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.

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1. Introduction

Urbanization has been an important driver of aquatic ecosystem degradation around the world (Milton, 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 (Claussen & 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-Coulymb, & 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 (Maxedt & 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, & Brashears, 2001; Urbanos & 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
locations (e.g., steep slopes, highly permeable soils, wetlands, etc.), whereas the latter includes the application of Low Impact Development strategies (e.g., rain gardens and permeable pavement) on subdivisions.

We focused our investigations on the following four questions:

1. How does urbanization affect streamflow metrics across different catchment basins? Which flow components may be more sensitive to development?
2. What might be the ecological consequences of projected flow regime alterations?
3. Are compact regional growth and integrated stormwater management effective approaches for maintaining streamflow regimes? If so, which is more important?
4. How might integrated modeling frameworks such as that demonstrated inform future efforts to link flow-ecology research to local watershed planning?

2. Methods

We conducted a three-step sequence of land use change simulation, hydrological modeling, and hydrological assessment (Fig. 1). We chose an agent-based model Envision (formerly Evoland) (Bolte, Hulse, Gregory, & Smith, 2006; Hulse et al., 2008) to simulate multiple development scenarios comprised of different combinations of regional growth and ISM strategies. A hydrological model, the Soil and Water Assessment Tool (SWAT) (Gassman, Reyes, Green, & Arnold, 2007), was applied to the resulting landscape of each scenario to model long-term daily streamflows. Finally, we used a set of 10 ecologically meaningful flow metrics to assess the degree of flow alterations in different future scenarios compared to reference conditions, and to explore watershed management implications.

Envision is a spatially explicit multi-agent framework for assessment of policies and alternative futures of land use change. Central to Envision are the interactions among three components: policies, actors (aka agents), and the landscape (Hulse et al., 2008). Policies are descriptors of land management actions. Actors make decisions about the portion of the landscape under their authority by selecting policies responsive to their objectives. Landscape changes resulting from actor decisions and other autonomous processes are simulated and assessed. Envision offered several key advantages: (1) its spatial reporting units of Integrated Decision Units (IDUs, described later) retained the integrity of taxlot boundaries, topography, and soil series units, allowing it to simulate the way landowners manage their land based on its physical characteristics and ownership boundaries; (2) it establishes a direct linkage between policies and land use trajectories; (3) it had been programmed to incorporate Oregon’s UGB-centered land use planning system; and (4) by supporting alternative policy sets, each of which can generate numerous future landscapes, Envision supports the evaluation of different plans of action in the context of plausible ranges of variability in how they might manifest.

SWAT is a watershed-scale, physically-based, long-term, continuous-event model for projecting the impacts of land management practices on water, sediment, and chemical yields (Gassman et al., 2007). We selected SWAT because: (1) it employs a comprehensive approach to integrate interactions among physical processes (e.g., weather, plant growth, and management); (2) its Hydrologic Response Unit (HRU) spatial structure accords well with Envision’s IDU structure; (3) its temporal scale (daily time step and long term) supports assessments of dynamic long-term flow alterations; (4) climate information can be easily incorporated; and (5) SWAT can simulate both urbanized and rural watersheds of various sizes.

Below we introduce the area of interest, the selection of flow metrics supported by SWAT calibration and validation, the land use change simulation and hydrological modeling processes, and methods for data analysis.

2.1. Study area

Oregon’s Willamette Valley population is projected to double from approximately 2 to 4 million between 1990 and 2050, providing a natural laboratory for experimenting with innovative planning strategies. The land use change simulation area (dashed outline, Fig. 2) closely corresponds to that (solid outline) of a precedent research project, the Southern Willamette Coupled Natural and Human Systems (SWCNH) project, which simulated the interactions and feedbacks among climate change, wildfire, vegetation, policies and landowner decisions (Johnson, unpublished data). The 409 km² hydrological modeling area includes three catchment basins (A, B, and C, Fig. 2) adjacent to the UGBs of Veneta, Creswell, and the Eugene-Springfield Metropolitan Area. Our simulations took advantage of a large dataset and parameterizations developed by the SWCNH project, including detailed statewide population projections that were localized to the modeling area through an intensive stakeholder engagement process. Table S1 (see Appendix A for all supplemental tables) describes data sources and quantitative tools used in this study.

The hydrological modeling area is primarily rural with ~0.27 people/ha. Urban, agricultural, forestry, and rural residential land uses occupy 3%, 19%, 57%, and 10% of the ca. 2000 landscape, respectively (Fig. 3-I). Average slope is 15%. Low permeability soils dominate the landscape, with <0.001% Hydrologic Soil Group (HSG) A, 7% HSG B, 60% HSG C, and 33% HSG D soils. Current landscape characteristics vary substantially across the three basins (Table S2).

![Fig. 1. The overall modeling process.](image-url)
The smallest Basin A is the flattest and most urban (11% urban) with the least permeable soils. The intermediate-sized Basin B (3% urban) has the most permeable soils. The largest Basin C is the steepest and least urban (2% urban).

2.2. Selection of flow metrics

Identifying a coherent suite of ecologically significant flow metrics is critical for a hydrological assessment intended to inform local watershed management. This proved challenging due to the absence of flow-ecology knowledge for small streams in the foothills of the southern Willamette Valley. We drew from research in nearby regions as well as consultation with regional professionals, basing our selection on the following four criteria: (1) the set of metrics circumscribes all major flow components (Olden & Poff, 2003); (2) each metric demonstrates biological significance in the U.S. Pacific Northwest (PNW) (D. Booth, M. Dieterich, and C. DeGasperi, personal communications, 2014); (3) metrics calculated from simulated hydrographs agree well with those from gauged data; and (4) annual values can be calculated directly from SWAT outputs or using the Indicators of Hydrologic Alteration (IHA) tool (Richter et al., 1996). The final set consisted of 10 metrics (Table 1): Annual Average Flow (Qmean), 1-day Maximum Flow (1DMAX), 7-day Minimum Flow (7DMIN), Low Pulse Count (LPC), High Pulse Count (HPC), Number of Zero-flow Days (N0D), Low Pulse Duration (LPD), High Pulse Duration (HPD), Date of Annual Minimum (TL1), and Richards–Baker Flashiness Index (RBI). Next, we elaborate the process of SWAT calibration and validation that played an essential role in supporting our metric selection.

2.3. SWAT calibration and validation

The SWAT model must be calibrated to ensure that local hydrological processes are represented appropriately. We went beyond the standard procedure of developing a general goodness-of-fit between simulated and observed daily hydrographs (Arnold et al., 2012) to achieve a specific calibration for the 10 flow metrics noted above.

Observed daily streamflow data from 1977 to 1987 at the discontinued USGS Coyote Creek gauge (Fig. 2) was used as a reference to evaluate simulated hydrographs. Water years (WY) 1978–1982 (1977/10/1–1982/9/30) were used as the calibration period, and WY 1983–1987 (1982/10/1–1987/9/30) for validation. Meteorological records were extracted from the Eugene/Mahlon Sweet Airport Weather Station. Calibration and validation were performed with the ca. 1990 land cover map due to absence of reliable earlier land cover information. Historic aerial photos (ca. 1968 and 1979) were carefully examined to confirm that few local land cover changes occurred during 1977–1990, following adoption of Oregon’s statewide land use planning laws in the early 1970s.

A large number of manual (~400) and auto-calibration (~400) repetitions were performed in SWAT and SWAT Calibration and Uncertainty Procedures (SWAT-CUP) (Abbaspour, 2007). In a standard procedure, the Nash and Sutcliffe Efficiency (NSE, range $-\infty$ to 1) and $r^2$ (coefficient of determination, range 0 to 1) are the most commonly used statistics to assess SWAT predictions (Arnold et al., 2012). Both NSE = 1 and $r^2 = 1$ represent a perfect correlation between the simulation and observation. In general, a value exceeding 0.5 for both statistics is deemed satisfactory for daily calibrations (Caldwell et al., 2015; Moriasi et al., 2007). Our final daily calibration achieved NSE = 0.775 and $r^2 = 0.777$ for the calibration period and NSE = 0.785 and $r^2 = 0.786$ for the validation period (Fig. 4). In addition, we applied the Wilcoxon Signed-Rank Test to compare the 10 flow metrics calculated from gauged and simulated data. Except for the 1-day Maximum Flow (1DMAX) and Richards–Baker Flashiness Index (RBI) (both consistently under-predicted), all other metrics presented non-significant differences when calculated from the two sources ($p > 0.05$) (Table S3), demonstrating that our calibration produced sufficiently accurate projections of the flow conditions. The 1DMAX and RBI were retained as important measures of their respective flow components with the caveat that their results were interpreted in the
context of consistent model under-estimation. Table S4 reports the values of calibrated parameters.

2.4. Land use simulation with Envision

In this section we introduce the processes of setting up the land use change simulation, important Envision mechanisms, and the scenario design and policy development.

2.4.1. Envision model setup

We followed the basic steps below to set up the land use change simulation.

(1) Develop an Integrated Decision Units (IDU) map for the study area. Over 80,000 IDUs (averaging 1 ha in area) were delineated in ArcGIS by intersecting taxlots, topography, and soil phase polygons.
Table 1
Description of the 10 selected flow metrics and rationale linking them to urbanization and biological responses.

<table>
<thead>
<tr>
<th>Component</th>
<th>Flow Metrics</th>
<th>Definition</th>
<th>Expected Response to Urbanization</th>
<th>Correlation with PNW B-IBI</th>
<th>Rationale Linking Flow Metrics to Urbanization and Biological Responses</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnitude</td>
<td>Qmean</td>
<td>Average daily flow rate for each water year</td>
<td>Varied</td>
<td></td>
<td>1) Critical component of the water balance with various uses to humans. 2) Related to water quality, habitat area, and fish and benthic assemblages.</td>
<td>KB2005, C2005, B2004, M2008</td>
</tr>
<tr>
<td></td>
<td>1D.MAX</td>
<td>Maximum daily flow rate for each water year</td>
<td>Increase</td>
<td></td>
<td>1) Measure of the largest annual flow disturbance. 2) An increase indicates larger disturbance for habitat structuring and floodplain exchange, more direct mortality or transport of organisms, and longer recovery time, etc.</td>
<td>KB2005, R1996</td>
</tr>
<tr>
<td>Frequency</td>
<td>7DMIN</td>
<td>Centered seven-day moving average annual minimum flow (calendar year)</td>
<td>Varied</td>
<td></td>
<td>1) A decrease indicates reduced aquatic habitat availability and more desiccation stress.</td>
<td>C2005, R1996</td>
</tr>
<tr>
<td></td>
<td>LPC</td>
<td>Number of times that the daily average flows are equal to or less than the low-flow threshold</td>
<td>Increase(^1)</td>
<td>Negative</td>
<td>1) An increase indicates more interruptions of the low-flow season. Frequent disturbances may degrade biological diversity.</td>
<td>C2005, D2009, KB2005, R1996</td>
</tr>
<tr>
<td></td>
<td>HPC</td>
<td>Number of times that the daily hydrograph rose above the high-flow threshold</td>
<td>Increase(^1)</td>
<td>Negative</td>
<td>1) An increase indicates more frequent high-flow disturbances that continually destabilize channels. 2) Provides the single most useful measure for benthic assemblages.</td>
<td>C2005, CB2000, D2009, K2002, R1996</td>
</tr>
<tr>
<td>Duration</td>
<td>NOD</td>
<td>Number of days with a daily average flow equal to zero for each water year</td>
<td></td>
<td></td>
<td>1) A measure of the accumulation of desiccation effects on aquatic organisms; may determine whether a particular life-cycle phase can be completed. 2) An increase indicates longer desiccation effects.</td>
<td>R1996</td>
</tr>
<tr>
<td></td>
<td>LPD</td>
<td>Annual average duration of low flow pulses during a calendar year</td>
<td>Decrease(^1)</td>
<td>Positive</td>
<td>1) Decrease indicates shorter recovery time between disturbances for stream organisms.</td>
<td>C2005, D2009, R1996</td>
</tr>
<tr>
<td></td>
<td>HPD</td>
<td>Annual average duration of high flow pulses during a water year</td>
<td>Decrease(^1)</td>
<td>Positive</td>
<td>1) A decrease means flow conditions alter more rapidly from high to low flow conditions, i.e., higher flashiness.</td>
<td>C2005, D2009, R1996</td>
</tr>
<tr>
<td>Timing of Low Flows</td>
<td>TL1</td>
<td>Julian day of the date of the minimum daily average flow during a calendar year</td>
<td>Decrease</td>
<td></td>
<td>1) Relates to life cycles of organisms, influences predictability of stress (e.g., higher temperatures).</td>
<td>CB2000, R1996</td>
</tr>
<tr>
<td>Flashiness</td>
<td>RBI</td>
<td>Richards-Baker Flashiness Index (Unitless)</td>
<td>Increase(^1)</td>
<td>Negative</td>
<td>1) Low interannual variability and thus greater power to detect trends in the daily rate of change. 2) An increase can indicate significant disturbance for organisms adapted to more stable flows.</td>
<td>B2004, C2005, D2009</td>
</tr>
</tbody>
</table>

\(^1\) Sensitivity to urbanization has been demonstrated in PNW literature.

Fig. 4. Mean daily flows from observed vs. simulated data for WY 1978–1987 (USGS 14167000 Coyote Creek near Crow, Oregon).
(2) Populate the IDUs with relevant static or dynamic site attributes, e.g., Hydrological Soil Group (static) and land use/land cover (LULC, dynamic). See Table S5 for a dictionary of 48 key attributes.

(3) Assign one of seven types of actors and associated actor values to each IDU. Each actor is associated with a set of values that reflect how their value systems influence land management decisions. A set of five rural actor types was developed and parameterized based on surveys of ~1000 rural landowners (Nielsen-Pincus, Ribe, & Johnson, 2015). Two additional types, urban residents and a public lands manager, were added to better incorporate urban and public land management.

(4) Develop a set of four land development scenarios and associated assumptions (described below).

(5) Define regional population projections for each scenario based on previous research from the SWCNH project.

(6) Develop a set of policies for each scenario that implements both the spatial population allocation needed to fulfill the selected regional growth scenario, and the spatial implementation (or absence) of specific ISM strategies. Table S6 offers an example policy for riparian conservation.

Once these components were implemented, the following processes operate in Envision to generate alternative landscapes for each scenario.

(1) As population grows, Envision prioritizes the locations of new residents in favor of IDUs with larger available population capacity. New population is allocated proportionally into UGBs or new rural residential zones based on scenario assumptions. Each IDU belongs to a zoning category whose allowable population density can be updated through policies.

(2) Envision mimics the mechanism of Oregon’s UGB-centered land use planning system and updates the UGBs every 10 years to meet capacity targets for maintaining at least a 20-year developable urban land supply.

(3) Actors make management decisions (or take no action) on their IDUs every 5 to 10 years depending on the actor type by selecting policies that best align with their values.

(4) IDU attributes are updated each annual time step based on population growth, policy applications, or vegetation succession.

(5) Replicate model runs can be conducted for each scenario to produce variations in landscape outcomes within and across scenarios based on stochastic mechanisms included in population allocation, actor decision-making, vegetation succession, etc.

2.4.2. Design and implementation of scenarios and policies

Our development scenarios consisted of $2 \times 2$ factorial combinations of regional growth and integrated stormwater management scenarios. To explore the consequences of potential changes to Oregon’s land use planning policies, we defined two regional growth scenarios, Compact vs. Dispersed Growth. To examine the combined effectiveness of various stormwater management strategies, we developed two management scenarios, with vs. without Integrated Stormwater Management (ISM). The four scenarios are referred to as Compact Growth with ISM (CM), Compact Growth without ISM (CnM), Dispersed Growth with ISM (DM), and Dispersed Growth without ISM (DnM), respectively.

The assumptions and policy emphases of the four scenarios differ in important ways (Table 2). The compact growth scenarios assumed that current statewide land use planning policies continue to accommodate 90% of new population within existing or expanded UGBs, and 10% within rural areas. In contrast, the dispersed growth scenarios relaxed land use planning policies and distributed only 65% of population growth into UGBs, allowing 35% to be dispersed into rural areas. The two management scenarios differed in ISM implementation. The no-ISM scenarios implemented very limited policies to mitigate stormwater impacts, whereas the ISM scenarios incorporated a variety of ISM strategies to mitigate stormwater impacts. Overall, seven categories of policies were developed to support urban and rural growth processes and ISM strategies, and selected policies were applied to each scenario to form scenario-specific policy sets (Table S7). Policies are not applied to all IDUs with qualifying site attributes, but rather at plausible rates and spatial extents commensurate with scenario assumptions.

Testing ISM policies is new in Envision applications. We drew from previous research to incorporate a variety of watershed planning strategies into ISM policy development. These strategies include: (1) limiting development on steep slopes and permeable soils (Yang & Li, 2011); (2) protecting large vegetative patches, riparian buffers, and wetlands (Alberti et al., 2007; Meador & Goldstein, 2003; Morley & Karr, 2002); (3) limiting overall watershed imperviousness (Schueler, Fraley-McNeal, & Cappiella, 2009); (4) reducing directly connected imperviousness by widespread re-infiltration LIDs (Booth et al., 2004; Lee & Heaney, 2003); (5) encouraging cluster or high-density development to protect natural vegetation and provide more open space (Berke et al., 2003; Girling & Kellett, 2002; USEPA, 2006); and (6) encouraging development close to existing infrastructure and permeable pavement on light-duty roads to reduce road impacts (Alberti et al., 2007). Each strategy was translated into single or multiple Envision policies (Table S7) that were parameterized with plausible adoption rates, spatial locations and extents, and landscape outcomes. When ISM policies were applied to mitigate development impacts on IDUs, runoff reduction effects were calibrated in SWAT through modifications of the runoff generation characteristics of these IDUs depending on their LULC and soil types (described later).

Ten replicates of every scenario were run in Envision from 2007 to 2050 at an annual time step. As noted before, each simulation run produces a unique future landscape. Because modeling every run of every scenario in SWAT was intractable due to the efforts required to set up each landscape, we selected one landscape for each scenario that represented that scenario’s central tendencies. Based on the most frequent LULC outcome (the mode) for each IDU, the run that generated the highest percentage of IDUs with the same LULC types as the modes was deemed representative of that scenario (Appendix B). The four selected landscapes were then subjected to hydrological modeling in SWAT.

2.5. Hydrological modeling with SWAT

Despite increasing application in urban environments, SWAT’s urban database was underdeveloped for our purposes. For instance, only four urban residential land types (<0.5, 0.5–1, 1–4, and >8 du/ac) were available, without the common 4–8 du/ac zone, let alone any differentiation for stormwater management. We therefore developed three procedures (Appendix C) to expand SWAT’s database for a more accurate representation of land cover types associated with stormwater management: (1) we developed Curve Numbers (Appendix C) for new prototype LULC and BMP associations, e.g., new high-density residential development with a full range of lot-level LIDs, using the model L-THIA (Long Term Hydrologic Impact Analysis) (Ahiablame, Engel, & Chaube, 2012); (2) to better account for the higher-density development encouraged in ISM scenarios, we measured the imperviousness in urban residential zones with densities ≥4 du/ac in Portland, OR; (3) to develop imperviousness data for rural residential development, we...
measured the impervious area associated with 40 local rural houses in different county zoning classes using Google Earth™.

With the expanded land cover database, the calibrated SWAT model was used to simulate 30-year daily streamflows for the four development scenario landscapes at each of the three basin outlets. Simulated daily streamflow based on the ca. 1990 landscape and historical climate (Wy 1978–2007) was chosen as the reference flow regime for each basin. To examine direct development impacts, simulations of future scenarios used the same historical climate of Wy 1978–2007. Given the unrealistic goal of returning the landscape to pre-Euro-American settlement conditions, we evaluated the degree of departure from the reference. The scenario resulting in the least flow regime departure was deemed the most preferable (Poff & Zimmerman, 2010). Upon completion of SWAT modeling, the 10 selected flow metrics were calculated either directly or in IHA (Richter et al., 1996). Our final raw data contained 30 annual values for each of the 10 metrics for 3 basins over a total of 5 scenarios (four development and one reference).

2.6. Data analysis

We applied multiple group comparison tests to compare individual flow metric responses under each development scenario for each basin. Because flow metric data were severely skewed, we applied a non-parametric repeated measures analysis of variance test (the Friedman’s ANOVA) to compare metrics among the four development and one reference scenarios, i.e., 30 annual values per metric per scenario for each basin. When \( p < 0.05 \), the Wilcoxon Signed-Rank Test with Bonferroni correction (significance level set as \( p < 0.05 \)) was used for post-hoc paired comparisons.

To interpret flow metric responses for watershed management, we developed a sensitivity classification system (Table 3) to categorize the metrics in each basin into three types according to the magnitude of change in their medians and the degree to which such changes could be mitigated: insensitive to development, sensitive to development and manageable by development alternatives, and sensitive to development and resistant to development alternatives. Insensitive refers to metrics not influenced by development in any future scenario compared to the reference. Sensitive and manageable (hereafter referred to as manageable) refers to metrics substantially affected by development, but for which impacts could be mitigated by compact growth and/or ISM in one or more scenarios. Sensitive and resistant (hereafter referred to as resistant) refers to metrics that were significantly affected by urbanization in all future scenarios, but were resistant to simulated planning and management strategies. The manageable metrics suggest important opportunities for flow management, whereas the resistant metrics indicate flow alterations that consistently follow future development with fewer opportunities to mitigate using the tools tested.

To evaluate overall flow regime differences between each future scenario and the reference, we created two summary variables using a rank-transformed flow metric dataset. For each metric in each year and basin, we ranked the values across all scenarios. For each Future scenario, we then took the differences between the scenario and reference ranks for each year and squared them. For each metric, we used the sum of these 30 annual values per scenario and basin, i.e., the Sum of Squares of rank differences (SSrd), to measure the relative difference of each future scenario from the reference. We then computed the Standardized Rank Deviation (SRD) from the reference for each future flow regime in each basin as the square root of the (SSrd across all metrics)/(number of metrics x number of years). The SRD thus measures the overall average difference in rank of each future flow regime relative to the reference, assuming each metric is of equal importance. Because the ranks of one scenario depend on those of other scenarios, we did not perform statistical comparisons and present the results for illustration only.

3. Results

3.1. Land development conditions

Future population outcomes (Table S8) and land development patterns (Fig. 3) varied substantially across scenarios and basins. In general, a tripling of the population from ca. 2000 was projected by 2050 across the three basins. The dispersed scenarios resulted in larger population increases than their compact counterparts because of the spatial population dynamics of the larger land use change simulation area (Fig. 2) used for the regional population growth model. Because the three basins contained high proportions of land suitable for rural development, dispersed scenarios resulted in 11% (DM/CM) and 18% (DnM/CnM) higher total populations than their compact counterparts, whereas ISM scenarios resulted in 18% (CM/CnM) and 11% (DM/DnM) higher total populations than their no-ISM counterparts.
Table 3
Typology for flow metric sensitivity to stressors and management. Each flow metric was classified in each basin as either insensitive to development, sensitive to development and manageable by development alternatives, or sensitive to development and resistant to development alternatives. For a metric to be classified insensitive, there was either no statistical difference from reference under any development scenario, or if there was a significant difference, the magnitude of change was <5% (or <3 days for NOD & TL1). For a metric to be classified sensitive, there must be statistically significant effects with a magnitude of change ≥5% (or ≥3 days for NOD & TL1) in one or more development scenarios. For a metric to be sensitive and manageable, there must be statistically significant effects with a magnitude between 5–25% (or 3–7 days for NOD & TL1) in one or more development scenarios. For a metric to be sensitive and resistant, there must be statistically significant effects of >25% (or >7 days for NOD & TL1) under every development scenario.

<table>
<thead>
<tr>
<th>Type</th>
<th>Sensitivity to change</th>
<th>Manageability</th>
<th>Magnitude of significant absolute median change for NOD/TL1</th>
<th>Magnitude of significant absolute median change for all other 8 metrics</th>
<th>Number of scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Insensitive</td>
<td>Not influenced by development</td>
<td>NA</td>
<td>Non-significant or &lt;3 days</td>
<td>Non-significant or &lt;5%</td>
<td>All scenarios</td>
</tr>
<tr>
<td>2. Sensitive and Manageable (i.e., Manageable)</td>
<td>Substantially influenced by development</td>
<td>Impacts mitigated by one or more alternatives</td>
<td>3–7 days</td>
<td>5–25%</td>
<td>One or more scenarios</td>
</tr>
<tr>
<td>3. Sensitive and Resistant (i.e., Resistant)</td>
<td>Substantially influenced by development</td>
<td>Impacts unmitigated by development alternatives</td>
<td>&gt;7 days</td>
<td>&gt;25%</td>
<td>All scenarios</td>
</tr>
</tbody>
</table>

The area of urban developed land increased an average of 63%, with more than twice the increases in the ISM scenarios than their no-ISM counterparts due to the area allocated for BMPs. The area of rural residential development increased an average of 79%, with more than twice the increases in the dispersed scenarios than their compact counterparts. When both urban and rural growth were accounted for, the total development footprint increased an average of 75%. Compact scenarios constrained increases to 1/2 of those of the dispersed scenarios, whereas ISM scenarios constrained increases to 2/3 of their no-ISM counterparts because strategic land conservation was employed as an ISM strategy. Total impervious area increased an average of 69%, and increases were 1/3 higher in dispersed than compact scenarios. Agricultural land decreased across all future scenarios due to urban and rural development and restoration of hydrologically-sensitive areas. However, losses amounted to only 18% in the no-ISM scenarios, compared to 63% in the ISM scenarios. In contrast, forested land increased 19% in the ISM scenarios due to maturing of natural vegetation and restoration of hydrologically-sensitive areas with only minor changes (−2%) in the no-ISM scenarios.

3.2. Flow metric responses

Of the ten flow metrics, 50% showed significant changes in all three basins under one or more development scenarios. This included 80% of metrics for Basins A and C, and 60% for B. For Basin A, LPD and HPD did not change. For Basin B, 7DMIN, NOD, LPD, and TL1 did not change. For Basin C, 7DMIN and HPD did not change. With important exceptions, most metrics showed the same direction of change from reference conditions across all future development scenarios. Even when the directions were the same, the magnitude of change varied substantially among scenarios. Fig. 5 highlights significantly different scenario groups for each metric and basin (see Table S9 for detailed statistics). Fig. 6 shows deviations from the reference for all metrics by basin and scenario. Below we examine changes in each individual metric.

3.2.1. Magnitude

3.2.1.1. Annual average flow (Qmean). The Qmean significantly changed (−2% to 5%) in all three basins under certain future scenarios, with varied directions of change across basins and scenarios. In Basins A and B, scenarios CM and DM caused a decrease, while CNM and DNm caused an increase. In Basin C, all future scenarios showed an increase.

3.2.1.2. Annual maximum flood (1DMAX). The 1DMAX increased (2–31%) in all future scenarios for all three basins. Basin C showed the greatest increase (13–31%), while B showed the smallest (2–25%). In terms of distance from the reference, the scenario rankings were identical for all three basins: CM < DM < CNM < DNm (Fig. 6). CM maintained the median changes within 6% for Basin A, 2% for B, and 13% for C. In contrast, DNm caused a 30% increase in Basin A, 25% in B, and 31% in C.

3.2.1.3. 7-day minimum (7DMIN). The 7DMIN substantially decreased in Basin A by nearly identical amounts (−85% to −90%) among the four future scenarios. The medians couldn’t decrease in Basins B and C because their values were already zero in the reference.

3.2.2. Frequency

3.2.2.1. Low pulse count (LPC). The LPC showed substantial but varied responses (0–600% increase) across scenarios and basins. Increases were pronounced in DM, CNM, and DNm for Basin A (25–50%), CNM and DNm for B (0–20%), and in all four future scenarios in C (400–600%). Basin C, with the largest increases, had only 1 continuous low-flow event/year under the reference, but the low flow was more frequently interrupted by 4–6 additional higher-flow events, indicating a much flashier dry season. DNm consistently generated the most increases for all three basins with 1–6 more low pulses/year.

3.2.2.2. High pulse count (HPC). In general, the HPC showed an increase in future scenarios. Changes in the medians ranged from 14–21% for Basin A, 0–13% for B, and 14–43% for C. DNm consistently generated the most increases for all three basins with 1–3 more high pulses/year.

3.2.3. Duration

3.2.3.1. Number of zero-flow days (NOD). The NOD significantly changed in all future scenarios in two basins (A and C) with varied directions of change. More dry days occurred in A but less in C. Basin A had year-long continuous flows under the reference, but dried out for an additional 7–10 days/year in all future scenarios. In contrast, Basin C showed 1–2 fewer dry days/year in all future scenarios.
### Flow metric responses across future development scenarios (ca. 2050) assessed with historical climate

Central column "REF" indicates the reference scenario (1990 landscape, historical climate). Scenarios are ranked from minimum to maximum according to median flow metric values. Median values may be similar even when statistical differences are present. Compact and dispersed scenarios are represented in green and purple, respectively. ISM scenarios are patterned with diagonal lines. Scenarios that are significantly different are separated by bold black outlines. * N0D and TL1 are represented with difference in "days" instead of % difference. † When the median value of the reference flow regime was 0, actual difference instead of % difference from the reference is reported. ‡ Means instead of medians are reported in this unique case (N0D in Basin A) to more appropriately represent the trend in this metric. § Direction of change compared to the reference conditions. + = increase, − = decrease, ns = no significant change. # Expected effects of significant changes on native aquatic biota as indicated by literature and regional professionals. NA = not applicable.

### 3.2.3.2. Low pulse duration (LPD)

The LPD only significantly decreased (−61%) in DnM in Basin C.

### 3.2.3.3. High pulse duration (HPD)

The HPD only significantly decreased (−26%) in DnM in Basin B.

### 3.2.4. Timing

#### 3.2.4.1. Date of annual minimum (TL1)

The TL1 significantly changed under certain future scenarios in two basins (A and C) with varied directions of change. The annual minimum occurred 5–13 days earlier in all future scenarios in Basin A, as compared to 2.5 days later in CM and DM in Basin C.
3.2.5. Flashiness

3.2.5.1. Richards–Baker Flashiness Index (RBI). The RBI increased in every future scenario for all three basins. It showed a slightly smaller increase in Basin B (6–31%) than in A (11–36%) and C (15–36%). Scenario rankings in departure from the reference were identical for all three basins: CM < DM < CnM < DnM (Fig. 6).

3.3. Sensitivity to urbanization and overall flow regime alteration

The flow metric classification system identified 43.3% of the metrics as insensitive, 46.7% as manageable, and 10% as resistant (Table 4). Metrics with no more than minor changes (insensitive) included Qmean (all three basins), 7DMIN, NOD, TL1, LPD, and HPD (two basins each). Metrics that were manageable under simulated strategies included 1DMAX, HPC, and RBI (all three basins), LPC (two basins), LPD, HPD, and TL1 (one basin each). Flow alterations that consistently followed future development and were mitigated by any scenario (resistant) included a substantial decrease in 7DMIN and increase in NOD (both in Basin A), as well as a substantial increase in LPC (Basin C).

Compact and ISM scenarios outperformed their dispersed and no-ISM counterparts in reducing flow alterations. The overall flow regime departures of future scenarios from the reference showed an identical pattern in all three basins: CM < DM < CnM < DnM (Fig. 7). Scenario CM, which consistently showed the least overall departure, constrained the absolute changes in the medians of the manageable metrics within 25% for Basin A, 6% for B, and 15% for C. In contrast, DnM restricted the corresponding changes within 50% for Basin A, 31% for B, and 58% for C (Fig. 5).

Basins A and C experienced more considerable changes than B (Fig. 7), with A being the most influenced, based on the SRD values for the four scenarios (Table S10). Basin A also showed the largest number of resistant and smallest number of insensitive metrics. Specifically, A had 30% insensitive, 50% manageable, and 20% resistant metrics; B had 50% insensitive and 50% manageable metrics; and C had 50% insensitive, 40% manageable, and 10% resistant metrics.

4. Discussion

The landscape change model and associated policy sets were designed to apply the guiding concepts underlying each scenario (Table 2) to the creation of plausible representations of the kinds of future landscapes being explored by contemporary planners and designers (Fig. 3-II). We consider detailed attention to the spatial and temporal processes of landscape change (Fig. 8 and supplemental animation) to be essential for applying a fine-grained, process-based hydrological model to proposals for watershed management and, in turn, for enabling planners and designers to interpret and use the results.

The projected hydrological impacts were largely consistent with those of other studies of urbanization impacts on streams, while highlighting the challenges of developing reliable rules of thumb for management. In particular, in contrast to the consistent scenario rankings for overall flow regime impacts, the effects on individual metrics varied substantially in both magnitude and occasionally sign across the three adjacent basins. Below we connect hydrological responses to watershed management by addressing our four original questions.

(Q1) How does urbanization affect streamflow metrics across different catchment basins? Which flow components may be more sensitive to development?

All future development scenarios tended to alter the majority of flow metrics, and in the same direction, across all basins (Fig. 5). In general, the projected metric responses were consistent with literature of urbanization impacts on stream hydrology (Coleman, Miller, & Mink, 2011; Konrad & Booth, 2005; Wenger et al., 2009). All three streamflows became flashier: the largest flood (1DMAX) intensified, extreme low flows (7DMIN) became lower, both low- and high-flow events occurred more frequently (LPC and HPC increased), and overall flashiness (RBI) increased.

However, results also differed among basins in important ways, showing varied catchment sensitivity to development even among
adjacent basins. For example, aquatic organisms experienced more dry days (N0D) in Basin A but fewer in C. Similarly, the annual minimum (TL1) occurred earlier in Basin A but later in C. The varied directions of change in these two metrics, both measures of extreme low flows, suggest that urbanization impacts on certain types of flow metrics may be more dependent on basin physiography than others.

Some flow metrics may be more sensitive to urbanization than others. Four metrics (1DMAX, LPC, HPC, and RBI) were identified as sensitive (Types 2 and 3) in at least 2 basins, whereas four others (Qmean, LPD, HPD, and TL1) remained insensitive (Type 1) in at least 2 basins and were never resistant in any basin (Table 4). In some cases, metrics showed high sensitivity in a certain basin as opposed to others (e.g., 7DMIN and N0D were resistant in Basin A but insensitive in B and C). Overall, the magnitude of extreme flow events (1DMAX and 7DMIN), frequency of high and low pulses (LPC and HPC), and flashiness (RBI) may be more sensitive to urbanization than annual average flow (Qmean), duration of high and low flows (LPD and HPD), and the timing of extreme low flows (TL1). Caution should be applied in interpreting the 7DMIN results due to SWAT’s poor performance in simulating summer low flows (Caldwell et al., 2015) and empirical evidence that summer low flows do not consistently decline in the PNW as a result of urbanization, but instead are more affected by water management activities such as regional wastewater conveyance (Konrad & Booth, 2005). Nonetheless, the pattern of varied metric sensitivity could be broadly applicable to other regions and was only possible to discern through the use of a suite of metrics that represented all major flow components across multiple basins.

Similarly, some flow components may be more manageable with mitigation strategies than others. All the manageable metrics except for one (1DMAX, LPC, HPC, LPD, HPD, and RBI vs. TL1) are measures of extreme high flows or flashiness, whereas all the resistant metrics (7DMIN, LPC, and N0D) are related to low flows. This
suggests that the mitigation strategies tested were effective in constraining increases in hydrologic variability, whereas maintaining historical low flows was more challenging.

(Q2) What might be the ecological consequences of projected flow regime alterations?

Given the paucity of knowledge about how various flow alterations may affect aquatic organisms in the southern Willamette Valley, it is difficult to evaluate the potential ecological ramifications of our results. Nonetheless, the consistently high levels of impact on four metrics (Fig. 5, DMAX, LPC, HPC, and RBI) in directions that have been shown to have negative ecological impacts in the PNW (Table 1) and more generally on ecological processes (Poff et al., 1997), suggests that projected human population growth is likely to impose detrimental effects on native aquatic organisms for the reasons described next.

First, because of more frequent flooding (e.g., 14–43% increase in HPC in 2 of 3 basins), increased scouring and sedimentation of stream beds is likely to affect both fish and macroinvertebrate population assemblages, likely favoring non-natives more tolerant of higher sediment loads (Coleman et al., 2011; Poff & Allan, 1995). Second, more extreme floods (e.g., 25–31% increase in DMAX in the worst-case scenario) could cause direct mortality. Third, the substantially flashier flow regimes (e.g., 31–36% increase in RBI in the worst-case scenario, and LPC being resistant with 400–600% increases in one basin) will likely favor fish species with more generalized feeding strategies over those with specialized strategies (Poff & Allan, 1995). Smaller and more mobile benthic invertebrate species that reproduce multiple times a year (i.e., multivoltine species) may be better adapted to increased flashiness than larger and univoltine or semivoltine species with limited mobility (Cassin et al., 2005). Fourth, lower summer flows (e.g., >85% decrease of 7DMIN in one basin) are likely to reduce the wetted perimeter and habitat availability, and to discourage lateral exchanges between the in-stream habitat and riparian corridor (Coleman et al., 2011). Associated indirect effects, such as increased water temperatures and reduced dissolved oxygen, will likely impose more stress on native stream biota. The potential for such direct and indirect impacts to aquatic organisms highlights the importance of regional flow-ecology studies that can link projections of hydrological modifications to their ecological consequences. Moreover, the projected greater flow regime flashiness points to the importance of riparian and wetland conservation. Species recovery after intensified flow disturbances may require greater reliance on nearby refugia (e.g., hyporheic zones, adjacent hydrodynamic dead zones) sustained by continuous and healthy riparian corridors (Lancaster & Belyea, 1997; Niemi et al., 1990).

(Q3) Are compact regional growth and integrated stormwater management approaches for maintaining streamflow regimes? If so, which is more important?

Our results provide strong evidence that an integrated stormwater management approach combined with compact regional growth can protect streamflow regimes. First, the compact and ISM scenarios outperformed their respective counterparts in limiting alterations not only to the overall flow regime (Fig. 7), but also to the majority of individual metrics (Fig. 6). Second, the small proportion of resistant metrics (overall 10%, Table 4) suggests that compact growth combined with ISM effectively constrained alterations to the majority of sensitive metrics to within the threshold we defined as manageable. Third, in every case but one (HPC in Basin A), when metrics were manageable, the best-case scenario (CM) incurred less than half the change of the worst-case scenario (DNM), highlighting the risks of not attempting to mitigate impacts. In particular, for the four metrics (1DMAX, LPC, HPC, and RBI) that showed consistent negative ecological impacts across all basins (Fig. 5), scenario CM reduced alterations 60–75% over DNM, suggesting that compact growth and ISM together provide a reliable means to reduce impacts on stream ecosystem health.

Integrated stormwater management, however, may be more important than compact regional growth at the scale and locations addressed in this study, as suggested by the consistent scenario rankings of CM < DM < CNM < DNM in overall flow regime differences from the reference for all basins. Moreover, compact growth appeared to provide limited additional flow alteration reduction in two of three basins (B and C) when ISM was in place (Fig. 7, CM vs. DM). In contrast, when ISM was absent, compact growth consistently outperformed dispersed growth in reducing the alterations in both individual metrics and the flow regime as a whole.

To some extent, these conclusions may be confounded by the differences in population outcomes across scenarios and basins (Table S8). Due to the complexities of the agent-based model (ABM), not only did different scenarios shift population allocation among basins, but different scenarios also had different total populations. In particular, compact scenarios accommodated less population growth than their dispersed counterparts, and ISM scenarios accommodated more population growth than their no-ISM counterparts. The former suggests that further investigations are necessary to assess whether compact scenarios would outperform dispersed counterparts on a per-person basis, while the latter suggests that ISM may allow greater population growth while still constraining impacts, strengthening the conclusion that ISM may be more important than compact growth.

Additionally, limiting the development footprint may not be the most important principle as long as ISM is applied. Comparisons between scenarios CM and CNM showed that, for every basin, DM featured more population growth and a larger total development footprint than CNM. Both urban and rural footprints in DM were either larger than or almost identical to those in CNM. Yet the former resulted in less flow alterations. This provides further evidence for the effectiveness of ISM in mitigating stormwater impacts. Finally, the best- and worst-case scenarios (CM and DNM) had almost identical future populations. Despite the varied population distribution across basins, CM led to markedly less flow alteration in every basin. This caution that dispersion of growth into rural areas without any mitigation may incur substantial hydrological impacts, while reinforcing the benefits of integrating compact growth and ISM.

(Q4) How might integrated modeling frameworks such as that demonstrated inform future efforts to link flow-ecology research to local watershed planning?

Our modeling framework presents four key innovations toward an integrated framework for flow ecology research intended to manage urbanization impacts on stream ecosystems.

First, the identification of a suite of ecologically important flow metrics that covers all major flow components establishes a bridge from hydrological impacts to ecosystem consequences. In the absence of empirical flow-ecology data, relying on a suite of metrics selected based on best available regional knowledge should make extrapolations to their effects on stream biota more robust. Whereas the specific metric selections may not be directly transferable to other geographies, the framework itself is broadly applicable.

Second, the typology of flow metric sensitivity creates a direct linkage from flow alterations to planning and management alternatives. For this typology to best inform decision-making, future flow-ecology research should emphasize identifying the ecological significance of each metric to ascertain the most important flow components for local stream biota. Acceptable values for the manageable metrics need to be determined to develop flow
management targets and to prioritize the implementation of strategies that are likely to successfully mitigate the key impacts. In addition, the identification of resistant metrics helps pinpoint where additional types of planning and management interventions deserve further exploration.

Third, the incorporation of an ABM into the modeling framework provided the capacity to simultaneously evaluate alternative forms of regional growth and stormwater management, and to disentangle their individual effects. This framework is highly adaptable and allows the testing of many different strategies in local landscape contexts. One challenge was that whereas the stochastic nature of the ABM allowed simulating multiple alternative futures for each scenario, the way SWAT operates made it infeasible to test all the alternative futures generated. Our identification of the individual run that represented the central tendencies of each scenario allowed the incorporation of information from multiple scenario runs without breaking down the integrity of a single run. This strategy was a step in the right direction compared to the lack of variability from deterministic models that assume one and only one outcome for each scenario.

Furthermore, the direct linkages between policies and land use trajectories in the ABM supported hydrological assessments directly linked to planning practices. The high performance of ISM scenarios emphasizes the importance of the suite of underlying ISM strategies including: (1) limiting development on steep slopes and permeable soils; (2) protecting large vegetative patches, riparian buffers and wetlands; (3) limiting overall watershed imperviousness; (4) reducing directly connected imperviousness; (5) encouraging cluster or high-density development; and (6) reducing road impacts. Sensitivity testing could be applied to identify which policies or combinations of policies in which locations appeared likely to produce the most cost-effective benefits.

Fourth, our investigations of multiple basins suggested potential relationships between watershed characteristics and hydrological responses that would not be revealed in studies of single basins. For example, the opposite directions of change of certain flow components (e.g., extreme low flows) provide a cautionary against assuming adjacent basins will respond in the same manner. Furthermore, certain basins may present higher sensitivity to urbanization than others. For example, the overall largest hydrological impacts occurred in the smallest basin (A) despite the lowest level of population growth. We suspect that this could be attributed to the amplification of runoff volume due to increased imperviousness, and the rapid flow concentration time resulting from a small catchment area, high initial urbanization level, as well as very impermeable soils.

Protecting stream ecosystem health under the pressures of population growth will continue to challenge our design and planning capabilities given the high flow regime sensitivities revealed. Even under the best-case development scenario, an imperviousness increase from 2.2% to 4.5% in one of the basins (C) created one resistant metric and >13% increase in three others, suggesting that even low levels of urbanization could substantially affect stream biota. Contemporary planning approaches, such as setting a low overall watershed impervious threshold (e.g., 5–10%), may not sufficiently protect aquatic ecosystem health. Rigorous but flexible approaches that link flow-ecology science to local watershed planning, such as that explored here, may be better able to sustain resilient stream ecosystems while continuing to meet societal expectations for development and growth.

5. Conclusions

Through integrating a human decision model with a hydrological model, we evaluated four distinctive future land development scenarios for their hydrological impacts in three urbanizing watersheds in southern Oregon. We summarize the major conclusions as follows.

(1) Near-future urbanization will likely result in significant flow regime changes in all three basins evaluated. Urbanization impacts aligned closely with increases in flow regime flashiness and severity of extreme events. Most changes were associated with negative impacts on native aquatic organisms in other studies of PNW streams.

(2) By concentrating 90% of the population growth within UGBs, the compact growth approach of Oregon’s land use planning policies better protected streams in all three basins than a more dispersed growth approach as would likely occur with a weakening of the statewide land use planning system.

(3) Integrated stormwater management (ISM), defined as the integration of strategic organization of land uses with site-scale stormwater BMPs, proved highly effective in reducing the flow regime impacts of urbanization. ISM was more important than compact growth, and the latter appeared to provide limited additional flow alteration reduction when ISM was in place.

(4) Certain flow metric alterations may consistently follow urbanization despite attempts to mitigate them (i.e., the sensitive and resistant metrics). Future flow-ecology research should identify the ecological significance of these metrics and explore additional management strategies targeted toward their protection.

(5) Other metrics sensitive to urbanization appear to provide greater opportunities for mitigation (i.e., the sensitive and manageable metrics). Future research should determine their ecological significance, develop specific flow management targets, and prioritize the identification of strategies that are likely to successfully mitigate their impacts.

(6) Significant hydrologic alteration and thus loss of stream ecosystem function could occur at very low urbanization levels.

(7) Despite substantially varied hydrological impacts across the three basins, the modeling framework was capable of teasing out both nuanced differences and generalizable trends. Such interdisciplinary frameworks can support collaborative research and planning efforts to investigate alternative local urbanization strategies, and to develop site-specific solutions. They hold promise for linking the mechanisms of land use planning to the goals of sustaining stream ecosystem health, and can serve as important tools to guide watershed planning and management.

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Appendices A–C. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.landurbplan.2015.08.012


