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Development of a spatially-distributed hydroecological model to simulate cottonwood seedling recruitment along rivers

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ABSTRACT

Dam operations have altered flood and flow patterns and prevented successful cottonwood seedling recruitment along many rivers. To guide reservoir flow releases to meet cottonwood recruitment needs, we developed a spatially-distributed, GIS-based model that analyzes the hydrophysical requirements for cottonwood recruitment. These requirements are indicated by five physical parameters: (1) annual peak flow timing relative to the interval of seed dispersal, (2) shear stress, which characterizes disturbance, (3) local stage recession after seedling recruitment, (4) recruitment elevation above base flow stage, and (5) duration of winter flooding, which may contribute to seedling mortality. The model categorizes the potential for cottonwood recruitment in four classes and attributes a suitability value at each individual spatial location. The model accuracy was estimated with an error matrix analysis by comparing simulated and field-observed recruitment success.

The overall accuracies of this Spatially-Distributed Cottonwood Recruitment model were 47% for a braided reach and 68% for a meander reach along the Kootenai River in Idaho, USA. Model accuracies increased to 64% and 72%, respectively, when fewer favorability classes were considered. The model predicted areas of similarly favorable recruitment potential for 1997 and 2006, two recent years with successful cottonwood recruitment. This model should provide a useful tool to quantify impacts of human activities and climatic variability on cottonwood recruitment, and to prescribe instream flow regimes for the conservation and restoration of riparian woodlands.

1. Introduction

Humans have long managed rivers for different purposes including navigation, domestic water supply, irrigation, flood protection, and hydroelectric energy production (Graf, 1999). Subsequently, river-damming and reservoir operations have provided some of the main human influences on freshwater environments worldwide. Economic benefits have been gained from river regulation, but unforeseen and often unevaluated ecological losses have also occurred. Dam operations have impacted riparian ecosystems around the world and changes to instream flows and to groundwater patterns have severely impacted cottonwood seedling recruitment in western North America and elsewhere in the Northern Hemisphere (Amlin and Rood, 2002; Benjankar et al., 2013; Braatne et al., 1996; Choi et al., 2005; O'Connor, 2001; Rood et al., 2005; Scott et al., 1999; Steiger et al., 2005; Stella et al., 2010).

Riparian forests occupy the important landscape interface between upland and aquatic ecosystems (Junk et al., 1989). These forests are highly productive, biologically diverse, and physically dynamic (Naiman et al., 1993). Periodic physical disturbances in riparian systems provide spatial and temporal heterogeneity, and regenerate new habitats (Arscott et al., 2002; Junk et al., 1989; Nakamura et al., 1997; Sparks and Spink, 1998). Flow-related physical processes are the dominant processes for floodplains and control the structure and function of riparian vegetation on floodplains (Arscott et al., 2002; Junk et al., 1989; Naiman et al., 2005; Tockner et al., 2000).

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Cottonwood (*Populus*) and willow (*Salix*) species are well-adapted to dynamic floodplains and dominate riparian ecosystems in arid and semiarid areas throughout western North America (Amlin and Rood, 2002; Braatne et al., 1996; Scott et al., 1999). These woody plants are very important to riparian biodiversity and wildlife habitat (Case and Kauffman, 1997), to stabilize stream banks, and to intercept nutrients and other chemicals from surface waters (Naiman et al., 1993). With favorable environmental conditions these native species can also resist invasion by exotic plants such as reed canary grass and salt cedar (Chant and Chant, 2004; Kim et al., 2006).

The life histories and ecophysiology of riparian cottonwoods vary across species, but they are commonly dependent on aspects of the natural flow regime. These tree species differ across geographic regions and climatic conditions, but all are dependent upon riverine processes such as high flow events and associated geomorphologic processes (Braatne et al., 1996). These fluvial geomorphologic processes shape the riverine landscape, which may include multiple braided channels or meandering single channels, for example (Rosgen, 1994). River hydrology is the driving force for these processes and especially involves high flows and floods during the late spring due to the combination of snowmelt and spring rains.

As a result of these high flows, bank erosion occurs along the concave or outside banks of the meander, and deposition occurs along the convex lobes or inside banks where point bars form (Leopold, 1994). Further, point bars are also formed due to channel accretion in the lateral direction. Local erosional and depositional areas are formed within the channel, along its banks and on the floodplains. The extent of these areas partly depends on the intensity of the near-bed shear stress throughout the flow hydrograph (Maturana et al., 2013).

Water surface elevations decline following the high over-bank flows, and expose barren and mineral-rich areas on the floodplains or point bars. These barren and moist soils are colonized by cottonwood seedlings from water- or wind-dispersed seeds (Braatne et al., 1996). However, the colonizing cottonwood seedlings may be destroyed by scouring and depositional processes as a result of subsequent flooding. Surface moisture conditions and water table decline rates during the early stage of cottonwood seedling recruitment also govern germination and seedling survival (Johnson, 1994; Mahoney and Rood, 1991). If the rate of water table decline exceeds the rate of root elongation, seedling mortality occurs due to drought stress (Braatne et al., 1996).

Seedling recruitment is the main process of cottonwood forest regeneration. Dam-altered flood patterns may prevent successful seedling recruitment at appropriate stream bank elevations because of drought stress, which increases mortality of newly recruited seedlings (Amlin and Rood, 2002; Mahoney and Rood, 1998; Stella et al., 2010). Attenuated flows due to dam operations also limit geomorphic disturbances that create bare surfaces needed for new seedling recruitment (Benjankar, 2009; Benjankar et al., 2011; Rood and Mahoney, 1995; Scott et al., 1997). For example, significantly less cottonwood recruitment has occurred in the downstream reaches along the Kootenai River due to regulated flows (Jamieson and Braatne, 2001; Polzin and Rood, 2000). Recently, modestly higher spring flow releases, intended to promote spawning for white sturgeon, enabled recruitment of new cottonwood stands along the Kootenai River (Burke et al., 2009; Jamieson and Braatne, 2001).

Successful cottonwood seedling recruitment is thus associated with channel and bank morphology, sediment transport, and the timing, magnitude and duration of high stream flows, as represented by the cottonwood recruitment box model (Amlin and Rood, 2002; Mahoney and Rood, 1998). Several previous studies have successfully used peak flow timing, stage recession rate, and elevation above a base flow level to predict areas for successful cottonwood seedling recruitment (Burke et al., 2009; Mahoney and Rood, 1998). Previous studies have also shown correlations between floods of different return intervals (RI) and cottonwood recruitment (e.g., Braatne et al., 2007; Bradley and Smith, 1986; Scott et al., 1997). Specific RI floods (e.g., 1-in-5 or 1-in-10 year) may create disturbances through scour and deposition that create suitable barren surfaces, and may also provide stage recession patterns favorable for cottonwood recruitment (Bradley and Smith, 1986; Mahoney and Rood, 1998). Lastly, Braatne et al. (2007) and Burke et al. (2009) used a three-day moving average of stage decline to estimate a 'mortality coefficient' to account for potential seedling mortality due to desiccation.

However, these previous analyses were based on river cross-sections and transect data, and lack local calculations of potential sediment erosion and deposition using mechanistic principles. Additionally, river bank topography and floodplain physical processes are heterogeneous. Therefore, linear interpolation-based approaches between cross-sections can produce uncertainties in the estimation of areas of cottonwood recruitment. Further, transects can be several hundred meters apart, which limits spatial continuity and projection. Riverine floodplain ecological systems are very dynamic and change over a variety of spatial and temporal scales due to various disturbances (Junk et al., 1989; Naiman et al., 2005). Therefore, spatially-distributed models are very appropriate to simulate hydroecological processes such as cottonwood recruitment.

In addition, the ground surface condition prior to seedling recruitment has not been explicitly addressed in the analyses of established cohorts. Cottonwood seedlings cannot recruit successfully if the surface is already occupied by vegetation (Johnson, 1994). It is thus important to assess the creation of bare substrate, which depends on sediment erosion and deposition and is partly a function of the magnitude of local near-bed shear stress (Partheniades, 1965). Shear stress is controlled by local flow hydraulics rather than simply by RI or flood magnitude. Specific RI floods (e.g., 1 in 5 year) may be sufficient as disturbance flows to create bare surfaces at certain positions, but may not be sufficient for other locations, for example those that are affected by backwater influences.

To overcome these limitations and to better predict favorable areas for cottonwood seedling recruitment, we developed the Spatially-Distributed Cottonwood Recruitment (SDCR) model using a rule-based fuzzy logic (Zadeh, 1965) approach and applied this analysis to the regulated Kootenai River. We anticipated that successful cottonwood recruitment would depend on shear stress (disturbance flow), peak flow timing relative to the cottonwood seed dispersal period, local stage recession rate, and elevation above base flow level. We compared model-simulated favorability classes with field-based favorability surveys to assess model accuracy using a cell-by-cell comparison approach. We then compared summer and winter survival potential (hereafter winter favorability) to quantify the prospective impact of high winter flows on successful cottonwood seedling recruitment. Further, the areas of predicted recruitment favorability were compared between the years of 1997 and 2006 to analyze the model performance for two recent years where cottonwood recruitment has been documented. We anticipated that if the SDCR model was appropriately constructed and parameterized, there would be comparable simulated favorability between these years due to their similar hydrologic and stage recession patterns.