Ecological Engineering 118 (2018) 73–83

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Assessing the accuracy of vegetative roughness estimates using unmanned aerial vehicles [UAVs]

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ARTICLE INFO

Keywords:
Aquatic vegetation
Image processing
UAV
Flow resistance
Resolution vs. accuracy
Roughness estimation

ABSTRACT

Cost-effective UAV (Unmanned Aerial Vehicle) technologies were utilized to map both submerged and emergent aquatic vegetation in natural rivers. This study was undertaken along reaches characterized by vegetative conditions ranging from homogeneously distributed to strongly heterogeneous and anisotropic. Spatial extent of vegetation was identified using both manual and automated image post-processing methods. For the study reaches assessed here, if 13,000 pixels/m^2 image resolution is maintained (which mostly depends on flight elevation and camera resolution) aquatic vegetation can be detected accurately. The methods presented here can be used to inventory aquatic vegetation in under one hour, as opposed to field data collection methods which would require approximately 9.5 h to achieve a comparable level of spatial resolution. Results were also applied to re-evaluate the accuracy of flow resistance formulations based on plants spatial distribution found in literature. It was found that there can be up to a 20% difference if vegetation is inventoried at the cross-sectional scale rather than at the planform scale, however for dense vegetation cover this difference is much lower.

1. Introduction

Accurate measurement of stream discharge under low-flow conditions is of upmost importance to many water resources practitioners. Methods of estimating discharge commonly occur at gauging stations using rating curves which relate observed water stage (z) to field measured discharge (Q) in the general form $Q = f(z)$ (Herschy, 1995). Often in low-gradient environments, water stage is seasonally affected by in-stream vegetation which can confound the unique stage vs discharge relationship (Gurnell and Midgley, 1994). Seasonal coincidence between vegetative growth and low-flow conditions can often result in large overestimates of discharge to the extent that many reporting agencies identify accuracy caveats or discontinue data reporting entirely during these periods.

Laboratory and field scale studies have shown that vegetation considerably increases resistance to flow (e.g. Green, 2005; Kouwen and Unny, 1973, 1980; Kouwen et al., 1981; Nikora et al. 2008; Ree and Palmer, 1949). Consequently, under these conditions, stage may be a function of many parameters:

$$z = f\,(Q,S,T_W,B_A,B_X,M,EI)_{t=1,\dots d} \quad (1)$$

where S denotes the channel slope, T_W the flowing top width, B_X and B_A are the cross-sectional blockage factor (Green, 2005) and surface area blockage factor (Green, 2005), respectively, M denotes vegetation stem density, and EI denotes flexural rigidity. Eq. (1) can be further confounded as all parameters can vary temporally (t) throughout the growing season until eventual dislodgement ($t = d$) and because the spatial heterogeneity in plant growth has been shown to affect flow resistance (e.g. Bal et al., 2011).

The principle objective is then to find the most predictive, repeatable and readily attainable parameters that can be quantified in the field to estimate low flow resistance and thus discharge. Both B_A and B_X have been used to estimate flow resistance (e.g. Green, 2005; Huntington and Whitehead, 1992; Nikora et al., 2008). B_X, or cross-sectional blockage factor (Green, 2005) is defined as the sum of submerged areas occupied by vegetation for a given cross section divided by the total cross-sectional area. Aerial cover (B_A) is defined as the planform area covered by plants divided by the total channel planform area. As the intent of this study was to use aerial imagery to map aquatic vegetation, B_A was chosen as the parameter of interest between the two with the definition:

$$B_A = \frac{\sum_{i=1}^{n} A_i}{A_T} \quad (2)$$

where A_i is the planform area of the i^{th} patch of vegetation (Fig. 1-1a) contained within the study reach planform area (A_T).

It is noteworthy that for proper calculation of B_A using Eq. (2), clear

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https://doi.org/10.1016/j.ecoleng.2018.01.005
Received 10 August 2017; Received in revised form 7 January 2018; Accepted 9 January 2018
Available online 26 April 2018
0925-8574/

List of parameters cited

A	Cross-sectional area (m^2)
A_T	Total area of reach (m^2)
A_i	Portion of reach occupied by vegetation (m^2)
A_R	Reference area (m^2)
B_A	Aerial cover (dimensionless)
B_X	Blockage factor (dimensionless)
CS_X	Spacing between two consecutive cross-sections (m)
d_i	Distance of a point from bank (m)
D_j	Distance between $(j)^{th}$ and $(j + 1)^{th}$ cross section (m)
E	Vegetation modulus of elasticity (N/m^2)
E_m	Error in the estimation of L_A (%)
E_Q	Error in the estimation of Q (%)
L_A	Reach-averaged blockage width (dimensionless)
$l_A(j)$	Cross-sectional blockage width (dimensionless)
M	Vegetation spatial density (m^{-2})
n	Manning's n ($sm^{-1/3}$)
n_b	Manning's n component excluding vegetation resistance ($sm^{-1/3}$)
n_v	Manning's n component due to vegetative resistance ($sm^{-1/3}$)
NCS	Normalized cross-sectional spacing (dimensionless)
Pix_D	Pixel density (m^{-2})
Q	Discharge (or flow rate) (m^3/s)
R	Hydraulic radius (m)
R^2	coefficient of correlation (dimensionless)
RMSD	Root mean square deviation (dimensionless)
RMSE	Root mean square error (dimensionless)
SD	Standard Deviation of $l_A(j)$ values
S	Reach slope (dimensionless)
S_F	Reach friction slope (dimensionless)
t	Time (h)
T_W	Cross-sectional top width (m)
Δl	Discrepancy between calculated and measured $l_A(j)$ (dimensionless)
θ	Dimensional constant in Manning's equation (dimensionless with SI units)

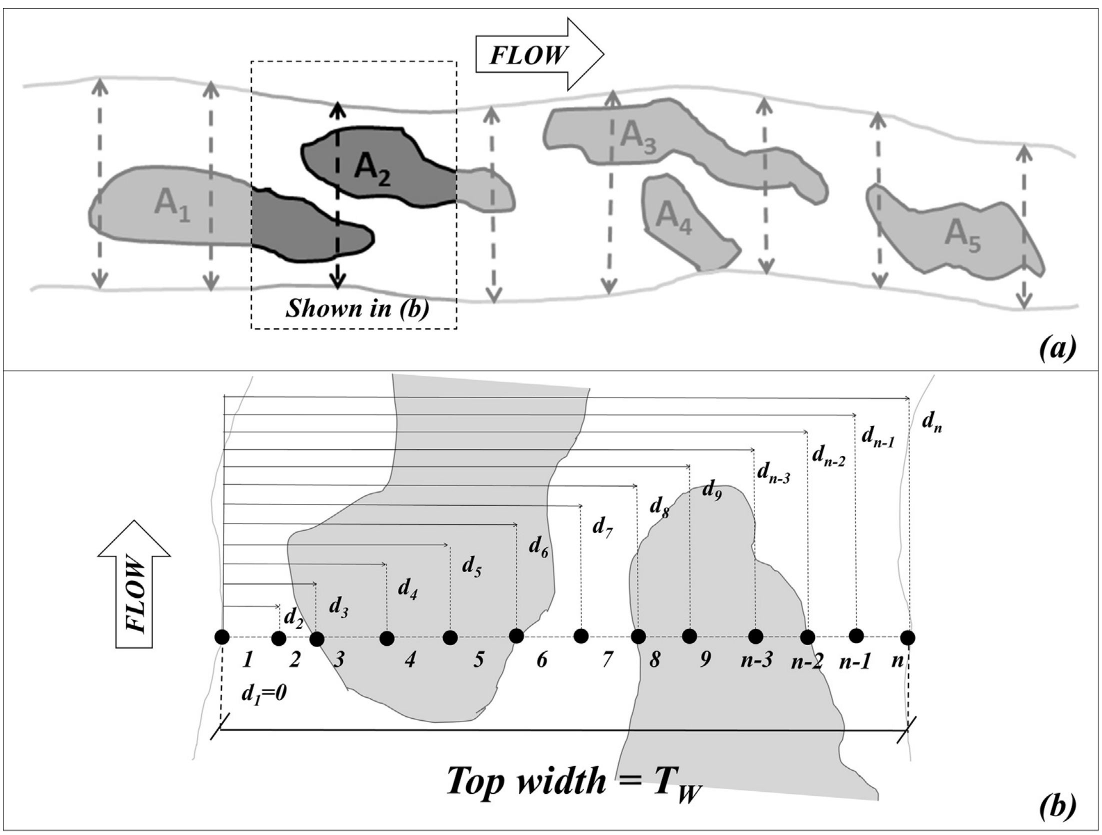

Fig. 1-1. (a) Schematic representation of macrophyte cover (gray patches) in a vegetated channel for the calculation of B_A. The detailed frame (b) illustrates the field survey discretization used in the calculation of the blockage width at the cross-sectional scale $l_{A,j}$.

boundaries to field identify each A_i (Fig. 1-2a) must exist (e.g. Huntington and Whitehead, 1992; Sand-Jensen and Pedersen, 2008). In natural channels, where ill-defined plant boundaries exist (Fig. 1-2b), defining each A_i patch, and thus the calculation of B_A becomes increasingly prone to error. Current techniques either estimate B_A qualitatively with visual techniques (e.g. Mean Trophic Rank by Holmes et al., 1999) or quantitatively using field survey methods at a series of cross-sections (e.g. Baattrup-Pedersen et al., 2002; Green, 2005; Champion and Tanner, 2000; Nikora et al., 2008; O'Hare et al., 2010). Following the quantitative methods for the j^{th} cross-section, a blockage width $l_A(j)$ can be obtained in the form (cf. Green, 2005):

$$l_A(j) = \frac{\sum_{i=2}^{n} \frac{1}{2}(d_i - d_{i-1})(F_i + F_{i-1})}{d_n} \quad (3)$$

$$\text{where } \begin{matrix} F_i = 0 \text{ if aquatic vegetation is not present} \\ F_i = 1 \text{ if aquatic vegetation is present} \end{matrix}$$

where i is the survey point of interest, d_i is the point distance from the