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CIVIL INFRASTRUCTURE

Determining Surface Velocity Coefficients in Headwater Streams for Natural Flood Management

With concerns about climate change, nature-based solutions for flood risk management have been increasing in popularity across Europe, and targeting headwater streams can be an effective approach by increasing forest floodplains through inundation of surrounding areas. However, accurately measuring stream discharge remains a challenge. One promising method is to measure the surface velocity and apply a surface velocity coefficient. This study investigates the determination of surface velocity coefficient in headwater streams using the float and current meter methods. The relationship between surface velocity coefficient and relative submergence (ratio of water depth to roughness height) is analysed. The results support prior modelling results that the surface velocity coefficient decreases with relative submergence and extend the range of prior work for very small relative submergence, using experimental and field observations. The surface velocity coefficient was observed to decrease from 0.85 to 0.53 as relative submergence decreased from 270000 in a smooth glass laboratory channel to 0.093 in a field setting. Field discharge measurements upstream of a channel-spanning engineered logjam were used to show used to predict local inundation and the uncertainty is reported.

Keywords:
Natural flood management, hydrometrics, surface velocity coefficient, relative submergence, engineered log jam.

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INTRODUCTION

Nature based solutions to flood risk management have been gaining significant traction across Europe over the last decade and a half with the Flood and Water Management ACT (2010) including a recommendation to better "work with natural processes" [1] due to concerns relating to the impacts of climate change [2].

Targeting headwater streams (which are often found in mountainous, forested regions), can result in increased forest floodplains by forcing inundation in areas surrounding these streams [3]. This approach holds significant promise for the deployment of Engineered Log Jams (ELJs) as a solution to reduce adverse catchment flooding [3], [4].

Characterising the physical properties of small water bodies, specifically headwater streams, is necessary for the design and assessment of natural flood management projects and of significant broader interest as headwater streams represent 73.4% of the UK river network [5].

A key metric is stream discharge. Calculating discharge of small streams remains an open issue due to the prevalence of shallow flows, variable bed roughness, and remote site location that complicates implementation of traditional measurement methods [6]–[8].

The most popular method of measuring discharge is the velocity-area method [6]–[11], specifically the midsection method [7] in which discharge is calculated by measuring the spatial average velocity (U) and cross-sectional area () of a section within a uniform stretch, and then summing the product of the two values together as follows:

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

Existing methods for measuring spatial average velocity include current meters, Acoustic Doppler Velocimetry, dilution gauging, remote sensing and surface Particle Image Velocimetry (PIV). Due to the shallow and remote nature of headwater streams, many of these methods are impractical [6]. One relatively simple method for obtaining spatial average velocity in headwater streams is by measuring surface velocity and applying a Surface Velocity Coefficient (λ) [7]. Surface velocity can be measured using the float method. Ideally, an object that lies below the surface (such as an orange) is preferred as it has a similar specific gravity to water and thus is resistant to air disturbances [8].

Previous studies have indicated that λ is highly variable and dependent on the conditions of the specific location being measured such as aspect ratio, depth, relative submergence, local vegetation, and Reynolds number [9]. Prior literature has suggested λ ranges from as low as 0.552 [10] in wide shallow streams to 0.85 in smooth uniform prismatic channels.

This study presents new measurements of surface velocity coefficients found in a headwater stream used for a natural flood management project at Nant Drysiog, Wales, UK (as shown in Fig. 1) and explores the range of variation of λ with relative submergence through lab measurements and comparison to prior results. Study results will inform use of the float method in headwater streams typical of natural flood management projects, filling a research gap for channels that are wide (aspect ratio > 5) but shallow (relative submergence close to or of the order of flow depth).

Fig. 1. Example of channel-spanning ELJ in a headwater stream (Nant Drysiog, Wales, UK, 16th February 2022.

In this study, the float method and current meter method were used to determine surface velocity and spatial average velocity (U) respectively across a range of aspect ratios, stream velocities, and relative submergences. The float method was chosen to measure surface velocity as it required no heavy or expensive equipment making it ideal for headwater streams which are typically situated in remote locations or as part of monitoring programmes led by volunteer groups.

Lab experiments were conducted to validate the methods with a built-in flow meter in a smooth rectangular channel. The float method was repeated multiple times with the aim of identifying the number of repeats necessary to reduce uncertainty of the method in laboratory and field conditions. The standard deviation was computed for all measurements. The discharge was then computed and subsequently used to calculate a dimensionless metric representing jam physical structure (C_A) to predict local inundation during high flow conditions and characterise structural change over time.

METHODS

Laboratory experiments were conducted in a smooth glass, 17m long, 1.2m wide, and 1m deep bi-directional recirculating tilting flume at the Hydraulics Lab at the Cardiff University School of Engineering. The current meter (OTT MF PRO) [12] midsection method and float method were used to measure spatial average velocity and surface velocity respectively [12]. The current meter was attached to a wading rod and was validated using a Controlotron 1020 Clamp-On Transit-Time Flow meter. Its software was used to calculate partial discharge in each section from the spatial average velocity and the area of the section, thus giving the total discharge. Since the flume is a smooth rectangular channel, current meter measurements were taken every 0.05m laterally across the cross section (*b - 1.2*0m) resulting in 24 stations in total. A series of time averaged measurements were taken along each vertical from the bed to the surface at 0.2h intervals using a wading rod. Data was collected for ten seconds at 50Hz and then time averaged via the current meter software.

In field observations, an orange was predominantly used for the float method. However, during low flow conditions (such as 8 July 2022), a stick was used instead due the orange diameter exceeding the depth of flow. As the site at Nant

Dyrsiog is well-protected by forest cover it is assumed that there is little wind as no surface ripples were observed [13] and therefore it is assumed that use of a stick did not bias the measurement.

Relative Submergence (RS) was determined using the following relationship [14]:

$$RS = \frac{h}{k_s}, \qquad (2)$$

where h is the depth of flow at the point of measurement and k_S is the equivalent Nikuradse sand grain roughness height as: $k_S = 6.8D_{50}$. D_{50} is the median sediment size. This was measured downstream of the ELJ by taking 1m x 1m samples and calculating the average diameter in three dimensions. The upstream was measured by taking a sample roughly 60mm deep and performing a sieve analysis.

RESULTS

Float method measurements were conducted to measure surface velocity and compute the surface velocity coefficient. The number of float method repeats required to obtain a value within ±2.5% of the moving average was explored in a field setting. To reduce error and obtain a more accurate mean float velocity, multiple repetitions of the measurement were conducted. On average, it took between 10 and 20 repeats for the cumulative average to drop within of the set average. Fig. 2 demonstrates the number of repeats it took to achieve this average velocity, where a total of 36, 30, 30, and 30 measurements were recorded at field visits (Nant Drysiog, Wales, UK) on 8 July 22, 16 February 23, 23 February 23, and 7 March 23 respectively. Dashed lines indicate ±2.5% of the set average.

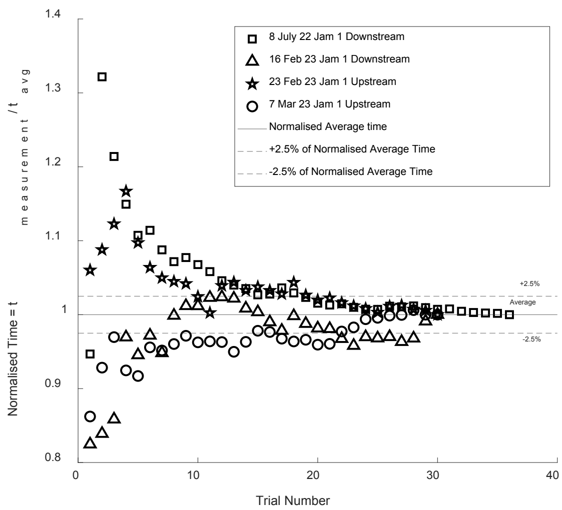

Fig. 2. Normalised time for float to cross measurement section relative to trial average.

To provide surface velocity coefficients for headwater streams in order to support use of surface velocity measurements for discharge calculation at natural flood management sites, the following relationship is defined to relate spatial average velocity (U) over the channel cross-section to surface velocity (u_{Surf}):

$$\lambda = U/u_{Surf} \qquad (3)$$

where λ is the surface velocity coefficient.

The lateral average flow depth ranged from 0.2m to 0.4m for lab observations and 0.041m to 0.365m for field observations. The shallowest field flow depths approached the range of operability of the OTT MFPro current meter (0.04 m, [12]). In the lab the standard deviation of λ ranged from 0.05 to 0.13; and in the field it ranged from 0.10 to 0.24 upstream of the ELJ and from 0.05 to 0.19 downstream of the ELJ.

Figure 3 below shows the values of λ for a range of relative submergences. λ was observed to remain relatively constant $\overline{\lambda_{\text{lab}}} = 0.84$ with relative submergence in flume experiments whilst decreasing with relative submergence for field conditions; with λ decreasing from 0.70 to 0.53 over relative submergence 26.8 to 0.093.

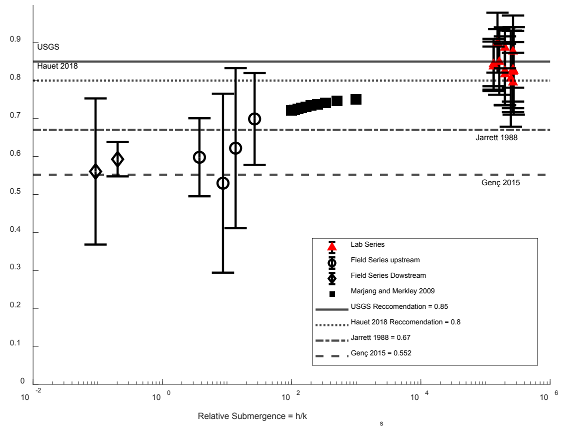

Fig. 3. Comparison of surface velocity coefficient against relative submergence observed in lab and field settings.

DISCUSSION

Field observations extend numerical modelling results from [15] (black squares Fig. 3), demonstrating a decrease in λ as Relative Submergence (RS) decreases. In their study, it was observed that changes in surface roughness height have no significant effect on the surface velocity but do slow the flow near the boundary, thereby reducing spatial average velocity.

The observed range of λ in this study supports this hypothesis and is in agreement with prior literature, with values spanning from 0.552 in shallow but wide streams [10] to 0.85 in smooth uniform prismatic channels [7], [8]. Although a direct relationship between λ and RS isn't explicitly documented in previous literature, the present results were connected to prior work by examining experimental conditions under which the studies were conducted.

Measurements from [10] (dashed line Fig. 3) show consistency with our findings that shallow and wide streams result in a reduced λ. Further support comes from the study by [11] (dotted line Fig. 3), which recommends using λ = 0.8 for water depths less than 2 meters and observes a decrease in λ with hydraulic radius. This is consistent with the hypothesis that λ reduces with RS, however, it is insufficient to describe the effects of very low RS as the study was conducted in relatively larger streams.

Lastly, [16]'s (dash-dotted line Fig. 3) estimation of λ = 0.67 in mountainous streams also concurs with our hypothesis. This estimation stems from the observation of S-shaped and nonlogarithmic flow profiles in such streams. This lowers the measurable depth of U from 0.6d to 0.5d and is due to the high velocity flow and exceptional drag from the cobble and boulder bed material impacting the flow surface.

In addition to examination of λ , field observations were used to record the logjam structural metric linking discharge to jam-generated backwater rise, C_A [17]:

$$H_2 = \sqrt{3} * \sqrt[3]{\frac{C_A q^2}{2g}} \tag{4}$$

Where H_2 is the backwater rise and $q = Q/B$ the discharge per unit channel width.

Discharge readings obtained in July 2022 using the float method and λ were used to calculate C_A as 15.8 ± 4.5, which was then used to predict the extent of backwater rise in February 2022 based on the discharge readings for that month, predicting = 0.393m ± 0.03m compared to the measured = 0.365m ± 0.0005m giving an absolute percentage error of only 7.56%. The cubic and square terms in (4) mean that whilst the error for C_A seems large, when used to predict , the measurement is fairly accurate.

The resulting values indicated that the ELJ site would experience localized flooding, which was observed during that visit and recorded in photographs.

Bedforms were not observed in the field and thus the effect of bedforms such as ripples and dunes due to the presence of a moveable boundary is to be further explored.

CONCLUSIONS

Surface velocity measurements present a method for determining discharge in headwater streams for effective implementation of natural flood management techniques. To use surface velocity, an accurate relationship to U must be made using an appropriate surface velocity coefficient.

In field and laboratory experiments, between 10 and 20 repetitions of the float method were necessary to reduce uncertainty caused by human error and flow profile variations. The results of field observations suggest that for small streams with water depths less than 0.365m, the surface velocity coefficient decreases with relative submergence, ranging from 0.72 to 0.53 for to 0.093. For a smooth rectangular laboratory channel, λ = 0.84 ± 0.084 (σ). No trend was observed with varying relative submergence in the laboratory tests.

Further analysis into the relationship between relative submergence and λ will be conducted, in addition to investigation of alternative methods to compute discharge including rhodamine dye dilution gauging and a forced weir constriction method to improve accuracy of results.

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Conflicts of interest
The authors declare no conflict of interest.

REFERENCES

[1] P. Metcalfe e*t al.*, K. Beven, B. Hankin, and R. Lamb, 'A modelling framework for evaluation of the hydrological impacts of nature-based approaches to flood risk management, with application to in-channel interventions across a 29-km2 scale catchment in the United Kingdom', *Hydrol Process*, vol. 31, no. 9, pp. 1734–1748, 2017. doi.org/10.1002/hyp.11140

[2] A. Black e*t al.*, 'Natural flood management, lag time and catchment scale: Results from an empirical nested catchment study', *J Flood Risk Manag*, vol. 14, no. 3, p. e12717, 2021. doi.org/10.1111/jfr3.12717

[3] S.J. Dixon, D.A. Sear, N.A. Odoni, T. Sykes, and S.N. Lane, 'The effects of river restoration on catchment scale flood risk and flood hydrology', *Earth Surf Process Landf*, vol. 41, no. 7, pp. 997–1008, Jun. 2016. doi.org/10.1002/esp.3919

[4] C. Linstead and A.M. Gurnell, *Large Woody Debris in British Headwater Rivers - Physical Habitat Role and Management Guidelines*, Research and Development Technical Report W185, Environment Agency, 1999.

[5] W.D. Riley e*t al.*, 'Small Water Bodies in Great Britain and Ireland: Ecosystem function, human-generated degradation, and options for restorative action', *Science of the Total Environment*, vol. 645. Elsevier B.V., pp. 1598–1616, Dec. 15, 2018. doi.org/10.1016/j.scitotenv.2018.07.243

[6] D.W. Clow and A.C. Fleming, 'Tracer gauge: An automated dye dilution gauging system for ice-affected streams', *Water Resource Res*, vol. 44, no. 12, 2008. doi.org/10.1029/2008WR007090

[7] D.P. Turnipseed, V.B. Sauer, and USGS, *Discharge measurements at gaging stations*, Reston, VA, 2010. doi.org/10.3133/tm3A8

[8] N.D. Gordon, T.A. McMahon, B.L. Finlayson, C.J. Gippel, and R.J. Nathan, *Stream hydrology: an introduction for ecologists*. John Wiley and Sons, 2004.

[9] F. Bandini e*t al.*, 'A drone-borne method to jointly estimate discharge and Manning's roughness of natural streams', *Water Resource Res.*, vol. 57, no. 2, p. e2020WR028266, 2021. doi.org/10.1029/2020WR028266

[10] O. Genç, M. Ardıçlıoğlu, and N. Ağıralioğlu, 'Calculation of mean velocity and discharge using water surface velocity in small streams', *Flow Measurement and Instrumentation*, vol. 41, pp. 115–120, 2015. doi.org/10.1016/j.flowmeasinst.2014.10.013

[11] A. Hauet, T. Morlot, and L. Daubagnan, 'Velocity profile and depth-averaged to surface velocity in natural streams: A review over alarge sample of rivers', in *E3s web of conferences*, 2018, vol. 40, p. 06015. doi.org/10.1051/e3sconf/20184006015

[12] OTT Hydromet, *Flow and Discharge Measurement with the OTT MF pro*, 2015. Accessed: Mar. 03, 2022. [Online]. Available: https://www.ott.com/download/ott-mf-pro-white-paper/

[13] G. Dolcetti, B. Hortobágyi, M. Perks, S. J. Tait, and N. Dervilis, 'Using noncontact measurement of water surface dynamics to estimate river discharge', *Water Resour. Res.*, vol. 58, no. 9, p. e2022WR032829, 2022. doi.org/10.1029/2022WR032829

[14] P.Y. Julien, *Erosion and Sedimentation*, 2nd ed. Cambridge University Press, 2010. doi.org/10.1017/CBO9780511806049

[15] N. Marjang and G.P. Merkley, 'Surface velocity coefficients for application of the float method in rectangular and compound open channels', *Irrig. Sci.*, vol. 27, no. 6, pp. 457–470, 2009. doi.org/10.1007/s00271-009-0162-3

[16] R.D. Jarrett, 'Hydrologic and hydraulic research in mountain rivers', *IAHS-AISH publication*, vol. 190, pp. 107–117, 1989.

[17] E. Follett, I. Schalko, and H. Nepf, 'Momentum and Energy Predict the Backwater Rise Generated by a Large Wood Jam', *Geophys. Res. Lett.*, vol. 47, no. 17, Sep. 2020. doi.org/10.1029/2020GL089346

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