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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.

2. Methodology

2.1. Study area

The study area (Fig. 1) is located within the Kootenai (or 'Kootenay' in Canada) Basin, which is an international watershed shared between Canada and the United States. The Kootenai River has been extensively altered since the late 1800s and initial river valley management predominantly included floodplain diking to limit valley flooding, and subsequent wetland drainage and conversion of the floodplain into agricultural fields. Since 1974, Libby Dam has altered flow patterns (Burke et al., 2009), sediment transport (Barton et al., 2005), river and floodplain physical processes (Burke et al., 2009), aquatic habitat (Hoffman et al., 2002), and riparian vegetation (Benjankar et al., 2012; Polzin and Rood, 2000). The 130 m tall hydroelectric dam and associated Koocanusa Reservoir have trapped alluvial sediments and altered the downstream flow regime. Flow regulation has severely impacted cottonwood seedling recruitment, leading to limited regeneration of the deciduous floodplain forests. In addition, the floodplain along the lower river has been impacted by changes to the naturally-occurring backwater influence of Kootenay Lake, due to the construction and operation of Corra Linn Dam at the outflow of that lake.

The SDCR model was applied to two geomorphologically different reaches downstream from Libby Dam: a braided reach (BR) and a meander reach (MR) (Fig. 1). The MR study area has plains cottonwood (*Populus deltoides*) as the naturalized and currently predominant species and includes the river banks along gradual meanders near Ball Creek, which is located between the town of Bonners Ferry and the Copeland Bridge hydrometric gage (Fig. 1). The MR consists of a wide floodplain that has been isolated by diking for agricultural use, with the river channel confined between levees. This downstream reach has been heavily influenced both historically and presently by the backwater effect from Kootenay Lake. The levees are farther from the river edge near Ball Creek, and this provides more extensive zones available for cottonwood seedling recruitment.

The BR study area primarily supports the native black cottonwood (*Populus trichocarpa*) and includes the river segment between the Moyie River inflow and the town of Bonners Ferry. It is located between an upstream confined canyon reach and the downstream MR. It represents a geomorphic transitional section with a wide floodplain and multiple braided channels that are inundated in most years. The reach contains several islands where cottonwood recruitment also occurs. For both the MR and BR, we only considered the floodplain bands between the river and the levees.

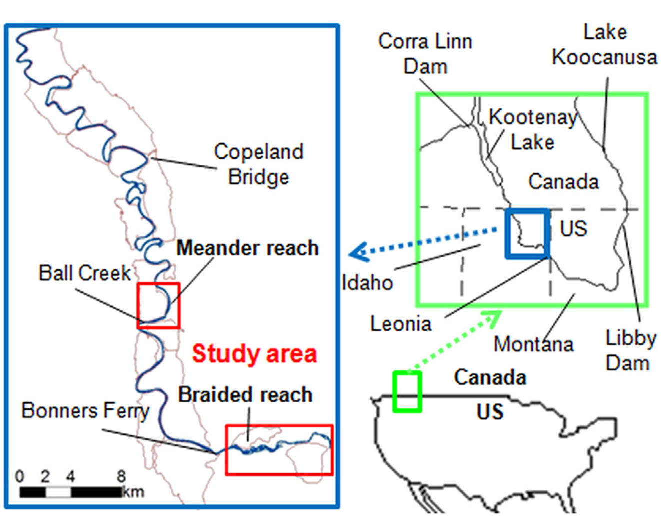

Fig. 1. Study area including braided (BR) and meander (MR) reaches.

2.2. Conceptual and numerical model development

The required criteria for successful cottonwood requirement are shown in Fig. 2, which represents the cottonwood recruitment box model (Mahoney and Rood, 1998). We defined successful cottonwood recruitment as seedling survival through the first year, which indicated favorability of the stage recession rate from seedling emergence until the end of September, and suitable winter flow conditions. The model developed for this study predicts favorability (FV) for successful cottonwood recruitment based on physical parameters using a fuzzy logic approach. Fuzzy logic is used to determine outcomes based on 'degrees of true or false' where both input and output data can be in the form of qualitative assessments (good, fair, poor) or numeric values (Bock and Salski, 1998; Foody, 1996; Roberts, 1996; Ruger et al., 2005; Salski, 1992). This approach is especially useful when data are difficult to combine strictly quantitatively because they represent different types of information, are difficult to transform to comparably precise numeric systems, or where quantitative relationships are not developed. The output assessments can be changed into numerical values from a 'defuzzification' process to enable subsequent analyses, such as assessment of variability and distribution. The fuzzy system uses a rule-based approach (e.g., "If A is X and B is Y then RESULT is C") rather than combining values for the input parameters through mathematical equations. For this study, the model outputs included fully-favorable (FF), partially-favorable (PF), less-favorable (LF) and not-favorable (NF) for prediction of recruitment potential at each location.

Based on prior studies (Braatne et al., 2007; Burke et al., 2009), we selected five hydrophysical parameters for predicting recruitment potential: (1) peak flow timing relative to the cottonwood seed dispersal period (peak timing); (2) shear stress, which is an index for the competence for sediment and vegetation erosion (shear stress); (3) the mortality coefficient (M), that reflects the trend in the 3-day average stage recession rate; (4) ground elevation referenced to the base flow stage (elevation); and (5) the duration of winter inundation (winter flood). The first four parameters were used to predict recruitment favorability over the summer and the last one assessed subsequent winter survival.

In simulation of FV, the model predicts summer recruitment favorability (through the end of September of the recruitment year) and winter favorability (for the subsequent winter period to March 31). Winter favorability was specifically assessed for the Lower Kootenai River system because based on field observations it was hypothesized that seedlings recruited during summer could be removed or killed by extended winter inundation or scour. High winter releases from Libby Dam and elevated winter water surface elevations maintained by the downstream Corra Linn Dam influence the water surface elevations along the study area.

We assigned equal weights to each parameter (see Section 2.3) because we assumed that each parameter plays an essential role for successful cottonwood seedling recruitment. Assessments of good (G), fair (F) and poor (P) were assigned for these parameters (except for peak timing) according to threshold values (Table 1). We formulated a number of rules that combine these assessments as inputs, which then provide favorability assessments (FF, PF, LF, NF) as outputs (Table 2). For example, if the shear stress was good (G), the mortality coefficient due to stage recession pattern was good (G), and elevation was good (G), then the overall summer favorability (FV) is fully-favorable (FF). If all three parameters (shear stress, mortality coefficient and elevation) were fair (F), summer FV is less-

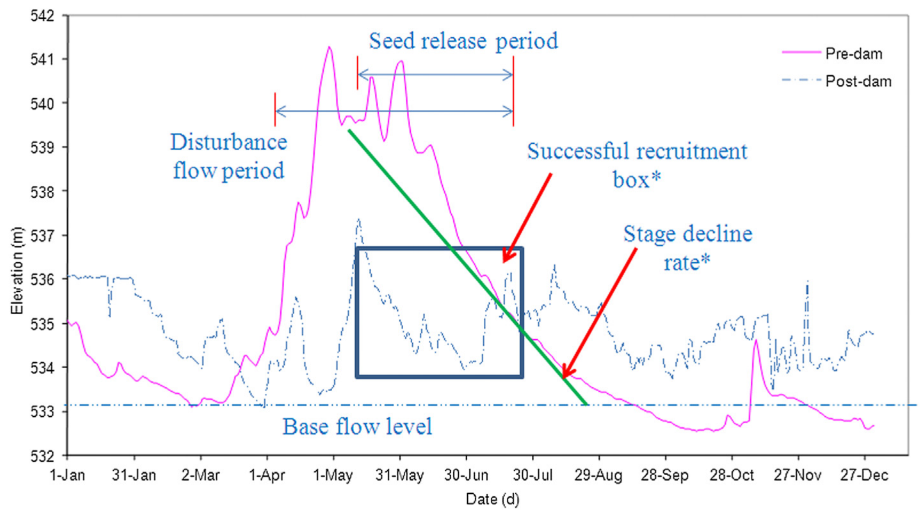

Fig. 2. Required physical criteria for successful cottonwood requirement. Recruitment box parameters and stage decline rate were based on Mahoney and Rood (1998). The hydrographs are from before (1934) and after (1976) Libby Dam at Bonners Ferry along the Kootenai River.

favorable (LF). If any two variables were good (G) and the remaining variable was fair (F), then the summer FV is PF. Conversely, if one of the parameters was poor (P), then FV is not-favorable (NF). These rules were coded into a numerical model using model builder in ArcGIS and python scripts. The physical parameters related to hydrology were calculated with a process-based hydrodynamic model and subsequently analyzed in the ArcGIS platform.

2.3. Model parameters

2.3.1. Peak timing

Cottonwood seeds are dispersed over long distances by water flow and wind. The dispersal period typically coincides with receding river flows following spring snowmelt and spring rains, and may extend into the summer (Braatne et al., 1996). We assigned a peak timing period from May 20 to July 15 for seed dispersal, based on Burke et al. (2009). Consequently, by default we assigned only the assessment of good (G) for this parameter. Because we constrained our analysis in this manner, this parameter did not further influence subsequent prediction of summer or winter favorability (FV). Later pulses of seed release have also been observed under certain circumstances and the weather conditions that lead to late pulses (Braatne et al., 1996) and the associated effect on recruitment success could be analyzed in future studies.

Table 1
Physical parameters considered for simulations of recruitment favorability and their threshold value ranges.

Parameter[a]	Condition	Reference
1. Peak timing	May-20–July-15	Braatne et al., 1996; Burke et al., 2009
2. Shear stress[b] (N/m^2)		
>13.00	Good	Based on simulated shear stress for year 2006 at the area where pioneer vegetation was mapped during field visit in the braided reach
7.00–13.00	Fair	
Other (<7.00)	Poor	
3. Mortality coefficient[c] (–)		
<20	Good	Braatne et al., 1996, 2007; Burke et al., 2009
20–30	Fair	
>30	Poor	
4. Elevation[d] (cm)		
50–200	Good	Mahoney and Rood, 1998; Burke et al., 2009; Polzin and Rood, 2006
200–400	Fair	
Other	Poor	
5. Winter flood[e] (d)		
0–30	Good	Smit, 1988; Rood and Mahoney, 1990
30–60	Fair	
Other (>60)	Poor	

[a] Range of these parameters can be altered and use as calibration parameters, but we did not alter for this study, instead used from previous studies.
[b] Maximum local shear stress during peak flood.
[c] Mortality coefficient threshold values.
[d] Elevation referenced to river base flow level.
[e] A number of days that newly recruited seedlings are under water during winter or subsequent spring flows.

2.3.2. Shear stress

Cottonwood seedlings are poor competitors with established vegetation (Johnson, 1994), and thus high shear stress is required to create barren surfaces for recruitment (Braatne et al., 1996; Mahoney and Rood, 1998). We quantified near-bed shear stress (Section 2.4) as an indicator of the mechanical forces that could scour existing vegetation and create barren sediment surfaces. We fixed the shear stress ranges based on simulated shear stresses at recruitment sites in the braided reach. In doing so, we extracted shear stress values for locations where we mapped gravel and sand bar, and pioneer vegetation in 2006. The minimum and 25th percentile values were approximately 7 N/m^2 and 13 N/m^2, respectively. We subsequently set shear stress ranges of

Table 2
Fuzzy rules to predict fully-favorable, partially-favorable, less-favorable and not-favorable conditions for cottonwood recruitment.

Fuzzy rules	Shear stress	Mortality coefficient	Elevation	Summer recruitment favorability[a]	Winter flow	Winter recruitment favorability[b]
Rule 1	Good	Good	Good	FF	Good	FF
Rule 2	Good	Fair	Good	PF	Good	PF
Rule 3	Good	Good	Fair	PF	–	–
Rule 4	Good	Fair	Fair	LF	Good	LF
Rule 5	Fair	Good	Good	PF	Fair	LF
Rule 6	Fair	Fair	Good	LF	–	–
Rule 7	Fair	Good	Fair	LF	Fair	NF
Rule 8	Fair	Fair	Fair	LF	–	–
Rule 9	–	–	–	FF	Fair	PF

FF – fully-favorable; PF – partly-favorable; LF – less-favorable; NF – not-favorable.
[a] Summer favorability a function of shear stress, mortality coefficient and elevation.
[b] Winter favorability a function of summer favorability and winter flow.

less than 7 N/m^2, between 7 N/m^2 and 13 N/m^2, and greater than 13 N/m^2, as poor (P), fair (F), and good (G), respectively. These ranges were characteristic of this study site, but may vary in other study areas because they are functions of the topography, vegetation, local hydraulics, and sediment particle size distributions.

2.3.3. Stage recession and the mortality coefficient

Rood and Mahoney (2000), Braatne et al. (2007), and Burke et al. (2009) used the convention of a 3-day moving average of the daily stage decline rate in their analyses. We refined those rates for this study, whereby from −0.1 to 5 cm/day, 5–10 cm/day and greater than 10 cm/day were considered favorable, stressful and lethal for seedling recruitment, respectively. A positive number indicates a decrease in average stage height, whereas a negative number indicates an increase in stage height.

To account for the natural variability of these stage recession rates (Fig. 3), Braatne et al. (2007) and Burke et al. (2009) subsequently applied the concept of a mortality coefficient (*M*), which is a function of the 3-day moving average stage recession rate. This coefficient indirectly accounts for the effect of the capillary fringe and root elongation, to the extent that they moderate the degree to which young cottonwoods desiccate due to occasional lethal recession rates. This is a weighting rule that allows a certain proportion of 'lethal days' to occur during the stage recession period. The principle behind the mortality coefficient is that a few days with abrupt declines may stress but not kill seedlings. Further, the negative effect of abrupt declines may be attenuated by groundwater infiltration and drainage, and substrate moisture retention, especially within the capillary fringe. We calculated the mortality coefficient from stage recession rates within the period from May 20 to the end of September based on the relationship (eq. (1)) given in Braatne et al. (2007) and Burke et al. (2009):

$$M = \frac{(\%\text{lethal} \times 3) + (\%\text{stressful} \times 1) + (\%\text{favorable} \times 0)}{3} \qquad (1)$$

The terms %lethal, %stressful, and %favorable indicate the proportion of days during the selected period whose moving 3-day average rate of stage decline is considered lethal, stressful, or favorable, respectively. We assigned mortality coefficients (*M*) of less than 20 as good (G), between 20 and 30 as fair (F), and greater than 30 as poor (P) (Table 1).

2.3.4. Elevation

The elevation relative to the base flow stage indicates the elevational range where cottonwood seedling recruitment can be successful. In this elevation band, seedlings are safe from drought stress that occurs at higher elevations and from scour disturbance that occurs at low elevations (Johnson, 1994; Polzin and Rood, 2006; Rood et al., 1998; Scott et al., 1997). This is measured as the vertical distance between the ground surface elevation and the adjacent river surface at base flow stage. Base flow is generally considered the minimum flow experienced toward the end of the growing season, and represents the lowest position to which the seedling roots must elongate to avoid desiccation following the summer recession and before dormancy. For this study, base flow elevations were estimated with hydrodynamic model simulations of average flows from August 15 to September 15. Cottonwood recruitment can often occur at an elevation range between 60 cm and 200 cm above the base flow stage, partly depending upon substrate texture and capillarity (Mahoney and Rood, 1998). Field studies at unregulated sites of the Kootenai/y River in British Columbia, upstream from the Koocanusa Reservoir, and at regulated sites downstream of Libby Dam, showed that black cottonwood seedlings established at elevations between 100 cm and 380 cm above the base flow level (Jamieson and Braatne, 2001; Polzin and Rood, 2000). Thus, following Burke et al. (2009), we used elevation thresholds of 50–200 cm as good (G), 200–400 cm as fair (F), and all other ranges as poor (P).

2.3.5. Winter flood

The winter flood parameter addresses inundation occurring in the period between October 1 and March 31 that immediately follows the summer recruitment period. This parameter is an indicator of the number of days that newly recruited seedlings were under water during winter or early spring flows. Mortality from extended inundation is typically associated with oxygen depletion in the root zone, although this may be less stressful when seedlings are dormant. In general cottonwood seedlings are tolerant of flooding and they can survive 6–8 weeks (Smit, 1988) of shallow inundation. Thus, we assessed inundation duration of less than 30 days as good (G), between 30 and 60 days as fair (F), and greater than 60 days as poor (P).

2.4. Simulation of physical parameters

We used MIKE11 (DHI, 2007) and MIKE11GIS (DHI, 2005) hydrodynamic models to simulate the required hydrological

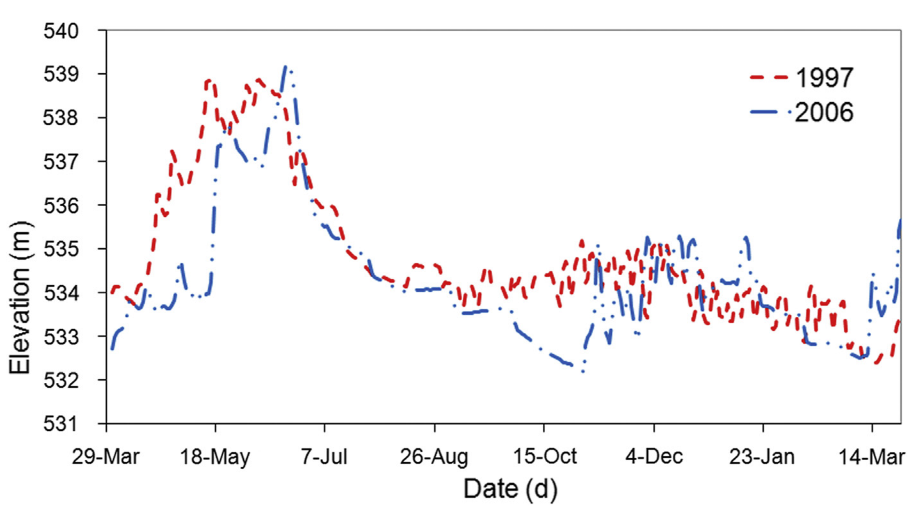

Fig. 3. Simulated stage hydrographs for the Kootenai River at Bonners Ferry for 1997 and 2006.

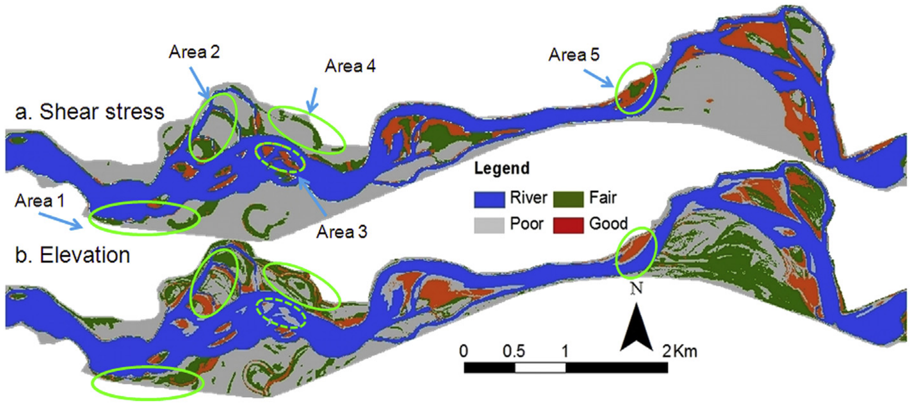

Fig. 4. Shear stress and elevation distribution for the 2006 hydrograph in the braided reach of the Kootenai River.

parameters as described in Benjankar (2009). MIKE11 was used to simulate water surface elevations (WSE) in the channel and over the surrounding floodplain. MIKE11GIS was subsequently used to distribute the calculated WSE over the full study domain using a grid with 5 m by 5 m cells. Local water depths were calculated with MIKE11GIS as functions of stream water surface elevations and floodplain topography provided by a LiDAR-derived digital elevation model (DEM).

Average WSE slope and water depth at each cell were subsequently calculated in ArcGIS with a moving window of 11 by 11 neighboring grid cells. We calculated the local shear stress τ ($\tau = \rho ghS$, where ρ is density of water and g is the gravitational acceleration), as a function of the local average water depth h, and slope S, for flows occurring a week before and after the peak flow event between April 1 and July 15 (Lorang et al., 2005; Manga and Kirchner, 2000; Mueller et al., 2005). Subsequently, the maximum shear stress in each grid cell was calculated based on highest product of h and S during the simulation period (Fig. 4). The rationale behind this approach was that high shear stress is a result of the peak flow and would create bare surfaces that were suitable for cottonwood seedling recruitment before the end of the seed dispersal period.

To evaluate the stage recession rates, the differences in WSEs from May 20 to the end of September were calculated between each successive day, averaged to calculate the 3-day moving average and combined to assess the mortality coefficient. We used the average WSE between August 15 and September 15 to calculate elevation relative to the base flow stage. This contrasts with Burke et al. (2009) and Braatne et al. (2002), who considered the WSE on September 15, and average flows during the month of August, as the base flow levels for the Kootenai and Snake Rivers, respectively.

2.5. Field-surveyed cottonwood recruitment

Vegetation surveys were conducted in the braided and meander reaches in late summer 2006 (Benjankar, 2009; Benjankar et al., 2011). During the field visit boundaries between different vegetation types were delineated on 2004 color aerial photographs (1:5000). Vegetation cover types were defined based on the areal coverage by specific vegetation community types according to Kovalchik and Clausnitzer (2004). The dominant plant species in BR and MR were plains cottonwood (*P. deltoides*), red top (*Agrostis stolonifera*), quackgrass (*Agropyron repens*), sand bar willow (*Salix exigua*), black cottonwood (*P. trichocarpa*), drummond willow (*Salix drummondiana*), yellow willow (*Salix lutea*), and reed canary grass (*Phalaris arundinacea*).

The spatially-distributed vegetation community maps (see, Benjankar, 2009) were converted into the different recruitment favorability classes to analyze the model performance. Relative to cottonwood recruitment, we assigned the areas with new pioneer vegetation as fully-favorable, cottonwood and willow shrub, and shrub-dominant reed vegetation as partially-favorable, reed-dominant shrub communities as less-favorable, and other types of communities as not-favorable (Table 3).

2.6. Analysis of predicted favorability for cottonwood seedling recruitment

We compared field-based favorability classes (Table 3) to the simulated summer favorability results using an error matrix (Congalton and Green, 2008) to analyze the model accuracy. The error matrix compares maps on a cell-by-cell basis and is a common method for reporting the site-specific accuracy of mapping. The agreement between the field-based and simulated maps was assessed by calculating the overall accuracy (OA). OA is the proportion of correctly predicted cells versus the total number of cells at the assessment site and is reported by diagonal elements in the error matrix (Congalton and Green, 2008).

We used the error matrix method with three alternative cases to evaluate the model results. First, the maps were compared

Table 3
Field-surveyed vegetation community and recruitment favorability classes.

Community types[a]	Favorability[c]	Description
1. Pioneer vegetation[b]	Fully-favorable	Newly recruited pioneer vegetation
2. Cottonwood and willow shrub[b]	Partially-favorable	Cottonwood and willow shrub vegetation
3. Shrub-reed[b]	Partially-favorable	Shrub-dominant reed vegetation (50–75% shrub)
4. Reed-shrub[b]	Less-favorable	Reed dominant shrub vegetation (50–75% reed)
5. All other types	Not-favorable	Deep marsh; Gravel and sand bar; Shallow marsh and wet meadow; Reed and forbs; Wet forbs and shrubs; Reed, forbs and shrub; Young cottonwood forest; Old cottonwood forest; Beaver grassland, Mature mixed forest

[a] Field-surveyed vegetation community types.
[b] Newly recruited cottonwood were observed in these habitats.
[c] Assumed recruitment favorability for cottonwood seedlings.

Table 4
Error matrix for simulated and field-based favorability classes for braided (a, c, e) and meander (b, d, f) reaches for 2006. The values reported in the error matrix are proportions (presented as percentages) of simulated and observed (field-based) favorability classes to total simulated area (ha) for each class. The values in the diagonal are proportions of each field class that were correctly predicted by the model at the same location.

a. Braided reach

Simulated	Field				Area[a]	OA
	NF	LF	PF	FF		
NF	61	7	15	16	62.5	
LF	65	10	24	0	16.4	47
PF	44	11	42	3	22.9	
FF	27	10	47	16	4.6	
Area[b]	60	9	25	12	**106.4**[c]	

b. Meander reach

Simulated	Field				Area[a]	OA
	NF	LF	PF	FF		
NF	79	0	10	11	16.2	
LF	50	0	50	0	1.4	68
PF	66	0	31	2	2.1	
FF	66	0	31	3	0.3	
Area[b]	15	0	3	2	**20.0**[c]	

c. Braided reach

Simulated	Field			Area[a]	OA
	NF	LF[d] PF[d]	FF		
NF	61	22	16	62.5	
LF[d] PF[d]	53	45	2	39.3	53
FF	27	57	16	4.6	
Area[b]	60	34	12	**106.4**[c]	

d. Meander reach

Simulated	Field			Area[a]	OA
	NF	LF[d] PF[d]	FF		
NF	79	10	11	16.2	
LF[d] PF[d]	60	39	1	3.5	71
FF	66	31	3	0.3	
Area[b]	15	3	2	**20.0**[c]	

e. Braided reach

Simulated	Field		Area[a]	OA
	NF[e] LF[e]	PF[f] FF[f]		
NF[e] LF[e]	70	30	78.9	64
PF[f] FF[f]	52	48	27.5	
Area[b]	69	37	**106.4**[c]	

f. Meander reach

Simulated	Field		Area[a]	OA
	NF[e] LF[e]	PF[f] FF[f]		
NF[e] LF[e]	77	23	17.6	72
PF[f] FF[f]	66	34	2.4	
Area[b]	15	5	**20.0**[c]	

OA – overall accuracy in %; FF – fully-favorable; PF – partly-favorable; LF – less-favorable; NF – not-favorable.
[a] Area associated with all simulated favorability.
[b] Area associated with all field-based favorability.
[c] Total area (ha) of all favorability classes (NF, LF, PF, FF). Total areas are 106.4 ha and 20 ha for the braided and meander reaches, respectively.
[d] Merged LF and PF to form a fuzzy-category or undecided-category.
[e] Merged NF with LF to form an unsuitable-category.
[f] Merged PF with FF to form a suitable-category.

considering all four recruitment favorability classes (FF, PF, LF, NF). Second, we merged cells with values of LF and PF to form a fuzzy (intermediate) category from both simulated and field-based favorability maps. This provided a comparison between maps with three-categories of NF, fuzzy and FF. Third, we merged NF with LF, and PF with FF classes to analyze differences caused by our specific class assignments. This case compares maps that have two-categories: favorable or unfavorable (e.g., Ruger et al., 2005). These three cases were intended to provide feedback on the potential applicability of the model for river management as well as other scientific purposes, including dam impact analysis and restoration design.

We also used the model predictions to assess the sensitivity of the summer favorability results to winter inundation, and to test the ability of the model to replicate its predictions for years with similar flow patterns. To do so, we compared total areas associated with each favorability class (i.e., NF, LF, PF, FF) between summer and winter recruitment favorability for 2006, and between the years 1997 and 2006. The comparison between summer and winter favorability would indicate impacts of winter flows on cottonwood seedling recruitment, whereas comparison between years 1997 and 2006 would investigate the influence of hydrology and the stage recession pattern. We emphasized the years 1997 and 2006 (Fig. 3) because these years have been previously correlated with observed cottonwood recruitment events (Burke, 2006; Jamieson and Braatne, 2001). For all analyses we endeavored to consider only areas without human influence and inundated by the 2006 peak discharge.

3. Results

3.1. Model accuracy analysis

The error matrix approach (Table 4) was used to analyze the agreement between the field-based and simulated summer favorability predictions. The majority (>50%) of the study areas (Table 4a,b) fell into the not-favorable (NF) class at both sites (MR and BR) for both field-based and simulated classifications (braided, Fig. 5 and meander, Fig. 6). The overall accuracies (OA) of the four-category comparisons were 47% and 68% for the braided and meander reaches, respectively (Table 4a,b). The model was able to predict NF with highest accuracy, followed by PF, FF and LF in both the braided and meander reaches. Generally, the model under-predicted FF and PF, and over predicted LF for both reaches. The field-based favorability maps did not include any LF in the meander reach, whereas the model did predict the LF class in that area.

As expected, the OA of the three-category comparison had a greater accuracy than the four-category case, with accuracies of 53% and 71% in the braided and meander reaches, respectively (Table 4c,d). The model was able to predict the fuzzy (intermediate) class formed by merging LF and PF 45% accurately at the braided reach, which was improved over 10% and 42% for these individual classes, respectively (Table 4a,c). The OA further increased for the two-category comparison (favorable/unfavorable) to 64% and 72% in the braided and meander reaches, respectively (Table 4e,f).

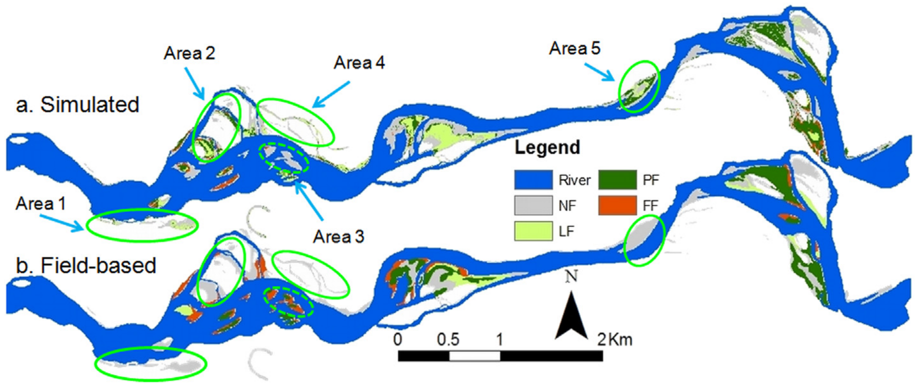

Fig. 5. Simulated and field-based recruitment favorability classes in the braided reach for 2006.

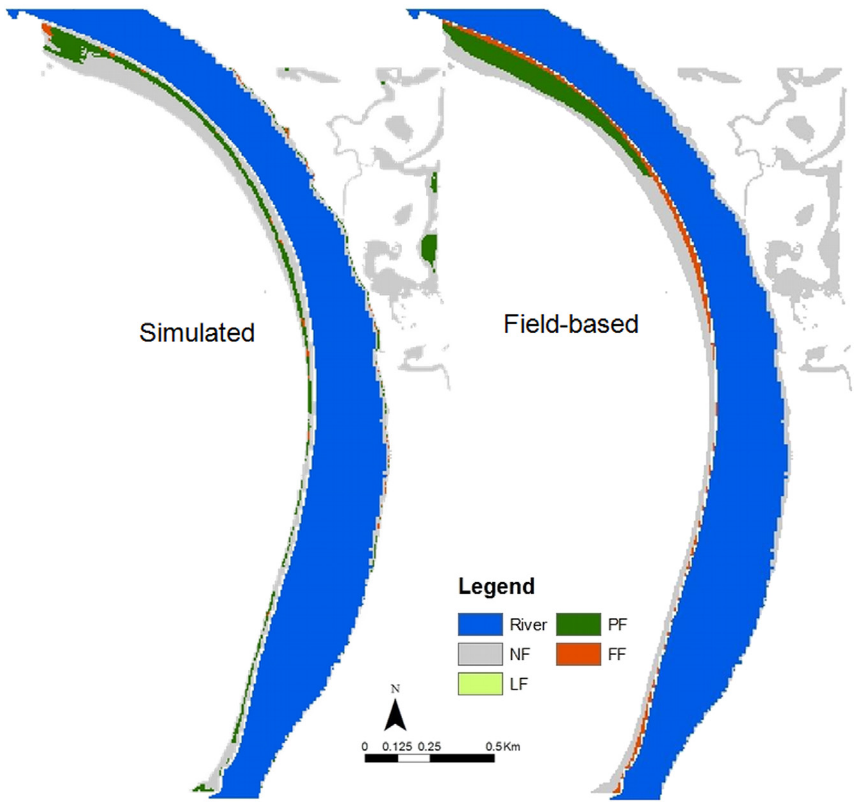

Fig. 6. Simulated and field-based recruitment favorability classes in the meander reach for 2006.

3.2. Impact of winter flows and stage recession pattern on cottonwood seedling recruitment

The largest difference between summer and winter favorability predictions was 1.2 ha for the NF class, which was followed by smaller changes in PF, FF and LF classes for the braided reach. In general, the differences were very small in the braided reach, being less than 1.2 ha (Table 5). The model predicted nearly the same areas during summer and winter periods for all favorability classes in the meander reach. The model predictions were thus not sensitive to winter flows.

The model predicted a greater total area of recruitment favorability (sum of LF, PF and FF classes) for cottonwood seedling recruitment in 2006 than in 1997 in the braided reach, but similar total area in the meander reach. This result was expected because peak flows during 2006 were higher than those of 1997. The largest difference in recruitment favorability between 1997 and 2006 was 2.1 ha for the NF class in the braided reach. The differences were small for all favorability classes in the meander reach (Table 5).

4. Discussion

4.1. Model evaluation

The spatially-distributed cottonwood recruitment (SDCR) model was developed to predict the potential areas for cottonwood seedling recruitment. The model combined the contributions of five physical parameters with equal weighting. The equal weight assumption was based on our observation of cottonwood seedling recruitment patterns and it was justified by relatively good OA (~50%) between field-based and simulated recruitment potential

Table 5
Areas (ha) associated with different recruitment favorability classes between summer and winter and between years 1997 and 2006 in braided and meander reaches.

	a. Braided reach						b. Meander reach					
	Winter flow			Stage recession[a]			Winter flow			Stage recession[a]		
	SS	WS	Δ	1997	2006	Δ	SS	WS	Δ	1997	2006	Δ
NF	321.2	322.4	1.2	324.5	322.4	2.1	73.0	73.0	0.0	73.0	73.0	0.0
LF	20.4	20.4	0.0	19.3	20.4	1.2	1.9	1.9	0.0	1.9	1.9	0.0
PF	25.3	24.3	1.1	24.3	24.3	−0.1	2.4	2.4	0.0	2.4	2.4	0.0
FF	4.9	4.9	0.1	3.9	4.9	1.0	0.4	0.4	0.0	0.4	0.4	0.0

FF – fully-favorable; PF – partly-favorable; LF – less-favorable; NF – not-favorable; SS – summer favorability area (ha); WS – winter favorability (ha). Δ – Difference in favorability area (ha) between summer and winter in 1997 and 2006.
[a] Shows influence of hydrology and stage recession patterns on seedling recruitment.

patterns (Table 4a,b). Nevertheless, the model could simulate the impacts of each physical parameter on cottonwood seedling recruitment using variable weights and this may provide an opportunity for future model refinement.

One of the main goals of the study was to analyze the accuracy of the model as compared with field-surveyed favorability classes for 2006, a specific single year that did support substantial cottonwood colonization. This analysis showed relatively good agreement between model-simulated and field-based patterns of favorability, as described above. Even so, the analysis outcomes can be further explained with a few additional considerations. First, even though the SDCR model evaluated all of the requirements for seedling establishment within a single year, cottonwood recruitment is often a multi-year process, in which geomorphic disturbance occurs in one year, followed by seedling recruitment in that same year and/or in the subsequent two or three years (Braatne et al., 2007; Burke et al., 2009). Additionally, we endeavored to compare simulated recruitment favorability in areas without other influences such as livestock grazing or agriculture. However, our field observations revealed that most of the areas were impacted to some extent by human activities. Further, the grid configuration in the model may also influence the extent of agreement. The model results are based on a 5 m by 5 m cell size, but cottonwoods commonly establish in arcuate bands that parallel the river channel, rather than in large blocks. Furthermore the seed release period can vary with local weather conditions and between the two species of cottonwood that are present in the study area (Braatne et al., 1996).

Our simulations generally predicted similar spatial distributions of recruitment potential to those observed in the field, as indicated by the overall agreement (OA) for all three alternative cases that included four-, three- and two-favorability classes. The results suggest that model accuracy improves by reducing the number of classes (e.g., Ruger et al., 2005). Hence, the model is quite robust even though its parameterization of stage recession rates and relative elevation criteria were based on prior studies.

Typically, prior studies have compared vegetation model results (vegetation maps) with field-surveyed, air-photo or satellite-image based vegetation maps using area-balance methods to analyze the model accuracy (Baptist et al., 2004; Poiani and Johnson, 1993). In the area-balance approach, the total areas simulated for specific vegetation classes are compared with calculated total areas from field-surveyed vegetation maps, but the spatial distribution association is largely ignored. We analyzed the model accuracy on a rigid cell-by-cell basis using an error matrix approach. This approach is very strict and may exaggerate errors (Pontius, 2002). This is due to the fact that when predicted and observed cells do not have the same result, there is zero agreement even if the correct result exists in a neighboring cell, or conversely if the difference is only by a single class, such as being assessed as LF instead of NF (see, Benjankar et al., 2010). If we had limited our analysis to an area-balance method, the accuracies of our model predictions would be much higher (Table 4).

We used a rule-based fuzzy logic approach (Foody, 1996; Roberts, 1996; Ruger et al., 2005), which can be particularly powerful and advantageous for predicting ecological and environmental processes that are non-linear and complex (Metternicht, 2001). The fuzzy logic approach is simple and flexible but can be somewhat subjective in the designation of specific categories (e.g., FF, PF, LF) (Salski, 1992). The process of generation of field-based recruitment potential maps from vegetation communities in our study may be also somewhat subjective. For example, we assigned LF for reed dominant shrub vegetation (Table 3), but others might assess this as PF. The proposed model expands the cottonwood seedling recruitment concepts applied successfully in other studies (Braatne et al., 2007; Burke et al., 2009; Mahoney and Rood, 1998) to provide maps of recruitment potential. The parameters are physically-based but the threshold values that separate the different categories may be adjusted for other rivers. However, the rule-based fuzzy approach is quite robust in terms of the assigned range of threshold parameter values and consequently these could be used in different applications, at least for determining initial parameter ranges (Mousavi et al., 2005).

Portions of the simulated LF (65%), PF (44%) and FF (27%) areas overlapped with the field-based NF (Table 4) areas in the braided reach. Reed canary grass was the dominant species in this NF class (Table 3) and in general it occupied low elevations and wet areas near the channel, such as Areas 2 and 5 in Fig. 4b (Jamieson and Braatne, 2001). The model simulated LF and PF classes at these locations based on physical parameters of mortality coefficient, shear stress and elevation. Most of the maximum simulated shear stresses for 2006 at these specific areas were between 7 and 13 N/m^2 but this magnitude may have been insufficient to erode the dense mats of reed canary grass (Jamieson and Braatne, 2001; Polzin and Rood, 2000). Subsequently, cottonwood seedlings may not have been able to compete with reed canary grass (Johnson, 1994). Conversely, field observations revealed that cottonwood seedlings were recruited within some reed canary grass habitats (Fierke and Kauffman, 2005), although they could later succumb due to competition with the reed canary grass. Thus, the presence of invasive reed canary grass complicates modeling and its resistance to scour may contribute to its success along the Kootenai River and many other rivers in the Pacific Northwest, particularly where extreme floods have been curtailed by regulation.

We used maximum shear stress as an indicator of disturbance flows that erode existing vegetation and create barren mineral surfaces. This parameter has considerable uncertainty because limited threshold data exist in the literature for shear stress that are sufficient for vegetation removal (e.g., Friedman and Auble, 1999; Prosser and Slade, 1994). We set shear stress thresholds based on the best available field observations and correlations in our study area. However, actual site-specific scour is complex and the critical shear stress required to remove existing vegetation depends on many factors (Friedman and Auble, 1999).

We used the average water surface level between August 15 and September 15 as the base flow level, but there is no definite criterion for this value, especially for severely-regulated rivers (Braatne et al., 2007; Burke et al., 2009). Further refinement of these values with longer-term observations of local field conditions should improve model accuracy. Generally, the model under-predicted FF areas in both the braided and meander reaches (Table 4). The model simulated NF at Area 3 (Fig. 5a) because it was less than 50 cm above the base flow stage, but this area was evaluated as FF in the field (Fig. 5b). This location has a low elevation and the observed vegetation could be removed by subsequent flows that would then convert the location to NF. The observed elevation range for successful cottonwood seedling recruitment in the study area was between 50 cm and 400 cm (in Table 1) and was greater than the typical 60–200 cm reported by Mahoney and Rood (1998). However, direct comparison between studies is complicated by the selection of the base stage, and this would be altered with the regulated flow regime.

Lastly, the method to calculate shear stress on the floodplain based on local water depth and water surface elevation slopes in the channel with 1D simulations may also contribute to model inaccuracy. For example, areas 1 and 4 (Fig. 5b) were former side channels and they were mapped as wetland habitat during the field visit. These areas connect with the main channel occasionally during high flows due primarily to back-water flow. For these locations, the simulated maximum shear stresses were more than 7 N/m^2 (Fig. 4a), and the model predicted LF and PF. For comparison, these areas would be NF based on field assessment. This suggests the need to simulate physical parameters such as shear stress and water depth more accurately for complex channel and floodplain locations. In these locations, a two-dimensional hydrodynamic model would probably have provided more accurate shear stress values (Tonina and Jorde, 2013), but the 1D model was used for this study to economize computational effort while focusing on SDCR model development. Additionally, two dimensional models require accurate and high resolution survey of both submerged and terrestrial topographies (Conner and Tonina, 2014).

4.2. Impact of winter flows and stage recession pattern on cottonwood seedling recruitment

There were no substantial differences between summer and winter favorability in 2006 for either reach (Table 5). Winter and subsequent early spring flows (October 1–March 31) were not predicted to lead to the mortality of newly recruited cottonwood seedlings (Table 1). Although seedlings may be tolerant of extended flood inundation, spring flows can still kill them through sediment scour or burial (Rood and Mahoney, 1990). Further, vegetation can also be destroyed by direct forces of water flow or by ice scour (Friedman and Auble, 1999). For example, Smith and Pearce (2000) found that mechanical ice breakups and ice drives physically damaged most cottonwood saplings and small trees along a sand-bedded braided reach of the Milk River. Therefore, it is important to consider the local physical forces in addition to inundation to characterize the impact of high winter or early spring flows on cottonwood seedlings.

As we had hypothesized, there were no substantial differences in favorable areas between 1997 and 2006 in both the braided and meander reaches (Fig. 7 and Table 5). This was expected because the hydrograph and stage recession patterns were similar in these recruitment years (Fig. 3). Our results showed that the 1997 hydrograph was suitable for seedling recruitment in both the braided and meander reaches as was field-observed for 2006. This result was consistent with prior studies along these segments of the Kootenai River (Burke, 2006; Jamieson and Braatne, 2001).

4.3. Model application

Mechanistic ecohydrology models have been used to analyze human impacts on natural riparian systems (e.g., Baptist et al., 2004; Benjankar et al., 2012; Carmel et al., 2001; Egger et al., 2012), hydrological processes of riparian systems (e.g., Zhang and Mitsch, 2005) and to contribute to the restoration of ecologically degraded systems (e.g., Hammersmark et al., 2005; Mitsch and Wang, 2000). Process-based quantitative models are important tools to provide scientific insight to managers and stakeholders for prospective restoration programs (Goodwin et al., 1997).

We suggest that quantitative analyses of hydrological and fluvial impacts should be included in planning for restoration of flow-dependent riparian ecosystems (Schmidt et al., 1998). Therefore, our model may provide useful information for riparian vegetation restoration designs. The model could also be used to quantify impacts of dam operations (e.g., Benjankar et al., 2012; Johnson et al., 2012), climatic variability (Politti et al., 2014; Rivaes et al., 2013), and water diversion on cottonwood seedling habitats. Information such as this should ultimately benefit the management of riparian woodlands and contribute to restoring various ecosystem processes. The model can thus be used for restoration project design and also to guide reservoir operation to sustain cottonwood seedling recruitment. However, parameter threshold values in the

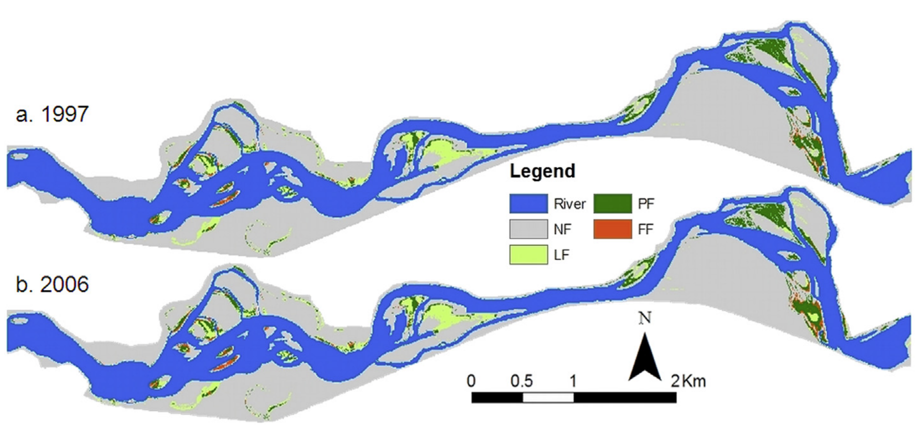

Fig. 7. Simulated recruitment favorability classes in 1997 and 2006 in the braided reach.

model should be validated and refined for local conditions, prior to application in restoration efforts.

5. Conclusions

We developed a new spatially-distributed GIS-based model to predict the hydrodynamic patterns and subsequent distribution of potential zones for successful cottonwood seedling recruitment. The simulated favorability areas showed reasonable agreement (~50%) with field-based favorability considering all four recruitment favorability classes (NF, LF, PF, FF) and model accuracies further increased as the numbers of categories were reduced. Our model appears superior to previous cross-section or transect based methods for mapping potential cottonwood recruitment. Furthermore, the model simulated comparable favorable areas for the hydrologically similar 1997 and 2006 flows in both study reaches. This provides evidence of replication and suggests that the model accounts for the main physical processes that underlie cottonwood recruitment. Lastly, the model tended to under-predict favorability relative to the field mapping, which also suggests that the core physical processes to enable recruitment are accounted for, while not explicitly addressing natural variability and local adaptations that may enable seedlings to opportunistically overcome marginal local conditions (i.e., observed cases of establishment within areas of reed canary grass).

Although our simulated results were in reasonable agreement with the field-based favorability mapping, before using this model for management and restoration in other rivers, the model parameter thresholds should be refined for local conditions. We particularly recommend clarification of the threshold values for base flow stage and subsequent elevation ranges and for shear stress thresholds for specific bank compositions and vegetation communities. We suggest that the use of two-dimensional hydraulic models could improve the model predictions, especially for geomorphically-complex segments, such as those with dynamic braided channels and islands. Conversely, the 1D simulation is an efficient first approach and probably reasonably effective for simple reaches such as those with single-thread, mildly-sinuous channels.

Overall, the SDCR model could become a valuable tool for the analysis of the impact of human activities such as dam operation, water diversion, and climate change on cottonwood seedling recruitment. Thus, the model could subsequently provide insights for riverine ecosystem restoration and management.

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