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Introduction

Aquatic vegetation provides many ecosystem services with an estimated annual value of more than four trillion dollars (Costanza et al. 1997, Thomaz 2021). The services are strongly mediated by the interaction with hydraulics. Vegetation attenuates waves and current, protecting shorelines from erosion (e.g., Barbier et al. 2011; Arkema et al. 2017; Fonseca et al. 2019). Narayan et al. (2017) estimated that coastal marshes reduced flood damage due to Hurricane Sandy by $625 million. Further, the low energy environments created within vegetation provide nursery habitat for important fisheries (Costanza et al. 1997; Thomaz 2021) and promote the capture and retention of carbon carried in suspension, which contributes to the ability of aquatic vegetation to sequester larger amounts of carbon per hectare per year than rainforests (e.g., Fourqurean et al. 2012). Increasing hydrodynamic intensity can enhance nutrient uptake by individual plants (e.g., Lei and Nepf 2016; Gillis et al. 2017), but can also threaten vegetation survival (van Katwijk et al. 2016). Because aquatic vegetation plays such an important role in protecting coastal environments and enhancing biodiversity, its protection and restoration have become a major focus in environmental management (Greiner et al. 2013; Sutton-Grier et al. 2015). However, excessive development of aquatic vegetation reduces channel discharge capacity, elevating flood risk. A better prediction of the hydrodynamic resistance generated by different species and areal distributions would enable managers to avoid this negative impact of vegetation. Management of vegetated landscapes, including restoration, depend on an understanding of the feedbacks between hydraulic conditions and vegetation growth and expansion (e.g., Van Hulzen et al. 2007; Vandenbruwaene et al. 2011; Kondziolka and Nepf 2014).

Similarly, the habitat selection and life-cycle behavior of aquatic invertebrates are closely linked to the organism-scale interaction with hydraulic conditions (e.g., Statzner et al. 1988; Smith et al. 2014; Lechner et al. 2016). Water depth, velocity, bed shear stress, and turbulence can influence habitat selection of macroinvertebrates and fish (e.g., Lamouroux et al. 1999; Dolédec et al. 2007); the swimming of fish larvae (Prada et al. 2018) and the migration of adult fish (Pavlov et al. 2008). Changes in land-use, installation of dams, and river regulation can all modify the hydraulic conditions, often having a negative impact on habitats and life-cycles. A better understanding of how hydraulics impact habitat and migration is needed to improve the restoration and management of freshwater fisheries and water resources.

Focus of the Special Issue

Motivated by the need to improve management and restoration decisions, this Special Issue considers recent progress to measure and model organism-scale interaction with hydraulic conditions. This Special Issue is part of a series coordinated by the organisers of the 13th International Symposium on Ecohydraulics (Lyon, France), initially planned in May 2020 and replaced by a virtual symposium in November 2020 due to the COVID-19 pandemic. The overall goal was to provide complementary overviews of progress made in understanding ecohydraulic interactions at the scale of individual organisms, of communities, and of landscapes in riverine, coastal and marine ecosystems.

This Special Issue on *Organism-scale Interaction with Hydraulic Conditions***,** explores how hydraulic conditions, such as velocity, turbulence, and bed shear stress, influence and are influenced by aquatic species. Two major themes emerged: 1) the response of hydraulic conditions to the introduction of aquatic vegetation, and 2) the response of individual vertebrate and invertebrate organisms to hydraulic conditions. Specifically, individual papers in this Special Issue (Table 1) focus on:

- *Influence of vegetation on hydraulic conditions* (papers by Carus et al, Villanueva et al., Taphorn et al, Lama et al). These papers explore how the characteristics of vegetation determine their influence on hydraulic conditions; how vegetation-induced changes to hydraulic condition might be harnessed to improve restoration success; and how the vegetation characteristics relevant to hydraulic mediation can be efficiently measured in the field.
- *Influence of hydraulic conditions on habitat selection and migration of fish and macroinvertebrates* (papers by Tinoco et al, Forcellini et al., and Zhang et al.) These papers explore how habitat selection and swimming patterns are impacted by velocity, turbulence, and bed shear stress, and introduce new imaging methods for tracking individual fish and relevant local hydraulic conditions.

Table 1. Topics and key points of the articles in this Special Issue

Authors / Topic	Key points
Carus *et al.*, artificial seagrass provides hydrodynamic protection in seagrass restoration	By reducing bed shear stress, artificial seagrass reduced the dislodgement and enhanced the survival of transplanted live shoots.
Villanueva *et al.,* wake length [sheltering distance] produced by artificial seagrass	A meadow with a length 1 to 2 m reduced velocity up to 70%, with smaller additional reduction for length > 2m. The length of the wake, which defines the shelter distance, is dependent on incident velocity.
Taphorn *et al*., wake behind seagrass blade surrogates	Flexural rigidity, buoyancy and diameter of surrogate blade impact the velocity ratio and vortex frequency in the wake.
Lama *et al.,* quantifying uncertainty in velocity associated with the uncertainty of Leaf Area Index (LAI)	LI-COR Plant Canopy Analyzer provides indirect LAI estimations with accuracy comparable to destructive harvesting estimates. Velocity uncertainty due to LAI uncertainty similar to uncertainty in measured velocity using acoustic Doppler velocimeter (ADV).
Tinoco *et al*., impact of turbulence on grass carp larvae	Flow features generated by submerged vegetation influence swimming patterns of fish larvae. Turbulent eddies with a length scale similar to larval length disrupt swimming capabilities.
Forcellini *et al.,* hydraulic parameters influence microhabitat selection	Parameters defining microhabitat selection by macroinvertebrate taxa are similar between sites. Bed shear stress, velocity and Froude number have comparable explanatory power.
Zhang *et al.,* hydraulic and bathymetric conditions influence migration of carp	New UAV image analysis demonstrates that migrating carp are attracted to high velocity and deep-water conditions. Diurnal variation in temperature and light alters the preference for hydraulic environment.

Gaps and perspectives

The papers in this Special Issue advance our understanding of and ability to model the influence of organisms on hydraulic conditions and the influence of hydraulic conditions on organisms. The first theme within this Special Issue is the modification of current, bed shear stress and turbulence by vegetation both at the scale of individual shoots (Taphorn et al.) and patches of multiple shoots (Carus et al.; Villanueava et al.). The damping of waves and current by vegetation has been noted and modeled in several previous studies (e.g., Mendez and Losada 2004; Reidenbach and Thomas 2018;

Lei and Nepf 2019; 2021; Zhang et al. 2021). However, papers within this special issue posited the exciting idea of harnessing the current dissipation provided by vegetation to create habitat suitable for restoration. Because of their shallow root depth, transplanted shoots and seedlings are vulnerable to sediment movement (Infantes et al. 2011). In this special issue, Carus et al. and Villanueava et al. describe how artificial seagrass can be designed to protect new shoots from dangerous hydrodynamic energy.

The second theme within this Special Issue is the influence of hydraulic conditions on habitat selection and migration and the need for models to accurately represent this behaviour. Synthesizing a large data set, Forcellini et al. provided new insight into the correlation between hydraulic parameters and microhabitat selection by stream organisms. Importantly, they confirmed that metrics of habitat selection were transferable between sites, indicating a universality in the behaviors captured in the model. Further, several hydraulic metrics (velocity, Froude number, bed shear stress) have comparable explanatory power, consistent with the expected physical correlation between these metrics, and this offers flexibility in the choice of metric used in habitat modeling. In addition to habitat suitability, the influence of hydraulic parameters on swimming and migration can also influence the spatial distribution of species. The role of turbulence as a hinderance to the swimming of fish larvae was highlighted in Tinoco et al., and the role of velocity and water depth in guiding migration routes of adult fish was highlighted in Zhang et al. Understanding the preference for and avoidance of specific hydraulic conditions is necessary to improve the design of fish passages and the restoration of spawning grounds (e.g., Hockley et al. 2019; Adeva-Bustos 2019).

In both directions of influence [influence of hydraulics on organisms and influence of organisms on hydraulics], a major knowledge gap exists in translating models for individual organisms (or small groups of organisms) to application in predicting landscape-scale biodiversity and hydraulic patterns relevant for policy and restoration decisions. Methods are needed for both the efficient collection and interpretation of the spatial and temporal variation in organisms and flow parameters at scales relevant to planning, management and policy. Two studies appearing in this issue illustrate methods for harnessing new sensing tools and data science to address this gap. First, Zhang et al. analyzed high-resolution areal images collected by unmanned aerial vehicles (UAVs) using structure from motion algorithms to efficiently track the spatio-temporal distribution of carp during their migration. Second, Lama et al. used LI-COR Plant Canopy Analyzer to provide rapid indirect measurements of vegetation frontal area (or, leaf area index, LAI). In addition, remotely sensed products at scales suitable for assessing the impact of vegetation heterogeneity on hydrodynamic response are now available (PlanetScope 2022, 3 m resolution) and are being used to measure biomass and other vegetation features (e.g., Miller et al. 2019). The development of data-intensive sensing methods should be guided by a clear discussion of the necessary spatial and temporal resolution needed to correctly interpret the impact of organism-scale processes on watershed, channel, and coastal-scale outcomes and management. At what scale do we need to measure vegetation heterogeneity to predict marsh-scale wave dissipation and sediment transport? At what scale do we need to define habitat to make accurate policy decisions?

To conclude, the articles in this special issue provide an exciting overview of organism scale interaction with hydraulic conditions, as well as an introduction of how organism scale processes can be scaled up to understand impacts at land-scape scales relevant to restoration and policy decisions.

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