***	-0.183	0.419	-0.148	-0.166	0.005	0.080
260	0.360	-0.189	0.416	-0.150	-0.170	0.001	0.034
270	0.366	-0.185	0.415	-0.151	-0.168	0.003	0.022
280	0.360	-0.189	0.414	-0.152	-0.170	0.001	0.019
290	0.359	-0.190	0.413	-0.152	-0.171	0.000	0.003
300	0.359	-0.190	0.413	-0.152	-0.171	0.000	

The unrecorded conductivity value has been determined assuming the linear change of values between two readings

Table 8. Dilution gauging calculation of the flow

$C_{0,av}$ (g/L)	-0.171
A (gs/L)	2.962
M (g)	754
Q (m^3/s)	**0.2546**

Float gauging

Table 9. The float gauging method cross-sections

(a) Upstream cross-section

N	Distance (m)	Depth (m)	A_i (m^2)	P_i (m)
1	0.00	0.000		
2	0.30	0.055	0.008	0.31
3	0.60	0.105	0.024	0.30
4	0.90	0.150	0.038	0.30
5	1.20	0.175	0.049	0.30
6	1.50	0.200	0.056	0.30
7	1.80	0.220	0.063	0.30
8	2.10	0.255	0.071	0.30
9	2.40	0.270	0.079	0.30
10	2.70	0.215	0.073	0.31
11	3.00	0.175	0.059	0.30
12	3.30	0.150	0.049	0.30
13	3.60	0.160	0.047	0.30
14	3.90	0.190	0.053	0.30
15	4.20	0.185	0.056	0.30
16	4.50	0.185	0.056	0.30
17	4.80	0.190	0.056	0.30
18	5.00	0.000	0.019	0.28

A_1= 0.855 m^2

P_1= 5.10 m

R_1= 0.167 m

(b) Downstream cross-section

N	Distance (m)	Depth (m)	A_i (m^2)	P_i (m)
1	0.00	0.000		
2	0.40	0.075	0.015	0.41
3	0.80	0.142	0.043	0.41
4	1.20	0.175	0.063	0.40
5	1.60	0.190	0.073	0.40
6	2.00	0.198	0.078	0.40
7	2.40	0.217	0.083	0.40
8	2.80	0.230	0.089	0.40
9	3.20	0.246	0.095	0.40
10	3.60	0.240	0.097	0.40
11	4.00	0.235	0.095	0.40
12	4.40	0.234	0.094	0.40
13	4.80	0.229	0.093	0.40
14	5.10	0.000	0.034	0.38

A_2= 0.953 m^2

P_2= 5.19 m

R_2= 0.184 m

Table 10. Float gauging measured data

	Positions of floats		Recorded time	
N	Upstream (m)	Downstream (m)	t_1 (s)	t_2 (s)
1	0.45	0.75	21.93	22.00
2	1.10	1.25	10.90	10.43
3	1.50	1.50	11.08	11.70
4	2.00	1.94	10.70	10.08
5	3.00	2.61	10.30	11.00
6	3.90	3.22	11.67	11.20

L_x=5.0 m

Table 11. Float gauging data processing

N	Float position at L/2 (m)	Calculation of surface V_x in flow direction			
		t_{av} (s)	L' (m)	V' (m/s)	V_x (m/s)
1	0.60	21.97	5.01	0.228	0.228
2	1.18	10.67	5.00	0.469	0.469
3	1.50	11.39	5.00	0.439	0.439
4	1.97	10.39	5.00	0.481	0.481
5	2.81	10.65	5.02	0.471	0.469
6	3.56	11.44	5.05	0.441	0.437

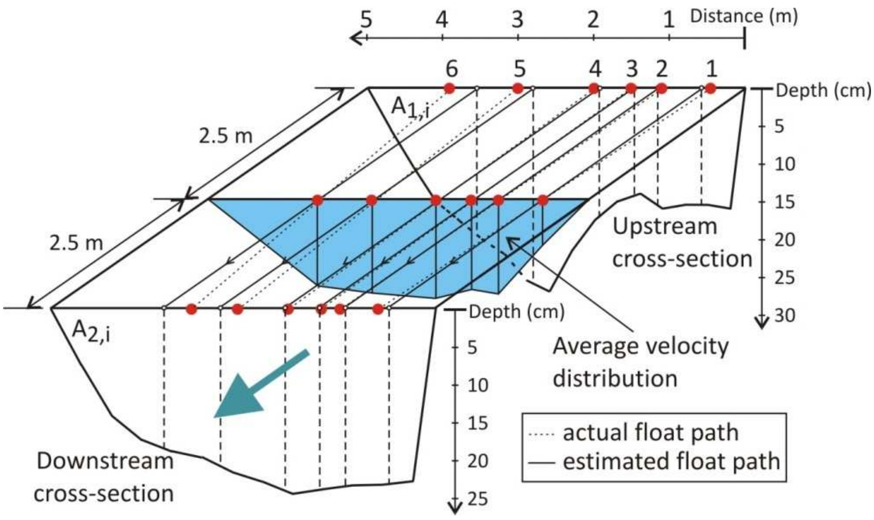

Figure 2. Float gauging data processing

Table 12. Float gauging calculation of the flow

$$Q = \sum_{i=1}^{8} q_i = \sum_{i=1}^{8} \frac{V_i + V_{i+1}}{2} A_{av}$$

N	Distance (m)	V (m/s)	A_1 (m^2)	A_2 (m^2)	A_{av} (m^2)	q (m^3/s)	q_{rel} (%)
1	0	0					
2	0.60	0.171311	0.032	0.033	0.033	0.0028	1.14
3	1.18	0.352823	0.083	0.084	0.083	0.0219	8.86
4	1.50	0.330365	0.061	0.059	0.060	0.0203	8.25
5	1.97	0.362161	0.102	0.090	0.096	0.0333	13.52
6	2.81	0.35332	0.206	0.179	0.192	0.0689	27.92
7	3.56	0.329065	0.126	0.182	0.154	0.0524	21.25
8	5.05	0	0.246	0.325	0.286	0.0470	19.06
	k=	0.753			**Q=**	**0.2466**	**m^3/s**