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TIME AND INTENSITY WEIGHTED INDICES OF FLUVIAL PROCESSES: A CASE STUDY FROM THE KOOTENAI RIVER, USA

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ABSTRACT

Within riparian landscapes, river flows and stages determine habitat gradients from less to more dynamic, and these support different plant species and their life history stages that are adapted to specific positions along these gradients. The gradients are characterized by physical processes that vary in magnitude and duration, and these shape the riparian vegetation communities. Consequently, natural riparian ecosystems are very dynamic, and the river disturbance regime is essential for sustaining ecosystem health. However, although the importance of disturbance is well accepted, disturbance regimes are poorly understood. This study was undertaken to develop indices capable of characterizing riparian habitats by considering flood magnitude and the elapsed time after flood disturbance, that is, the history that influenced the present vegetation composition. The indices were tested along two reaches of the Kootenai River in Idaho, USA, with braided versus meandering channel forms. The case study spanned a 31-year period and emphasized two major disturbance components, the morphodynamic influence of velocity and shear stress and the flood or inundation duration. Computed indices were tested for consistency and then used to characterize different riparian vegetation development and succession phases. The statistical analysis revealed high correspondence among the calculated indices and differences across the different successional stages and between the two reaches. This demonstrated the utility of the time and intensity weighted indices to analyse the fluvial patterns that support different riparian vegetation communities, and this could be applicable for riparian management, mitigation, conservation and restoration. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: disturbance regime; flood history; riparian vegetation; Kootenai River; plant succession

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INTRODUCTION

The distribution of riparian, or streamside, vegetation is the result of the long-term interactions of physical and biological processes (Whited *et al.,* 2007). Consequently, the present state of a riparian landscape is not simply the result of the current biophysical conditions, but it also reflects the past conditions, including the hydrogeomorphic and vegetation histories (Scott *et al.,* 1996; Dykaar and Wigington, 2000). The vegetation successional trajectories and the corresponding formation of associated landforms follow a bidirectional path, subject to forward (succession) or backward (retrogression) shifting (Corenblit *et al.,* 2007; Formann *et al.,* 2014). Along this path, the early stages are more sensitive to hydrologic patterns, including floods and droughts, and associated geomorphic disturbances, including erosion and sedimentation (Karrenberg *et al.,* 2002; Polzin and Rood, 2006). Conversely, later stages are more resistant towards physical stresses (Stromberg *et al.,* 1993), and they retain in their spatial and morphological configurations the effects of past biophysical interactions (Ward *et al.,* 2002).

Considering the importance of the history that influences the present vegetation status, in this study, we propose a new index of riparian habitat characteristic to account for the intensity and timing of elapsed events. The focus of this paper is thus on the formulation and assessment of a new methodology to contribute to dynamic analyses of riparian ecosystems. The calculation of these time and intensity weighted indices (TIWI) incorporates two ecosystem processes: the geomorphic-mechanical disturbance and the physiological stress of flood inundation. As an index of the former, the bed or bank shear stress (N/m^2) is analysed, while flood duration and particularly inundation days provide the measure for the latter. In principle, the TIWI could work with any scalar dimension either measured in the field or simulated through hydrodynamic modelling. In our case study, mechanical disturbance and the physiological stress TIWIs were used to investigate

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the correspondence between vegetation succession phases and physical habitat conditions.

The indices were calculated and tested for two very different river reaches along the regulated Kootenai River in the American Pacific Northwest. Along these two reaches, vegetation patches were sampled and classified into succession phases, and that component was described and analysed in Egger *et al.* (2015). This subsequent paper provides a more complete characterization of the TIWI approach and applies several hydrodynamic models to simulate shear stress, flood duration and mean water stages for different recurrence interval floods.

TIWI: TIME AND INTENSITY WEIGHTED INDICES

The concept underpinning these measures is that biological communities are influenced by the counterbalance between the intensity of physical disturbance events versus the biological communities' resistance and resilience, with further consideration for the disturbance frequency and the recovery interval (Pickett and White, 1985). The indices capture this concept in a measurable quantity by considering the magnitude and timing of past flood events, with major and recent events being more heavily weighted than minor and older ones. Within riparian landscapes (sensu Church, 2002), the most prominent disturbance factors are probably those deriving from the morphodynamic disturbance and the flood inundation stress (Egger *et al.,* 2013). Shear stress was selected as a proxy of morphodynamic disturbance (Egger *et al.,* 2012) while flood duration represented physiological stress (Glenz *et al.,* 2008; Benjankar *et al.,* 2011).

Subsequently, TIWI of morphodynamic disturbance (MDi) and flood inundation duration (FDi) are calculated from shear stress and flood duration maps as weighted averages over a given interval (Egger *et al.,* 2015). These indices of morphodynamic (MDi) and flood duration (FDi) are spatially explicit and are defined as follows:

$$\mathrm{MDi} = \frac{\sum\left\{\frac{\tau_1}{1} + \frac{\tau_2}{2} + \frac{\tau_3}{3} + \ldots + \tau_{(T-1)}[T-1] + \frac{\tau_T}{T}\right\}}{\sum\left\{\frac{1}{1} + \frac{1}{2} + \frac{1}{3} + \ldots + 1[T-1] + \frac{1}{T}\right\}} \quad (1)$$

MDi is calculated by summing the ratio of shear stress τ (N/m^2) divided by the corresponding year ordinal number (top axis in Figure 1), and this sum is then divided by the reciprocal values of the year ordinal numbers. In the present case study, the yearly ordinal numbers start with 2007 (year 1) and extend back to 1977 (year 31)

$$\mathrm{MDi} = \frac{\sum_1^T \frac{\tau_t}{t}}{\sum_1^T \frac{1}{t}} \quad \text{for } t = 1(1)T \quad (2)$$

The Tth partial sum of the harmonic series H_T produces the Tth harmonic number H_T:

$$\begin{aligned} H_T &= \sum_{t=1}^{T} \frac{1}{t} \\ &= 1 + \frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \ldots + 1[T-1] + \frac{1}{T} \end{aligned} \quad (3)$$

Replacing the counter $\sum_1^T \frac{1}{t}$ by the term H_T then produces

$$\mathrm{MDi} = \frac{\sum_1^T \frac{\tau_t}{t}}{H_T} \quad (4)$$

A similar approach is used to calculate FDi with the number of flood inundation days of the half-year hydrograph

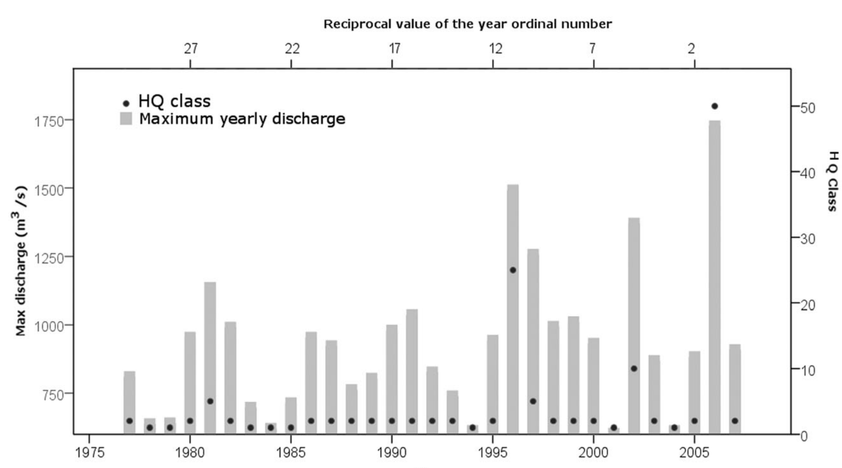

Figure 1. Maximum discharges and recurrence interval flood classifications (Q class) of the years considered in the study. The Year Index represents the ordinal number of the year from 2007 (year 1) extending back to 1977 (year 31)

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from April to the end of September, which represents the primary interval of physiological activity of vegetation for temperate ecoregions of the Northern hemisphere; this interval could be adjusted to represent regional phenologies. Formula 4 subsequently assumes the form

$$\mathrm{FDi} = \frac{\sum_{1}^{T} \frac{y_t}{t}}{H_T} \tag{5}$$

In practice, the MDi and FDi are calculated with spatial datasets from hydrodynamic modelling that provides the shear stress and flood duration for each year of the period of interest. MDi and FDi are calculated using the information of the disturbance timing and for the shear stress and flood duration (disturbance intensity), respectively. To investigate the relationship of the vegetation succession phases with the MDi and FDi TIWIs, the spatial datasets are overlaid and then tabulated for statistical analysis.

METHODS

Study site

The transboundary Kootenai River basin has an area of 41 910 km^2 and is located in British Columbia, Canada (as 'Kootenay'), and in Montana and Idaho, USA ('Kootenai'). The two study segments include a reach upstream of Bonners Ferry that consists of a braided channel (Reach 1 = R1) and a downstream reach with a meandering channel form (Reach 2 = R2), where the river flows through the current valley and ancient lakebed from the expanded Kootenay Lake (Figure 2). The study zone along the braided reach had an area of 481 ha, while the zone along the meander reach was 544 ha. Both sites are affected by Libby Dam that became operational in 1973. Upstream of that dam, the natural flow regime of the Kootenay displays a nival, or snowmelt-dominated hydrograph, with annual maximum discharges occurring in late spring (May–June), and flows gradually declining through the summer to minimum flows in the winter (Figure 3).

Because of dam operations that are particularly intended for flood control and hydroelectric power generation, the flow pattern is attenuated and somewhat inverted (Polzin and Rood, 2000). For two decades after damming (1973–1992), the monthly mean discharges were relatively constant through the year (Figure 3). After 1992, environmental flows have been released especially in the months of May and June and were initiated to promote the spawning of white sturgeon (Figure 3). This resulted in a seasonal flow pattern that was intermediate between the natural regime and the stabilized pattern after damming.

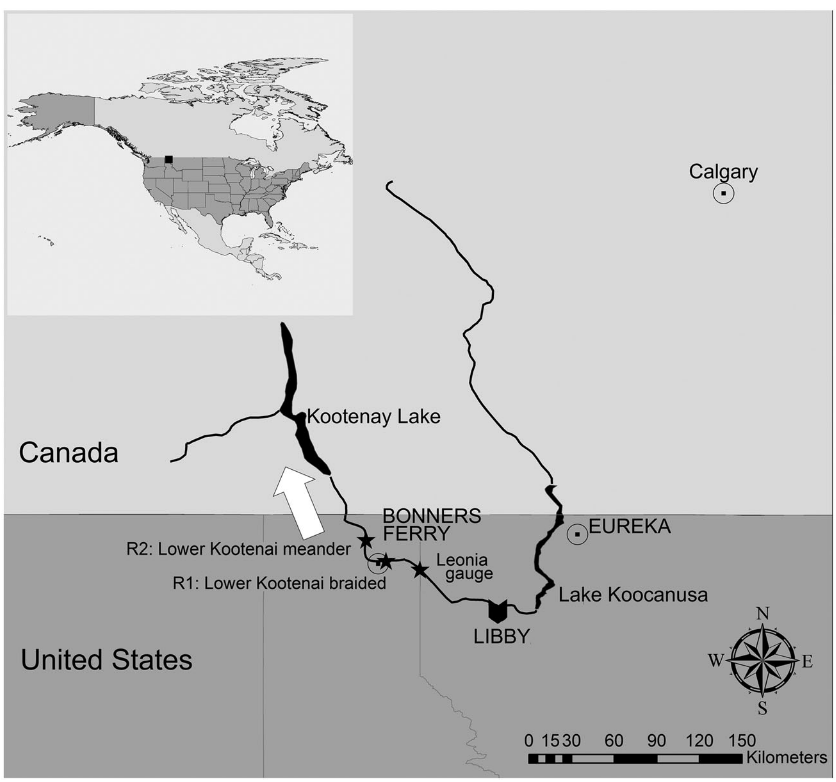

Figure 2. Location of the study sites, Libby dam and Leonia gauging station

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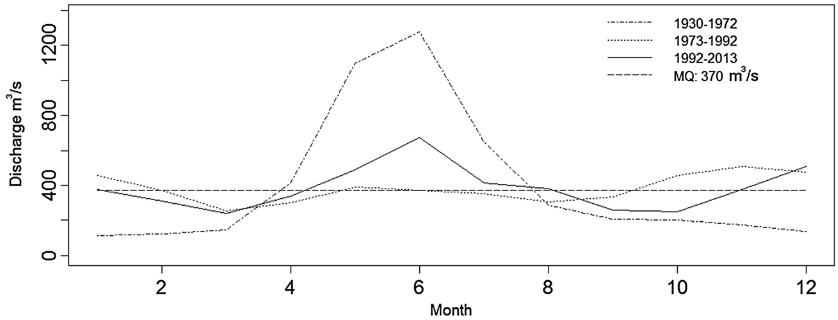

Figure 3. Historical and contemporary monthly mean discharges at Leonia gauging station (6 = June); MQ: mean annual discharge. (USGS http://waterdata.usgs.gov/usa/nwis/uv?12305000). This gauge is downstream of the Libby Dam that was completed in 1973 and thus a pre-dam interval and two post-dam intervals are represented

Field data sampling and classification of vegetation types and succession phases

The study sites were mapped based on aerial photos from August 2006, while the ground field sampling was conducted in August 2007. The extent of the mapped area covered the full extent of the historical floodplain area and was intended to cover the full range of environmental and vegetation successional conditions. Vegetation types and succession phases were sampled in homogeneous patches and subsequently sketched in a shape file polygon format. Further description of the vegetation measures is provided in Egger *et al.* (2015). For this present study, the data used in the statistical analyses were the spatial arrangements of the riparian vegetation succession phases as defined after Egger *et al.* (2013) with initial, pioneer, herb, shrub, early successional woodland, established forest and mature. These succession phases belonged to either the primary succession (PS) or secondary succession (SS) sequences (Figure 4 and Table I).

Hydrodynamic modelling

Habitat characteristics as a function of hydraulic variables at the sites during the period from 1977 to 2007 were simulated using MIKEFLOOD (DHI, 2004). In order to calculate flow magnitude of different recurrence interval floods (e.g. 1-, 2- and 50-year), frequency analysis for the yearly maximum flow series was performed for discharge data from the Leonia gauge station, which is located upstream of the braided reach. For this analysis, the yearly maximum flow series was fitted with a Log Pearson Type III distribution.

MIKEFLOOD is a programme that integrates the 1D MIKE11 River and the 2D MIKE21 floodplain models into a single, dynamically coupled modelling system. A river channel is thus represented in one dimension (stage or height), and the floodplain is represented in two dimensions. A special feature of MIKEFLOOD includes momentum preservation through lateral links that enables the simulation of over-bank flow from the river channel onto the floodplain (DHI, 2004). The specific hydraulic parameters used in this study were taken from Benjankar (2009).

A primary calibration parameter for the MIKEFLOOD model is Manning's roughness that represents the channel bed and floodplain resistances. During calibration, simulated water surface elevations were compared against measured values at five different gauge stations along the Kootenai River (Benjankar, 2009). The Manning's roughness values were refined to provide the best-fit curve between the measured and simulated values for the different gauge stations. Further, we also performed sensitivity of the Manning roughness in order to examine effects of floodplain vegetation on flow hydraulics (e.g. water depth and velocity) (Benjankar, 2009). This analysis revealed minimal effect of vegetation on the simulated flow depths and velocities for the study locations, and we concluded that the effect of vegetation on simulated shear stress would be minor for this study. Confirming applicability, the root mean square error of the contemporary MIKEFLOOD model, which simulated hydraulic variables as a function of discharges from 1973 to 2007, was only 0.11 m for the Bonners Ferry gauge station, located just downstream from the braided reach (Benjankar, 2009).

Maximum annual shear stress (N/m^2) was chosen as the indicator of morphodynamics (Friedman and Auble, 1999; Benjankar *et al.,* 2011; Politti *et al.,* 2014). For the inundation period, the flood duration was calculated as the days of inundation in April through September, the in-leaf interval for the deciduous vegetation. We concluded that the simulations for single-year discharges required extensive computation time with limited further analytical merit, and consequently for the model application, each year was classified according to the recurrence interval categories: HQ1 (1-year Recurrence Interval Flood), HQ2, HQ5, HQ10, HQ25, HQ50 (50-year Recurrence

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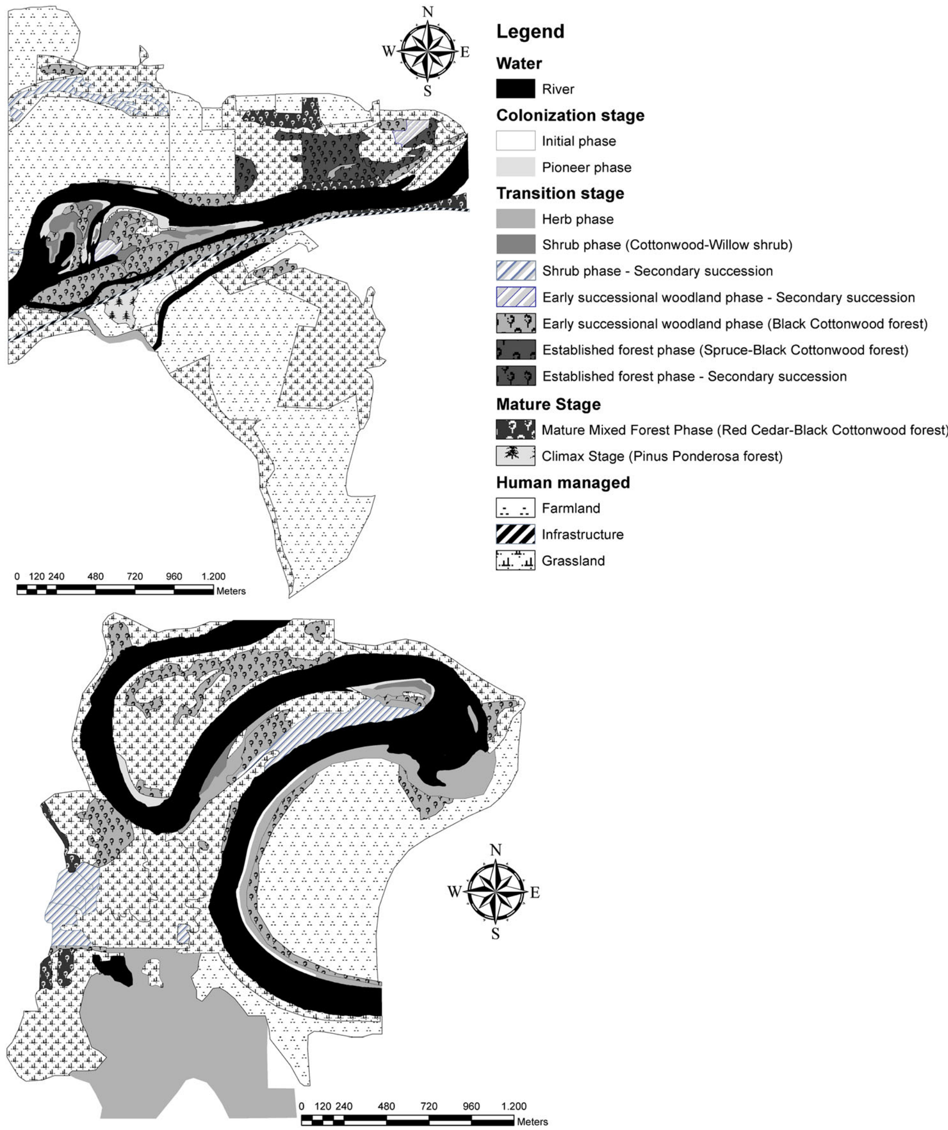

Figure 4. Succession phases mapped at the braided (top, R1) and meander (bottom, R2) reaches along the lower Kootenai River (modified from Egger *et al.,* 2015). This figure is available in colour online at wileyonlinelibrary.com/journal/rra

Interval Flood) classes, and the analyses grouped those HQ categories.

The hydrodynamic modelling subsequently produced a pair of raster grids with 10 m cell size portraying shear stress and flood duration for different flood frequency classes. The succession phases map (Figure 1) was then converted from the shape files to the 10 m cell size raster and overlaid to provide the comparative spatial dataset encompassing the field data succession phases and modelled MDi and FDi TIWIs. The spatial overlay was then converted in tabular form, thus yielding one record of succession phase and associated FDi and MDi for each pixel of the study site.

Statistical analysis

Statistical analysis considered the tabular data provided by the TIWI calculation procedure and included two steps. The first tested the consistency of the proposed TIWI habitat measures, while the second tested the degree of association between the TIWI values and the succession phases. Both analyses considered only the data points where natural primary succession vegetation occurred; anthropogenic cover types including cleared grassland pasture and crop farmland were excluded. The analysis compared the primary succession phase (marked by a PS superscript): initial, pioneer, herb,

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Table I. Relative area of the succession phases at the study sites. PS: primary succession; SS: secondary succession

Succession phase	Braided reach (%)	Meander reach (%)
Water	12.2	21.9
Colonization stage		
Initial phase	0.0	0.4
Pioneer phase	0.9	0.5
Transitional stage		
Herb phase	1.3	18.3
Shrub phase ^{PS}	1.3	0.4
Shrub phase ^{SS}	1.1	3.6
Early successional woodland ^{PS}	6.9	7.8
Early successional woodland phase ^{SS}	0.7	0.0
Established forest phase ^{PS}	3.6	0.0
Mature stage		
Mature mixed forest phase	2.0	0.8
Climax stage	0.6	0.0
Human managed		
Farmland	43.7	19.1
Grassland	24.6	27.2
Infrastructure	1.0	0.0
Total	100.00	100.00

shrub^{PS}, early successional woodland^{PS}, established forest^{PS} and the mature stage consisting of the mature mixed forest and climax stage. All analyses were performed separately for the braided (R1) and meander (R2) reaches.

The within site correlation of the indices MDi and FDi were calculated using Spearman correlation and an assessment of the significance with *t*-tests.

The succession phases were statistically characterized as a function of TIWI, at first with summary statistics of means and standard errors and then by analysis of variance (ANOVA) with Eta^2. Eta^2 (η^2) describes the dependent variable's proportion of variance explained by the predictor variables, while controlling for other predictors. It ranges from 0 to 1 with $\eta^2 < 0.08$ indicating a low effect size and $\eta^2 > 0.15$ representing a large one. The ANOVA considered the null hypothesis that the same phases at the two study sites had similar distributions of MDi and FDi.

RESULTS

Field data sampling and classification

Succession phases that were mapped at the two sites are displayed in Figure 4, and Table I lists the percentages of area occupied by each succession phase. These reveal the extensive artificial land uses along two reaches, with large areas of farmland with cultivated crops or grassland with hayfields and pastures. These agricultural zones were largely set back from the river channel, and especially along the braided reach, the natural riparian woodlands were still prominent. This also applied to the meander reach where the typical 'swale and ridge' pattern of arcuate vegetation bands (Everitt, 1968; Perucca *et al.,* 2006) was evident primarily on the meander lobe point bars along the insides of the meanders.

Physical habitat parameters consistency

Considering the indices individually, MDi exhibited greater within-site differences in the braided reach than in the meander reach. MDi mean values (Figure 5) in the braided reach were distinct for the early succession phases, while conversely, in the meander reach, MDi appeared relatively constant across the whole site. MDi values at the braided reach show in fact a decreasing trend from the early (pioneer) to the more mature (early successional woodland) phases. This indicates that the earliest phases occupy habitat segments with differing but overlapping morphodynamic characteristics.

For the FDi, the within-site and between-site differences were less pronounced. The differences were largely confined to the early colonization phase, and values were relatively consistent for the woodlands across the sequential successional phases (Figure 5).

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The Spearman correlation provides a measure of association between two variables, ranging from 0 for no correlation to +1 or −1 for complete correspondence. The sign indicates whether the two variables are positively or negatively correlated.

Spearman coefficients for pairings of MDi and FDi had high and positive correlations with 0.775 for the braided reach and 0.876 for the meander reach ($p < 0.01$).

Succession phases association to time and intensity weighted indices

In both sites, vegetation phases progressed towards older stages as MDi and FDi decreased. Younger phases have higher values indicating sustained flood-induced recycling activity. However, the patterns displayed substantial differences between the TIWI values associated with each succession phase (Figure 4).

The ANOVA confirmed this differentiation ($p < 0.01$), and the null hypothesis was consequently rejected, therefore demonstrating some difference in the magnitude of the physical processes affecting the same succession phases in the sites R1 and R2. Additionally, the η^2 values from the ANOVA test show that the proportion of the variances for the primary succession phases can be explained by the single indices MDi and FDi with a large effect size (braided: MDi = 0.484, FDi = 0.436; Meander: MDi = 0.541, FDi = 0.351).

DISCUSSION AND CONCLUSIONS

In this study, we first proposed TIWI that considered the elapsed time from flood events as a strategy for characterizing current riparian vegetation and, consequently, habitat distributions. The analysis proceeded first by testing the degree of association between the two different TIWIs derived from different hydrophysical measures, and second, by observing the association of these TIWIs with the succession phases mapped at two sites that are different in the channel form and geomorphic context.

The correlation analyses revealed high degrees of association among maximum shear stress and flood duration; these indices were strongly associated because they all depend upon the river flow regime that is the river and riparian master variable (Poff *et al.,* 1997; Lytle and Poff, 2004). One could argue that because the indices were strongly correlated and the calculation of both is somewhat redundant and unnecessary. Conversely, the associations were incomplete, and we consider that both are necessary because they reflect different fluvial processes, which interact with different ecological aspects of vegetation colonization and successional trajectories. While morphodynamics account for vegetation retrogression through mechanical disturbance, sedimentation and erosion (Bendix, 1999; Bendix and Hupp, 2000; Asaeda and Rashid, 2012), inundation duration is responsible for physiological stress (Glenz *et al.,* 2006). Consequently, the combination of these different fluvial processes determines the habitat gradients that host different vegetation life stages and species combinations (Egger *et al.,* 2013).

When compared for particular vegetation phases, the between-site differences of MDi and FDi were substantial for the earlier phases (initial, pioneer, shrub and herb), while the older stages (early successional woodland, established forest and mature stage) displayed less differentiation of the indices for the two geomorphic site types. This response is in line with riparian vegetation-landform evolution models that conceptualize how riparian vegetation and landforms evolve as a consequence of vegetation-mediated influences on sedimentation and reduced erosional processes. These processes result in planform vertical accretion, with consequent increase of the vertical distance above the river. As a consequence, vegetation stands located on the rising zones are progressively sheltered from physical disturbances (Corenblit *et al.,* 2009, 2010). Following from the steeper slope in the braided river reach R1 (0.019%), flow velocity and shear stress are generally much higher than in the meander reach R2 (0.0006%) (Snyder and Minshall, 1994). Interestingly, MDi and FDi exhibited substantial changes in their mean values at the transitions from the shrub and herb phases to the later stages. This suggests that these sequential phases occur over two distinct habitat gradients. One is characterized by high dynamics and disturbance frequency, typically occupied by initial and pioneer phases, versus the more stable and less disturbed riparian environments hosting more mature stage. There is also another complexity in that the sequence from colonization to shrubs and forest can involve black cottonwoods (*Populus trichocarpa*) with low-elevation seedling recruitment and then shrub and subsequently tree-sized plants as the cottonwoods grow. For this progression, the shrub phase would represent the intermediate between the seedlings and trees. Alternately, other shrubs such as the obligate riparian willows (*Salix exigua* and other species) or the facultative shrubs such as mountain alder (*Alnus incana*) or dogwood (*Cornus sp.*) would probably have different hydrogeomorphic preferences and would thus not be intermediate between the seedling and tree zones.

The development of these fluvial indices should complement the research by other authors who have characterized habitat conditions of different vegetation life stages and along different river types (Dykaar and Wigington, 2000; Corenblit *et al.,* 2010). However, the prior characterizations of such habitats rely on extensive inventories (Steiger *et al.,* 2005) and do not directly link succession phases with measureable hydrophysical properties. Other studies have related riparian vegetation to environmental variables such as soil, pH (Ferreira and Moreira, 1999) and single flood events

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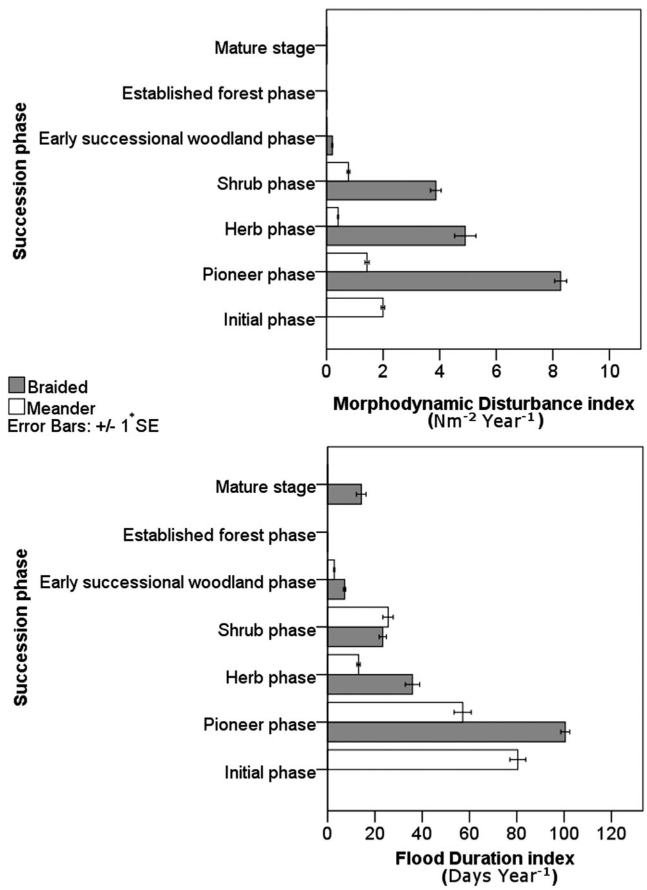

Figure 5. Time and intensity weighted indices for morphodynamic disturbance (MDi) and flood duration (FDi) for the primary succession phases in the braided (R1) and meander (R2) study sites. *SE (in legend): standard error

[e.g. 20 years return period (Bendix, 1998)], but prior analyses have not sought to integrate the temporal sequence of past events. The TIWI afford the possibility of considering elapsed events while at the same time avoiding erroneous considerations resulting from the study after a single flood event, which would provide conditions that are not representative of the typical habitat conditions over time.

An application of the TIWI to other case studies must take into account several aspects related to the planimetric evolution of the river. In our case study, the two sites were subject to dam regulation over 30 years, and as a result, the river channel configuration has been substantially stabilized (Polzin and Rood, 2000). Consequently, the hydrodynamic calculations for the physical measures of shear stress and flood duration that were used to calculate the TIWI applied the same river geometry settings for all years from 1977 to 2007. The application of the TIWI method to different rivers should consider variation over time and may apply different river geometry settings for the hydraulic modelling.

The novelty of our method involves the conceptual foundation and methodology. The fundamental concept acknowledges the importance of hydrophysical disturbances and their temporal regimes, and while this concept is well accepted in ecological studies (Reeves *et al.,* 1995; Turner *et al.,* 2003; Formann *et al.,* 2014), it is less commonly applied in practice. We therefore recommend the consideration of these morphologic and hydraulic aspects when designing management measures or evaluation schemes for riparian landscapes. We thus propose the TIWI that incorporate morphodynamics and flood duration not only for the characterization of vegetation succession phases and habitat (Egger *et al.,* 2015) but also when planning restoration or mitigation measures. Such measures could seek to moderate potential impacts from any human alterations to river flows and riparian zones, such as with river damming and flow regulation (Rood *et al.,* 2005), or with bank alterations such as levees and channelization.

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