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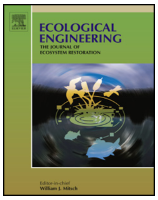

A spatially based area–time inundation index model developed to assess habitat opportunity in tidal–fluvial wetlands and restoration sites

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ABSTRACT

A geographic information system (GIS)-based Area-Time Inundation Index Model (ATIIM) was developed to predict and evaluate availability of hydrologically connected habitats in estuarine and tidal–fluvial regions. The model establishes and describes patterns in the spatial and temporal relationships of the land and water including non-dimensional area–time and volume–time inundation indices. The processing integrates in situ or modeled water-surface elevation (WSE) data with high-resolution elevation data, using established terrain generation and spatial hydrologic analysis methods which are applied in a new geographic domain: the low-relief microtopography characteristic of coastal wetlands. The ATIIM links these data to newly developed, spatially continuous wetted-area algorithms in a GIS module and determines site average bankfull elevation, two- and three-dimensional inundation extent, and other spatial, tabular, and graph-based metrics. It is a cost-effective, rapid assessment tool suitable for the desktop planning environment, and represents an advance over methods that estimate inundation but do not enforce hydrological connectivity. Example model outputs for 11 tidal wetland areas in the lower Columbia River floodplain and estuary illustrate habitat opportunity for threatened and endangered salmon. Outputs for wetland reference sites (tidal marshes and tidal forested wetlands) are compared with river-restoration sites where objectives include increasing salmon access to beneficial habitats by hydrologically reconnecting channels in diked areas of the floodplain. Hydrological process metrics produced by the model, both new and commonly used, support the prioritization of proposed restoration sites, pre-construction planning, and post-construction evaluation. For example, the model can help determine relationships between WSE and habitat opportunity, contrast alternative restoration designs, predict impacts of altered flow regimes, estimate nutrient and biomass fluxes, and provide standardized site comparisons to support effective monitoring of the developmental trajectories of restoration sites.

1. Introduction

Floodplains represent a biodiverse and dynamic ecotone possessing specific processes attributable to the interface between terrestrial and aquatic ecosystems (Naiman and Décamps, 1997). In river floodplain wetlands, the flow regime is a major determinant of the physical and biological components of the ecosystem (Bunn and Arthington, 2002). In coastal large-river regions, tides induce more complex hydrologic processes (Jay et al., 2015). The flora and fauna are adapted to a complex suite of spatiotemporal interactions between the land and the water (Welcomme, 1979; Junk, 1999), and the re-establishment of a natural hydrological regime is important for ecosystem restoration to succeed (Poff et al., 1997). Spatially explicit modeling of such complex inundation regimes presents a significant interdisciplinary challenge, requiring techniques in geoinformatics and hydrology, and the selection of methods has implications for floodplain ecosystem research and restoration.

The hydrological regime of floodplains has been altered by flow regulation, climate cycles, and channel fragmentation, which have strongly affected many large river systems and fisheries throughout the world (Dynesius and Nilsson, 1994; Mote et al., 2005; Battin et al., 2007). Therefore the strategic reconnection of rivers and floodplains at large scales has been recommended to regain the

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values associated with floodplain ecosystems (Opperman et al., 2009). Hydrological process metrics are important in restoration because fluctuations in water level are controlling factors in the development of ecosystem structure and function. The total area, volume, frequency, duration, and timing of inundation over a wetland restoration site or entire riverscape can provide an index of the floodplain disturbance regime and habitat opportunity, and improve understanding of the rates of ecosystem subsidies such as nutrients, detritus, and biomass, which flux between the floodplain and channel network (White and Pickett, 1985; Toth, 1995; Polis et al., 1997; Welcomme, 2008; Junk, 1999).

The characterization of inundation patterns is particularly challenging in managed tidal river floodplains such as the 234-km lower Columbia River floodplain and estuary (LCRE) on the west coast of North America (Fig. 1). The influence of tides and coastal processes interacts with basin-wide multi-objective hydropower operations, water withdrawals, and the dynamics of seasonal and weather-affected river flows (Jay et al., 2015). In this region, juvenile salmon use shallow estuarine and tidal freshwater habitats to feed and rear (Levings and Bouillon, 1994; Johnson et al., 2015). However, the managed hydrograph and passage barriers (e.g., dikes, culverts, and tide gates) diminish opportunities for fish to enter tidal floodplain wetlands (Bottom et al., 2005). Typical for large rivers globally (Tockner and Stanford, 2002), diking and flow reduction have significantly reduced the shallow-water habitat area available to juvenile salmon (Kukulka and Jay, 2003). Thus, the reconnection of lateral floodplain and estuarine habitat with the main-stem river by breaching dikes and removing or replacing culverts and tide gates is a primary activity of the landscape-scale Columbia Estuary Ecosystem Restoration Program (CEERP) (NMFS, 2008; Diefenderfer et al., 2011).

Several methods to quantify the inundation regime of floodplain wetlands have been reported in the literature. Typical examples include direct measurement of water levels using piezometers for groundwater and pressure gauges for surface water as the basis for stage-discharge curves (e.g., Siebentritt et al., 2004). The hydrological parameters developed from such measurement methods depend on the purpose of the study. For example, patterns of discharge and recharge in groundwater flow have been assessed using piezometers and paired shallow wells to characterize reference wetland hydrological conditions (Ehrenfeld et al., 2003). To predict sediment transport events, Florsheim et al. (2006) calculated flow-duration curves because the process depends on both the magnitude and duration of overbank flooding. Research on salt marshes along the U.S. Gulf of Mexico and the southeastern Atlantic coast produced a flood area index suitable for tidal areas, which factors in duration and extent of flooding from within 10-m of an established marsh edge (Minello et al., 2012). Methods range from the complex and expensive (e.g., hydrodynamic modeling (Silvestri et al., 2004)) to the simple (e.g., the number of months per year in which standing water is observed (Meyer et al., 2008); extracting a single-value inundation surface (NOAA, 2010)). In practice, many coastal restoration planners produce visualizations of inundation by marking up paper maps or using contours from a digital elevation model (DEM) to represent low, average and maximum water levels.

1.1. Rationale for a new model

Existing methods and models provide various levels of complexity for inundation modeling (Bates et al., 2005; Poulter and Halpin, 2008; NOAA, 2010; Savant and McAlpin, 2014). However, none are able to integrate high-resolution spatiotemporal inundation patterns with the types of data and metrics required to assess habitat opportunity on a tidal–fluvial floodplain, enforce hydrologic connectivity, and produce an array of beneficial decision support metrics for stakeholders and restoration practitioners in a practical, cost-effective manner. The Area Time Inundation Index Model (ATIIM) can be characterized as a community-driven model where the features and capabilities developed are a direct result of stakeholder, restoration practitioner, researcher, program manager, etc. communicated needs. For example, restoration program managers need to quantify opportunities for habitat access at existing and proposed wetland restoration sites (Simenstad et al., 2000), assess restoration trajectories (Simenstad and Thom, 1996), quantify the volumetric

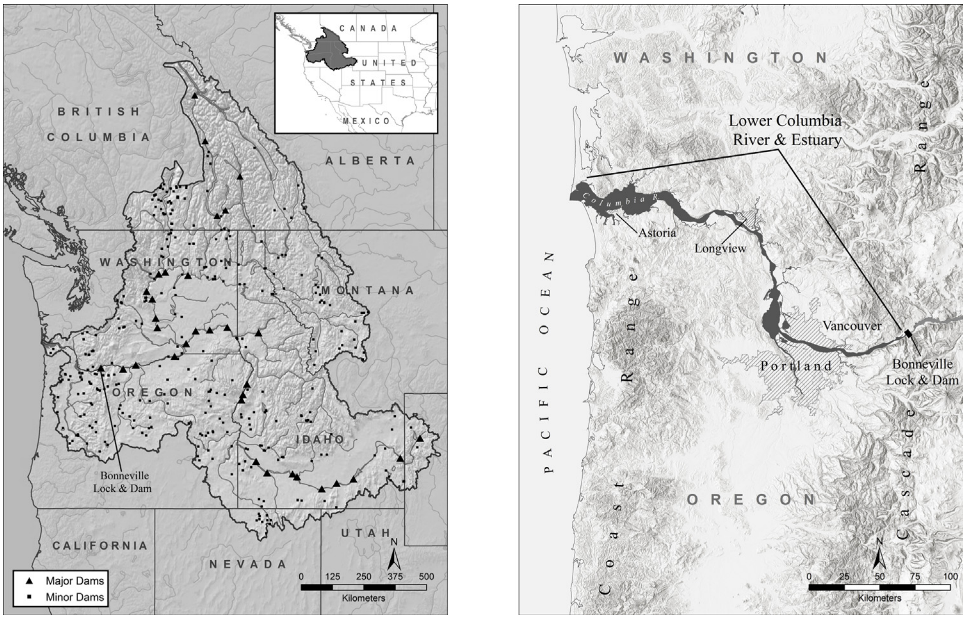

Fig. 1. The Columbia River watershed spans several states within the U.S. and a Canadian province. The hydrologic regime is affected by 32 major dams and approximately 100 minor dams (left). The lower Columbia River and estuary is a 234-km-long tidal–fluvial system and is downriver of all dams (right).