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Research paper

A scenario-based approach to integrating flow-ecology research with watershed development planning

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HIGHLIGHTS

- We simulate four development scenarios with an agent-based landscape change model.
- We evaluate scenario impacts with 10 ecologically significant flow metrics.
- A flow metric sensitivity typology links flow alterations to plans of actions.
- Integrated stormwater management (ISM) is crucial for reducing flow alterations.
- Compact regional growth may be most important in the absence of ISM.

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ABSTRACT

The ability to anticipate urbanization impacts on streamflow regimes is critical to developing proactive strategies that protect aquatic ecosystems. We developed an interdisciplinary modeling framework to evaluate the effectiveness of integrated stormwater management (i.e., integration of strategic land-use organization with site-scale stormwater BMPs) or its absence, and two regional growth patterns for maintaining streamflow regimes. We applied a three-step sequence to three urbanizing catchment basins in Oregon, to: (1) simulate landscape change under four future development scenarios with the agent-based model Envision; (2) model resultant hydrological change using the Soil and Water Assessment Tool (SWAT); and (3) assess scenario impacts on streamflow regimes using 10 flow metrics that encompass all major flow components. Our results projected significant flow regime changes in all three basins. Urbanization impacts aligned closely with increases in flow regime flashiness and severity of extreme flow events. Most changes were associated with negative impacts on native aquatic organisms in the Pacific Northwest. Scenario comparisons highlighted the importance of integrated stormwater management for reducing flow alterations, and secondarily, compact growth. Based on a flow metric sensitivity typology, six flow metrics were insensitive to development in multiple basins, and four were sensitive to development and manageable with mitigation in multiple basins. Only three metrics were ever sensitive to development and resistant to mitigation, and only in one basin each. Our findings call for regional flow-ecology research that identifies the ecological significance of each flow metric, explores potential remedies for resistant ones and develops specific targets for manageable ones.

1. Introduction

Urbanization has been an important driver of aquatic ecosystem degradation around the world (Miltner, White, & Yoder, 2004). The efficient routing of stormwater off large areas of urban impervious surfaces and into storm sewer systems results in fundamental changes to flow regimes of the downstream rivers and streams (Walsh, Fletcher, & Ladson, 2005). Despite extensive research, the complexity of the problem, insufficient analytical tools, and conflicts among socioeconomic forces have constrained the development of effective solutions that arrest stream degradation. Anticipating the impacts of anthropogenic changes to rivers and streams is critical to developing proactive strategies to maintain *healthy* aquatic ecosystems that, in the words of Meyer (1997) are "sustainable and resilient, maintaining (their) ecological structure and function over time while continuing to meet societal needs and expectations".

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Because the natural flow regime plays a central role in shaping and maintaining stream ecosystems (Poff et al., 1997), understanding how urbanization alters flow regimes is essential for assessing its ecological ramifications. Five flow components – magnitude, frequency, duration, timing, and rate of change – are all critical to the life histories of stream biota, making it necessary to examine a spectrum of flow conditions rather than any single one (Poff et al., 1997). Environmental scientists have developed an array of metrics to quantify pre- and post-disturbance flow conditions and establish direct linkages between urbanization and stream ecology (Clausen & Biggs, 2000; Olden & Poff, 2003; Richter, Baumgartner, Powell, & Braun, 1996). Metrics that are sensitive to human perturbations while also demonstrating ecological significance are the most useful for defining watershed management targets (Arthington, Bunn, Poff, & Naiman, 2006; Bunn & Arthington, 2002; Poff et al., 1997). However, identifying a tractable and biologically relevant suite of metrics that circumscribes all major facets of the flow regime is challenging. The scarcity of paired long-term hydrologic and biologic time-series for deriving flow-ecology relationships typically makes it necessary to rely on general guidance from regional environmental flow studies or best available expert knowledge (Poff et al., 2010). In the work that follows, we have relied on both.

Anticipating urbanization impacts on flow regimes presents multiple challenges. Planners are first confronted with uncertainty about human population growth and land development projections. Future land uses may unfold in unexpected ways due to changes in socioeconomic drivers and land use policy. For example, Oregon has employed a statewide land use planning system that uses Urban Growth Boundaries (UGBs) to create compact urban footprints since the 1970s. By guiding regional growth patterns and concentrating 90% of growth into UGBs, this mechanism has effectively protected Oregon's forests and agricultural lands. However, recent debates on private property rights have led to voter initiatives that called for a substantial relaxation of constraints on rural development (Bassett, 2009), raising concerns about how stream ecosystems would respond to new rural subdivisions.

Scenario-based alternative futures research offers a means to guide landscape decision-making in the face of uncertainty (Hulse, Branscomb, Enright, & Bolte, 2008). Scenarios are essentially plausible and internally consistent narratives (IPCC, 2013) that frame key choices for the future. Scenario analysis explores and evaluates the consequences of different courses of action and associated uncertainties (Peterson, Cumming, & Carpenter, 2003). Unlike forecasts, scenarios are not intended to represent the most probable future conditions, but rather to explore key leverage points that could help shape the future (Mahmoud et al., 2009). For this reason, it is important for scenarios to represent realistic and relevant choices while simultaneously bracketing plausible ranges of uncertainty that could affect the reliability of achieving acceptable outcomes (Davis, Bankes, & Egner, 2007). One of the advantages of scenario-based modeling and assessment is that it can help people understand the long-term consequences of different courses of action applied at large spatial scales (Steinitz et al., 2003). Moreover, scenarios can be designed to support the direct identification of policies that may be targeted (or avoided) to achieve desired outcomes (Mahmoud et al., 2009), and the inclusion of multiple *contrasting* scenarios allows for comparison of a range of policy options.

Another pressing issue is that current knowledge and analytical tools limit our ability to project complex interactions between urbanization and streamflows, let alone to rigorously assess management alternatives. There has been a dramatic increase in the application of dynamic simulation modeling, and many studies have successfully connected land use change models with hydrological models to assess the hydrological impacts of urbanization (e.g., Beighley, Melack, & Dunne, 2003; Legesse, Vallet-Coulomb, & Gasse, 2003; Lin, Hong, Wu, & Lin, 2007). Nonetheless, better characterization of socio-hydrologic dynamics using cross-disciplinary models is needed to meaningfully inform policy choices (Choi & Deal, 2008; Nilsson et al., 2003). As an emerging and promising tool, agent-based models (ABM) (Parker, Manson, Janssen, Hoffmann, & Deadman, 2003) have made it possible to link spatially fine-grained human decisions to their potential landscape-scale consequences through the simulation and evaluation of large ensembles of alternative futures (Guzy, Smith, Bolte, Hulse, & Gregory, 2008).

There has been an increasing call to integrate two approaches for mitigating development-related impacts on aquatic ecosystems: the application of stormwater Best Management Practices (BMPs), and organizing development in hydrologically-sensitive patterns (Alberti et al., 2007; Brabec, 2009). Stormwater BMPs are "techniques, measures or structural controls for managing the quantity and improving the quality of stormwater runoff in the most cost effective manner" (USEPA, 1999), whereas development pattern refers to the spatial organization of land uses (Alberti, 1999).

Integration of these two approaches at the watershed scale holds promise for better protecting streamflow regimes, and through this aquatic ecosystem health, than either strategy alone. Despite its ability to provide some level of watershed protection, current BMP design and implementation may subject stream channels to longer erosive flows (Maxted & Shaver, 1999). A watershed approach to planning, evaluating, and regulating BMPs would likely improve their capacity to adequately manage a broader range of flows (Emerson, Welty, & Traver, 2005; Roesner, Bledsoe, & Brashear, 2001; Urbonas & Wulliman, 2007). Similarly, landscape planners and ecologists have long wrestled with exploring "good" development patterns with respect to stream health. Although many studies have shown that development patterns account for much of the variability in stream ecological conditions, they offer few generalizations about how ecosystem health and human well-being could simultaneously be achieved through innovative planning and design (Alberti et al., 2007; Collinge, 1996; Opdam, Foppen, & Vos, 2001). In particular, there have been few studies that have rigorously tested the capacities of alternative development patterns to maintain streamflow regimes.

We argue that three investigative components need to be fully integrated to simultaneously assess urbanization impacts on stream ecosystems and inform watershed management. The first is that broad spatial patterns of regional population growth must be considered in concert with localized stormwater management. The second is that alternative forms of regional growth and stormwater management should be assessed simultaneously, rather than in isolation, to disentangle their individual effects and discern how they can be integrated at the watershed scale. Finally, we argue that such an approach must assess not only development impacts on individual flow metrics but also on the flow regime as a whole.

To test these ideas, we established an interdisciplinary modeling framework and applied it in three urbanizing catchment basins in Oregon's Willamette Valley. Specifically, we connected an agent-based model of landscape change under contrasting regional growth and integrated stormwater management (ISM) scenarios with a hydrological model to quantitatively evaluate the effects of future urbanization on streamflow regimes. For the purposes of this study, we define the pattern of regional population growth vis à vis urbanization as the spatial and proportional allocation of new urban and rural development, which typically arises from a combination of regulatory policies and market-based forces. We include the implementation of Oregon's statewide land use planning system in this category. In contrast, we define ISM as the combination of localized spatial patterns of development with stormwater BMPs in areas where development is to occur. For example, the former refers to strategies such as limiting overall watershed imperviousness and avoiding development on hydrologically sensitive