Simulated effects of streambed vegetation on river hydraulics and the habitat suitability of freshwater macroinvertebrates

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Abstract We modelled the effects of flexible and rigid streambed vegetation on river hydraulics and macro-invertebrate habitat suitability in flows/discharges ranging from near-dry to floods, in the Oinoi Stream (Attica, Greece). Vegetation was mapped in spring and summer, simulated using two-dimensional ecohydraulic models (VEG_{SP}: spring model, corresponding to moderate vegetation cover; VEG_{SU}: summer model, corresponding to dense vegetation cover), and the results were compared to those of a non-vegetation-including model (VEG_O). Flow velocity (V) was negatively correlated and water depth (D) was positively correlated with vegetation type and density. Compared to VEG_O, mean D was 22-40% higher and mean V was 20-34% lower in high/near-flood flows. In low/near-dry flows, V and D were only slightly influenced by vegetation (approx. 10-15% change). Macroinvertebrate habitat suitability (HSI) was higher in densely vegetated areas in both spring and summer, and remained high in near-flood flows, in contrast to the VEG_O model (max. HSI change 49.5%). We conclude that streambed vegetation shapes slow-flowing, deeper habitats, and is also a key element for maintaining suitable macroinvertebrate habitats. Ecohydraulic models could be applied to differentiate vegetated river reaches that need flood protection from those that need geomorphic and habitat restoration within accurately designed river management plans.

Keywords: Bottom vegetation, riparian vegetation, hydraulic-habitat models, hydrodynamic models, telemac

1. Introduction

Streambed vegetation is a major but understudied driver of river hydraulics, sediment transport (Vargas-Luna et al., 2015) and of the habitat suitability of freshwater biota (Huttunen et al., 2017). If left unmanaged, it can be a cause of flooding by increasing local water depths, thus inducing overbank flows (Benifei et al., 2015). But if adequately managed, it can serve both as a geomorphic (flow reducing, erosion preventing) and as an ecological (habitat diversity enhancing) asset in streams and rivers (Tessier et al., 2004; Benifei et al., 2015). Although the fundamentals of flow through vegetation in channels have long been studied, little is known on the effects of different types (flexible vs. rigid) and densities of streambed vegetation on channel hydraulics, and how these hydraulic patterns ultimately influence macro-invertebrate habitat suitability (Kiesel et al., 2009).

The aim of this study was to assess the effects of streambed vegetation on the hydraulic patterns (flow velocity (V) and water depth (D)) and the habitat suitability of benthic macroinvertebrates (HSI) in the Oinoi Stream (Attica, Greece). Building on a previously validated two-dimensional ecohydraulic model, we simulated the presence of rigid and flexible streambed vegetation patches in two seasons and explored mean V, D and HSI differences between the vegetated and non-vegetated models in flows ranging from low/near-dry to high/near-flood, to advance our understanding on the hydraulic and habitat processes taking place in streams/rivers in the presence of streambed vegetation.

2. Materials and methods

2.1. Site, vegetation mapping and hydraulic simulation

Our study site was a 370-m long reach in the Oinoi Stream (Attica, Greece), downstream of the Marathon Reservoir. Topography was mapped with 459 points recording longitude (X), latitude (Y) and bottom elevation (H), using a real-time kinematic GPS and an unstructured, triangular mesh (3,938 nodes; 7,140 elements; 0.9 spatial resolution) was constructed from the acquired topography. Substrate types (S) and streambed vegetation were visually assessed on site in two periods (spring and summer 2015), by walking across the reach, drawing/recording and photographing substrates and vegetation types (differentiated in flexible (grasses) and rigid (bushes and trees). For rigid vegetation, average diameter and density (the average distance between stems) were also recorded. The TELEMAC 2D hydrodynamic model was used to simulate water depths (D) and flow velocities (V) at each node of the mesh for the following discharges (Q): 0.01, 0.03, 0.05, 0.07, 0.09, 0.1, 0.3, 0.5, 0.7, 0.9, 1, 1.5, 2, 3 and 5 m^3/s. Three different meshes were simulated (1) VEG_O: no vegetation (only inorganic, rocky substrate; calibrated and validated in three discharge scenarios; see Theodoropoulos et al., 2018); (2) VEG_{SP}: spring model; moderate vegetation cover; (3) VEG_{SU}: summer model; dense vegetation cover. Flexible vegetation was simulated by adding an appropriate Manning's roughness coefficient (n) to that of the area's inorganic substrate depending on vegetation-patch density and based on the n values given in USGS (1989). Rigid vegetation was simulated based on diameter and density, following the approach of Lindner, implemented in TELEMAC 2D (Folke et al, 2019). In total, 15 discharges x 3 meshes = 45 hydraulic simulations were applied. The study area was divided in three zones (zone-1: dense, mostly rigid vegetation; zone-2: moderate, mostly flexible vegetation; zone-3: sparse, flexible vegetation). The same patterns/zones were recorded for both seasons, but in summer, vegetation in zones 1 and 2 was slightly denser compared to spring.

2.2. Habitat suitability mapping

The habitat suitability (HSI) of benthic macro-invertebrates was simulated by a fuzzy rule-based Bayesian algorithm (FRB), trained and cross-validated using a reference macroinvertebrate dataset, described in detail in Theodoropoulos et al. (2018), and implemented in the HABFUZZ software (Theodoropoulos et al., 2016). The dataset includes 380 microhabitats, in which V, D and S are related to HSI, calculated using macroinvertebrate community metrics (No. of families, No. of Ephemeroptera-Plecoptera-Trichoptera families, Shannon Wiener diversity and total community abundance). Based on the dataset and using the FRB algorithm, V, D (simulated) and S (visually assessed) values at each node of each mesh were assigned an appropriate HSI.

2.3. V, D and HSI comparisons

At each zone of the VEG_O, VEG_{SP} and VEG_{SU}, we calculated mean V, mean D and mean HSI and comparisons were applied both between zones of the same mesh (no vegetation; spring; summer) and between meshes to acquire a thorough understanding of the spatial and temporal effects of streambed vegetation on stream hydraulics and macroinvertebrate habitat suitability.

3. Results

3.1. Water depth

Vegetated areas in both seasons were characterized by higher water depths (Figure 1). This effect varied by vegetation type and density, being clearly evident in dense, rigid-vegetation dominated zones (zone-1), less clear but evident in moderate, flexible vegetation zones (zone-2) and almost absent in sparsely vegetated zones (zone-3). It also varied by discharge: in low/near-dry discharges, the D-increasing effect was lower (ranging from 6.34% to 15.60% for Q between 0.01 and 0.1 m^3/s; zone-1, both seasons), but greatly increased as Q increased (ranging from 24.54% to 40.22% for Q between 0.3 and 5 m^3/s; zone-1, both seasons).

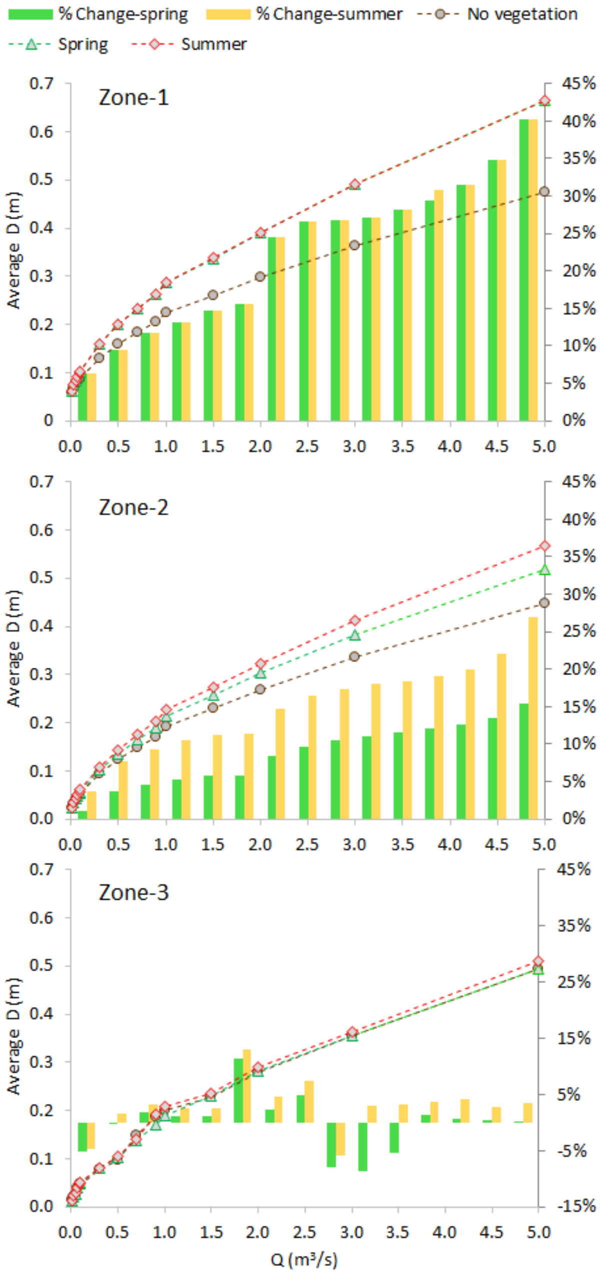

Figure 1. Average water depth per discharge (Q) for each zone (zone-1: dense, rigid vegetation; 2: moderate, flexible vegetation; 3: sparse, flexible vegetation) at each season (primary axis), and percent change of water depth per season and zone compared to the no-vegetation model (secondary axis).

3.2. Flow velocity

Vegetated areas in both seasons were characterized by lower velocities with the effect being slightly increased during summer (Figure 2). This effect varied by vegetation type and density, being clearly evident in dense, rigid-vegetation dominated zones (zone-1), less clear but evident in moderate, flexible vegetation zones (zone-2) and almost absent in sparsely vegetated zones (zone-3). It also varied by discharge, but with lower variation compared to the D-increasing effect: in low discharges, the V-decreasing effect was lower (ranging from 15.55% to 17.85% for Q between 0.01 and 0.1 m^3/s; zone-1, summer), and increased as Q increased (ranging from 20.75% to 33.75% for Q between 0.3 and 5 m^3/s; zone-1, summer).

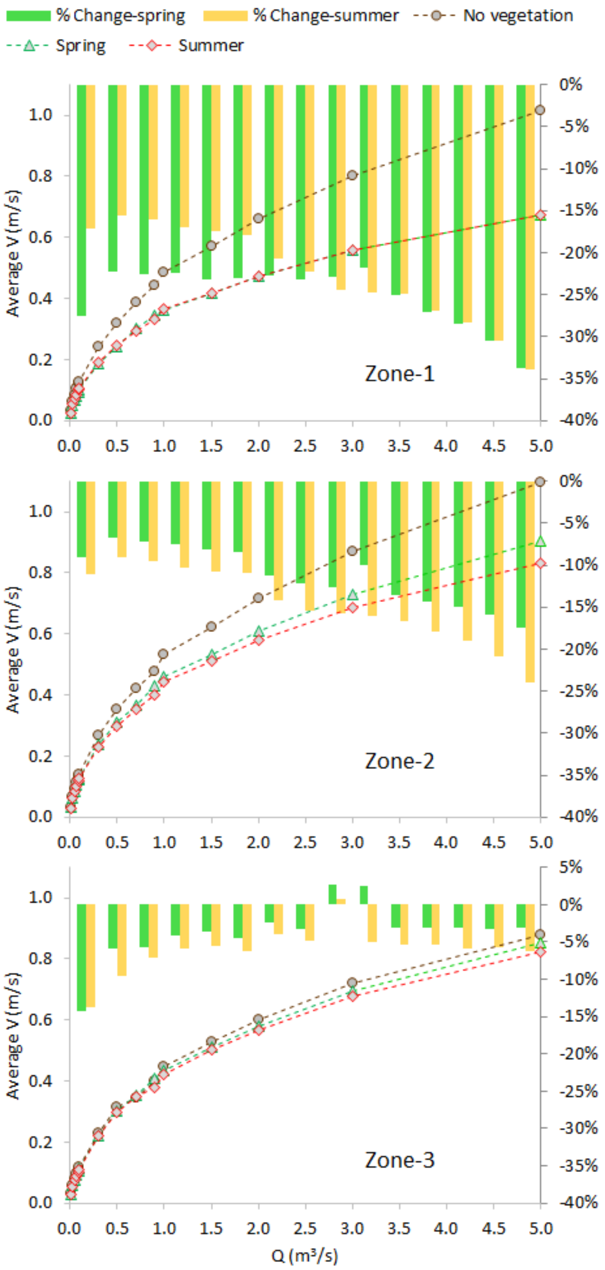

Figure 2. Average flow velocity per discharge (Q) for each zone (zone-1: dense, rigid vegetation; 2: moderate, flexible vegetation; 3: sparse, flexible vegetation) at each season (primary axis), and percent change of flow velocity per season and zone compared to the no-vegetation model (secondary axis).

3.3. Macroinvertebrate habitat suitability

Vegetated areas in both seasons were characterized by similarly higher HSI (Figure 3). This effect varied by vegetation type and density, and by discharge: in dense, rigid-vegetation dominated zones (zone-1), HSI increased in both seasons from low/near-dry discharges (0.3 m^3/s) and further increased compared to VEG_O as discharge increased (reaching +36.77% in 5 m^3/s, zone-1, summer). In flexible vegetation zones (zones 2 and 3) no HSI increase was evident in low/moderate discharges (0.01 to 1.5 m^3/s) but the increase was high in Q > 1.5 m^3/s, reaching +49.52% in zone 2.

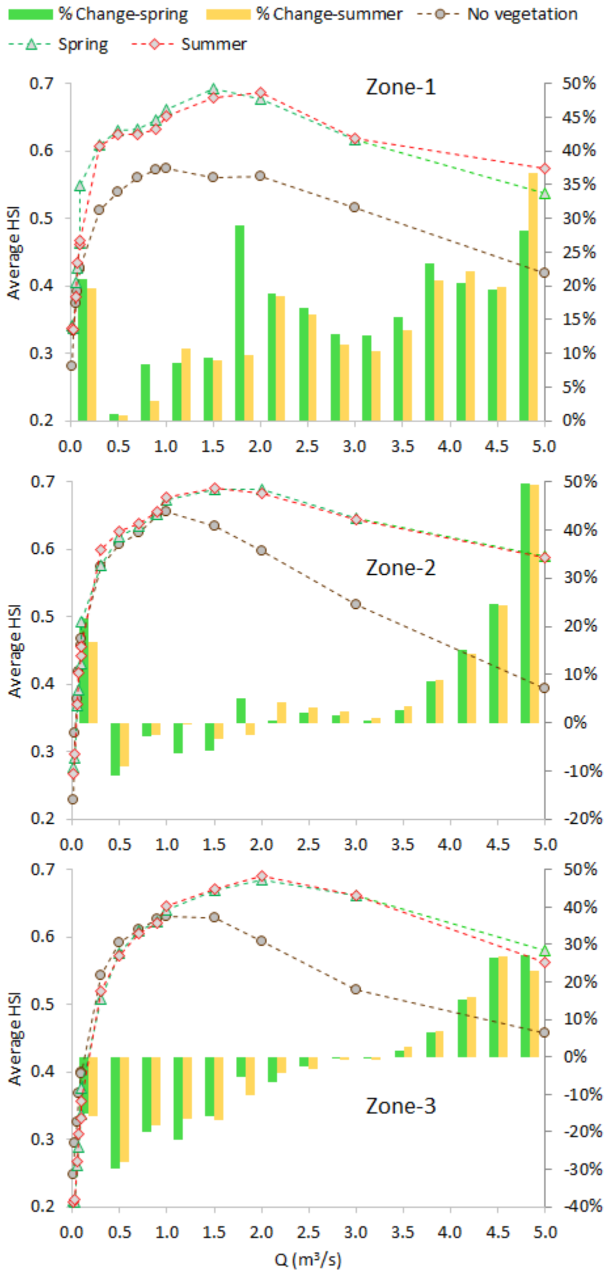

Figure 3. Average habitat suitability (HSI) per discharge (Q) for each zone (zone-1: dense, rigid vegetation; 2: moderate, flexible vegetation; 3: sparse, flexible vegetation) at each season (primary axis), and percent HSI change per season and zone compared to the no-vegetation model (secondary axis).

4. Discussion

Our results are in agreement with previous studies highlighting that the presence of streambed vegetation reduces flow velocities and increases water depths (Bronte, 2013). We further found that this effect was greater in dense, rigid-vegetation dominated areas, less evident in moderate, flexible-vegetation dominated areas and almost absent in sparsely vegetated ones. Consequently, the presence of streambed vegetation may locally shape slow flowing deep waters, and this may cause adverse hydraulic effects for humans, such as local flooding in higher flows, as previously reported (Bronte, 2013; Benifei et al., 2015). In contrast, overall macro-invertebrate habitat suitability was positively influenced by streambed vegetation, either rigid or flexible. This was highly evident in densely vegetated areas, while HSI was higher in high/near-flood flows at all areas compared to the no-vegetation model, being greatly increased in densely vegetated areas and moderately increased in sparsely vegetated ones. Contrasting results, however, were obtained for near-dry flows, in which HSI increased in densely vegetated areas but decreased in moderately and sparsely vegetated areas.

Based on the results of this study, and in accordance with previous literature, we could conclude that appropriate management of streambed vegetation would require: (1) accurately planned removal/clearance of streambed vegetation patches in areas prone to flooding; this would locally reduce water depths (by up to 40% as evident from our results), but would increase flow velocities (by up to 34% in our particular case study) (Bronte, 2013; Benifei et al., 2015); (2) accurately planned restoration of streambed vegetation in non-flooding (wider) areas to enhance geomorphic stability (Admiraal, 2007), and habitat suitability, diversity and quality (Huttunen et al., 2017; Khudhair et al., 2019) by locally increasing water depths and reducing flow velocities. Ecohydraulic models can be of valuable help to both ends, and could be case-specifically applied to inform accurate management practices regarding the removal or restoration of streambed vegetation. Both practices will benefit riverine processes and ecosystems, and associated human societies, if applied within accurately designed river management plans.

Acknowledgments

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References

Admiraal D.M. (2007), Streambank stabilization using traditional and bioengineering methods: a literature review. *University of Nebraska-Lincoln, NDOR Research Project* SPR-1(2) P549.

Benifei R., Solari L., Vargas-Luna A., Geerling G. and Van Oorschot M. (2015), Effect of vegetation on floods: the case of the river Magra. *E-proceedings of the 36th IAHR World Congress.* 28 June – 3 July 2015, The Hague, Netherlands.

Bronte S. (2013), The role of vegetation in catastrophic floods: A spatial analysis. Bachelor of Environmental Science (Honours): *School of Earth & Environmental Science, University of Wollongong*, 2013.

Folke F., Kopmann R., Dalledonne G. and Attieh M. (2019), Comparison of different vegetation models using TELEMAC-2D. *XXVIth Telemac & Mascaret User Club*. 16-17 October, Toulouse, France.

Huttunen K.L., Mykrä H., Oksanen J., Astorga A., Paavola R. and Muotka T. (2017), Habitat connectivity and in-stream vegetation control temporal variability of benthic invertebrate communities. *Scientific Reports*, **7**, 1448.

Khudhair N., Yan C., Liu M. and Yu H. (2019), Effects of habitat types on macroinvertebrates assemblage structure: Case study of Sun Island Bund Wetland. *BioMed Research International*, **2019**, 2650678.

Kiesel J., Hering D., Schmaltz B. and Fohrer N. (2009), A transdisciplinary approach for modelling macro-invertebrate habitats in lowland streams. *Proceedings of JS1 at the Joint IAHS & IAH Convention.* September 2009. Hyderabad, India.

Vargas-Luna A., Crosato A. and Uijttewaal, W.S.J. (2015), Effects of vegetation on flow and sediment transport: comparative analyses and validation of predicting models. *Earth Surface Processes and Landforms*, **40**, 157-176.

Tessier C., Cattaneo A., Pinel-Alloul B., Galanti G. and Morabito G. (2004), Biomass, composition and size structure of invertebrate communities associated to different types of aquatic vegetation during summer in Lago di Candia (Italy). *Journal of Limnology*, **63**, 190-198.

Theodoropoulos C., Georgalas S., Mamassis N., Stamou A. and Skoulikidis N. (2018), Comparing environmental flow scenarios from hydrological methods, legislation guidelines and hydrodynamic habitat models downstream of the Marathon Dam (Attica, Greece). *Ecohydrology*, **11**, e2019.

Theodoropoulos C., Skoulikidis N. and Stamou A. (2016), HABFUZZ: A tool to calculate the instream hydraulic habitat suitability using fuzzy logic and fuzzy Bayesian inference. *Journal of Open Source Software*, 1(6), 82.