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Land use legacies of the Ohio River Basin: Using a spatially explicit land use change model to assess past and future impacts on aquatic resources

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ABSTRACT

Land uses and their legacies are a major driver of human impacts on the environment. Decision makers have recognized that the legacies of land-use activities continue to influence ecosystems, particularly aquatic ones, for decades or centuries. The main objectives of this paper are to develop land use legacy maps to (1) assess historical and future (predicted) shifts in dominant land use classes (urban, agriculture, forest) in the Ohio River Basin (ORB), and (2) determine the past and future location of catchments in the ORB exceeding critical land use thresholds (10% and 38% urban and agricultural use of catchment respectively) for water quality and other aquatic resources. Our land use legacy simulations show that approximately 80% of the ORB has remained as agriculture (~37%), forest (~34%), urban (~7%) and other classes (~2%) from 1930 to 1990. Within the remainder of landscape, agriculture to forest (~16%) and agriculture to urban (~1.5%) transitions were the most common land use changes between 1930 and 1990. Our forecast model shows that approximately 94% of the ORB will remain as forest (~47.46%), agriculture (~35.77%), urban (~8.84%) and other classes (~2.07%) between 2000 and 2050. 1.44% and 1.37% of the ORB is predicted to transition from forest to urban and agriculture to urban between 2000 and 2050, respectively. Our results also demonstrate that 13% and 74% of the catchments in the ORB already exceeded critical urban and agricultural land use thresholds in 1930, respectively. We predict that 37% of catchments in the ORB will have exceeded critical urban land use thresholds by 2050, whereas the proportion of catchments to exceed critical agricultural use will decrease to 45%.

Introduction

Land use legacies

Past and current human land uses influence a variety of environmental processes that occur currently. The effects of human land use on biophysical processes, termed land use legacies (Pijanowski, Ray, Kendall, Duckles, & Hyndman, 2007; Tayyebi, Delavar, Saeedi, Amini, & Alinia, 2008), have been shown to impact stream hydrology (Ray & Pijanowski, 2010; Ray, Pijanowski, Kendall, & Hyndman, 2012), soil properties (Foster et al., 2003; Islam & Weil, 2000), biodiversity (Pekin, 2013; Pekin & Pijanowski, 2012), and aquatic resources (Allen et al., 2004). Historical land use maps in particular are useful for informing sustainable management and restoration planning (Swetnam, Allen & Betancourt, 1999) because they provide valuable information about baseline (reference condition) as well as legacy signals from the past.

Assessments at large spatial scales, such as those in North America (Kumar, Merwade, Rao, & Pijanowski, 2013; Rhemtulla, Mladenoff, & Clayton, 2007), show that general land use change (LUC) has proceeded from natural (e.g., grasslands, forests, wetlands) land covers to human dominated use, commonly agriculture, and then finally to urban (Tayyebi, Tayyebi, & Khanna, 2014). Some previously agricultural rural areas have also experienced a "greening" of the landscape as marginal cropland is converted

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either to secondary forests as agricultural land is set aside, through such programs as the United State NRCS Conservation Reserve Program, or to mixed rural residential/secondary forests as urban areas expand along the urban/rural fringe. However, analysis of landscape scale changes (Jenerette and Wu, 2001) show that patterns can shift rapidly and even transitions from one class to another (agriculture to forest, and back to agriculture) can be quick. It is thus important to make assessments for every decade, or over shorter time frames, so as to not miss any important land use changes that may have occurred within an area.

In this paper, we sought to understand landscape dynamics and their legacies on regional aquatic ecosystem resources in a large part of the upper Midwestern United States. We thus explored land use transitions in the Ohio River Basin (ORB) which is a challenging landscape for water and aquatic resource management due to its highly dynamic and mixed land use history. We focused on both past and future shifts in three dominant land use classes (agriculture, forest and urban; Fig. 1, Items #1, #2, #3 and #4). In doing so we assess the location and time of past and future critical land use transitions for aquatic resources in the region.

Land use change and aquatic resources

Human dominated landscapes produce high levels of pollutants (Brown et al. 2009; Fitzpatrick, Long, & Pijanowski, 2007; Miller, Schoonover, Williard, & Hwang, 2011), and both urban and agricultural catchment land area have been directly linked with reduced water quality and biotic integrity (Allan, Erickson, & Fay, 1997; Hrodey, Sutton, Frimpong, & Simon, 2009; Riseng, Wiley, Seelbach, & Stevenson, 2010; Utz, Hilderbrand, & Boward, 2009). Accordingly, mitigating human impacts on aquatic resources requires estimating risk from both urban and agricultural lands (Allan, 2004; Mattikalli & Richards, 1996). Maps showing past and current land use (Fig. 1, Item #5) inform land managers regarding where stress to aquatic/water resources is potentially strongest and most critical. Future land use maps (Fig. 1, Item #6) can similarly be used to assist in determining areas that are under greatest risk from urbanization and agricultural expansion and provide early warnings that enable managers to more efficiently allocate their resources within their region. It is crucial to consider past land uses along with current and future land uses because resorting stressors such as land use to less damaging levels in already degraded ecosystems does not always result in ecosystem recovery (Groffman et al., 2006).

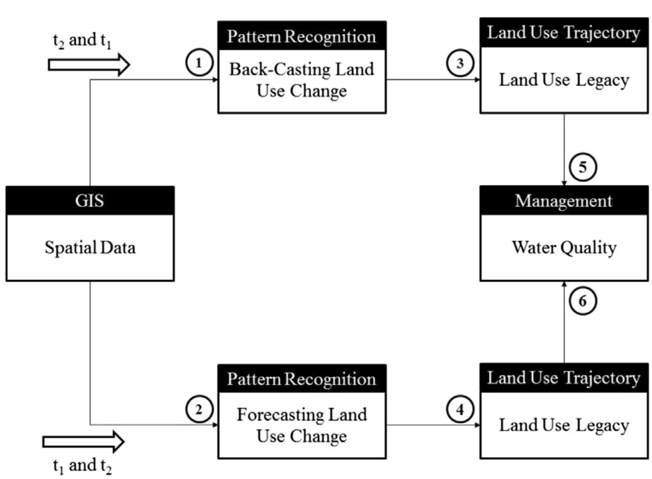

Fig. 1. Two main objectives of this study.

Interest into sustainable integrated water management on a watershed scale, and into supporting research, has increased recently within the Environmental Protection Agency (EPA) and other organizations active in monitoring water quality and water use. A recently initiated EPA study to evaluate integrated sustainable watershed management and planning in the ORB at various spatial scales requires information on historical land use patterns and maps illustrating spatial and temporal changes in land use in relation to aquatic resources in the region. The latter information, combined with aquatic resource-related information on water quality, quantity and ecosystem service value, is expected to provide a quantitative basis for scenario exploration and optimization in support of sustainable integrated watershed management over short and longer periods of time.

Accordingly, one of our primary objectives is to use past and future land use maps for informing watershed management in the ORB (Fig. 1, Items #5 and #6) where land use patterns are likely to strongly impact water quality and other aquatic resources. Our land use simulations may serve as a valuable example that greatly facilitates collaboration in water resources management research and encourages undertaking of similar activities by EPA colleagues, non-EPA collaborators and other local land managers.

Structure of paper

In summary, this study aims to produce basin-wide maps of historical land use patterns (at decadal time steps from pre-settlement to current; Fig. 1, Item #3), future land use trends (also decadal, from current to 2050; Fig. 1, Item #4) and demonstrate the application of these maps for assessing risk to aquatic resources from human land uses in the ORB (Fig. 1, Items #5 and #6). This effort is expected to guide managers in sustainable watershed management planning and contribute to the 'Safe and Sustainable Water Research Program'.

Section 2 provides an overview of our artificial neural network (ANN) based LUC model which we use for back-casting and forecasting LUC in the ORB, describes the idea of developing land use legacy maps using historical (between 1930 and 1990) and future land uses (between 2000 and 2050), and assessing the impact of these land use changes on water quality across the ORB. Section 3 presents the results of our land use back-cast and forecast simulations, critical landscape changes (between 1930 and 1990 and between 2000 and 2050), and potential impacts of past and future land uses on aquatic resources. Sections 4 and 5 provide the discussion and conclusion, respectively.

Methods

Summary of back-cast model

We used a GIS and ANN based approach (Pijanowski, Brown, Shellito, & Manik, 2002; Tayyebi, 2013; Tayyebi & Pijanowski, 2014) for back-cast LUC modeling. A few studies have recently used a similar approach to back-cast LUC (Pijanowski et al., 2007; Ray & Pijanowski, 2010; Ray et al., 2012). The technical details of this back-cast model are described in detail in Tayyebi, Tayyebi, Pekin, and Pijanowski (in press).

Our back-cast model is a spatial-temporal model that uses two reference land use maps in a reverse manner (t_2 and t_1 instead of t_1 and t_2; Fig. 2, Item #1) and historical data from the agricultural census (U.S. Department of Agriculture, 1997) and US population (U.S. Bureau of the Census, 2000) to construct historical land uses. In contrast to the forward manner (Fig. 1, Item #3), the factors or drivers that impact the LUC in the past should be in t_2 instead of t_1 and the output of the model is LUC from t_2 to t_1 (Fig. 1, Item #1). For