PROTECTING STREAM ECOSYSTEM HEALTH IN THE FACE OF RAPID URBANIZATION AND CLIMATE CHANGE

by

HONG WU

A DISSERTATION

Presented to the Department of Landscape Architecture
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DISSERTATION ABSTRACT

Hong Wu

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Title: Protecting Stream Ecosystem Health in the Face of Rapid Urbanization and Climate Change

The ability to anticipate and evaluate the combined impacts of urbanization and climate change on streamflow regimes is critical to developing proactive strategies that protect aquatic ecosystems. I developed an interdisciplinary modeling framework to compare and contrast the effectiveness of integrated stormwater management, or its absence, with two regional growth patterns for maintaining streamflow regimes in the context of climate change. In three adjacent urbanizing watersheds in Oregon's Willamette Valley, I conducted a three-step sequence to: 1) simulate land use change under four future development scenarios with the agent-based model Envision; 2) model resultant hydrological change under the recent past and two future climate regimes using the Soil and Water Assessment Tool; and 3) assess scenario impacts on streamflow regimes using 10 ecologically significant flow metrics. I evaluated each scenario in each basin using a flow metric typology based on the magnitude of change in each metric and the degree to which such changes could be mitigated, i.e., *insensitive*, *sensitive and manageable*, and *sensitive and resistant*.

My results demonstrated distinct signatures of urbanization and climate change on flow regimes. Urbanization and climate change in isolation led to significant flow alterations in all three basins. Urbanization consistently led to increases in flow regime flashiness and severity of extreme flow events, whereas climate change primarily caused a drying trend. Climate change tended to exacerbate the impacts of urbanization but also mitigated urban impacts on several metrics. The combined impacts of urbanization and climate change caused substantial changes to metric sensitivities, which further differed by basin and climate regime, highlighting the uncertainties of streamflow regime responses to development and the value of spatially explicit modeling that can reveal complex interactions between natural and human systems. Scenario comparisons demonstrated the importance of integrated stormwater management and, secondarily, compact regional growth. My findings reveal the need for regional flow-ecology research that substantiates the ecological significance of each flow metric, develops specific targets for manageable ones, and explores potential remedies for resistant ones. The interdisciplinary modeling framework shows promise as a transferable tool for local watershed management.

This dissertation includes previously unpublished co-authored material.

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Last but not least, I cannot thank my family enough for their patience and love. To my husband Lei, my mother and in-laws, and my baby boy Kevin, I sincerely thank you all for unconditionally supporting my dream, for better or for worse.

Written in loving memory

of

Xuan Wu

13th September 1956 - 10th August 2010

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CHAPTER I

INTRODUCTION

For decades, a wide array of disciplines has wrestled with stream ecosystem degradation. Since 1990, the United States has spent >$1 billion annually on various stream restoration projects (Bernhardt et al., 2005). However, because of the complexity of the problem, a shortage of knowledge and analytical tools, and conflicts among different socioeconomic forces, current mainstream reach-scale restoration approaches have shown limited effectiveness in restoring aquatic ecosystem functions (Bernhardt and Palmer, 2007; Bernhardt et al., 2005; Kondolf et al., 2007; Palmer et al., 2007). Because rivers are products of their landscapes (Hynes, 1975), there is increasingly a call to look to the entire catchment basin for a more holistic approach to addressing stream ecosystem degradation (Walsh et al., 2005). My dissertation contributes to this research frontier by investigating the combined effects of urbanization and climate change on stream hydrology, and testing the effectiveness of watershed management alternatives in maintaining historical streamflow regimes.

Urbanization has long been recognized as a major driver of aquatic ecosystem degradation (Miltner et al., 2004; Wang et al., 2001). The efficient routing of stormwater off large areas of urban impervious surfaces and into storm sewer systems results in a fundamental change in flow regimes of the downstream rivers (Walsh et al., 2005). Global climate change is also expected to have far-reaching impacts on streams, from altering temperature and flow regimes to increasing the frequency and intensity of droughts and floods (Bates et al., 2008; Meyer et al., 1999; Milly et al., 2005). The combined effects of climate change and urbanization on stream ecosystems are difficult to predict due to the challenges and uncertainties of projecting the impacts of either factor at local scales, and the potential for interactions between them. Yet, anticipating impacts of such anthropogenic changes is critical to developing proactive strategies for protection of stream ecosystems.

The concept of *stream health* has recently been embraced as a simple and understandable concept that can be supported by the public and policy makers (Boulton, 1999; Karr, 1999; Meyer, 1997; Norris and Thoms, 1999). Meyer (1997) defined *a healthy stream* as "an ecosystem that is sustainable and resilient, maintaining its ecological structure and function over time while continuing to meet societal needs and expectations". *Biological integrity*, on the other hand, emphasizes a biotic community comparable to that of regional natural habitat (Karr and Dudley, 1981). I applied the concept of *stream ecosystem health* rather than *biological integrity* as the major conservation target to acknowledge that, in human-dominated watersheds, stream ecosystem health is a more realistic goal to achieve.

Because the natural flow regime plays a central role in shaping and maintaining stream ecosystems (Poff et al., 1997), understanding how urbanization and climate change alter long-term flow regimes is essential for assessing their aquatic ecosystem consequences. 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 comprehensive spectrum of flow conditions rather than any single measure (Poff et al., 1997). Environmental flow scientists have developed an array of metrics to quantify pre- and post-disturbance flow conditions and establish direct linkages between aspects of urbanization and stream ecology (Clausen and Biggs, 2000; Olden and Poff, 2003; Richter et al., 1996). Metrics that are sensitive to human perturbations while also demonstrating ecological significance are the most useful for defining watershed management targets (Arthington et al., 2006; Bunn and Arthington, 2002; Poff et al., 1997). However, identifying a tractable and biologically relevant suite that circumscribes all five 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).

Anticipating the impacts of urbanization and climate change on flow regimes is an enormous challenge. Researchers are first confronted with deep uncertainty in human population growth and land development projections. Future land uses may unfold in unexpected ways due to factors that include changes in socioeconomic drivers and land-use policy. For example, since the 1970s, Oregon has employed a statewide planning system that uses Urban Growth Boundaries (UGBs) to create compact urban footprints. By guiding regional population growth patterns and concentrating 90% of the growth into UGBs, this mechanism has effectively protected Oregon's forested and agricultural land from urban sprawl. However, recent debates on private property rights have led to voter initiatives (e.g., Measure 7 in 2000 and Measure 37 in 2004) that called for a substantial relaxation of constraints on rural housing development. Potential legislative changes that would allow more rural subdivisions raised deep concerns about the ways stream ecosystems would respond (Bassett, 2009).

Compounding the uncertainties of land use change, climate change also may unfold in unexpected ways. Planners must take into account both the deep uncertainties of climate projections and the mismatch in spatial and temporal scales between available climate change information and on-the-ground watershed management. The most comprehensive climate projections so far come from atmosphere-ocean general circulation models (AOGCMs or GCMs), which operate at the global scale (e.g., 200~300km resolution). However, projections from different GCMs can vary dramatically, even under the same greenhouse gas emissions scenario. Additionally, GCM outputs need to be translated to relevant spatial and temporal scales to support local decision-making. Statistical or dynamic *downscaling* of GCM outputs has now been established as an appropriate method to post-process GCM results for assessments at regional or local scales (Bronstert et al., 2002; Wilby and Wigley, 1997).

With current knowledge and analytical tools, our ability to anticipate complex interactions between urbanization, climate, and streamflows remains rudimentary. Despite a dramatic increase in the application of scientific tools such as dynamic simulation modeling, major progress in both intra- and inter- disciplinary research is needed to advance our modeling capacity (Nilsson et al., 2003). Not only should individual disciplines continue to refine their own models, but also closer cross-disciplinary collaboration is needed to fill in the substantial gaps in knowledge and data that have constrained the development of integrated modeling systems that could capture more core interactions among complex human and natural systems.

Integrated modeling systems are particularly important if planners are to act proactively by not only assessing potential impacts of climate change and urbanization, but also testing and assessing the outcomes of different management alternatives. Although many efforts have successfully connected land use change models with hydrological models for assessments of hydrological impacts, integration of models in ways that inform policy and planning choices remains a major challenge (Choi and Deal 2008). In addition, although various strategies have been proposed for the mitigation of development-related stormwater impacts, our ability to rigorously test them at a watershed scale remains limited. One promising approach to addressing these challenges is alternative future scenarios analysis. Scenario-based alternative futures approaches increasingly have been incorporated to explore plausible policy approaches to guiding landscape change in the face of future uncertainty (Godet 1987; Hulse and Gregory, 2004). In particular, the emergence of agent-based models (Ostrom 1998; Parker et al. 2003) has made it possible to link spatially fine-grained human decisions to their potential landscape-scale consequences through the evaluation of large ensembles of alternative futures (Guzy et al., 2008; Hulse et al., 2009).

The ultimate goal of impact assessments that inform decision-making highlights the importance of investigating promising watershed management strategies. In particular, there increasingly has been a call to integrate the following two approaches for mitigation of development-related stormwater impacts: the application of stormwater Best Management Practices (BMPs), and the planning of development patterns in a hydrologically-sensitive manner (Alberti et al., 2007; Brabec, 2009). Stormwater BMPs refer to "techniques, measures or structural controls for managing the quantity and improving the quality of stormwater runoff in the most cost effective manner" (USEPA 1999). In contrast, development pattern refers to the spatial organization of land uses (Alberti, 1999).

Integration of stormwater BMPs with strategic planning of development patterns holds promise for better protecting the streamflow regime and thus aquatic ecosystem health. First, the application of stormwater BMPs for over 30 years in the U.S. has demonstrated their ability to achieve some level of watershed protection (e.g., flood protection) (Marsalek and Chocat, 2002). However, because they often have a single target (e.g., peak-flow attenuation or pollution control), current BMP design and implementation do not adequately protect downstream aquatic ecosystems (Emerson et al., 2005; Maxted and Shaver, 1997; Roesner, 1999; Schueler, 1999). A watershed approach to regulating, evaluating, and planning BMPs will likely improve their ability to manage a broader range of flow conditions and thus better protect streams (Pomeroy et al., 2008; Roesner et al., 2001; Urbonas and Wulliman, 2007; Wu et al., 2006; Zhen et al., 2004). Second, landscape planners and ecologists have long wrestled with the question of what constitutes "good" development patterns with respect to stream health. Although extensive studies have shown that development patterns account for much of the variability in water quality and stream ecological conditions (Alberti et al., 2007), current theories do not offer a generalization of how stream ecosystem health and human well-being could simultaneously be achieved through innovative urban planning and design (Alberti, 1999; Collinge, 1996; Collins et al., 2000; Forman, 1995; Grimm et al., 2000; Opdam et al., 2001; Pickett et al., 2001). Additionally, very few studies have rigorously tested the ability of alternative development patterns to maintain streamflow regimes. Exploring this research frontier may reveal important implications for watershed management.

Dissertation Research

The primary objective of my dissertation was to develop a transferable framework to investigate the combined effects of urbanization and climate change on stream ecosystems, and to test potential strategies to mitigate the impacts. In particular, I focus on evaluating the effectiveness of regional growth pattern and integrated stormwater management for maintaining streamflow regimes. For the purposes of this research, I define the pattern of regional population growth vis à vis urbanization as the spatial and proportional allocation of new urban and rural development. In contrast, I define the integrated stormwater management (ISM) approach as the combination of localized spatial patterns of development with stormwater BMPs in those areas where urbanization or rural development is to occur.

I argue that at least four components that to date have not been well integrated within a single study are necessary to better assess the impacts of urbanization and climate change and to inform watershed management. The first is that broad spatial patterns of regional population growth must be considered in concert with localized applications of stormwater management. The second is that rather than simply assessing a particular approach to regional growth and stormwater management, alternative forms of each should be tested and assessed simultaneously to help disentangle their individual effects, and to help discern how they can best be integrated at the watershed scale. The third is that assessments of these approaches should be conducted in the context of long-term climate change to explore the deep uncertainties in future flow regime responses and identify potential interactions between development and climate. Finally, hydrological assessments should focus on the flow regime as a whole rather than individual flow metrics because of the central role flow regime plays in shaping and maintaining stream ecosystems. In the following chapters of my dissertation, I detail the processes of developing an interdisciplinary modeling framework that incorporates all the four components above. Below I introduce the major objectives of each individual chapter.

In Chapter II, entitled "Exploring the hydrological impacts of land use change in the southern Willamette Valley, Oregon, USA", I evaluate the hydrological impacts of urbanization and test the effectiveness of alternative planning and management strategies in maintaining streamflow regimes. Towards that end, I established a multi-disciplinary modeling framework and conducted a three-step sequence of land use change simulation, hydrological modeling, and hydrological assessment in three urbanizing catchment basins outside of the Eugene-Springfield Urban Growth Boundary in Oregon's Willamette Valley. Additionally, I used this study to examine i) potentially ecologically significant flow metrics for this region, ii) potential land use change trajectories resulting from plausible projections of regional population growth, iii) the extent and intensity of urbanization impacts on flow metrics, iv) potential ecological consequences of projected flow alterations, and v) the potential of watershed planning and management strategies for maintaining historical flow regimes. This work is co-authored with John Bolte, David Hulse, and Bart Johnson.

In Chapter III, entitled "Interactive impacts of urbanization and climate change on streamflow regimes in the southern Willamette Valley, Oregon, USA", I build on the modeling framework established in Chapter II and continue to investigate the combined effects of climate change and urbanization on flow regimes. This is important for the intermittent streams assessed because their flow regimes are particularly sensitive to changes in the form, amount, and timing of precipitation, all of which are likely to be altered in the coming century by a changing climate. By developing and incorporating two sets of fine-resolution future climate data, I examined: i) the extent and intensity of climate change impacts on flow regimes, ii) the distinct signatures of urbanization and climate change impacts; iii) potential interactions between climate change and urbanization, and iv) the effectiveness of compact regional growth and ISM under the uncertainties of future climate. This work is co-authored with Bart Johnson.

In Chapter IV, I summarize the results from chapters II and III and conclude with implications for watershed planning and management.

CHAPTER II

EXPLORING THE HYDROLOGICAL IMPACTS OF LAND USE CHANGE IN THE SOUTHERN WILLAMETTE VALLEY, OREGON, USA

A paper co-authored with John Bolte, David Hulse, and Bart Johnson. John Bolte provided substantial help modifying Envision model codes for my research purposes. David Hulse played an important role guiding the research design, the development of the modeling framework, and the organization of the manuscript. Bart Johnson provided extensive assistance with research design, development of the modeling framework, data analysis methods, and reviewing and editing the manuscript.

1. Introduction

Urbanization has been an important driver of aquatic ecosystem degradation around the world (Miltner et al., 2004; Wang et al., 2001). The efficient routing of stormwater off large areas of urban impervious surfaces and into storm sewer systems results in a fundamental change in flow regimes of the downstream rivers (Walsh et al., 2005). Despite extensive research, the complexity of the problem, insufficient analytical tools, and conflicts among socioeconomic forces with conflicting interests have constrained the development of effective solutions that slow or 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 its ecological structure and function over time while continuing to meet societal needs and expectations".

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 for streams. 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 measure (Poff et al., 1997). Environmental flow scientists have developed an extensive array of metrics to quantify pre- and post-disturbance flow conditions and establish direct linkages between aspects of urbanization and stream ecology (Clausen and Biggs, 2000; Olden and Poff, 2003; Richter et al., 1997). Ideally, metrics that are sensitive to human perturbations while demonstrating ecological significance are the most useful for defining watershed management targets (Arthington et al., 2006; Bunn and Arthington, 2002; Poff et al., 1997). However, identifying a tractable and biologically relevant suite 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, I have relied on both.

Anticipating urbanization impacts on flow regimes presents multiple challenges. Planners are first confronted with deep uncertainty in human population growth and land development projections. Future land uses may unfold in unexpected ways due to factors that include changes in socioeconomic drivers and land-use policy. For example, Oregon has employed a statewide planning system that uses Urban Growth Boundaries (UGBs) to create compact urban footprints since the 1970s. By concentrating 90% of population growth into UGBs, this mechanism has effectively protected Oregon's forests and agricultural land from urban sprawl by guiding regional population growth patterns. However, recent debates on private property rights have led to voter initiatives (e.g., Measure 7 in 2000 and Measure 37 in 2004) that called for a substantial relaxation of constraints on rural housing development. Potential legislative changes that would allow more rural subdivisions raised deep concerns about ways the stream ecosystems would respond (Bassett, 2009).

Furthermore, current knowledge and analytical tools limit our ability to project complex interactions between urbanization and streamflows, let alone to rigorously assess the outcomes of different management alternatives - equally essential if planners are to act proactively. 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 for the assessments of urbanization impacts on hydrology (e.g., Beighley et al., 2003; Legesse et al., 2003; Lin et al., 2007; Schulze 2000). Nonetheless, major progress in both intra- and inter- disciplinary research is needed to better characterize important socio-hydrologic dynamics and connect cross-disciplinary models in ways that inform policy and planning choices (Choi and Deal, 2008; Nilsson et al., 2003). The alternative futures approach offers a promising overarching framework for such cross-disciplinary integration. Scenario-based alternative futures increasingly have been incorporated to explore plausible policy approaches for guiding landscape change in the face of future uncertainty (Godet 1987; Hulse and Gregory, 2004). In particular, the emergence of agent-based models (Ostrom 1998; Parker et al. 2003) has made it possible to link spatially fine-grained human decisions to their potential landscape-scale consequences through the evaluation of large ensembles of alternative futures (Guzy et al., 2008; Hulse et al., 2009; Hulse et al., in review).

Developing hydrological impact assessments that inform decision-making requires investigating promising watershed management strategies. In particular, there has been an increasing call to integrate two mitigation approaches for development-related stormwater impacts: the application of stormwater Best Management Practices (BMPs), and locating development patterns in a hydrologically-sensitive manner (Alberti et al., 2007; Brabec, 2009). Stormwater BMPs refer to “techniques, measures or structural controls for managing the quantity and improving the quality of stormwater runoff in the most cost effective manner” (USEPA 1999). In contrast, development pattern refers to the spatial organization of land uses (Alberti, 1999).

Integration of stormwater BMPs with strategic planning of development patterns holds promise for better protecting the streamflow regime and thus aquatic ecosystem health. First, over 30 years of stormwater BMP application in the U.S. has demonstrated their ability to achieve some level of watershed protection (Marsalek and Chocat, 2002). However, because they often have a single target (e.g., peak-flow attenuation or pollution control), current BMP design and implementation do not adequately protect downstream aquatic ecosystems (Emerson et al., 2005; Maxted and Shaver, 1997; Roesner, 1999;

Schueler, 1999). A watershed approach to regulating, evaluating, and planning BMPs will likely improve their capacity to manage a broader range of flow conditions and thus better protect stream ecosystems (Pomeroy et al., 2008; Roesner et al., 2001; Urbonas and Wulliman, 2007; Wu et al., 2006; Zhen et al., 2004). Second, landscape planners and ecologists have long wrestled with the question of what constitutes “good” development patterns with respect to stream health. Although extensive studies have shown that development patterns account for much of the variability in water quality and stream ecological conditions (Alberti et al., 2007), they offer few generalizations about how ecosystem health and human well-being could simultaneously be achieved through innovative urban planning and design (Alberti, 1999; Collinge, 1996; Collins et al., 2000; Forman, 1995; Grimm et al., 2000; Opdam et al., 2001; Pickett et al., 2001). Additionally, very few studies have rigorously tested the ability of alternative development patterns to maintain streamflow regimes.

We argue that three components that to date have not been well integrated within a single study are necessary to better assess the impacts of urbanization on stream ecosystems and to inform watershed management. The first is that broad spatial patterns of regional population growth must be considered in concert with localized applications of stormwater management. The second is that rather than simply assessing a particular approach to regional growth and stormwater management, alternative forms of each should be tested and assessed simultaneously to help disentangle their individual effects,and discern how they can best be integrated at the watershed scale. Finally, we argue that such an approach must hydrologically assess not only individual flow components but also the flow regime as a whole for the reasons described above. In the following paragraphs we distinguish techniques for stormwater management from broader patterns of land use change related to population growth, and link these to a framework in which their hydrological impacts can be tested through an alternative futures scenario analysis.

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, as described above. In contrast, we define integrated stormwater management (ISM) as the combination of localized spatial patterns of development with stormwater BMPs in those areas where urbanization or rural development is to occur. Finally we refer to the combination of a regional growth strategy with a stormwater management approach as a development scenario.

We used the knowledge and challenges posed above to establish an interdisciplinary modeling framework and test its utility in three urbanizing catchment basins outside of the Eugene-Springfield Urban Growth Boundary in Oregon's Willamette Valley. We implemented a three-step process that connected an agent-based model of landscape change under contrasting regional growth and ISM scenarios with a hydrological model to quantitatively evaluate the effects of future urbanization on streamflow regimes. In particular, we focused our investigation on the following four questions:

(1) How does urbanization affect streamflow metrics across different basins? Which flow metric 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?

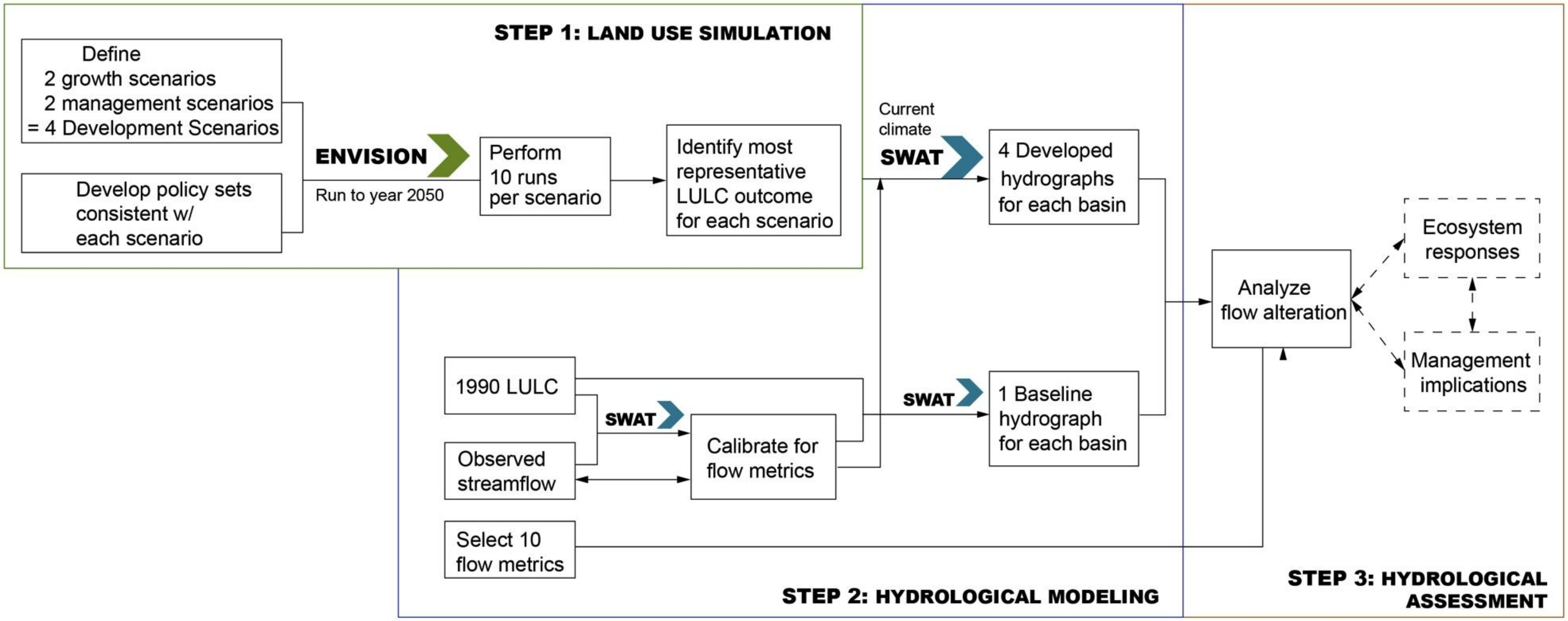
(4) How might integrated modeling frameworks such as that demonstrated here inform future efforts to link flow-ecology research to local watershed planning?

2. Methods

We conducted a three-step sequence of land use change simulation, hydrological modeling, and hydrological assessment (Figure 2.1). We chose an agent-based model Envision (Bolte et al., 2007; Hulse et al., 2009) 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 et al., 2007), was then applied to the resulting landscape of each scenario to model long-term daily streamflows. Next, we used a set of 10 flow metrics to assess the degree of flow alterations from different future scenarios and develop watershed management implications.

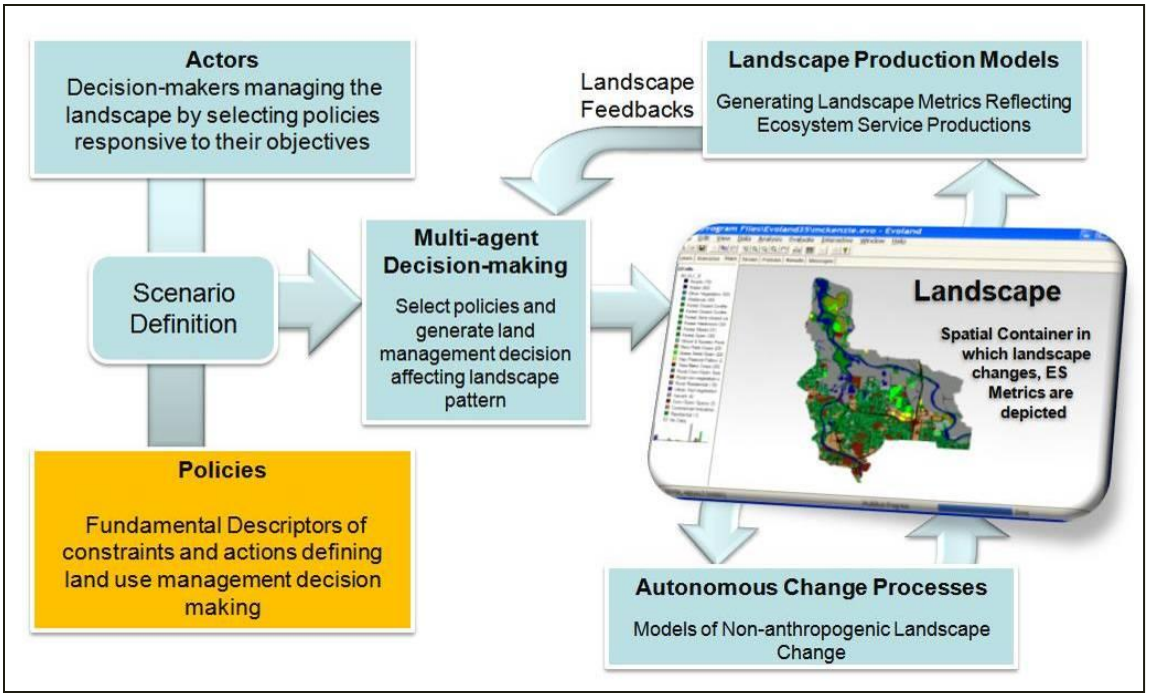
The simulation models Envision and SWAT constitute the core of this modeling framework. Envision is a spatially explicit multi-agent framework for assessment of policies and alternative futures (Figure 2.2). Central to Envision are the interactions among three components: actors (aka agents), policies (plan of actions), and the

Figure 2.1. The overall modeling process under urbanization impacts alone.



landscape (Hulse et al., 2009). Actors make decisions about the portion of the landscape for which they have authority by selecting policies responsive to their objectives. Landscape changes resulting from these decisions as well as other autonomous processes such as vegetation succession are simulated and assessed. Envision offers several key advantages for our modeling: 1) by retaining the taxlot boundaries in its spatial reporting structure, i.e., the *Integrated Decision Units* (IDU, described later), Envision operates at a spatial scale where land use decisions are made; 2) it establishes a direct linkage between policies and land use trajectories; 3) Envision can specifically incorporate Oregon's unique UGB-centered statewide land use planning system; and 4) by supporting multiple policy sets, each of which can generate numerous alternative future landscapes, Envision enables the evaluation of planning actions across large ensembles of plausible futures (Hulse et al., 2009).

Figure 2.2. Conceptual structure of the Envision model (Bolte et al., 2007).



SWAT is a physically-based continuous-event model developed to predict the impact of land management practices on water, sediment and chemical yields in watersheds with varying soils, land use, and management conditions over long periods of time (Gassman et al., 2007). We selected SWAT for multiple reasons: 1) it employs a comprehensive approach to integrate interactions among physical processes (e.g., weather, plant growth, management, etc.); 2) its *Hydrologic Response Unit* (HRU) spatial structure (Nietsch et al., 2009) accords well with the IDU structure of Envision; 3) its temporal scale (daily time step and long term) supports our objective to assess long term flow alteration; 4) climate information can be easily incorporated; and 5) SWAT can simulate both urbanized and rural watersheds of various sizes.

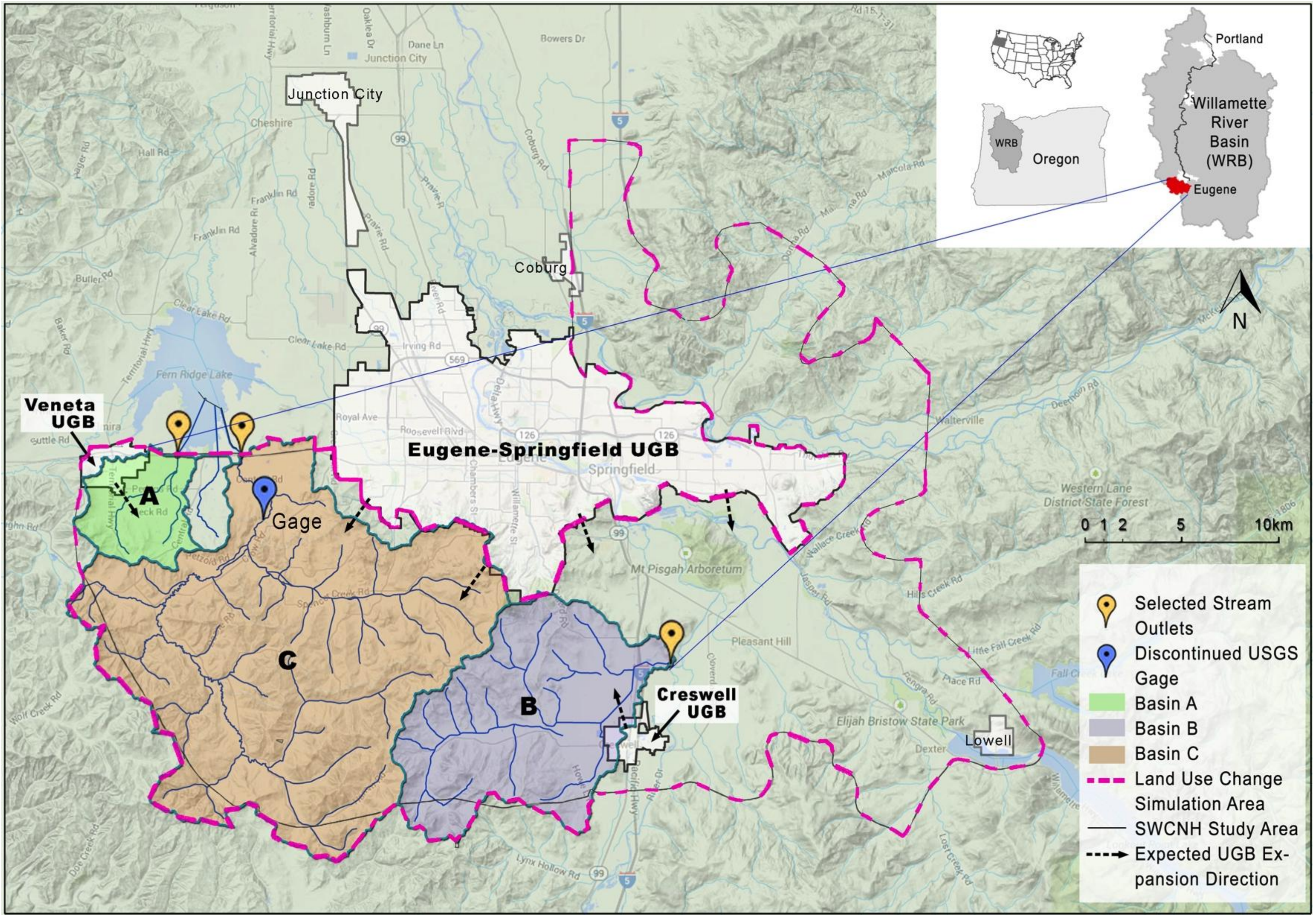
Below we introduce the area of interest, the selection of flow metrics supported by calibration and validation of SWAT, the processes of setting up the land use change simulation and hydrological modeling, and methods for data analysis.

2.1. Study Area

Oregon's Willamette Valley population is projected to double between 1990 and 2050, growing over this 60-year period from approximately 2 million to 4 million people, providing a natural laboratory for experimenting with innovative planning strategies (Baker et al., 2002). The land use change simulation area (dashed outline, Figure 2.3) 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 et al., in prep). The 409 km^2 hydrological modeling area includes three catchment basins (A, B, and C, Figure 2.3) adjacent to the UGBs of Veneta (2010 population 4,561), Creswell (population 5,031), and the larger Eugene-Springfield Metropolitan Area (population 215,588). Our simulation took advantage of a large amount of data compiled or developed by the SWCNH project, including detailed statewide population projections that were localized to the modeling area through an intensive stakeholder engagement process. Data sources and characteristics for this study are introduced in Table S1 (see Appendix A for all supplemental tables).

The hydrological modeling area as a whole is primarily rural with ~0.27 people/ha (70 people/mi^2). Urban, agricultural, forestry, and rural residential land uses occupy 2.8%, 18.5%, 56.8%, and 9.8% of the landscape ca. 2000 (Figure S1, see Appendix A for all supplemental figures), respectively, providing substantial capacity for urbanization as well as rural residential growth. Average slope of the three basins is 14.8%. Low infiltration capacity soils dominant the landscape, with <0.001% Hydrologic Soil Group (HSG) A, 7% HSG B, 60% HSG C, and 33% HSG D soils. Landscape characteristics vary substantially across the three basins (Table S2). The Strahler orders of the basins are second-order for A and B, and fourth-order for C. The smallest Basin A is the flattest and most urban with the least permeable soils. The intermediate-sized Basin B has the most permeable soils. The largest Basin C is the steepest and most rural. We use the same alphabetic character to describe the catchment basin and its outlet.

Figure 2.3. Study area in southern Willamette Valley, Oregon.



2.2. Selection of Flow Metrics

As noted above, identifying a plausible set of ecologically significant flow metrics is critical for subsequent hydrological assessment to be useful for local watershed management. Such a task proved challenging due to the absence of existing 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 and based our selection on the following four criteria: 1) the set of metrics circumscribes all major flow components for intermittent streams (Olden and Poff, 2003); 2) they demonstrate biological significance in the U.S. Pacific Northwest (Derek Booth, Martin Dieterich, and Curtis DeGasperi, personal communications, 2014); 3) metrics calculated from simulated hydrographs are in reasonably good agreement with those calculated from gauged data; and 4) annual values can be calculated either directly or using the Indicators of Hydrologic Alteration (IHA) tool (Richter et al., 1997; Richter et al., 2003). Because it is important to simulate the metrics accurately, the SWAT model calibration process examined the goodness of fit between simulated and observed values for the candidate metrics. Our final selection included the following 10 metrics: 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). See Table 2.1 for definitions and the rationale for linking each metric to urbanization and biological responses. Next, we elaborate the process of SWAT calibration and validation.

Table 2.1. Description of the 10 selected flow metrics and rationale linking them to urbanization and biological responses.

Component	Flow Metrics	Definition	Rationale Linking Flow Metrics to Urbanization and Biological Responses	Reference
Magnitude	**Qmean** Annual Average Flow (cfs)	Average daily flow for each water year	1) Critical component of the water balance with various uses to humans. 2) Related to water quality, habitat area, and fish and benthic assemblages. 3) Expected response to urbanization: varied.	Konrad and Booth, 2005; Monk et al., 2008
	1DMAX 1-Day Maximum (cfs)	Maximum daily flow rate for each water year	1) Measure of the largest annual flow disturbance. 2) Expected response to urbanization: increase. 3) An increase indicates larger disturbance for habitat structuring and floodplain exchange, more direct mortality or transport of organisms, and longer recovery time, etc.	Konrad and Booth, 2005; Richter et al., 1996
	7DMIN 7-Day Minimum (cfs)	Centered seven-day moving average annual minimum flow (calendar year)	1) A decrease indicates reduced aquatic habitat availability and more desiccation stress. 2) Expected response to urbanization: varied.	Cassin et al., 2005; Richter et al., 1996
Frequency	**LPC** Low Pulse Count (Count)	Number of times that the daily average flows are equal to or less than the low-flow threshold (set at 50% of the long term daily average flow-rate) for each calendar year	1) Negatively correlated with the Benthic Index of Biotic Integrity (B-IBI) in the Pacific Northwest (PNW). 2) Demonstrated sensitivity to urbanization in the PNW, expected response: increase. 3) An increase indicates more interruptions of the low-flow season. Frequent disturbances may degrade biological diversity.	Cassin et al., 2005; DeGasperi et al., 2009; Konrad and Booth, 2005; Richter et al., 1996

Table 2.1. (continued).

Component	Flow Metrics	Definition	Rationale Linking Flow Metrics to Urbanization and Biological Responses	Reference
	HPC High Pulse Count (Count)	Number of times that the daily hydrograph rose above the high-flow threshold (set at twice the long term daily average flow-rate) for each water year	1) Negatively correlated with B-IBI in the PNW. 2) Demonstrated sensitivity to urbanization in the PNW, expected response: increase. 3) An increase indicates more frequent high-flow disturbances that continually destabilize channels. 4) Provides the single most useful measure for benthic assemblages.	Cassin et al., 2005; Clausen and Biggs, 1997; DeGasperi et al., 2009; Konrad et al., 2002; Richter et al., 1996
Duration	**N0D** Number of 0 Days (Days)	Number of days with a daily average flow equal to zero for each water year	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.	Richter et al., 1996
	LPD Low Pulse Duration (Days)	Annual average duration of low flow pulses during a calendar year	1) Positively correlated with B-IBI in the PNW. 2) Demonstrated sensitivity to urbanization in the PNW, expected response: decrease. 3) A decrease indicates shorter recovery time between disturbances for stream organisms.	Cassin et al., 2005; DeGasperi et al., 2009; Richter et al., 1996
	HPD High Pulse Duration (Days)	Annual average duration of high flow pulses during a water year	1) Positively correlated with B-IBI in the PNW. 2) Demonstrated sensitivity to urbanization in the PNW, especially during the wet season; expected response: decrease. 3) A decrease means flow conditions alter more rapidly from high to low flow conditions, i.e., higher flashiness.	Cassin et al., 2005; DeGasperi et al., 2009; Richter et al., 1996

Table 2.1. (continued).

Component	**Flow Metrics**	**Definition**	**Rationale Linking Flow Metrics to Urbanization and Biological Responses**	**Reference**
Timing of Low Flows	**TL1** Date of annual minimum (Julian date)	Julian day of the date of the minimum daily average flow during a calendar year	1) Relates to life cycles of organisms, influences predictability of stress (e.g., higher temperatures). 2) Expected response to urbanization: earlier.	Clausen and Biggs, 2000; Richter et al., 1996
Flashiness	**RBI** Richards-Baker Flashiness Index (Unitless)	A dimensionless index of flow oscillations relative to total flow based on daily average discharge measured during a water year	1) Negatively correlated with B-IBI in the PNW. 2) Low interannual variability and thus greater power to detect trends in the daily rate of change. 3) Demonstrated sensitivity to urbanization in the PNW, expected response: increase. 4) An increase can indicate significant disturbance for organisms adapted to more stable flows.	Baker et al., 2004; Cassin et al., 2005; DeGasperi et al., 2009;

2.3. SWAT Calibration and Validation

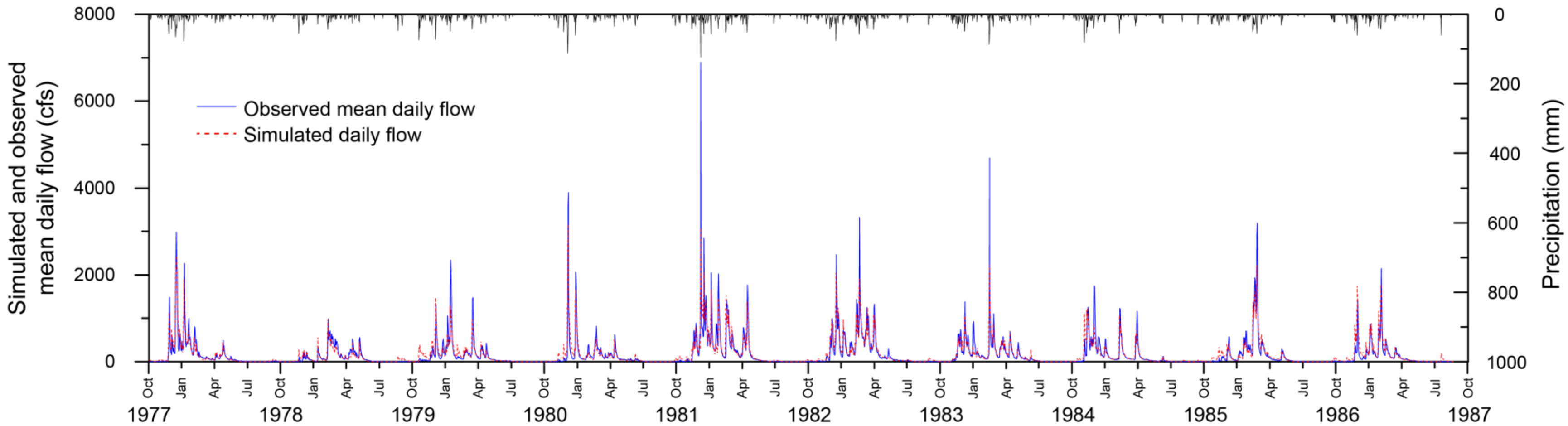
The SWAT model must be calibrated to ensure that local hydrological processes are represented appropriately. We went beyond the standard procedure of developing a general goodness of fit between simulated and observed daily hydrographs (Arnold et al., 2012; Douglas-Mankin et al., 2010) to achieve a specific calibration for the 10 flow metrics noted above.

Observed daily streamflow data from 1977 to 1987 at the discontinued USGS Coyote creek gauge (Station ID 14167000, Figure 2.3) was used as a reference to evaluate simulated hydrographs. Water years (WY) 1978 through 1982 (1977/10/1 to 1982/9/30) were used as the calibration period, and WY 1983 through 1987 (1982/10/1 to 1987/9/30) for validation. Meteorological data were extracted from historic records at the Eugene/Mahlon Sweet Airport Weather Station. Calibration and validation was performed with the ca. 1990 land cover map due to a lack of reliable earlier land cover or climate information. Historic aerial photos (ca. 1968 and 1979) were carefully examined to ensure that few land cover changes occurred within the study area during 1977-1990, following adoption of Oregon's statewide planning laws enacted in the early 1970s. In particular, the Oregon Forest Practices Act (1971) set limits on intensive forest clear-cuts (Oregon Department of Forestry, 2012), and the nation's first UGB system was in place since 1973 (Nelson and Moore, 1996).

A large number of manual (~400) and auto-calibration (~4000) repetitions were performed in either SWAT or SWAT Calibration and Uncertainty Procedures (SWAT-CUP) (Abbaspour, 2007). In a standard procedure, the Nash and Sutcliffe Efficiency (NSE) and r^2 (coefficient of determination) tests are the most commonly used statistics to assess SWAT predictions (Arnold et al., 2012). Ranging from -∞ to 1, NSE measures how well the simulation matches the observation along a 1:1 line, where NSE=1 indicates a perfect fit. Similarly, ranging from 0 to 1, an r^2=1 statistics represents a perfect correlation. In general, a value exceeding 0.5 for both NSE and r^2 is deemed satisfactory for monthly calibrations. This criterion could be appropriately relaxed for daily evaluations (Arnold et al., 2012; Moriasi et al., 2007). Our final daily calibration achieved an 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 (Figure 2.4). In addition to these two measures, 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 and Richards-Baker Flashiness Index (both consistently under-predicted), all the other metrics presented non-significant differences when calculated from the two sources (p>0.05) (Table S3). In fact, tests of another 32 default metrics in the IHA tool revealed an 84% passing rate, providing further evidence that our calibration produced sufficiently accurate projections of the flow conditions. The values of calibrated parameters are reported in Table S4.

It is notable that metrics calculated with gauge and simulated data are not expected to be identical. Gauged data reflect an integration of environmental changes over time, while simulations can only account for a single static land cover due to data or model limitations (Cassin et al., 2005). Consequently, the fit between observed and simulated metrics was not the sole criterion for identifying which flow metrics were suitable for use. The 1-day Maximum Flow and Richards-Baker Flashiness Index were retained as important measures of their respective flow components with the caveat that their results were interpreted in the context of their consistent model under-estimation.

Figure 2.4. Mean daily flows from observed vs. simulated data for WY 1978-1987 (USGS 14167000 Coyote Creek near Crow, Oregon).



2.4. Land Use Simulation with Envision

In this section we briefly overview the three major components of Envision (landscape, policies, and actors), basic steps for setting up the land use change simulation, and important model mechanisms in Envision. We follow with detailed descriptions of our scenario design and policy development.

2.4.1. Basic Envision Structure

The landscape simulated in Envision is represented by a vector-based space-filling map of *Integrated Decision Units* (IDU). IDUs were delineated in ArcGIS by intersecting taxlots, topography, and soil phase polygons, mimicking the way landowners manage their land based on its physical characteristics and ownership boundaries (Hulse et al., in review). Each IDU is associated with a large number of static or dynamic attributes, e.g., Hydrological Soil Group (static), land use land cover type (dynamic), number of dwelling units (dynamic), etc. Dynamic attributes are updated each annual time step corresponding to land management actions or autonomous processes.

Policies are the fundamental descriptors of land management actions in Envision. They define the characteristics of the land (i.e., site attributes) to which they will be applied, the goals they are intended to accomplish (i.e., outcomes), and the probability that the policy will be adopted (i.e., adoption rates) by an actor should their IDU be eligible. Table 2.2 offers an example of a riparian conservation policy.

Table 2.2. Example of policy representation in Envision.

Conservation Easement on Riparian Vegetated Lands with Highly Permeable Soils		
	Site Attributes:	**Outcome:**
Envision Syntax	CONSERVE = 0 and BUFF_DIST = 120 {within the 120ft riparian buffer} and (Lulc_A = 4 {Forest} or Lulc_A = 5 {Wetlands} or Lulc_A = 6 {Other Vegetation}) and (HYDGRP = "A" or HYDGRP = "B" {have highly permeable soils})	Expand(TAXLOTID=@TAXLOTID {same taxlot as nucleus IDU} and CONSERVE = 0 and Publands = 0 and (Lulc_A = 4 {Forest} or Lulc_A = 5 {Wetlands} or Lulc_A = 6 {Other Vegetation}) and (HYDGRP = "A" or HYDGRP = "B" {have highly permeable soils}), 40469 {10ac}, Publands = 33 {Unbuildable, DEQ easement or R/W} and Conserve = 1 {Conservation Easement} and EXP_POLICY=151) and EXP_POLICY=-151 {RIP1. Conservation Easement on Riparian Vegetated Lands with Highly Permeable Soils } : **50**
English	The site must be within 1000m distance to a stream. Site contains highly permeable HSG A or B soils; land cover is forest, wetlands, or other vegetation.	Conservation easements will be established in 50% of the cases to protect all the natural vegetation within the 120 ft. buffer. This policy will expand to adjacent IDUs with the same site attributes within the same taxlot, for up to a total area of 10 ac.

Individual actors make management decisions on IDUs under their control. Each actor is associated with a set of values that reflect how their value systems influence land use and management decisions. Actors adopt available policies that are consistent with their values, resulting in a temporal series of changes to the IDUs. A set of five rural actor types was developed and parameterized based on surveys of nearby 1,000 rural landowners in the southern Willamette Valley, and an actor assigned to each IDU based on its site attributes (Nielsen-Pincus et al., in press). We added two additional actor types, urban residents and a public lands manager, to better incorporate urban areas into the model.

The following steps were used to set up land use change simulations in Envision.

1) Develop a study area IDU map with over 40,000 IDUs averaging 1 ha in area. Populate the IDUs with potentially relevant site attributes. A dictionary of 52 key attributes is included in Table S5.
2) Assign one of seven types of actors and associated actor values to each IDU (Nielsen-Pincus et al., in press).
3) Develop a set of four land development scenarios and associated assumptions.
4) Define the regional population projections for each scenario, i.e., proportions of population growth directed into urban vs. rural areas, based on previous research from the SWCNH project.
5) Develop a specific set of policies for each scenario that implement both the spatial population allocation needed to fulfill the selected regional

growth scenario, and the spatial implementation (or absence) of specific ISM strategies.

Once these essential components are assembled, the following processes operate in Envision to generate landscape outcomes for each scenario.

1) Population growth is allocated according to the available population capacity of each IDU. Every IDU belongs to a zoning category with an allowable population density, and which can be updated through policies. 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 existing or expanded UGBs, or into new rural residential zones based on scenario assumptions.
2) Envision mimics the mechanism of Oregon's UGB-centered planning systems and updates the UGBs every 10 years to meet capacity targets based on maintaining at least a 20-year urban land supply. When total population within a UGB reaches 80% of the build-out capacity, that particular UGB is expanded.
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 simulated through the Climate-Sensitive Vegetation State-and-Transition sub-model (Yospin et al., 2014).

5) Because of Envision’s stochastic processes, replicate model runs can be conducted for each scenario to examine variations in landscape outcomes within and across scenarios.

2.4.2. Design of Scenarios and Policies

Below we introduce the design of our scenarios and policies. Our development scenarios consisted of 2 x 2 factorial combinations of regional growth and stormwater management scenarios. In response to the recent challenges to Oregon’s land use planning laws mentioned above, we defined two contrasting regional growth scenarios, i.e., *Compact* vs. *Dispersed Growth*, to explore the consequences of potential legislative changes. To examine the effectiveness of various stormwater management strategies, we developed two contrasting management scenarios, i.e., *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 emphasis of the four scenarios differ in important ways (Table 2.3). The compact growth scenarios assumed that current statewide 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 state planning laws and distributed only 65% of population growth into UGBs, allowing 35% to be dispersed into the rural landscape. The two management scenarios differed mainly in implementation of ISM strategies. The no-ISM scenarios (CnM and DnM) involved very limited protection of hydrologically sensitive areas, whereas the ISM scenarios (CM and DM) incorporated a wide range of ISM strategies to mitigate stormwater impacts. We structured the scenarios in this manner to explore potential remedies in case of a much more populated rural landscape.

Table 2.3. Contrasts in scenario assumptions and policy emphasis.

	Scenarios	*Assumptions*	*Policy Emphasis*
Regional Growth Scenarios	Compact Growth	Anticipated population growth primarily (90%) absorbed into UGBs, 10% into rural developments.	Retain UGBs; Encourage urban infill and redevelopment; Promote high density development.
	Dispersed Growth	Constraints on rural development relaxed, 35% of new residents live in the rural landscape.	Relax constraints on UGBs; Allow more rural residential development; Continued emphasis on low density development.
Integrated Stormwater Management Scenarios	With ISM	More willingness and better capacity to mitigate stormwater impacts at both landscape and site scales.	Strategically plan watershed-scale stormwater BMPs; Minimize effective impervious area; Conservation and rehabilitation of hydrologically sensitive areas; Promote site-scale Low Impact Development (LID) strategies.
	Without ISM	Conventional urban drainage management continues with little motivation or efforts for mitigating stormwater impacts.	Little consideration for watershed scale stormwater BMPs; Limited conservation and rehabilitation of hydrologically sensitive areas; Development built in conventional ways without LIDs.

Testing integrated stormwater management strategies is new in Envision applications. We drew from previous research to incorporate a variety of watershed planning strategies into the development of plausible ISM policies. These include: 1) limiting development on steep slopes and permeable soils (Yang and Li, 2011); 2) protecting large vegetative patches, riparian buffers and wetlands (Alberti et al., 2007; Meador and Goldstein, 2003; Morley and Karr, 2002); 3) limiting total impervious surface percentage to 10-25% (10% for relatively undeveloped and 25% for developed catchments) of the watershed area (Schueler, 1994; Schueler et al., 2009); 4) minimizing runoff impacts by reducing directly connected impervious area using widespread re-infiltration LIDs (Booth et al., 2004; Lee and Heaney, 2003); 5) encouraging cluster or high density development to protect natural vegetative cover and provide more open space (Berke et al., 2003; Booth et al., 2002; Girling and Kellett, 2002; May and Horner, 2002; Richards, 2006; USEPA, 2006); and 6) encouraging development close to existing infrastructure and permeable pavement on light-duty roads to reduce the impacts of roads (Alberti et al., 2003).

Seven categories of policies were developed to incorporate urban and rural growth processes and ISM strategies (Table S6): i) urban development, ii) urban conservation & restoration, iii) rural development, iv) public lands conservation & restoration, v) rural upland conservation & restoration, vi) riparian conservation & restoration, and vii) Low Impact Development. A specific policy set was assembled for each scenario. The compact growth scenarios and their dispersed counterparts generally employed the same policies sets, whereas a majority of the ISM policies (e.g., UC, RC, RIP, and LID) were exclusively applied to the ISM scenarios. Note that policies with the same titles can have variations (e.g., in their site attributes or adoption rates) when applied to different scenarios. For example, the urban development policies for scenarios

CM and DM (as compared to CnM and DnM) further protected highly permeable soils (HSG A and HSG B) from developing into high-density residential uses.

Next, 10 replicates of every scenario, with its associated policy set, were run in Envision from ca. 2007 until the year 2050 using an annual time step. As noted before, multiple model runs in Envision can produce a large number of alternative futures for each scenario. Evaluation of the hydrological impacts of each scenario needs to consider potential within-scenario variation resulting from differences in policy and land cover outcomes. Because modeling every run of every scenario in SWAT is cumbersome, we developed a procedure (Appendix B) to select one alternative future for each scenario that represented the scenario's central tendency. Based on the most frequent land use/land cover (LULC) outcome (the *mode*) for each IDU, the model run that generated the highest percentage of IDUs with the same LULC types as the modes was deemed representative of that scenario. A total of four LULC maps were generated. These four alternative landscapes were then subjected to hydrological modeling in SWAT.

2.5. Hydrological Modeling with SWAT

As noted before, both intra- and inter-disciplinary development is necessary to enhance current modeling capacity, in our case to incorporate stormwater management. Below we introduce the curve number runoff estimation method in SWAT and several procedures we developed to expand the SWAT databases and achieve a more accurate representation of land cover types associated with stormwater management. We then introduce the hydrological modeling processes for the future development scenarios.

2.5.1. Curve Number Modeling

SWAT estimates surface runoff through two approaches, one of which is the curve number (CN) procedure (SCS, 1984). CN reflects the rainfall-runoff relationship for each unique combination of land cover and hydrologic soil group (HSG) (Srinivasan and Arnold, 1994). Ranging from 0 to 100, a larger CN corresponds to a lower infiltration capacity (e.g., a concrete road has a CN of 98).

Despite increasing application in urban environments, SWAT's urban CN database remains underdeveloped for incorporating stormwater management. For instance, only four urban residential land cover types were available, i.e., high, medium, medium-low, and low density residential development, with no differentiation in stormwater management strategies. For this reason, we applied three procedures to modify and expand SWAT's urban CN database. First, our major means to incorporate BMPs on an IDU basis was to develop CNs for new prototype land use/land cover and BMP associations (LULC-BMP) such as "new high-density residential development with a full range of lot-level LIDs". This was achieved by engaging an outside model called Low Impact Development L-THIA (Long Term Hydrologic Impact Analysis) (Ahiablame et al., 2012). An L-THIA application example and complete list of new LULC-BMP associations and Curve Numbers are included in Appendix C. Furthermore, hydrologic soil groups on developed lands were adjusted (i.e., HSG A shifted to C and HSG B shifted to D) during modeling to account for severe impacts on soil integrity by construction (Ahiablame et al., 2012; Lim et al., 2006). Second, given that high density development was encouraged in certain scenarios, we needed to provide further evidence for the widely-applied, but rarely-verified assumption that total imperviousness in urban residential zones doesn't significantly increase once density reaches 20 du/ha (8 du/ac). We conducted an ArcGIS analysis on a high-resolution land cover map (9 x 9m. resolution) of the Portland metropolitan area. Under Oregon's compact urban center practices, residential zones with densities from 20-60 du/ha (8-24 du/ac) have an identical imperviousness of about 58%, in good agreement with the existing SWAT database. Third, given the scarcity of local high-resolution imperviousness data for rural residential development, we measured 40 rural residential houses in different county zoning classes in Google Earth Pro. Impervious area per dwelling unit information was translated to IDU-based CNs through the L-THIA model (Appendix C).

2.5.2. Scenario Modeling

With the expanded CN database, the previously calibrated SWAT model was next used to simulate the 30-year daily streamflows for the four development scenarios at each of the three outlets. Simulated daily streamflow based on the ca. 1990 landscape over the period of WY 1978 to 2007 was chosen as the reference flow regime for each basin. To examine development impacts alone, simulations of future scenarios used the same climate data as the reference scenario. We acknowledge that the reference flow regime may be different from the pre-Euro-American settlement natural flow regimes, which could be considered an "ideal" target for native stream biota. However, given both the problematic nature of comparing streamflows under contemporary climate to those of over 150 years ago, and the unrealistic goal of returning the landscape to its pre-settlement conditions, we focused on evaluating the degree of departure from the reference. As in other studies, the scenario resulting in the least flow regime departure was deemed the most preferable (Poff et al., 1997; Bunn and Arthington, 2002). Upon completion of the SWAT modeling, the 10 selected flow metrics were calculated either directly or in the IHA tool. Our final raw data thus contained 30 annual values for each of the 10 metrics for 3 basins over a total of 5 development scenarios.

2.3. Data Analysis

We applied multiple group comparison tests to compare responses of individual flow metrics under each development scenario for each basin. Based on the specific responses, we developed a classification system that categorizes the flow metrics into three different sensitivity categories based on each metric's sensitivity to the types of changes represented in each development scenario. In addition, we evaluated the overall flow regime difference from the reference for each future scenario based on a parameter we derived and named the *Equivalent Standard Deviation* (ESD).

Because our flow metric data were severely skewed (and of different units), we applied a non-parametric repeated measures analysis of variance statistical test (the Friedman's ANOVA) to compare flow metrics among the five development scenarios (1 baseline and 4 future), i.e., 30 annual values per metric per scenario, for each of the three basins. 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 metrics responses for watershed management, we developed a sensitivity classification system (Table 2.4) that categorizes the flow metrics 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

Table 2.4. 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 conditions under *any* development scenario, or if there was a significant difference the magnitude of change was < 5% (or <3 days for N0D and TL1). For a metric to be classified as *sensitive*, there must be statistically significant effects with a magnitude of change >5% (or >3 days for N0D and TL1) in *one or more* development scenarios. For a metric to be classified as *sensitive and manageable*, there must be statistically significant effects with a magnitude between 5%-25% (or 3-7 days for N0D and TL1) in *one or more* development scenarios. For a metric to be classified as *sensitive and resistant*, there must be statistically significant effects of >25% (or >7 days for N0D and TL1) under *every* development scenario.

Type	**Sensitivity to Change**	**Manageability**	**Magnitude of Significant Absolute Median Change**		**Number of scenarios**
			For N0D/TL1	For all other 8 metrics	
1. Insensitive	Not influenced by development	NA	non-significant or < 3 days	non-significant or < 5%	All scenarios
2. Sensitive and Manageable	Substantially influenced by development	Impacts mitigated by one or more alternatives	3 - 7 days	5% - 25%	One or more scenarios
3. Sensitive and Resistant	Substantially influenced by development	Impacts unmitigated by development alternatives	> 7 days	> 25%	All scenarios

and manageable by development alternatives, and s*ensitive* to development *and resistant* to development alternatives. *Insensitive* refers to metrics not influenced by development in *any* future scenario compared to the reference (historical climate/current landscape) scenario. *Sensitive* and *manageable* (aka *manageable*) refer to metrics substantially affected by development, but for which impacts could be mitigated by compact growth and/or ISM. *Sensitive and resistant* (aka *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.

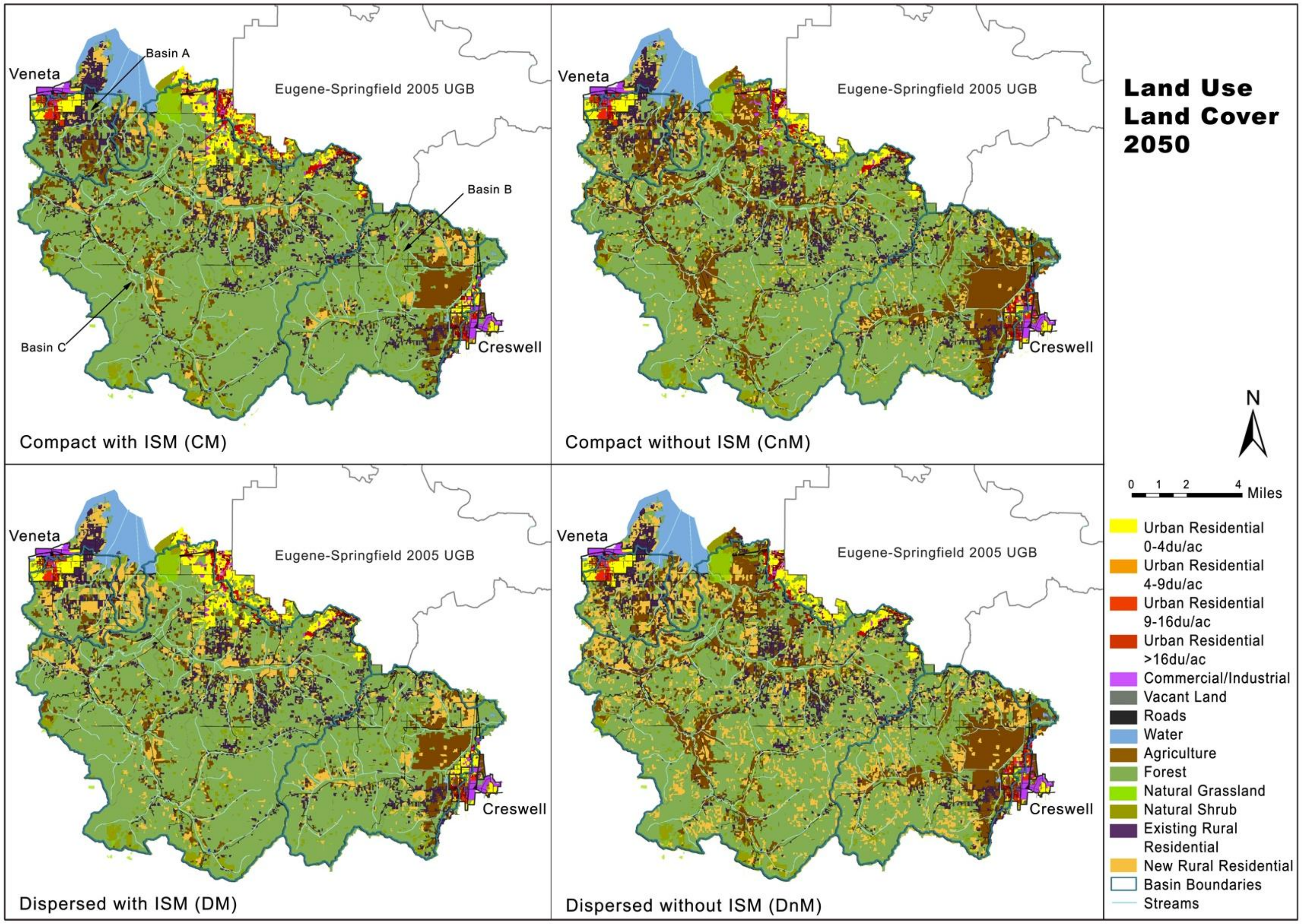
Additionally, we developed a procedure with a rank-transformed flow metrics dataset to explore the overall difference between each future scenario and the reference. For each flow metric in each year and basin, we calculated the rank difference between the reference and each future scenario, and then the sum of the squares of the 30 rank differences (SSrd). We then computed the equivalent of a standard deviation (hereafter called ESD) for each future flow regime from the reference, based on the square root of the (sums of the squares of all the rank differences across all years for each scenario)/(the number of flow metrics x the number of years). The SSrd of each future scenario for each flow metric thus indicates the relative difference of that scenario from the reference. The ESD measures the overall difference of each future flow regime relative to the reference, assuming each metric is of equal importance.

3. Results

3.1. Land Development Conditions

Future population outcomes and land development patterns varied substantially across the four scenarios and three basins. In general, a tripling of the population was projected by 2050 across the three basins (Table S7). The dispersed scenarios (DM and DnM) resulted in larger total population numbers than their compact counterparts (Table S7) because more growth was distributed into the rural areas of the larger study area used for the population growth model (Figure 2.3). Moreover, the ISM scenarios (CM and DM) created more compact overall development patterns than their no-ISM counterparts because land conservation at strategic locations was employed as an ISM strategy (Figure 2.5). The amount of urban land uses increased in all future scenarios, with the three-basin total averaging a 79% increase across the four scenarios (range 33-86%). ISM scenarios showed larger increases than their no-ISM counterparts due to the area required within urban areas for BMPs (Table S7). The amount of agricultural land uses decreased an average of 40% across all future scenarios (range 14-59%) due to urban and rural residential expansion as well as restoration of hydrologically-sensitive areas, and was nearly twice as large in no-ISM scenarios as their ISM counterparts. The amount of forested land uses increased ~20% in the two ISM scenarios due to maturing of natural vegetation and restoration of hydrologically-sensitive areas and showed only a small increase or decrease in the no-ISM scenarios. The amount of rural residential land uses increased an average of 80% with the largest increase in DnM (+144%) and smallest in CM (+34%).

Figure 2.5. Land use land cover outcomes of the four future development scenarios.



3.2. Flow Metric Alteration

Next, we report changes in individual flow metrics. In general, most metrics showed the same direction of change from reference conditions across all future development scenarios, although there were important exceptions. Even when the direction and effect were the same, the magnitude of change varied substantially among scenarios. Figure 2.6 highlights significantly different scenario groups for each flow metric and basin. See Figure S2 for the same results by catchment basin and Table S8 for detailed statistics.

Of the ten flow metrics, 50% showed significant changes in all three basins (80% for Basins A and C, 60% for B) for one or more development scenarios. For Basin A, Low and High Pulse Duration did not change. For Basin B, 7-day Minimum, Number of Zero Days, Low Pulse Duration, and Date of Annual Minimum did not change. For Basin C, 7-day Minimum and High Pulse Duration did not change. Below we examine the detailed changes in each individual metric under each flow component.

Figure 2.6 (next page). 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 not significantly different are bounded by a bold black outline.
*: 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.

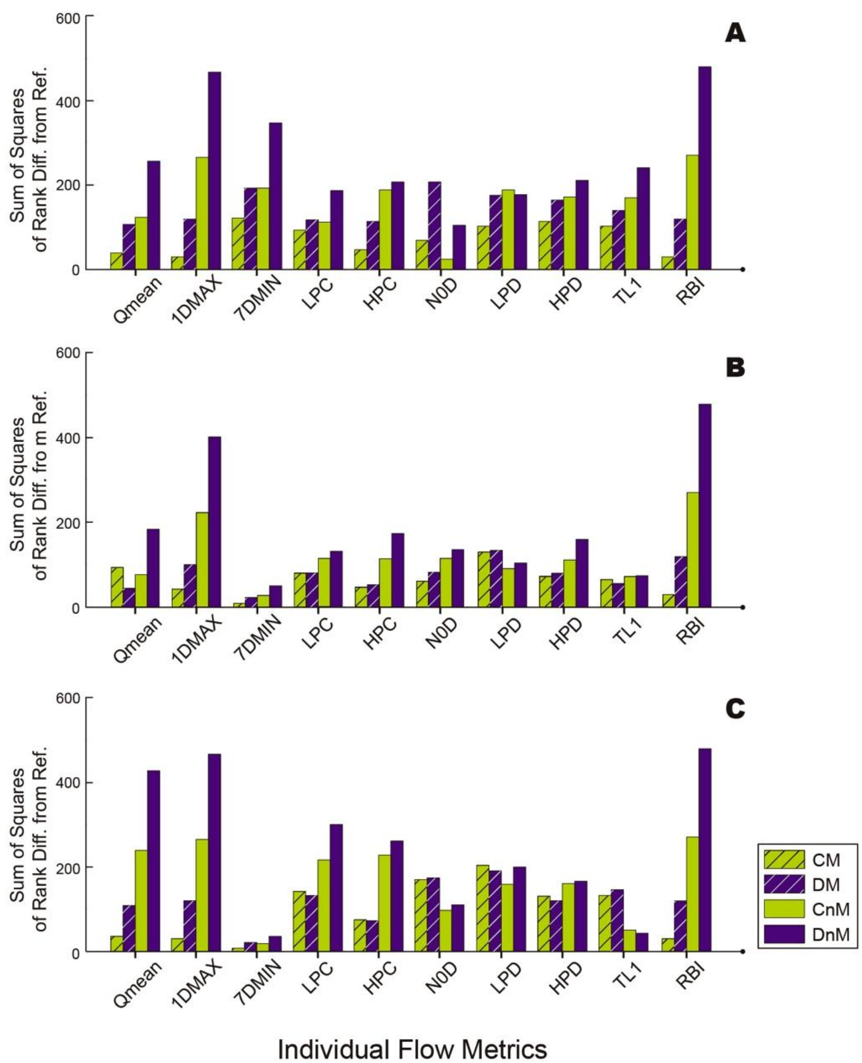
	No.	Flow Metric	Basin	MIN → MAX									Direction of change§	Expected effects on native aquatic biota?#
Magnitude	1	Annual Average (Qmean)	A			DM -2%	CM -1%	REF	CnM 3%	DnM 4%			+ or ns	indeterminate
			B			CM -1%	DM -1%	REF	CnM 4%	DnM 5%			+/- or ns	indeterminate
			C					REF	CM 0%	DM 0%	CnM 4%	DnM 5%	+	indeterminate
	2	1-Day Maximum (1DMAX)	A					REF	CM 6%	DM 14%	CnM 21%	DnM 30%	+	negative
			B					REF	CM 2%	DM 4%	CnM 18%	DnM 25%	+	negative
			C					REF	CM 13%	DM 15%	CnM 25%	DnM 31%	+	negative
	3	7-Day Minimum (7DMIN)	A	DnM -90%	CnM -88%	DM -87%	CM -85%	REF					-	negative
			B	DnM 0†	CnM 0†	CM 0†	DM 0†	REF					ns	NA
			C		DnM 0†	CnM 0†	DM 0†	REF	CM 0†				ns	NA
Frequency	4	Low Pulse Count (LPC)	A					REF	CM 25%	DM 25%	CnM 25%	DnM 50%	+ or ns	negative
			B			DM -10%	CM 0%	REF	CnM 0%	DnM 20%			+ or ns	negative
			C					REF	CM 400%	DM 500%	CnM 500%	DnM 600%	+	negative
	5	High Pulse Count (HPC)	A					REF	CM 14%	DM 21%	CnM 21%	DnM 21%	+	negative
			B				CM -6%	REF	DM 0%	CnM 6%	DnM 13%		+ or ns	negative
			C					REF	CM 14%	DM 14%	CnM 43%	DnM 43%	+	negative
Duration	6	Number of 0 Days (N0D)*	A‡					REF	CM +7d	DM +9d	CnM +9d	DnM +10d	+	negative
			B	DnM -2.5d	CnM -2d	DM -1.5d	CM -1.5d	REF					ns	NA
			C	CnM -2d	DnM -2d	DM -1.5d	CM -1d	REF					-	indeterminate
	7	Low Pulse Duration (LPD)	A	DnM -30%	DM -29%	CnM -16%	CM -2%	REF					ns	NA
			B			CnM -33%	DnM -26%	REF	CM 30%	DM 30%			ns	NA
			C	DnM -58%	CnM -47%	DM -45%	CM -43%	REF					- or ns	negative
	8	High Pulse Duration (HPD)	A	DnM -20%	CnM -20%	DM -20%	CM -20%	REF					ns	NA
			B	DnM -26%	CnM -16%	DM -16%	CM -11%	REF					- or ns	negative
			C	CnM -31%	DnM -25%	CM -25%	DM -25%	REF					ns	NA
Timing	9	Date of Annual Min. (TL1)*	A	DnM -13d	CnM -11.5d	DM -8d	CM -5d	REF					-	indeterminate
			B					REF	DnM 0	CM +0.5d	DM +0.5d	CnM +3.5d	ns	NA
			C				DnM -4d	REF	CnM +1d	CM +2.5d	DM +2.5d		+ or ns	indeterminate
Rate of Change	10	Richards-Baker Flashiness Index (RBI)	A					REF	CM 11%	DM 23%	CnM 25%	DnM 36%	+	negative
			B					REF	CM 6%	DM 9%	CnM 21%	DnM 31%	+	negative
			C					REF	CM 15%	DM 18%	CnM 29%	DnM 36%	+	negative

SCENARIOS: CM DM CnM DnM

a) Magnitude

Annual Average Flow (Qmean). Qmean differed from the reference in certain future development scenarios for all three basins, although the overall degree of change in medians was small (-2% to 5%). The sign of change varied across scenarios and basins. In Basins A and B, CM and DM led to a decrease, while CnM and DnM led to an increase. In Basin C, all the future scenarios led to an increase. The SSrd for Qmean suggested only one consistent scenario ranking: DnM led to the most departure for all three basins (Figure 2.7, see full data in Table S9), with changes in the medians varying from 4% to 5%.

Figure 2.7. Individual flow metric impacts across scenarios as indicated by the sum of squares of rank differences (SSrd) from the reference. The SSrd of each future scenario for each flow metric indicates the relative difference of that scenario from the reference. Calculations of SSrd were based on the rank differences between each future scenario and the reference calculated for each of the 30 annual values of the flow metrics.



Annual Maximum Flood (1DMAX). The 1DMAX increased in all future scenarios for all three basins. Degree of change in the medians varied from 2% to 31%. Basin C showed the greatest change (13% to 31%), while B presented the smallest (2% to 25%). The SSrd for 1DMAX suggested an identical scenario ranking for all three basins in terms of distance from the reference: CM < DM < CnM < DnM (Figure 2.7). The CM scenario maintained the changes in the medians within 6% for Basin A, 2% for B, and 13% for C. In contrast, the DnM scenario caused a 30% increase in Basin A, 25% in B and 31% in C.

7-day Minimum (7DMIN). The 7DMIN only substantially decreased (-85% to -90%) in Basin A, where differences among the four future scenarios were minimal. The medians couldn't decrease in Basins B and C because their values were already zero.

b) Frequency

Low Pulse Count (LPC). In general, the LPC showed an increase in future scenarios. Overall degree of change in the medians was substantial, i.e., -10% to 600%. Basins presented varied responses to different scenarios. Changes were pronounced in DM, CnM, and DnM for Basin A (+25% to +50%), CnM and DnM for Basin B (0% to +20%), and in all four future scenarios in Basin C (+400% to +600%). Basin C, with the largest changes, had only 1 continuous low-flow event per year under the reference conditions, but the summer low-flow was projected to be more frequently interrupted by 4-6 additional higher-flow events, resulting in a much flashier dry season. The SSrd for LPC suggested that either CM or DM was the closest to the reference (CM for Basins A and C, CM and DM equal for Basin B) (Figure 2.7). DnM generated the most increase for all three basins with 1 to 6 more low pulses/year.

High Pulse Count (HPC). In general, the HPC showed an increase in future scenarios. Degree of change in the medians ranged from 14% to 21% for Basin A, -6% to 13% for B, and 14% to 43% for C. The SSrd for HPC suggested that either CM or DM was the closest to the reference (CM for Basins A and B, DM for Basin C) (Figure 2.7). DnM generated the most increase for all three basins with 1-3 more high pulses/year.

c) Duration

Number of Zero-flow Days (N0D). The N0D significantly changed in future scenarios, with varied responses across basins. More dry days occurred in Basin A but less in B and C. Changes were the most pronounced in Basin A (reflected in means instead of medians). Basin A had year-long continuous flows under the reference, but in all the future scenarios, it was projected to dry out for an additional 7.5-10 days/year on average. In contrast, Basins B and C showed 1-2.5 fewer dry days/year under future scenarios.

Low Pulse Duration (LPD). The LPD only showed a significant decrease in the median (-61%) in one scenario (DnM) in one basin (C).

High Pulse Duration (HPD). The HPD only showed a significant decrease in the median (-26%) in one scenario (DnM) in one basin (B).

d) Timing

Date of Annual Minimum (TL1). The TL1 significantly changed in future scenarios in two basins (A and C), although the directions of change were different. In Basin A, the first annual minimum will likely occur earlier, with a median change of 5 (in scenario CM) to 13 days (in DnM). In Basin C, scenarios CM and DM caused a slight delay (an average of 1-2.5 days).

e) Flashiness

Richards-Baker Flashiness Index (RBI). The RBI increased in every future development scenario for all three basins. Overall degree of change in the medians ranged from 6% to 36%. Basin B showed a slightly smaller increase (6%-31%) than A (11%-36%) and C (15%-36%). The SSrd for RBI revealed a consistent scenario ranking in departure from the reference, CM < DM < CnM < DnM, for all three basins (Figure 2.7). Scenario CM maintained the change in medians within 6% to15%.

3.3. Flow Metric Sensitivity Classification

The flow metric classification system identified 43.3% of the metrics as *insensitive*, 46.7% as *manageable*, and 10% as *resistant* (Table 2.5). Metrics that showed no more than minor changes (*insensitive*) included Qmean (all three basins), 7DMIN, N0D, and TL1 (Basins B and C), LPD (Basins A and B), and HPD (Basins A and C). Metrics that were *manageable* under simulated strategies include 1DMAX, HPC, and RBI (all three basins), LPC (Basins A and B), LPD (Basin C), HPD (Basin B), and TL1 (Basin A). Flow alterations that consistently followed future development and were not mitigated by any scenario (*resistant*) included a substantial decrease in 7DMIN and increase of N0D in Basin A, as well as a substantial increase in LPC in Basin C.

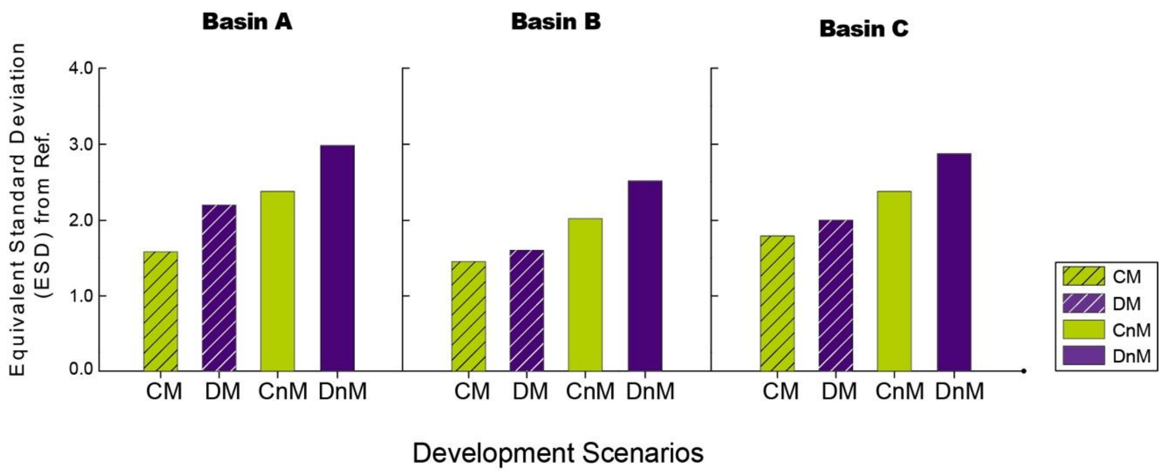
The overall flow regime differences of future scenarios from the reference presented an identical trend in all three basins, i.e., CM < DM < CnM < DnM (Figure 2.8). Compact scenarios caused less flow alteration than their dispersed counterparts, and ISM scenarios caused less flow alteration than their no-ISM counterparts. Scenario CM, which consistently showed the least overall difference from the reference, 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.

Table 2.5. Sensitivity classifications of flow metrics by basin under urbanization impacts alone.

	Flow Metric	**Type 1** ***Insensitive***	**Type 2** ***Sensitive and Manageable***	**Type 3** ***Sensitive and Resistant***
Magnitude	**Qmean**	ABC		
	1DMAX		ABC	
	7DMIN	BC		A
Frequency	**LPC**		AB	C
	HPC		ABC	
Duration	**N0D**	BC		A
	LPD	AB	C	
	HPD	AC	B	
Timing	**TL1**	BC	A	
Rate of Change	**RBI**		ABC	
Total Counts		13	13	3
		43.3%	46.7%	10%

Basins A and C experienced more considerable changes than B, as indicated by the consistently larger ESD values in A and C under every development scenario (Figure 2.8). Basin A was the most influenced based on the average ESD values for the four scenarios (Table S9). Basins A and C also had more *resistant* metrics than B. Specifically, A had 30% *insensitive*, 50% *manageable*, and 20% *resistant* flow metrics; B had 50% *insensitive* and 50% *manageable* flow metrics; and C had 50% *insensitive*, 40% *manageable*, and 10% *resistant* flow metrics.

Figure 2.8. Overall flow regime differences from the reference for each future scenario as evaluated by the Equivalent Standard Deviation (ESD).



4. Discussion

Our overall modeling results were largely consistent with those of other studies of urbanization impacts on streams, while also highlighting the challenges of developing reliable rules of thumb for management purposes. In particular, although there were consistent effects of different regional growth and integrated stormwater strategies on overall flow regimes, the impacts to individual flow metrics varied substantially in both sign and magnitude across the three adjacent basins. Below we connect hydrological responses with watershed management by addressing our four original questions.

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

All future development scenarios tended to change the majority of flow metrics, and to do so in a consistent direction across all basins (Figure 2.6). In general, the projected flow metric responses were consistent with literature generalizations of urbanization impacts on stream hydrology (Coleman et al., 2011; Konrad and Booth, 2005; Wenger et al., 2009). All three streamflows became flashier under future development: the magnitude of the largest flood (1DMAX) increased, extreme low flows (7DMIN) became lower, both low- and high-flow events occurred more frequently (LPC and HPC increased), and the overall flashiness (RBI) increased.

However, results also differed among basins in important ways, showing the varied basin sensitivity to development even among adjacent catchments. For example, aquatic organisms will likely experience more summer dry days (N0D) in Basin A under all development scenarios, but fewer in C. Similarly, the first annual minimum flow (TL1) will likely occur earlier in Basin A but later in C. The varied directions of change in these two metrics across different basins, 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.

Certain flow metrics may be more sensitive to urbanization impacts than others. The sensitivity classification system identified the 1DMAX, LPC, HPC, and RBI as being *sensitive* in at least 2 out of 3 basins, whereas Qmean, LPD, HPD, and TL1 remained *insensitive* in at least 2 basins and were never *resistant* in any basin (Table 2.5). 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 Basins B and C) (Table 2.5). Overall, the magnitude of extreme flow events (1DMAX and 7DMIN), frequency of high and low flow events (LPC and HPC), and flashiness (RBI) may be more sensitive to urbanization than average flows (Qmean), duration of both high and low flows (LPD and HPD), and the timing of extreme low flows (TL1). This pattern of varied sensitivity could be broadly applicable to other geographic locations and was only possible to discern through our use of a broad suite of variables across multiple basins.

Similarly, certain flow components may be more manageable with mitigation strategies than others. All the *manageable* metrics except for TL1 (1DMAX, LPC, HPC, LPD, HPD, and RBI) are measures of flow regime flashiness or extreme high flows, 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 flow conditions may be more challenging.

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

Given the paucity of knowledge about how alterations of different flow components 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 of the flow metrics (1DMAX, LPC, HPC, and RBI, Figure 2.6) in directions that have been shown to have negative impacts on aquatic organisms in the PNW, and more generally on ecological processes (Poff et al., 1997), suggests that projected human population growth is likely to impose substantial detrimental effects on aquatic organisms.

First, as a consequence of more frequent flooding (e.g., HPC being *resistant* with 21-43% increase in 2 of 3 basins), increased scouring and sedimentation of the stream beds are likely to affect both fish and macroinvertebrate population assemblages, likely favoring non-natives more tolerant of higher sediment loads (Coleman et al., 2011;

Matthaei et al. 1999; Poff and Allan, 1995). Second, more extreme floods (e.g., 25-31% increase of 1DMAX in the worst-case scenario) could cause direct mortality. Third, flow regime flashiness during the low-flow season also showed an increase (e.g., LPC being *resistant* with 400-600% increase in one basin). The overall substantially flashier flow regime (e.g., 31-36% increase in RBI in the worst-case scenario) will likely favor fish species with more generalized feeding strategies over those with specialized strategies (Poff and Allan, 1995). Smaller and more mobile benthic invertebrate species that reproduce multiple times a year (i.e., multivoltine species) may be better adapted than larger and univoltine or semivoltine species with limited mobility (Cassin et al., 2005). Fourth, as a result of lower summer flows (e.g., >85% decrease of 7DMIN in Basin A), reductions in the wetted perimeter are likely to reduce habitat availability and discourage lateral exchanges between the in-stream habitat and riparian corridor (Coleman et al., 2011). Projected lower summer flows also are likely to have indirect effects such as increased water temperatures and reduced dissolved oxygen, imposing 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.

(Q3) Are compact regional growth and integrated stormwater management effective 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, scenario rankings for overall flow regime differences from the reference were identical for all three basins: CM < DM < CnM < DnM (Figure 2.8). In addition, the compact and ISM scenarios outperformed their counterparts in limiting alterations to the majority of individual flow metrics, as shown by the same scenario rankings for most metrics (Figure 2.7). Second, the small proportion of *resistant* metrics (overall 10%) suggests that, at least under the relatively low population growth rate tested, compact growth combined with ISM may effectively constrain alterations to the majority of *sensitive* flow metrics to within the threshold we defined as *manageable*. Third, the substantial differences in magnitude of flow metric alterations across the four scenarios underscore the importance of compact growth and ISM. 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). This highlights the risks of not attempting to mitigate urbanization impacts. For example, the increase in annual maximum flood intensity (1DMAX) can be trivial (2%) under the best-case scenario (CM), but considerable (>25%) under the worst-case scenario (DnM). The real-world increase under DnM would likely exceed model predictions given the tendency of the SWAT model to under-predict this metric. Despite the consistent, negative ecological impacts of population growth and urbanization on the four flow metrics described above (1DMAX, LPC, HPC and RBI), scenario CM reduced flow alterations 60-75% over DnM across these metrics, suggesting that ISM and compact regional growth provide a reliable means to reduce impacts on stream ecosystem health.

Integrated stormwater management may be more important than compact regional growth at the scale addressed in this study. First, ISM scenarios outperformed the no-ISM scenarios in maintaining overall flow regimes in all three basins, i.e., CM < DM <

CnM < DnM (Figure 2.8). Second, compact growth appeared to provide limited additional reduction in overall flow regime alteration when ISM was in place. 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.

However, the conclusions above may be confounded by the differences in population outcomes across scenarios and basins (Table S7), when less flow alterations could in fact be partially attributed to lower levels of population increase. To further explore the relative importance of compact growth vs. ISM, we carefully examined the development variables calculated for each scenario and basin (Table S7) and specifically analyzed seven pairwise scenario comparisons in which scenarios with equal or larger population growth still generated less flow alterations than their counterparts. We detail the comparisons in Appendix D and discuss key lessons below.

Several nuanced lessons about the relative importance of compact growth and ISM emerged from better accounting for differences in overall population growth among scenarios. Due to the complexities of the agent-based model, not only did different scenarios shift population allocation among basins, but different scenarios also had different total population growth because they altered population distribution within the larger study area. On average, future scenarios accommodated a tripling of population from 11,000 to 33,000 residents in the three basins. However, dispersed scenarios averaged 14% larger final populations than their compact counterparts and ISM scenarios averaged 15% larger populations than their no-ISM counterparts. This interaction meant that CM and DnM resulted in almost identical populations, whereas at the extremes DM had 30% greater population than CnM. In turn, this means that compact scenarios, which performed better than their dispersed counterparts, had to accommodate somewhat less total population growth, whereas ISM scenarios accommodated more growth than their no-ISM counterparts. The former suggests that further investigations would be necessary to conclusively assess the effectiveness of compact growth, whereas the latter further emphasized the importance of ISM. The caveats above show that the complexities of the agent-based model, a critical foundation of this work, also created certain challenges for deconvolving the impacts of key factors in isolation. One approach for future research could be to apply greater experimental control of population projections within and among basins to reduce the number of confounding factors.

At the same time, the scenario-specific differences in population increase also strengthen other conclusions. The fact that compact regional growth scenarios incorporated less population increase than dispersed scenarios gives further reason to infer that ISM may be more important than compact regional growth. The fact that ISM scenarios incorporated more growth than non-ISM counterparts suggests that ISM may allow greater population growth while still limiting impacts. The comparison that becomes more difficult to interpret is the degree to which compact growth outperformed dispersed growth in terms of reducing flow alterations. There are many reasons why compact regional growth may provide benefits to society over more dispersed growth. However, it might be relatively unimportant from a stormwater management perspective in the presence of ISM. With that said, our results provide a cautionary that compact regional growth without ISM may increase the risk of stream degradation.

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

The modeling framework developed presents four key innovations toward an integrated framework for flow ecology research intended to manage the impacts of urbanization on stream ecosystems. First, the identification of key regional flow metrics with both ecological importance and modeling tractability establishes a bridge from hydrological impacts to ecosystem consequences. Second, the typology of flow metric sensitivity to development creates a direct linkage from flow alterations to planning and management alternatives. Third, the incorporation of an agent-based land use change model not only revealed specific effects of contrasting alternative futures, but also provided the ability to directly assess policies. Lastly, investigations of multiple catchment basins generated useful insights on potential variations in hydrological responses across different catchment characteristics.

By identifying a suite of ecologically relevant flow metrics that cover each major flow component (rather than a single or a small set of isolated metrics), our modeling framework begins to link mechanisms of landscape planning to the goals of anticipating aquatic ecosystem consequences. Reliance on a suite of metrics selected based on best available regional knowledge should make extrapolations to their effects on stream biota more robust in the absence of empirical local flow-ecology knowledge. Whereas the specific selection of flow metrics may not be directly transferable to other geographies, the framework itself is broadly applicable. In addition, the specific patterns of sensitivity and manageability for different flow components can help guide flow metric selection for future urbanization impact studies.

One of the pressing needs for addressing urbanization impacts on aquatic ecosystems is to link flow regime alterations to the means to manage them through planning and management prescriptions. By distinguishing the sensitivity and manageability of individual flow metrics, the classification system developed holds promise for guiding future watershed planning and research. For this typology to best inform planning decisions, future flow-ecology research should emphasize the identification of the ecological consequences of each flow metric to ascertain which flow components are the most important to local stream biota. Acceptable values for the *manageable* metrics need to be identified 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 sensitive metrics that were *resistant* to mitigation under the approaches tested helps to pinpoint the types of planning and management interventions that should be explored further.

Incorporation of an agent-based model (ABM) of land use change 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 of the challenges was that whereas the stochastic nature of ABM allows simulating multiple alternative futures for each scenario, the way SWAT was structured made it very inefficient and thus infeasible to test all the alternative futures generated. To this end, we developed an approach to identify the individual run of each scenario that represented the central tendencies of that scenario. This allowed the incorporation of information from multiple scenario runs of the ABM without breaking down the integrity of a single run. Although not as nuanced as evaluating the hydrological outcomes of multiple scenarios runs, it was a step in the right direction compared to the lack of variability from deterministic scenario models of the future that assume one and only one possible outcome. Despite using only a single landscape for each scenario, the use of 30 years of data provided the basis for tests of statistical differences.

Furthermore, the direct linkages between policies and land use trajectories in the agent-based model allowed us to specifically assess the effectiveness of applied policies. The high performance of scenarios incorporating ISM emphasizes the importance of the suite of underlying ISM strategies. They included: 1) limiting development on steep slopes and permeable soils; 2) protecting large vegetative patches, riparian buffers and wetlands; 3) limiting overall watershed imperviousness by encouraging cluster or high density development; 4) reducing directly connected imperviousness by re-infiltration LIDs; and 5) reducing road impacts by encouraging compact development and re-infiltration LIDs. Moreover, the greater flow regime flashiness projected under population growth specifically points out 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 a continuous and healthy riparian corridor (Lancaster and Belyea, 1997; Matthaei et al., 1999; Niemi et al., 1990). Future modeling could be used to explore the relative importance of the five strategies above, so that public budgets could be targeted to implementing the most effective policies in strategic locations.

By investigating multiple basins, our analyses also suggested potential relationships between watershed characteristics and hydrological responses, which would not have been revealed if only a single basin had been studied. For example, as discussed above, responses of certain flow components (e.g., extreme low flows) may be more dependent on basin physiography than others, highlighting the importance of river classification prior to developing regional flow-ecology relationships. Furthermore, some basins are likely to present higher sensitivity to urbanization than others, although further research is needed to identify the dominant reasons. 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 increases in imperviousness, and the rapid flow concentration time resulting from a small catchment area, high initial urbanization level, as well as very impermeable soils in this basin. Future research could incorporate more sensitivity analyses that reduce the number of confounding factors to reveal the underlying causes.

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 created one *resistant* metric and >13% increase in three others, suggesting that even low levels of urbanization could have substantial impacts on 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 our major conclusions as follows.

1) Expected population growth in the near future will likely result in significant flow regime changes in all three catchment basins evaluated. Urbanization impacts aligned closely with increases in flow regime flashiness and severity of extreme flow events. Most of the 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 statewide land use planning policies better protected streams in the three basins assessed than a more dispersed growth approach as would likely occur with a weakening of Oregon's 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 to be 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 reduction in overall flow regime alteration when ISM was in place.

4) Certain flow component alterations may consistently and inevitably follow urbanization despite attempts to mitigate them (i.e., the *sensitive and resistant* metrics). Future flow-ecology research is required to determine the ecological significance of these metrics and to explore additional management strategies targeted toward their protection.
5) A number of other metrics sensitive to urbanization appear to provide greater opportunities for mitigation (i.e., the *sensitive and manageable* metrics). Future research should emphasize identification of their ecological significance to develop specific flow management targets and to prioritize the implementation of specific strategies that are likely to successfully mitigate the impacts on these metrics.
6) Significant hydrologic alteration and thus loss of stream ecosystem functions could happen at very low urbanization levels.
7) Our ability to anticipate complex interactions between urbanization, streamflows, and ecosystem consequences is still rudimentary. Despite the substantially varied hydrological impacts across the three basins, the modeling system demonstrated was able to tease out both nuanced differences and generalizable trends.
8) Interdisciplinary modeling frameworks such as that demonstrated in this study can support collaborative efforts by planners and researchers to examine the implications of 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.

6. Bridge to Chapter III

In this chapter, we examined the hydrological impacts of urbanization itself and tested the effectiveness of compact regional growth and integrated stormwater management strategies in maintaining streamflow regimes. We found significant flow alterations under every future scenario, and development consistently led to increases in flow regime flashiness and severity of extreme flow events. Additionally, both compact growth and integrated stormwater management proved effective in reducing development-related flow alterations, with the latter more important than the former. In the following chapter, we further explore the combined hydrological impacts of urbanization and climate change by incorporating fine-resolution future climate projections from two climate models. We were particularly interested in understanding the potential interactions between development and climate change. Additionally, we wanted to explore the effectiveness of compact regional growth and ISM in maintaining flow regimes under the uncertainties of future climate.

CHAPTER III

INTERACTIVE IMPACTS OF URBANIZATION AND CLIMATE CHANGE ON STREAMFLOW REGIMES IN THE SOUTHERN WILLAMETTE VALLEY, OREGON, USA

A paper co-authored with Bart Johnson, who provided extensive assistance with research design, identifying the data analysis methods, and reviewing and editing the manuscript.

1. Introduction

Global change is expected to have far-reaching impacts on stream ecosystems through both broad-scale climate change effects on the hydrological cycle (Thomson et al. 2005) and more localized effects from expanding urbanization (Walsh et al. 2005). The combined effects of climate change and urbanization on stream ecosystems are difficult to predict due to the challenges and uncertainties of projecting the impacts of either factor at local scales, and the potential for interactions between them. Responding to these challenges requires a plausible assessment of their joint impacts at relevant spatial and temporal scales. In this article we build on a previous study that investigated the hydrological impacts of urbanization alone (Chapter II) and focus on the interactive effects of climate change and urbanization on stream hydrology.

To understand the ecological consequences of climate change and urbanization vis-à-vis hydrology, it is essential to evaluate their impacts on streamflow regimes. Characterized by the five components of magnitude, frequency, duration, timing, and rate of change, the natural flow regime plays a central role in shaping and maintaining stream ecosystems (Poff et al. 1997). While changes in even one flow component can have substantial impacts on aquatic organisms, it is critical to assess flow regimes in their totality (Poff et al. 1997). In this study we evaluate potential flow regime alterations through a set of ecologically meaningful hydrological metrics that provide direct linkages between urbanization and stream ecosystems (Eisele et al. 2003; Booth et al. 2004; Cassin et al. 2005).

Incorporating such knowledge into local watershed planning is both essential and challenging. On the one hand, changes in climatic regimes, especially precipitation, may alter multiple flow regime components and could, in turn, lead to cascading ecosystem consequences (Poff et al. 1997). On the other hand, planners must take into account the deep uncertainties of climate projections and the mismatch in spatial and temporal scales between available climate change information and on-the-ground watershed management. So far, the most comprehensive climate projections come from atmosphere-ocean general circulation models (AOGCMs or GCMs), which operate at the global scale (e.g., 200-300 km resolution). However, projections from different GCMs can vary dramatically, even under the same emissions scenario. Additionally, GCM outputs need to be translated to relevant spatial and temporal scales to support local planning decisions. Statistical or dynamic *downscaling* of GCM outputs has been established as an appropriate method to post-process GCM results for assessments at regional or local scales (Wilby and Wigley 1997; Bronstert et al. 2002).

Compounding the uncertainties of climate change, land use change also may unfold in unexpected ways, causing significant alterations of streamflow regimes. For example, Oregon has employed a statewide planning system that uses Urban Growth Boundaries (UGBs) to create compact urban footprints since the 1970s. By concentrating 90% of population growth into UGBs, this mechanism has effectively protected Oregon's rural forest and agricultural land. However, recent debates on private property rights have led to voter initiatives (e.g., Measure 7 in 2000 and Measure 37 in 2004) that called for a substantial relaxation of constraints on rural housing development. Potential legislative changes that would allow more rural subdivisions raised deep concerns about ways the stream ecosystems would respond (Bassett 2009).

Anticipating the potential impacts of climate and land use change is not enough. Testing and assessing the outcomes of different management alternatives is also essential if planners are to act proactively. A wide array of disciplines has wrestled with the issues of protecting stream ecosystem health. Various strategies have been proposed for the mitigation of development-related stormwater impacts on streamflow regimes, from limiting watershed total imperviousness (e.g., paved surfaces) to applying Low Impact Development (LID) practices in subdivisions (Forman 1995; Collinge 1996; Alberti 1999; Collins et al. 2000; Grimm et al. 2000; Opdam et al. 2001; Pickett et al. 2001). Increasingly, there has been a call to integrate the spatial organization of land uses (i.e., development patterns) with local stormwater Best Management Practices (BMPs) to protect a wider range of streamflow conditions (Roesner et al. 2001; Zhen et al. 2004; Wu et al. 2006; Alberti et al. 2007; Urbonas and Wulliman 2007; Pomeroy et al. 2008; Brabec 2009). Chapter II defined such integration as the *Integrated Stormwater Management* (ISM) approach and evaluated its effectiveness in mitigating development-related stormwater impacts and maintaining historical flow regimes. However, the degree to which ISM may be effective under future climatic regimes remains to be investigated.

Exploring watershed management alternatives requires an interdisciplinary approach that blends a wide range of expertise and research tools. A wealth of quantitative methods for anticipating landscape change and assessing environmental impacts are currently available, including simulation modeling. For instance, scenario-based alternative futures approaches increasingly have been used to explore land management options in the presence of deep uncertainty (Godet 1987; Hulse et al. 2004; Liu et al. 2007). However, a major constraint in current modeling capacity is that most models can only capture limited system components and mechanisms out of the many core interactions among human and natural systems. A closer integration of disciplines and models is necessary to better inform local planning and management decisions that may affect stream ecosystem health.

In a previous study, we established a three-step interdisciplinary modeling framework (Chapter II) that incorporated land use simulation, hydrological modeling, and hydrological assessment to evaluate the impacts of urbanization on streamflow regimes in three urbanizing catchment basins in the southern Willamette Valley, Oregon (Figure 2.3). Alterations of historical flow regimes, as measured by 10 ecologically meaningful flow metrics (Table 2.1), were used as surrogates (Poff et al. 1997) of ecological consequences. An agent-based land use change model, Envision (Guzy et al. 2008; Hulse et al. 2009), was used to generate four spatially explicit alternative futures for three catchment basins for the year 2050 based on two regional population growth scenarios (Compact vs. Dispersed Growth) crossed with two stormwater management approaches (with or without *Integrated Stormwater Management*) in a fully factorial design. A watershed-scale hydrologic model, the Soil and Water Assessment Tool (SWAT) (Gassman et al. 2007), was then applied to simulate long-term daily streamflows under baseline (1990 landscape) and the four future development scenarios (2050 landscapes). To explicitly simulate development impacts on streamflow regimes, all hydrological modeling consistently used historic climate records for WY 1978-2007.

Our results suggested that projected population growth over the next 3-4 decades is likely to result in substantial flow regime changes in all three basins. Urbanization impacts consistently led to increases in flow regime flashiness and severity of extreme flow events. Both compact growth and ISM proved to be important strategies for maintaining critical aspects of the flow regime. ISM, in particular, was more effective than compact growth at reducing flow alterations.

While it was useful to assess the possible impacts of urbanization in isolation from other factors, the potential for additional, and critically, interactive effects with climate change make it equally important to investigate whether the compact growth and ISM strategies continue to protect stream ecosystem health under the uncertainties of future climate. In the Willamette Valley, this is especially important because the flow regimes of intermittent streams are particularly sensitive to changes in the form, amount, and intensity of the precipitation (Gibson et al. 2005; Konrad and Booth 2005). For these reasons, we investigated the consequences of future climatic projections in the region, adapting the modeling framework (Figure 3.1), and investigating the following five questions.

(1) How does climate change impact streamflow regimes in comparison to urbanization? Will different future climate regimes lead to different effects?

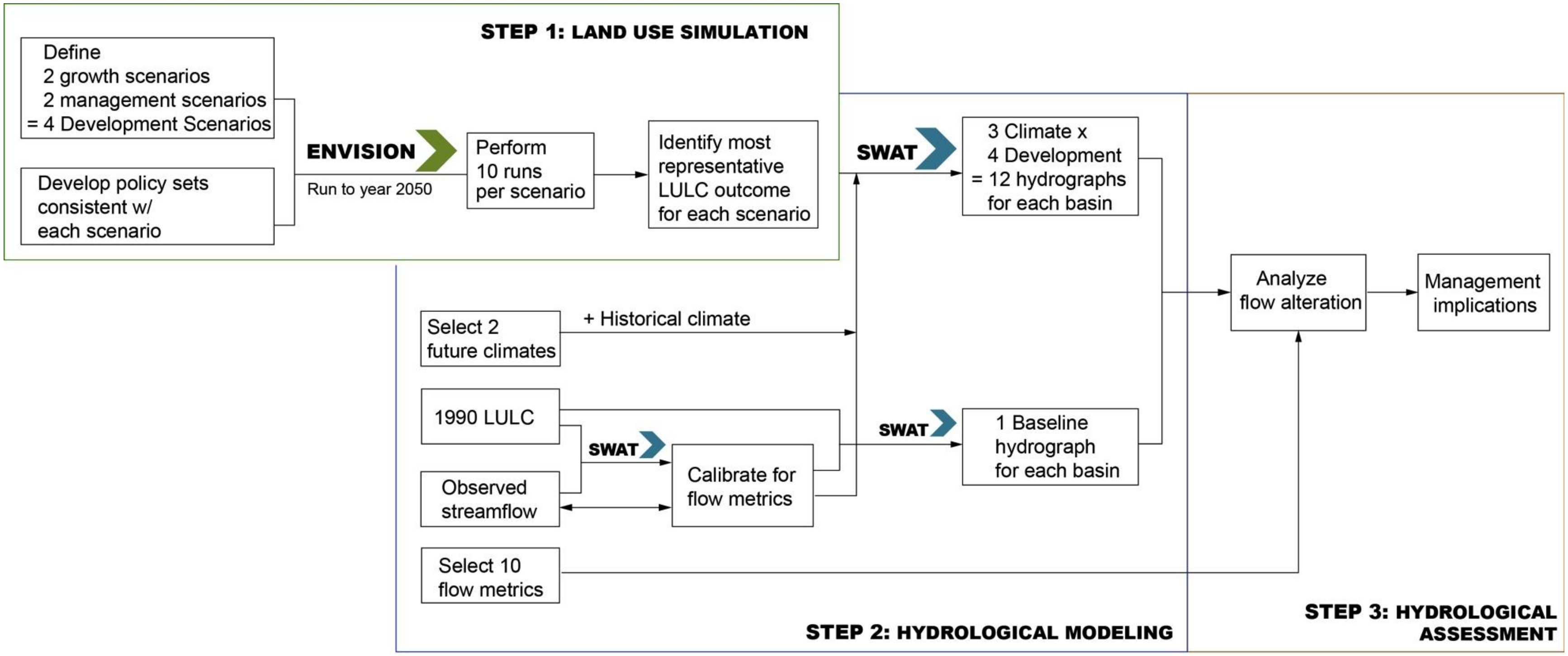
(2) How might climate change and urbanization interact to influence the overall flow regimes as well as individual flow metrics? Is climate change likely to exacerbate or attenuate urbanization impacts?

(3) Will compact regional growth and integrated stormwater management remain effective strategies in reducing flow alterations under different climate regimes?

(4) How will the manageability of the overall flow regime as well as individual flow metrics change?

(5) Do differences in catchment basin characteristics lead to different local effects from climate and urbanization?

Figure 3.1. The modeling process under the combined impacts of urbanization and climate change.



2. Methods

In the simulation modeling section, we briefly introduce the study area, the selection of 10 flow metrics, the creation of 4 future land development scenarios and 3 future climate regimes, and the processes of hydrological modeling and assessment. We follow with descriptions of statistical analysis for climate impacts, combined impacts, and flow regime displacement.

2.1. Simulation Modeling

2.1.1. Study Area

The Willamette Valley population is projected to double between 1990 and 2050, growing over this 60-year period from approximately 2 million to 4 million people, providing a natural laboratory for experimenting with innovative planning strategies (Baker et al. 2002). The 409 km^2 hydrological modeling area includes three catchment basins (A, B, and C, Figure 2.3) adjacent to the UGBs of Veneta (2010 population 4,561), Creswell (population 5,031), and the larger Eugene-Springfield Metropolitan Area (population 215,588). The three basins as a whole are primarily rural with ≈70 people/mi^2. Urban, agricultural, forestry, and rural residential land uses occupy 2.8%, 18.5%, 56.8%, and 9.8%, respectively (Figure S1), providing substantial capacity for urbanization as well as rural residential growth.

Landscape characteristics vary substantially across the three basins (Chapter II). The Strahler orders of the basins are second-order for A and B, and fourth-order for C. The smallest Basin A is the flattest and most urban with the least permeable soils. The intermediate-sized Basin B has the most permeable soils. The largest Basin C is the steepest and most rural. We use the same alphabetic character to describe the catchment basin and its outlet.

2.1.2. Selection of Flow Metrics

We selected a suite of flow metrics based on the literature, regional ecological knowledge, and our ability to simulate them accurately and assess them efficiently. Specifically, we applied the following criteria: 1) the set of metrics circumscribes all major flow components for intermittent streams (Olden and Poff 2003); 2) they demonstrate biological significance in the Pacific Northwest (Derek Booth, Martin Dieterich, and Curtis DeGasperi, personal communications, 2014); 3) metrics calculated from simulated hydrographs are in good agreement with those calculated from gauged data; and 4) annual values can be calculated either directly or using the Indicators of Hydrologic Alteration (IHA) tool (Richter et al. 1997; Richter et al. 2003). The final set included the following 10 metrics: 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). Additionally, we specifically calibrated the SWAT model for these flow metrics (Chapter II).

2.1.3 Land Development Scenarios

As described above, we designed a 2 x 2 factorial combination of land development scenarios representing two regional population growth patterns (Compact vs.

Dispersed Growth) and two stormwater management approaches (with vs. without 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. Major assumptions of the four scenarios are provided in Table 2.3.

The Compact Growth scenarios assumed a continuation of current statewide planning practices by concentrating 90% of new population growth into UGBs, whereas the Dispersed Growth scenarios allowed 35% of new population growth to be dispersed into rural areas. To achieve these targets, the land use change model Envision generated population growth and land development processes from 2007-2050, under a 7% annual population growth rate during which it distributed population growth spatially using the above proportions (Chapter II).

The ISM scenarios incorporated both spatial organization of land uses and site-scale BMPs to address stormwater impacts, whereas the no-ISM scenarios continued with only limited protection of hydrologically sensitive areas. The no-ISM scenarios (CnM and DnM) implemented just enough ISM policies to seem plausible, whereas the ISM (CM and DM) blended a wide range of ISM strategies that include: 1) limiting development on steep slopes and permeable soils (Yang and Li, 2011); 2) protecting large vegetative patches, riparian buffers and wetlands (Morley and Karr 2002; Meador and Goldstein 2003; Alberti et al. 2007); 3) limiting watershed total imperviousness (Schueler 1994; Schueler et al. 2009); 4)reducing directly connected impervious area through widespread re-infiltration LIDs (Lee and Heaney 2003; Booth et al. 2004); 5) encouraging cluster or high density development to protect natural vegetative cover and more open space (Booth et al. 2002; Girling and Kellett 2002; May and Horner 2002; Berke et al. 2003; Richards 2006; USEPA 2006); and 6) encouraging development close to existing infrastructure and permeable pavement on light-duty roads to reduce the notorious impacts of roads (Alberti et al. 2003). A complete list of policies employed in scenario simulations is included in Table S6.

2.1.4. Future Climate Regimes

We next elaborate the process of developing two sets of fine-resolution future climate regimes. This involved a) selecting 2 GCMs that performed well in replicating historical climate in the U.S. Pacific Northwest, b) selecting 2 contrasting Representative Concentration Pathways (RCPs), c) statistically downscaling the GCM outputs to the weather station location used in SWAT calibration, and d) performing tests of all four resultant climate scenarios (2 GCMs x 2 RCPs) to determine the two that produced the greatest contrasts for scenarios evaluation.

We first selected two GCMs from the latest generation of climate models coordinated by the Coupled Model Inter-Comparison Project 5 (CMIP5) (Taylor et al. 2012) based on the evaluation by Rupp et al. (2013) of the performance of 41 CMIP5 models in replicating the historical climate of the U.S. Pacific Northwest (Figure S3). The French model CNRM -CM5 and Canadian model CanESM2 ranked the highest with the least total relative error from historical conditions for the combined set of all climate variables assessed. In particular, they performed the best in reproducing precipitation-related variables.

We then selected two Representative Concentration Pathways to apply to the GCMs. The RCPs are a set of four new climate trajectories (i.e., RCP 2.6, 4.5, 6, and 8.5) that integrate emission, concentration, land use change, and socio-economic responses (Van Vuuren et. al. 2011). We selected an intermediate trajectory of RCP 4.5 to represent a future with relatively ambitious emissions reductions, and an extreme trajectory of RCP 8.5 for a future with no policy changes to reduce emissions. Specifically, RCP 4.5 refers to a "stabilization without overshoot" pathway with the radiative forcing stabilizing at 4.5 W/m^2 after 2100 (Clarke et al. 2007). In contrast, RCP 8.5 represents a rising pathway leading to 8.5 W/m^2 by 2100 (Riahi et al. 2007).

Next, we downscaled and bias-corrected each of the four GCM x RCP combinations (CanESM2_RCP4.5, CanESM2_RCP8.5, CNRM-CM5_RCP4.5, and CNRM-CM5_RCP8.5) to the weather station location used in SWAT calibration for historical climate (Chapter II) using the latest Multivariate Adaptive Constructed Analogs (MACA) data product (version v2-LIVNEH, see details in Table S10) (Abatzoglou 2013; Livneh et al. 2013). MACA employs a statistical downscaling approach that uses an observation dataset to eliminate historical biases meanwhile matching model output spatial patterns (Abatzoglou and Brown 2012). Because the MACA data are based on 4 km grid cells, microclimate differences within a cell can be substantial, especially for the temperature and precipitation variables. As a result, the grid values of the cell containing our study area were bias-corrected to the SWAT climate station location through the non-parametric EDCDFm quantile-mapping method described in Li et al. (2010).

Finally, we compared the four resulting climate datasets (Table S11) for WY 2036-2065 and selected two, the CanESM2_RCP4.5 and CNRM-CM5_RCP4.5, to represent the driest and wettest future conditions among the four. The CanESM2_RCP4.5 showed the largest increase in both annual precipitation (+3%) and the largest storm intensity (+14%), while CNRM-CM5_RCP4.5 featured the largest decrease in annual precipitation (-6%) and smallest increase in annual maximum storm (+4%). For ease of interpretation, we call the CanESM2_RCP4.5 the “wet” future climate, and the CNRM-CM5_RCP4.5 the “dry” future climate. It is notable, however, that the “wet” climate has wetter winters but drier summers due to a greater intensification of Mediterranean summer drought.

2.1.5. Hydrological Modeling and Assessment

The ca. 2050 landscape outcomes of the four development scenarios were then subjected to hydrological modeling in SWAT under observed and two future climate regimes. Each SWAT simulation was run for 30 years (WY 2035-2065). A total of 12 (3 climate regimes x 4 development scenarios) daily time-step hydrographs were produced for each basin outlet. As in Chapter II, we defined the reference hydrograph as the modeled results from the ca. 1990 landscape under the WY 1978-2007 observed climate. We acknowledge that this reference may be different from the pre-Euro-American settlement natural flow regimes, which could be considered an “ideal” target for native stream biota. However, given both the problematic nature of comparing streamflows under contemporary climate to those of over 150 years ago, and the unrealistic goal of returning the landscape to its pre-settlement conditions, we focused on evaluating the degree of departure from the recent past. As in other studies (Poff et al. 1997; Bunn and Arthington 2002), future flow regimes with the least departure from the reference were deemed the most preferable. Thirty annual values for each flow metric were then calculated from the 12 hydrographs to evaluate flow alterations in each basin. Our final raw data thus includes 30 annual values for 10 flow metrics for 3 basins over a total of 12 combinations of development and climate scenarios.

2.2. Data Analyses

We applied three types of non-parametric statistical tests to address our research questions, rather than parametric tests, because the flow metric data were in general severely skewed to the right (i.e., large events were rare) (Sokal and Rohlf 1995). The *Climate Impacts Alone* test compared flow metrics under the three different climatic regimes *within* the same development scenario for each basin. The *Combined Impacts* test evaluated flow metric differences *among* all future development x climate combinations in relation to the reference flow regime for each basin. The *Flow Regime Displacement* test integrated the 10 flow metrics to represent the flow regime as a whole, and then visualized the dissimilarities among the 12 developed flow regimes (3 climate x 4 development) and the reference for each basin.

Climate Impacts Alone. We used multiple Kruskal–Wallis tests (non-parametric one-way ANOVA) to examine whether climate change alone will trigger significant flow metric responses. Flow metrics were compared on a group basis, with 30 annual values in each group. Within each development scenario, we compared the 3 flow metric groups under the three climate regimes (historical, wet, and dry) for each metric and basin. A total of 120 (10 flow metrics x 4 development scenarios x 3 basins) tests were performed. When $p<0.05$ for the Kruskal-Wallis test, post-hoc Mann-Whitney U tests (non-parametric two-sample comparison) with Bonferroni correction were applied to identify whether the differences occurred between the historical and future climates, or between the two future climates.

Combined Impacts. Using the reference flow regime as the control, we conducted 240 pairwise Mann-Whitney comparisons (10 flow metrics x 2 future climates x 4 development x 3 basins) to explore instances when future scenarios significantly changed a flow metric. As above, flow metrics were compared on a group basis, with 30 annual values in each group. Pairwise comparisons were conducted between the reference and each of the 8 combinations of future development and climate (CM, DM, CnM, and DnM under either dry or wet future climate) for each basin. When $p<0.05$ for the Mann-Whitney U tests, we calculated the differences in the flow metric medians between the future scenarios and the reference.

Adapting the sensitivity classification system developed in Chapter II, we categorized the flow metrics into three types according to the magnitude of change in their medians and the degree to which such changes could be mitigated (Table 2.4): *insensitive* to development and/or climate change, *sensitive* to development and/or climate change *and manageable* by development alternatives, and *sensitive* to development and/or climate change *and resistant* to development alternatives. *Insensitive* refers to metrics not influenced by development and/or climate change in *any* future scenario compared to the reference (historical climate/current landscape) scenario. *Sensitive* and *manageable* (aka *manageable*) refer to metrics significantly affected in one or more scenario, but for which impacts could be mitigated by compact growth and/or ISM. *Sensitive and resistant* (aka *resistant*) refers to metrics that were significantly affected by development and/or climate change 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 and climate change with fewer opportunities to mitigate using the tools tested in our scenarios. Lastly, we compared the magnitudes of change in the medians of the flow metrics and their categories with the results under urbanization impacts alone to explore potential interactions between urbanization and climate change.

Flow Regime Displacement. We used Non-metric Multidimensional Scaling (NMDS) to visualize and interpret differences among the 12 future flow regimes (3 climate x 4 development) and the reference flow regime as a whole for each basin. NMDS is an ordination technique commonly used in ecological research for differentiating communities (Kenkel and Orloci 1986). It allowed us to collapse information from all 10 flow metrics into a small number of dimensions. Additionally, its non-parametric character makes it extremely flexible (McCune et al. 2002), for instance, for accommodating a variety of metrics of different scales, including multiple metrics with variously skewed distributions. Because only one value per metric could be used in the NMDS, we used the median of the 30 annual values to represent the central tendency of each flow metric, and thus a total of ten medians to together describe a certain flow regime. A separate NMDS was initially performed for each basin. Because the axes loadings for Basins B and C were very similar (Table S12), we used a single ordination for B and C (NMDS-BC), while keeping Basin A in a separate ordination (NMDS-A).

3. Results

In this section we first describe responses of individual flow metrics for each basin under the *Climate Impacts Alone* and *Combined Impacts* tests, and then examine overall flow regime alterations in relation to climate, regional growth pattern, and ISM through the *Flow Regime Displacement* test.

3.1. Individual Flow Metric Responses

The *Climate Impacts Alone* test examined differences among flow metric groups under historical vs. dry vs. wet climate regimes *within* each development scenario for each basin. The results showed that five of the ten flow metrics (7DMIN, LPC, N0D, TL1, and RBI) were sensitive to climate change under certain development scenarios (Table 3.1). Four of these five are measures of low flow conditions. All differences occurred between historic and future climate rather than between the two future climates. Not all significant scenario differences resulted in significant pairwise comparisons. In most cases with significant pairwise differences, the historical results differed from those of both future climates. When only one future climate scenario was different, it was always the "wet" future climate (CanESM2_RCP4.5), and never the "dry" future climate (CNRM-CM5_RCP4.5).

In terms of individual metrics, 7DMIN was affected by climate under all development scenarios in all basins, with the exception of Basin A under scenario CM. When individual climate contrasts were significant, 7DMIN showed a decrease from the historical to the future climate. The LPC decreased under the wet climate in one basin (A) in one scenario (DnM). The N0D increased in one basin (A) under all development

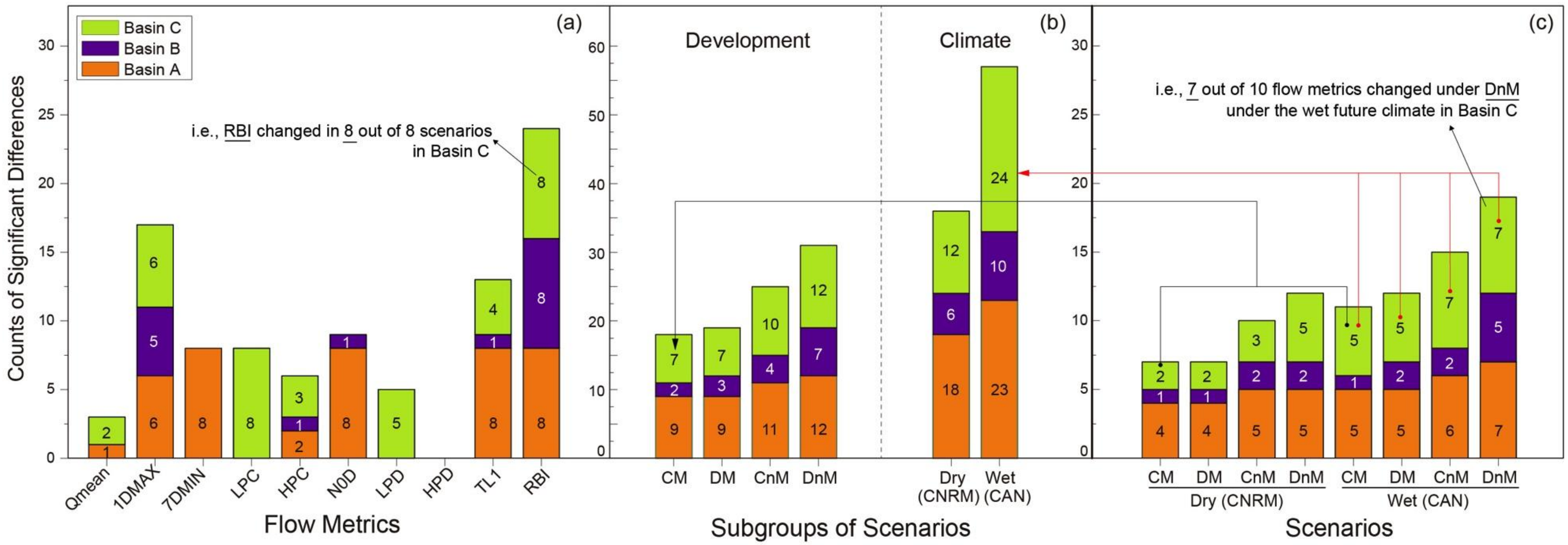
Table 3.1. Climate change impacts alone on flow metrics under each development scenario for each basin. Each Kruskal-Wallis *p*-value indicates the significance of a test for differences among climate scenarios (historical v. wet v. dry) for each flow metric within each development scenario for each basin (A, B, or C). Only significant scenario results are shown When p<0.05 (*) for the Kruskal-Wallis Test, a Mann-Whitney U Test, adjusted using the Bonferroni correction, was used to examine pairwise comparisons among climate scenarios with the significance level set as p<0.10(†). Not all significant scenario differences resulted in significant pairwise comparisons. N=30 for all data groups. Development scenarios were color coded for easier visualization of the patterns. ★ indicates differences between historical vs. dry future climate. ● indicates differences between historical vs. wet future climate (i.e., his vs. wet).

his vs. dry vs. wet Kruskal–Wallis comparisons					Post-hoc Mann-Whitney U Tests with Bonferroni adjusted Exact Prob>|U|							
Flow Metric		**A** ***p***	**B** ***p***	**C** ***p***		**Pairs**	**A Diff.**	**A *p***	**B Diff.**	**B *p***	**C Diff.**	**C *p***
7DMIN	CM	ns	*	*	CM	his v. dry		ns		ns		ns
						his v. wet		ns		ns		ns
						wet v. dry		ns		ns		ns
	DM	*	*	*	DM	his v. dry		ns		ns		ns
						his v. wet	● -100%	†		ns		ns
						wet v. dry		ns		ns		ns
	CnM	*	*	*	CnM	his v. dry	★ -100%	†		ns		ns
						his v. wet	● -100%	†		ns		ns
						wet v. dry		ns		ns		ns
	DnM	*	*	*	DnM	his v. dry	★ -100%	†		ns		ns
						his v. wet	● -100%	†		ns		ns
						wet v. dry		ns		ns		ns
LPC	DnM	*	ns	ns	DnM	his v. dry		ns				
						his v. wet	● -33%	†				
						wet v. dry		ns				
N0D	CM	*	ns	ns	CM	his v. dry	★ +13d	*				
						his v. wet	● +10d	†				
						wet v. dry		ns				
	DM	*	ns	ns	DM	his v. dry	★ +15d	*				
						his v. wet	● +12d	†				
						wet v. dry		ns				
	CnM	*	ns	ns	CnM	his v. dry	★ +16d	*				
						his v. wet	● +15d	†				
						wet v. dry		ns				
	DnM	*	ns	ns	DnM	his v. dry	★ +17d	†				
						his v. wet	● +17d	†				
						wet v. dry		ns				
TL1	CnM	ns	ns	*	CnM	his v. dry						ns
						his v. wet					● -23d	*
						wet v. dry						ns
	DnM	ns	ns	*	DnM	his v. dry						ns
						his v. wet					● -18d	*
						wet v. dry						ns
RBI	DnM	ns	*	ns	DnM	his v. dry				ns		
						his v. wet			● +6%	*		
						wet v. dry				ns		

scenarios for both future climates. The TL1 advanced in one basin (C) under the wet climate in both no-ISM scenarios (CnM and DnM). The RBI increased in one basin (B) under the wet future climate for the DnM scenario.

In contrast to the *Climate Impacts Alone* test, the *Combined Impacts* test used 240 paired comparisons between the future flow metrics and the reference and explored when and how much future climate x development combinations changed individual flow metrics. First, counts of significant flow metric changes across all scenario x climate combinations show which flow metrics were altered most often and which basins experienced the most alterations (Figure 3.2a). The 1DMAX, RBI, and TL1 showed the greatest numbers of changes across the three basins, whereas HPD, Qmean, and LPD showed the fewest. Basin A showed the most changes across the 8 scenarios (2 future climate x 4 development) and Basin B had the fewest (<1/2 of those of A and C). The same data also shows which development and climate scenarios incurred the most instances of flow alterations (Figure 3.2b and 3.2c). Scenario DnM generated the most total counts for every basin, while CM and DM generated the fewest (Figure 3.2b). The dispersed scenarios generated more counts of changes than their compact counterparts for every basin, while the no-ISM scenarios similarly generated more counts than their ISM counterparts for every basin (Figure 3.2b). The wet climate scenarios generated more counts than the dry climate scenarios overall and did so consistently for every basin (Figure 3.2b). Finally, the wet/dispersed/no-ISM scenario showed the greatest number of impacts across all metrics and basins (Figure 3.2c).

Figure 3.2. Counts of significant differences in flow metrics summarized by basin, flow metric, and scenario. This figure summarizes the results of the *Combined Impacts* test and reveals when and how much future climate x development combinations changed individual flow metrics. (a) shows which flow metrics were altered most often, and which basins experienced the most alterations. The maximum possible count of significant differences for each basin is 8. (b) shows which development and climate scenarios incurred the most instances of flow alterations. The maximum possible count of significant differences for each basin is 20 for the development scenarios (left) and 40 for the climate scenarios (right). (c) breaks down the results of (b) into individual climate x development combinations. The maximum possible count of significant differences for each basin is 10.



When flow metrics were altered under both climate scenarios, the directions of changes were always the same, and the magnitudes tended to be very similar (Table 3.2-I). However, as noted above, there were more alterations under the wet future climate than the dry future climate. Furthermore, when more than one basin was impacted, the directions of changes were always the same, but the magnitudes could be substantially different. Finally, it is notable that under both future climates, metrics affected under the ISM scenarios were also affected under the no-ISM scenarios but that the only scenarios showing additional changes were the no-ISM ones.

Changes incurred by the combined impacts (Table 3.2-II column M1) exceeded those under urbanization impacts alone (column M2) under at least one future climate regime in 57% of all occasions where there were substantial differences in flow metric medians between the two assessments. In particular, changes to 1DMAX (all basins), N0D (Basin A), and TL1 (all basins) were substantially amplified over urbanization alone, while Qmean (Basin C), 7DMIN (Basin A), LPD (Basin C), and RBI (all basins) were increased to lesser degrees. On the other hand, changes to three other flow metrics, LPC (for all basins), HPC (Basins A and B) and HPD (for Basin B), were reduced under the combined impacts.

Finally, the combined impacts changed the sensitivity categories of 7 of the 10 flow metrics (except for 7DMIN, HPC, and RBI) from those of urbanization impacts alone. For those 7 metrics, over one-half (12 of 21) of the metric x basin sensitivity ratings were altered. Of those changes, ¾ increased sensitivity or resistance, and ¼ attenuated them (Table 3.3). These alterations changed overall sensitivities across all metrics from 43% *insensitive*, 47% *manageable*, and 10% *resistant* metrics under

Table 3.2. The *Combined Impacts* test. Panel I reports median changes from the reference (1990 landscape, historical climate) for the significantly altered flow metrics for all the eight future scenarios. N=30 for all data groups. Panel II compares changes in medians between those assessed with the combined impacts (Column M1) and the urbanization impacts alone (Column M2). In Panel II, 0% represents non-significant differences in medians. Codes: * = Means instead of medians are reported to more appropriately represent the trend. † = Evaluates whether changes in medians were amplified or attenuated (M1 vs. M2). Varied = different directions of change across scenarios; minor = minor changes (≤5% or 3 days for N0D); **bold text** = substantial differences between M1 and M2.

		Panel I								**Panel II**			
		Change in the Medians from the Reference in Future Scenarios								**Range of Sig. Diff. in Medians**			**Amplify (+) or attenuate (-)†**
		Dry (CNRM)				**Wet (CAN)**				**M1** Combined		**M2**	
Flow Metric	**Bsn**	**CM**	**DM**	**CnM**	**DnM**	**CM**	**DM**	**CnM**	**DnM**	Dry	Wet	Devel. only	
Qmean	A								+13%	0	0-13%	0-4%	varied
	B									0	0	-1-5%	minor
	C							+14%	+15%	0	0-15%	0-5%	**+ (wet)**
1DMAX	A			+25%	+37%	+34%	+45%	+51%	+61%	0-37%	34-61%	6-30%	**+ (wet)**
	B			+23%	+32%		+30%	+46%	+58%	0-32%	0-58%	2-25%	**+ (wet)**
	C			+35%	+41%	+34%	+37%	+51%	+61%	0-41%	34-61%	13-31%	**+ (wet)**
7DMIN	A	***-100%***	***-100%***	***-100%***	***-100%***	***-100%***	***-100%***	***-100%***	***-100%***	-100%	-100%	-90% to -85%	**+ (dry & wet)**
	B									0	0	0	
	C									0	0	0	
LPC	A									0	0	0-50%	**- (dry & wet)**
	B									0	0	0-20%	**- (dry & wet)**
	C	+400%	+400%	+400%	+400%	+350%	+350%	+400%	+500%	400%	350-500%	400-600%	**- (dry & wet)**
HPC	A							+29%	+29%	0	0-29%	14-21%	**- (dry)**
	B								+13%	0	0-13%	0-13%	**- (dry)**
	C				+43%			+43%	+43%	0-43%	0-43%	14-43%	varied
N0D (days)	A	+13d	+15d	+16d	+18d	+11d	+12d	+15d	+18d	+13 to +18d	+11 to +18d	+7 to +10d*	**+ (dry & wet)**
	B								+13d	0	0 to +13d	0	varied
	C									0	0	-2 to -1d	minor
LPD	A									0	0	0	
	B									0	0	0	
	C				***-57%***	***-57%***	***-59%***	***-55%***	***-54%***	-57% to 0	-59 to -54%	-58% to 0	**+ (wet)**
HPD	A									0	0	0	
	B									0	0	-26% to 0	**- (dry & wet)**
	C									0	0	0	
TL1 (days)	A	***-10d***	***-14d***	***-17d***	***-18d***	***-10d***	***-17d***	***-18d***	***-23d***	-18 to -10d	-23 to -10d	-13 to -5d	**+ (dry & wet)**
	B								***-18d***	0	-18d to 0	0	**+ (wet)**
	C					***-20d***	***-20d***	***-22d***	***-22d***	0	-22 to -20d	0 to +2.5d	**+ (wet)**
RBI	A	+13%	+24%	+27%	+38%	+13%	+23%	+28%	+39%	13-38%	13-39%	11-36%	minor
	B	+11%	+13%	+25%	+35%	+12%	+14%	+28%	+38%	11-35%	12-38%	6-31%	minor
	C	+18%	+21%	+32%	+39%	+19%	+22%	+34%	+41%	18-39%	19-41%	15-36%	minor

urbanization impacts alone, to 40% *insensitive*, 47% *manageable*, and 13% *resistant* metrics under the dry future climate, and 37% *insensitive*, 37% *manageable*, and 26% *resistant* metrics under the wet future climate. The total counts of metrics in each sensitivity category altered little under the dry future climate but substantially under the wet future climate. In particular, the *resistant* metrics more than doubled under the wet future climate over urbanization impacts alone. In fact, even when the total counts remained similar, substantial turnover of metric types occurred (Table 3.3). Under the *insensitive* category, 30-40% of development-only *insensitive* metrics shifted to *sensitive* under the combined impacts. Under the *manageable* category, the dry future climate resulted in nearly 1/3 metric turnover, whereas the wet future climate caused removal of ½ of the original metrics and addition of 4 other metrics. No metrics were removed from the *resistant* category under the combined impacts. The dry future climate added 1 metric, whereas the wet future climate added 5.

In terms of individual metrics, 7 out of 10 metrics changed their sensitivity categories under the combined impacts. The other 3 (7DMIN, HPC, and RBI) remained in their original categories under the combined impacts. The majority of the changes (5 out of 7 metrics) progressed from less to more affected, i.e., from *insensitive* (T1) to *manageable* (T2) to *resistant* (T3), whereas 2 other metrics changed in the opposite direction. Specifically, the following 5 metrics became more affected: the Qmean (Basins A and C), N0D (Basin B), and TL1 (Basin B) changed from T1 *insensitive* to T2 *manageable* under both climates; the 1DMAX (Basins A and C) and LPD (Basin C) changed from T2 *manageable* to T3 *resistant* under the wet future climate; the TL1 (Basin A) changed from T2 *manageable* to T3 *resistant* under both climates; and the TL1

Table 3.3. Sensitivity classifications of flow metrics under the combined impacts in comparison to under urbanization impacts alone.

Flow Metrics	Type 1 (T1) *Insensitive*			Type 2 (T2) *Sensitive and Manageable*			Type 3 (T3) *Sensitive and Resistant*			Change of Types
	Devel. Only	Combined Impacts		Devel. Only	Combined Impacts		Devel. Only	Combined Impacts		
		Dry	Wet		Dry	Wet		Dry	Wet	
Qmean	A**B**C	**B**	**B**		AC	AC				2 T1s → T2s under both future climates
1DMAX				A**B**C	**ABC**	**B**			AC	2 T2s →T3s under wet future climate
7DMIN	**BC**	**BC**	**BC**				**A**	**A**	**A**	No change – T1 in 2 basins, T2 in 1 basin
LPC		AB	AB	AB			**C**	**C**	**C**	2 T2s →T1s under both future climates
HPC				**ABC**	**ABC**	**ABC**				No change – T3 in all basins, all scenarios
N0D	B**C**	**C**	**C**		B	B	**A**	**A**	**A**	1 T1 →T2 under both future climates
LPD	**AB**	**AB**	**AB**	C	**C**				**C**	1 T2 →T3 under wet climate
HPD	**AC**	**A**B**C**	**A**B**C**	B						1 T2 →T1 under both future climates
TL1	BC	**C**		A	B	B		A	AC	1 T1 →T2 and 1 T2 → T3 under both future climates, 1 T1 →T3 under wet future climate
RBI				**ABC**	**ABC**	**ABC**				No change – T3 in all basins, all scenarios
Tot. Counts	13	12	11	14	14	11	3	4	8	
Unchanged		9	8		10	7		3	3	
Added		+3	+3		+4	+4		+1	+5	
Removed		-4	-5		-4	-7		0	0	

Bold letters = development-only impact (ca. 2050 development w/ historical climate) unchanged under both combined impacts scenarios (ca. 2050 development with wet or dry future climate); underlined letters = added to this category for one or both combined impacts scenario; double underlined letters = removed from this category for one or both combined impacts scenarios.

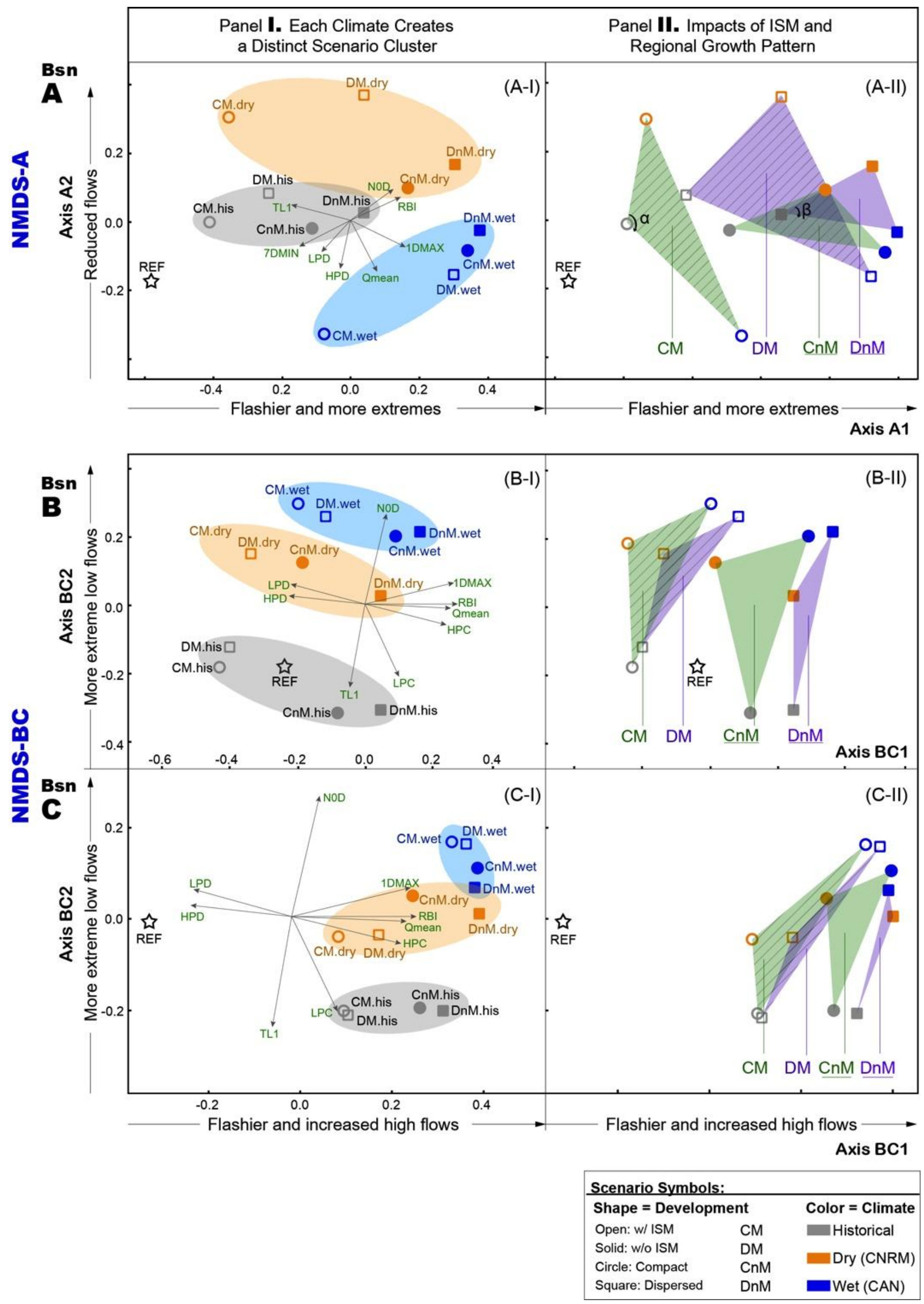
(Basin C) changed from T1 *insensitive* to T3 *resistant* under the wet climate. In contrast, the 2 metrics of LPC (Basins A and B) and HPD (Basin B) became less affected, changing from T2 *manageable* to T1 *insensitive*.

3.2. Flow Regime Displacement

Both ordinations NMDS-A and NMDS-BC (Figure 3.3) preserved the original dissimilarities among the scenario flow regimes in reduced dimensions, with stress = 0.104 for NMDS-A, and 0.098 for NMDS-BC ($0.05 < \text{stress} < 0.1$ considered excellent representation, McCune et al. 2002). We first interpret the NMDS axes based on the loadings of individual flow metrics (Table S13) and then describe the patterns of flow regime displacement in relation to climate, regional growth pattern, and ISM across the three basins.

Flow metric loadings in each ordination showed related but distinctive patterns. In NMDS-A, flow metrics that loaded ≥0.5 on Axis A1 included RBI, 1DMAX, N0D, and HPC (all positive, in order of decreasing magnitude), and TL1, 7DMIN, and LPD (all negative, in order of decreasing magnitude). Those that loaded ≥0.5 on Axis A2 included LPC and N0D (both positive, in order of decreasing magnitude), and HPD, Qmean, LPD, and HPC (all negative, in order of decreasing magnitude) (Table S13). We interpret the left-to-right gradient along Axis A1 as reflecting an increase in flow regime flashiness and magnitude of extreme flow events, while the upward gradient along Axis A2 indicates a trend of flow reduction. In NMDS-BC, flow metrics that loaded ≥0.5 on Axis BC1 included Qmean, RBI, 1DMAX, and HPC (all positive, in order of decreasing magnitude), and HPD and LPD (both negative, in order of decreasing magnitude). Those

Figure 3.3. Patterns of flow regime alterations as revealed by the NMDS ordinations. Rows show basins (A, B, C). Columns show themes. Panel I depicts scenario clusters under different climates (colored ellipses: grey = historical climate, blue = wet future climate, sienna = dry future climate). Panel II reclassifies the individual scenario x climate results to show the effects of regional growth patterns and management (colored triangles: green = compact, purple = dispersed; ISM = diagonal lines, no ISM = no pattern). Legend shows symbols used to identify each scenario by growth and management class (star = reference landscape and climate, circle v. square = Compact v. Dispersed, open v. solid = with v. without ISM). Flow metric vectors were rescaled to 1/2 of their original lengths for graphic clarity.



that loaded ≥0.5 on Axis BC2 included N0D (positive), and TL1 and LPC (both negative, in order of decreasing magnitude) (Table S13). Axis BC1 thus reflects a gradient associated with increasing flashiness and magnitude of high flows from left to right, whereas upward along Axis BC2 primarily represents changes in frequency, duration, and timing of low flows leading to more extremes.

Each climate regime imposed a distinctive effect on streamflow regimes as shown by the distinct clustering of scenario flow regimes by climate in all three basins (ellipses of Figure 3.3 Panel I). Climate impacts aligned closely with advancement and increased duration of extreme low flows (all basins), and increased flashiness (Basin A). In general, the 2050 landscapes under future climate (yellow and blue ellipses) showed greater displacement from the reference (the star symbol) than did the 2050 landscape under historical climate (grey ellipse). Moreover, the wet future climate scenarios showed greater flow regime displacement from the reference than the dry future climate scenarios in all basins, as indicated by the larger distances from the reference to the wet climate flow regimes (blue symbols) than to their dry climate counterparts (yellow symbols). This result is supported by the *Climate Impacts Alone* and *Combined Impacts* tests in which the wet climate produced more instances of significant differences in flow metrics in all three basins (Table 3.1 and Figure 3.2).

Similarly, the ordinations revealed generalizable patterns of development impacts across the three basins (triangles of Figure 3.3 Panel II). Urbanization impacts aligned closely with increases in flow regime flashiness (all basins) and magnitude of high (Basins B and C) or both high and low extreme flow events (Basin A). Both compact growth and ISM scenarios led to less flashiness and fewer extreme high flow events than their dispersed and no-ISM counterparts, respectively (i.e., they are to the left of their counterparts in almost all comparisons). This is also supported by the *Combined Impacts* test where compact growth and ISM produced fewer instances of flow metric alterations than their respective counterparts in all basins (Figure 3.2). In addition, ISM constrained flow regime displacement more than compact regional growth. The distances between the ISM scenarios and their no-ISM counterparts (triangles with vs. without diagonal lines) were larger than those between the compact growth and their dispersed counterparts (green vs. purple triangles of Figure 3.3 Panel II) in all three basins.

Furthermore, the *Dispersed without ISM* (DnM) scenarios exhibited the greatest displacement from the reference conditions for every basin, as indicated by the longest distance from the star symbol to the plain purple triangle (Figure 3.3 Panel II). This was also verified by the *Combined Impacts* test where DnM produced the most instances of significantly altered flow metrics for every basin (Figure 3.2-b). In addition, DnM showed the least flow regime variability under different climate conditions, as illustrated by the smallest area of the plain purple triangle compared to the other three triangles (Figure 3.3 Panel II).

The relative importance of urbanization vs. climate change varied across the three basins. The effects of urbanization alone are shown by the distances between the star symbol (1990 landscape, historical climate) and the grey ellipse (future landscapes, historical climate) in each basin (Figure 3.3 panel I). The effects of the two future climate regimes are shown by the distance between the grey ellipse and the yellow and blue ellipses, respectively. In Basin A, urbanization and climate appear to have effects of similar magnitude. In Basin B, climate change caused a larger impact than urbanization.

In Basin C, urbanization produced a stronger impact than climate, as indicated by the close clustering of all future scenarios (grey ellipse of Figure 3.3, C-II) far away from the reference.

Individual basins showed several specific responses. In Basin A, the *Compact with ISM* (CM) scenarios were particularly effective in constraining the flow regime displacement across all three climates, as indicated by the clear separation of the green patterned triangle from the others (Figure 3.3, A-II). Additionally, although the ISM scenarios (triangles with diagonal lines) constrained the overall displacement, they allowed greater differences between the effects of the two future climates (e.g., the large angle of α) than the no-ISM scenarios (e.g., the small angle of β). In Basin C, both compact growth and ISM effectively reduced the flashiness of the flow regime (left shift along Axis BC1 in Figure 3.3, C-I) under the historical or dry climate regimes. However, under the wet future climate, growth patterns and management mattered little (all four blue points all clustered closely together).

4. Discussion

The key opportunities presented in this research lie in the integration of an alternative futures planning analysis, an agent-based model of landscape change, and a hydrological assessment of the landscape-level outcomes under past and projected future climates, the latter through the lens of a suite of 10 ecologically meaningful metrics of streamflow regimes. The complex interactions among climate, urbanization, and hydrology generated a diverse set of flow regime responses among alternative development scenarios and across catchment basins. We use these results to address our five original questions.

(Q1) How does climate change impact streamflow regimes in comparison to urbanization? Will different future climate regimes lead to different effects?

Climate change by itself significantly altered flow regimes across all three basins with highly individualistic responses among metrics (Table 3.1). Importantly, all pairwise climate x scenario differences within individual metrics occurred between historic and future climates rather than between the two future climates. Of the 10 flow metrics, five were affected by climate change in at least one basin and scenario. Four out of the five were measures of low flows (7DMIN, LPC, N0D, and TL1), suggesting that climate change in our region is most likely to lead to a drying trend with more dry days, lower low flows, and earlier annual minimums. Only two of the metrics (7DMIN and N0D) were affected by climate change in all scenarios and only the former was affected in all basins, suggesting the climate change effects are likely to be sensitive to both geography and the pattern of development.

The NMDS ordinations further support the conclusion that climate change is most likely to affect low flows based on the distinct signatures of climate and development on flow regimes as a whole (Figure 3.3, Panels I vs. II). Climate scenarios were consistently separated along Axis 2 (either reduced flows in NMDS-A or more extreme low flows in NMDS-BC), but not well differentiated along Axis 1 (flashiness and either high flows in NMDS-A or both high and low flows in NMDS-BC). Conversely, development appears to exert greater control over flashiness and extreme flow conditions, showing strong differentiation along Axis 1, but no such differentiation along Axis 2. This is also consistent with the flow metric responses evaluated under urbanization alone (Chapter II). The specific signatures of climate change and urbanization may be a direct consequence of how both future regional climate regimes project reduced precipitation inputs in at least 2 out of 4 seasons while increasing summer evapotranspiration (Table S11), whereas development reduces sponginess of the landscape and in doing so increases the magnitude of extreme events as well as the overall flashiness of the flow regime. Given that future climate projections may be much more variable across different geographies than urbanization, the former mechanism may be less applicable to regions other than the Pacific Northwest than the latter.

Whereas the two future climate regimes affected streamflows through a consistent mechanism as elaborated above, the intensity of their effects differed. The wet future climate (CanESM2_RCP4.5) resulted in 60% more instances of flow metric alterations than the dry future climate (CNRM-CM5_RCP4.5) (Figure 3.2-c). However, when metrics were altered under both future climates, the directions of changes were always the same, and the magnitudes were similar (Table 3.2-I). The similarities of effect type but differences in intensity from the two future climate regimes begin to help bracket the range of uncertainty in the potential hydrological effects of local climate change projections, while highlighting the importance of investigating multiple future climates. Future evaluation of more regionally downscaled climate regimes would allow an assessment of the consistency of their effects and better bracket the range of variability in potential hydrological responses.

(Q2) How might climate change and urbanization interact to influence the overall flow regimes as well as individual flow metrics? Is climate change likely to exacerbate or attenuate urbanization impacts?

In general, climate change exacerbated rather than attenuated the impacts of urbanization, as evidenced by both the *combined impacts* and the *flow regime displacement* tests. The *combined impacts* test demonstrated that six of the ten metrics showed amplified changes due to climate change over urbanization alone in one or more basins (Table 3.2). The *flow regime displacement* test further illustrated that climate change caused greater flow regime displacement from the reference landscape under historical climate than under urbanization alone for every basin (Figure 3.3).

A review of the individual metrics reveals how climate projections affected different flow components. Annual runoff (Qmean) tended to increase; both high and low extreme flow events became more extreme (1DMAX and N0D increased and 7DMIN and TL1 decreased); and the overall flashiness (RBI) increased. Magnitude of amplification could be substantial, especially under the wet future climate. In Basin A for example, the increase in the largest annual flood intensity (1DMAX) was minor (+6%) under the best-case scenario (CM) simulated with the historical climate (Figure 2.6), but much greater (+34%) under the same scenario with the wet future climate (Table 3.2). The wet future climate added at least a 30% increase in 1DMAX under every future development scenario in this basin. Furthermore, this basin (A) historically had almost year-long continuous flows (N0D$\approx$0), but will likely experience 11-18 more dry days with no flows under both future climates. Additionally, in two out of three basins (A and C), annual minimums were anticipated to occur much earlier under the wet future climate than the historical climate, regardless of the development scenario. Degree of advancement was as substantial as 3-3.5 weeks in Basin C. The amplified effects in a majority of flow metrics highlight the importance of incorporating potential climate change into watershed impact assessments. Enacting management plans for future development based solely on assessments under historical climate may not provide the required capacity for streams to cope with future flow regimes.

In contrast, a small number of metrics showed attenuated effects under the combined impacts, suggesting that climate change may in some cases counteract the effects of urbanization. Specifically, changes to three measures of flashiness (LPC, HPC, and HPD) were reduced under the combined impacts. This is potentially due to the "drying" effects of climate change compensating for the “wetting” effects of urbanization. This suggests the intriguing possibility that climate change under certain combinations of geography and urbanization pattern could in fact offset effects on certain flow components, whereas other components may require specific, individualized management responses to prevent amplification of urbanization effects.

More extreme high and low flow events under the combined impacts of climate change and urbanization will likely amplify the negative effects on native aquatic organisms resulting from urbanization alone. More direct mortality may occur during high-flow seasons because of more extreme floods. More desiccation may occur during low-flow seasons due to earlier and reduced low flows that may lead to higher water temperatures and reduced dissolved oxygen (Coleman et al., 2011). On the other hand, reduced changes in measures of frequency and duration (LPC, HPC, and HPD) under the combined impacts that in combination affect flow regime flashiness may offset certain negative impacts brought by urbanization alone, e.g., increased scouring and sedimentation of the stream beds.

(Q3) Will compact regional growth and integrated stormwater management remain effective strategies in reducing flow alterations under different climate regimes?

As demonstrated by all three tests, compact regional growth and integrated stormwater management proved effective in reducing flow regime impacts, just as under urbanization impacts alone (Chapter II). This conclusion is based on analyses from the three basins as a whole. The *Climate Impact Alone* test showed that the compact and ISM scenarios provided less opportunity for future climate regimes to generate significant flow alterations than their dispersed and no-ISM counterparts (Table 3.1). The *Combined Impacts* test further showed that the dispersed scenarios generated more instances of flow alterations than their compact counterparts for every basin, and the no-ISM scenarios similarly generated more instances of changes than their ISM counterparts for every basin (Figure 3.2-b). Furthermore, the relatively small increase in the number of instances where metrics became resistant in one or more basins shows that compact growth and ISM effectively maintained the majority of flow metrics within the specific threshold for the *manageable* category even under climate change. Specifically, 87% and 73% of metric x basin instances remained in the *insensitive* or *manageable* categories under the dry and wet future climate, respectively, as compared to 90% under the historical climate. Only three metrics exhibited instances where they became *resistant* in one or more basins (a total of 5 instances) under the combined impacts. All but one of these instances occurred only under the wet climate regime. In addition, in all cases where metrics were *manageable*, the best-case scenario incurred less than half the change than the worst-case scenario (Table 3.2), highlighting the effectiveness of compact growth and ISM. Last but not least, as visualized by the NMDS ordinations, compact growth and ISM scenarios are closer to the references than their dispersed and no-ISM counterparts in almost all comparisons.

In particular, ISM was more effective than compact growth in reducing flow regime alterations, a consistent conclusion across all basins. The NMDS ordinations illustrated smaller flow regime displacement by the ISM scenarios than compact growth (Figure 3.3). Furthermore, the differences in the counts of metric alterations between the compact scenarios and their dispersed counterparts were always smaller than those between the ISM and their no-ISM counterparts, with one exception (Basin B under the wet future climate) (Figure 3.2c).

When individual basin x climate combinations were considered, the relative importance of compact growth vs. ISM showed a more complex pattern. Under the dry climate, compact growth itself appeared to have little effect, as indicated by the identical counts of metric alterations between the compact vs. their dispersed counterparts across all three basins with only one exception of Basin C when ISM was absent (Figure 3.2c). Under the wet climate, the effectiveness of compact growth improved in Basin B, especially when ISM was absent, but remained limited in the other two basins A and C (Figure 3.2c). It is notable that this picture is different from that provided by the NMDS ordinations (Figure 3.3), which showed that, when the median values (rather than counts) of the metrics were taken into account, compact growth consistently did better than dispersed growth in reducing flow regime displacement in Basin A, but only had a substantial effect in the absence of ISM in Basins B and C (Figure 3.3).

(Q4) How will the manageability of the overall flow regime as well as individual flow metrics change?

Despite the effectiveness of compact growth and ISM, the overall manageability of the flow regimes decreased with the combined impacts, especially under the wet future climate. The decrease of *insensitive* and *manageable* metrics was minor (-3%) under the dry future climate, but considerable (-17%) under the wet future climate with a doubling of the *resistant* metrics over historical climate.

Not only did the overall manageability of the flow regimes change, substantial turnover of metric types occurred under the combined impacts, highlighting the complex ways climate change and urbanization may interact with each other. Three metrics (7DMIN, HPC, and RBI) exhibited no change in category, two metrics (LPC and HPD) saw a tendency for climate change to offset development impacts, and five metrics (Qmean, 1DMAX, N0D, LPD, and TL1) showed increased impacts with climate change. Sensitivity changes in measures of both high and low extreme flows tended to be more predictable (1DMAX, N0D, and TL1 all became less manageable) due to the distinct signatures of urbanization and climate change, i.e., urbanization exerted greater control over extreme flow conditions, whereas climate change itself primarily led to more extreme low flows. In particular, the fact that no metrics were removed from the *resistant* category suggests that the low flow components (7DMIN, LPC, and N0D), which were difficult to manage under urbanization alone, will likely remain resistant to mitigation under the combined impacts. In contrast, measures of flow regime flashiness exhibited more complex patterns of category change, i.e., LPC and HPD became more manageable, LPD became less manageable, and HPC and RBI exhibited no change in category. This is potentially due to the tendency of climate change to offset urbanization's effects on flashiness. We suspect that such counteracting effects will create large uncertainties in the responses of flashiness measures in future investigations under different urbanization levels or future climate regimes, not only for our basins, but also for other regions. Once again, the uncertainties in flow metric manageability highlight the value of spatially explicit modeling in revealing complex site-specific interactions among climate, urbanization, and hydrology.

The changes in flow metric sensitivity types also suggest important implications for watershed management. On the one hand, the majority of changes progressed from less to more affected, i.e., from *insensitive* (T1) to *manageable* (T2) to *resistant* (T3). Changes from T1 to T2 (*insensitive* to *manageable*) revealed possible benefits of implementing compact growth and ISM that were not evident under urbanization alone. Those from T1 or T2 to T3 (*insensitive* or *manageable* to *resistant*) provided important clues about the potential risks of not implementing mitigation strategies based on assessments under historical climate. On the other hand, changes from more to less affected (T2 to T1, *manageable* to *insensitive*) provide a cautionary against overreliance on the success or failure of current management efforts. The limited number of these occurrences (only two metrics exhibited such change), however, indicates that such counteracting effects between climate change and urbanization are likely to be small.

(Q5) Do differences in catchment basin characteristics lead to different local effects from climate and urbanization?

Each basin responded differently to the combination of urbanization and climate change, as indicated by the complex responses of individual flow metrics. First, the smallest, flattest, and most urban basin with the least permeable soils (A) appeared to be particularly susceptible to both development and climate change. This basin experienced the most instances of individual metric alterations under both the combined impacts (Figure 3.2-a) and urbanization impacts alone (Chapter II). This is potentially due to the amplified runoff volume from increased impervious surfaces and the relatively short flow concentration time to the watershed outlet in Basin A. Second, the combined impacts imposed nearly as large a set of flow alterations on the largest, steepest, and most rural basin (C), suggesting a potentially significant phenomenon that remains to be verified with further research: flow regime alterations in undeveloped basins may occur with even a small increase in imperviousness (e.g., from 2.2% to 4.5% in Basin C). Impacts of the dry future climate were only half of those under the wet future climate in Basins B and C, but only modestly less in Basin A (Figure 3.2b), highlighting how expressions of climate change impacts can substantially vary even in adjacent basins. Lastly, the basin of intermediate size and urbanization level but with the most permeable soils (B) showed the smallest overall flow regime changes under all three circumstances (urbanization impacts alone, climate impacts alone and combined impacts), again reinforcing the importance of local conditions. With that said, the need for local lessons to be transferable to other geographies calls for further research (e.g., sensitivity analyses) that reveals the underlying reasons (e.g., size, topography, soil, characteristics of development, etc.) for the varied basin sensitivity to urbanization and/or climate change.

5. Conclusions

Using spatially downscaled daily future climate data from two climate models, we modeled the hydrological impacts of four land development scenarios in three urbanizing watersheds in southern Oregon where human populations are projected to double in coming decades. We evaluated the combined effects of urbanization and climate change in comparison to the results of our previous study of urbanization impacts alone. Despite substantially varied hydrological impacts across the three adjacent basins, the modeling framework allowed us to tease out both nuanced differences and generalizable trends. We summarize the major conclusions as follows.

1) Climate change appears likely to significantly alter future flow regimes across diverse development scenarios and watershed types, primarily causing a drying trend with more dry days, reduced low flows, and earlier annual minimums. The types of impacts were similar but their intensity differed substantially under the two climate models considered among the most suitable for the U.S. Pacific Northwest.

2) Climate change generally exacerbated the impacts of urbanization, making it more challenging to mitigate flow regime impacts under future climate. At the same time, a few flow alterations that were resistant to mitigation under urbanization and historic climate became more manageable under the combined impacts of urbanization and climate change. This provides a caution against overreliance on either modeling results that do not consider future climate or the success or failure of current management efforts.

3) In general, both compact regional growth and integrated stormwater management were effective strategies for reducing flow regime impacts of urbanization under all three climate regimes assessed (two future and one historical) for all three basins. ISM was always more effective than compact growth and compact growth provided little additional benefit when ISM was implemented across both the urban and rural portions of the landscape.

4) Some flow metrics were relatively insensitive to either development or climate change, whereas at the other extreme were those consistently impacted despite attempts to mitigate them (i.e., metrics that are *sensitive* to change but *resistant* to mitigation). For 7 (out of 9) metrics that were sensitive to the combined impacts in at least one basin, however, the strategies of compact growth and ISM were able to mitigate their effects (i.e., *sensitive and manageable*) in at least one basin. Future flow-ecology research should endeavor to determine the ecological significance of each flow metric. In particular, efforts should focus on developing specific flow management targets for the *sensitive and manageable* metrics and prioritizing the implementation of specific strategies that are likely to successfully mitigate their impacts. In addition, further investigations are required to explore management policies other than those tested here to identify potential means of mitigation for the *sensitive and resistant* metrics.

5) The effects of both climate change and urbanization differed among adjacent catchment basins due to differences in geography, development or both. Some flow metrics were consistently affected across all basins, whereas others were impacted in one or two basins. Which basins were most affected and how they were affected could be

explained to some degree by their size, topography and soils in relation to the amount and distribution of urban and rural development.

6) Our ability to anticipate complex interactions between climate, urbanization and streamflows across different watersheds is still rudimentary. A fundamental assumption of this research, like that of many other hydrological studies, has been that maintaining extant streamflow regimes under urbanization is preferable to their alteration. However, many flow regimes already have been substantially modified by development and may be poorly aligned to the needs of native stream biota. Particularly under climate change uncertainties, questions of what is an appropriate reference to target and the degree to which novel flow regimes will require adjustments to what is considered acceptable or desirable, including the species toward whose needs flow regimes are targeted, become central. Such issues make assessing the ecological consequences of development-related hydrological alterations even more complicated. Interdisciplinary modeling frameworks that can guide watershed management by linking the mechanisms of landscape planning to the goals of sustaining stream ecosystem function and biodiversity will become increasingly important as such futures unfold.

CHAPTER IV

CONCLUSIONS

Watershed planning and management is a challenging field to work in, which in turn indicates considerable potential for emerging research and knowledge. Over the past two decades, researchers and planners have been seeking cures for the degradation of aquatic ecosystem health through both site-scale stream restoration techniques as well as watershed scale planning approaches. Despite extensive efforts, cross-disciplinary integration remains insufficient for the purposes of anticipating aquatic ecosystem consequences as well as informing planning decisions. With this research, I attempt to advance this emerging field by developing a transferable methodology that better links the approaches of landscape planning to the goal of sustaining stream ecosystem health. In particular, I explored the combined hydrological impacts of urbanization and climate change, and tested the effectiveness of compact regional growth and integrated stormwater management in maintaining streamflow regimes in three adjacent watersheds in the southern Willamette Valley, Oregon.

Summary of Flow Regime Responses

1. Expected population growth in the next 3-4 decades in the Willamette River Basin will likely result in significant flow regimes changes in all three catchment basins evaluated. Urbanization appears to exert greater control over flow regime flashiness and extreme flow conditions. The magnitude of extreme flow events, frequency of high and low flow events, and flashiness are likely to be more sensitive to urbanization than average flows, duration of both high and low flows, and the timing of extreme low flows.
2. Climate change by itself also significantly changed the flow regime with highly individualistic metric responses, primarily leading to a drying trend with more dry days, even lower low-flows, and earlier annual minimums.
3. In general, climate change exacerbated the impacts of urbanization by causing further displacement of the flow regimes from the reference conditions. However, under circumstances where the "drying" effect of climate change compensated the "wetting" effect of urbanization, alterations of three measures of flashiness were reduced. This suggests the intriguing possibility that climate change under certain combinations of climate, geography and urbanization pattern could in fact offset effects on certain flow components, whereas other components may require specific, individualized management responses to prevent amplification of urbanization effects.

Implications for Management

1. By concentrating over 90% of the population growth within UGBs, the *Compact Regional Growth* approach representing Oregon's current statewide planning systems outperformed the *Dispersed Regional Growth* in reducing hydrological alterations in the three basins assessed under both the historical climate and the two future climate regimes tested. However, compact growth appeared to have limited added reduction of flow alterations when ISM was also present. Further investigations would be necessary to determine the transferability of this statement to other geographies due to confounding factors created by the complexity of the agent-based landscape change model.
2. Integrated stormwater management (ISM), i.e., the integration of localized spatial patterns of development with site-scale stormwater BMPs, proved to be highly effective in protecting the flow regimes under both the historical climate and the two future climates. In particular, ISM was always more effective than compact growth.
3. The high performance of ISM emphasizes the importance of the suite of underlying strategies it represented. Watershed planning and management programs should create opportunities to implement the following ISM strategies: a) limiting development on steep slopes and permeable soils; b) protecting large vegetative patches, riparian buffers and wetlands; c) limiting overall watershed imperviousness by encouraging cluster or high density development; d) reducing directly connected imperviousness by re-infiltration LIDs; and e) reducing road impacts by encouraging compact development and re-infiltration LIDs.

4. Some flow metrics were relatively *insensitive* to either development or climate change, whereas at the other extreme were those consistently impacted despite attempts to mitigate them (i.e., *sensitive* and *resistant* metrics). For a large number of metrics sensitive to the combined impacts, however, the strategies of compact growth and ISM were able to largely mitigate their effects (i.e., *sensitive and manageable*). Future flow-ecology research should endeavor to determine the ecological significance of each flow metric. In particular, efforts should focus on developing specific flow management targets for the *sensitive and manageable* metrics and prioritizing the implementation of specific strategies that are likely to successfully mitigate their impacts. In addition, further investigations are required to explore management policies other than those tested here to identify potential means of mitigation for the *resistant* metrics.
5. The effects of both climate change and urbanization differed among adjacent catchment basins due to differences in geography, development or both. Some flow metrics were consistently affected across all basins, whereas others were impacted in one or two of them. Which basins were most affected and how they were affected could be explained to some degree by their size, topography and soils in relation to the amount and distribution of urban and rural development.
6. Protecting stream ecosystem health under the pressure of population growth will continue to challenge our design and planning capabilities because significant hydrologic alteration that may prove critical to the stream biota could happen at a very low urbanization level. 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. By developing detailed hydrological foundations and revealing site-specific hydrological responses to projected urbanization, our modeling results provide valuable contributions that will further the ability of local planners to set specific targets for watershed planning and management. At the same time, the demonstrated interdisciplinary framework established a transferable methodology that begins to link the mechanisms of landscape planning to the goals of sustaining stream ecosystem health, which could be broadly applicable to other geographic locations.

Methodological Contributions

The modeling framework developed presents seven key methodological innovations toward an integrated framework that begins to link the mechanisms of landscape planning to the goals of sustaining stream ecosystem health.

1. The identification of a coherent suite of ecologically relevant flow metrics that cover each major flow component established a bridge from hydrological impacts to ecosystem consequences, and made it possible to anticipate the ecological ramifications of projected urbanization in the absence of quantitative and spatially explicit local flow-ecology knowledge.
2. The flow metric sensitivity classification system created a direct linkage between flow alterations and the ability to manage them through planning and management prescriptions. It furthers the ability of local planners to set specific

flow management goals and holds promise for broader applications in future watershed planning and management.

3. Incorporation of an agent-based landscape change model not only provided the capacity to simultaneously evaluate alternative forms of regional growth and stormwater management and disentangle their individual effects, but also to do so in a way that extracts the central tendencies of contrasting alternative futures.
4. The agent-based landscape change model provided the ability to directly assess plans of actions by establishing direct linkages between policies and landscape change trajectories.
5. By incorporating the Long-Term Hydrologic Impact Assessment (L-THIA) model and analyzing high resolution land cover data from both urban and rural areas, the framework improved the ability of SWAT to incorporate stormwater management, and to more accurately represent the hydrological characteristics of both high and low density developments.
6. By spatially downscaling GCM projections to the study area, the framework was able to assess the localized hydrological impacts of urbanization in the context of climate change. And by investigating multiple future climate regimes, the framework revealed the substantially varied flow responses under different future climates. More importantly, it informed the potentially distinct signatures of climate change vs. urbanization on flow regimes and demonstrated the complex interactions between climate change and urbanization.
7. Lastly, by investigating multiple catchment basins, the framework generated useful insights on potential relationships between watershed characteristics and

hydrological responses, which would not have been revealed if only a single basin had been studied.

Methodological Limitations

1. A major limitation of the *integrated modeling approach* we adopted is that it focuses on exploring *what* might happen by simultaneously modeling multiple changing variables, rather than identifying the reasons beneath the modeling outcomes (i.e., *"why"*). Future research could build upon this modeling framework and conduct more *sensitivity analyses* that apply greater control of real-world complexities to reveal the underlying causes of the phenomenon (e.g., why a certain basin was more affected by urbanization and/or climate change, which ISM strategy may be the most effective in reducing flow alterations, etc.)
2. The lack of quantitative and spatially explicit local flow-ecology knowledge made it challenging to justify the selection of specific flow metrics and to quantify the ecological consequences of the modeled flow alterations on native aquatic biota. This is likely to be true in most other parts of the country due to the paucity of paired biological and hydrological data.
3. The difficulties of integrating Envision and SWAT made it computationally challenging to model the hydrological outcomes of multiple alternative futures for each scenario. At the same time, the approach of identifying the scenario that best represented the mode of scenario outcomes across all land units (IDUs) allowed us to represent the central tendencies of the model without decoupling the

complex interactions and feedbacks that lead to landscape-scale scenario outcomes.

4. A key caveat in the landscape simulation in Envision is that the importance of compact regional population growth could not be definitively determined at the scale addressed in this study because of the confounding factor of varying population growth across scenarios and basins. Future research could apply greater experimental control of population projections within and among basins.
5. For computational efficiency, the hydrological modeling in SWAT was based on a static landscape representation (i.e., the ca. 2050 landscape) over the 30-year time span (WY 2036-2065) for each future scenario. However, the landscape change model Envision in fact provided the opportunity to incorporate dynamic landscape change by generating landscape representations for each annual time step. Future research could model dynamic landscape representations for each scenario to explore the degree to which the resulting flow regimes might be different from those simulated with a static landscape. One step even further would be to incorporate SWAT as a plug-in to Envision so that hydrological change could influence agent decisions and other processes during the course of a simulation.

My research contributes original knowledge to the fields of flow-ecology research, watershed planning and stormwater management, alternative futures research, and hydrological modeling. Having demonstrated the utility and transferability of my integrated modeling framework, I hope to transform the way scholars investigate the hydrological impacts of climate change and/or urbanization with an ultimate goal to inform real-world decision-making.

APPENDIX A

SUPPLEMENTAL TABLES AND FIGURES

Table S1. Data sources and quantitative tools.

Data and Sources			
Category	**Timeframe**	**Description**	**Source**
Mixed	Mixed	Integrated Decision Units database	SWCNH Research Project
Weather	1970-2013	Historical climate	National Weather Service
LULC	1968/1979	Historical aerial photography	University of Oregon Map library
LULC	1990/2000	30m x 30m raster	Pacific Northwest Ecosystem Research Consortium
Hydrology	1977-1987	Observed daily streamflow	USGS National Water Information System
LULC	2007	High resolution (30 ft. x 30 ft.) land cover for Portland	Portland Metro Regional Land Information Database (RLID)

Quantitative Tools		
Model Name	**Developer**	**URL**
Envision Integrated Modeling Platform (Version 6)	Oregon State University	http://envision.bioe.orst.edu/
The Soil and Water Assessment Tool (SWAT) (Version 2012)	Texas A&M University	http://swat.tamu.edu/
SWAT Calibration and Uncertainty Procedures (SWAT-CUP)	Swiss Federal Institute of Aquatic Science and Technology (Eawag)	http://www.eawag.ch/forschung/siam/software/swat/index
L-THIA (Long-Term Hydrologic Impact Assessment) Low Impact Development Model	Purdue University	https://engineering.purdue.edu/mapserve/LTHIA7/lthianew/lidIntro.php
Indicators of Hydrologic Alteration (IHA, version 7.1.0.10)	The Nature Conservancy	https://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/MethodsandTools/IndicatorsofHydrologicAlteration/

Table S2. Catchment basin characteristics.

		Basin A	Basin B	Basin C
Area (km^2)		28	111	270
Ave. Slope (%)		6%	13%	17%
Soil Permeability	HSG A	0%	0%	0%
	HSG B	1%	14%	5%
	HSG C	36%	48%	65%
	HSG D	63%	38%	30%
Land Uses (ca. 2000)	Urban	11%	3%	2%
	Rural Residential	23%	8%	9%
	Agricultural	24%	26%	15%
	Forest	31%	53%	61%

Table S3. Comparison of flow metric values calculated with stream gauge and SWAT data.

	Flow Metric		**N**	**Mean**	**Median**	**Std. Dev.**	**Minimum**	**Maximum**	**Wilcoxon *p***	**Pass?**
1	**Qmean (cfs)**	Observed	15	154.51	145.22	75.12	15.69	305.19	0.12	Pass *
		Simulated	15	159.90	150.78	70.91	27.73	306.44		
2	**1DMAX (cfs)**	Observed	15	2946.26	2979.85	1833.96	388.11	6889.89	0.00	*Fail*
		Simulated	15	2009.92	2051.08	1007.13	424.84	4191.85		Under-predict
3	**7DMIN (cfs)**	Observed	15	0.12	0.00	0.25	0.00	0.77	0.72	Pass **
		Simulated	15	0.10	0.00	0.24	0.00	0.90		
4	**N0D (days)**	Observed	15	25	23	22	0	72	0.20	Pass *
		Simulated	15	16	10	18	0	53		
5	**LPC (count)**	Observed	15	5.07	5.00	1.98	2.00	8.00	0.91	Pass **
		Simulated	15	5.21	4.00	2.91	2.00	10.00		
6	**HPC (count)**	Observed	15	6.87	7.00	2.72	1.00	11.00	0.46	Pass *
		Simulated	15	7.13	7.00	2.29	3.00	11.00		
7	**LPD (days)**	Observed	15	24.82	7.50	42.08	2.00	128.50	0.55	Pass **
		Simulated	15	33.50	11.50	43.43	4.50	121.50		
8	**HPD (days)**	Observed	15	5.27	5.00	2.07	2.00	10.50	0.83	Pass **
		Simulated	15	5.67	4.50	3.94	1.00	16.00		
9	**TL1 (Judian**	Observed	15	235	235	23	197	279	0.18	Pass *
	Date)	Simulated	15	223	217	23	193	276		
10	**RBI**	Observed	15	0.30	0.31	0.05	0.22	0.39	0.00	*Fail*
	(unitless)	Simulated	15	0.26	0.25	0.03	0.22	0.31		Under-predict

Table S4. Calibrated SWAT parameters. Parameters were calibrated by identifying either fixed values or global modification terms that scale the initial parameter values by a multiplicative, or an additive term. The following scheme (consistent with that in the SWAT-CUP tool) is used for the parameter identifiers (Abbaspour, 2013):

x__<parname>.<ext>__<landuse>__<subbsn>

Where x__ = Code to indicate the type of change to be applied to the parameter:

v__ means the existing parameter value is to be replaced by the given value,

a__ means the given value is added to the existing parameter value, and

r__ means the existing parameter value is multiplied by (1+ a given value).

<parname> = SWAT parameter name.

<ext> = SWAT file extension code for the file containing the parameter <landuse> = name of the land use category

<subbsn> = subbasin number(s)

Parameter Identifiers	Definition	Calibration	Specifications
v__IPET.bsn	Potential evapotranspiration (PET) method	2	Hargreaves method
v__ICN.bsn	Daily curve number calculation method	1	Calculate daily CN value as a function of plant evaporation
v__CNCOEF.bsn	Plant ET curve number coefficient	1.141	
v__SURLAG.bsn	Surface runoff lag coefficient	0.185	
r__SOL_AWC.sol	Available water capacity of the soil layer (mm H_2O/mm soil)	-0.055	
r__CN2.mgt	Initial SCS runoff curve number for moisture condition II	0.042	
v__ALPHA_BF.gw	Baseflow alpha factor (days)	0.0657	
v__GWQMN.gw	Threshold depth of water in the shallow aquifer for return flow to occur (mm H_2O)	100	
v__GW_DELAY.gw	Groundwater delay time (days)	100	
v__GW_REVAP.gw	Groundwater "revap" coefficient	0.101	
v__REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" or percolation to deep aquifer to occur (mm H_2O)	366.25	
v__RCHRG_DP.gw	Deep aquifer percolation fraction	0.5	

Table S4. (continued).

Parameter Identifiers	Definition	Calibration	Specifications
v__CANMX.hru	Maximum canopy storage (mm H_2O)	5	
v__ESCO.hru	Soil evaporation compensation factor	0.451	
r__HRU_SLP.hru	Average slope steepness	0.123	
v__LAT_TTIME.hru	Lateral flow travel time (days)	3	
v__OV_N_FRSD.hru	Manning's "n" value for overland flow	0.743	For LULC “Forest – Deciduous”
v__OV_N_FRST.hru		0.793	For LULC “Forest – Mixed”
v__OV_N_FRSE.hru		0.8	For LULC “Forest – Evergreen”
v__CH_N(1)_1&6.sub	Manning's "n" value for the tributary channels	0.05	For subbasins 1 and 6
v__CH_N(1)_2&3&7.sub		0.065	For subbasins 2, 3, and 7
v__CH_N(1)_4&5&8.sub		0.1	For subbasins 4, 5, and 8
v__CH_N(2)_1.sub	Manning's "n" value for the main channels	0.05	For subbasin 1
v__CH_N(2)_2&4&5&8.sub		0.1	For subbasins 2, 4, 5, and 8
v__CH_N(2)_3&7.sub		0.065	For subbasins 3 and 7
v__CH_N(2)_6.sub		0.025	For subbasin 6

Table S5. Dictionary of 52 most important IDU attributes.

No.	**Categories**	**Attributes**	**Definition**
1	*ID*	**IDU_INDEX**	Unique IDU Identifier used by ENVISION
2	*Spatial*	**AREA**	Area of polygon in m^2
3	*Topography*	**SLOPEAV**	Area weighted average topographic slope
4	*Topography*	**ASPECT**	Area weighted dominant topographic aspect classification
5	*Soil*	**MUKEY**	NRCS SSURGO Map Unit primary identifier
6	*Soil*	**CURSI**	Site index
7	*Soil*	**FUTSI**	Future site soil productivity index maintained by ENVISION during modeling
8	*Soil*	**SOILACCC**	Soil agricultural capability class
9	*Soil*	**SEPSUITPC**	Fraction of IDU area with soils suitable for septic systems
10	*Soil*	**HYDGRP**	Soil hydrological groups
11	*Location*	**SUBBSN**	Specifies which watershed the majority of the IDU area is in
12	*Location*	**BUFF**	Specifies whether the IDU is inside the 120ft riparian buffer
13	*Location*	**FLD100**	Specifies whether the majority of the IDU is inside a FEMA 100 year flood zone
14	*Wetland*	**WETLAND**	Area of significant NWI wetlands within IDU
15	*Location*	**CRO/COA**	Specifies whether the majority of the IDU is inside Conservation and Restoration Opportunities areas
16	*Ownership*	**PUBLANDS**	Area weighted dominant public land ownership type
17	*Taxlot*	**TAXLOTID**	County taxlot map parcel identifier
18	*Taxlot*	**TLAREA**	Area of parent taxlot of IDU
19	*Taxlot*	**PCNTTL**	Fraction of parent taxlot area in IDU
20	*Taxlot*	**RMVLAND00**	Ca. 2000 assessed real market value of land of parent taxlot
21	*Taxlot*	**RMVIMP00**	Ca. 2000 assessed real market value of improvements of parent taxlot
22	*Lulc*	**STARTLULC**	Ca. 2000 land use land cover type
23	*Lulc*	**LULC_A**	Area weighted dominant land use land cover classification - Coarse
24	*Lulc*	**LULC_B**	Area weighted dominant land use land cover classification - Intermediate
25	*Lulc*	**LULC_C**	Area weighted dominant land use land cover classification - Fine
26	*Vegetation*	**VEGCLASS**	Highly articulated vegetation classification

Table S5. (continued).

No.	Categories	Attributes	Definition
27	*Vegetation*	**PVT**	Potential vegetation type
28	*Distance*	**D_ROADS**	Average distance to roads and highways for the IDU
29	*Distance*	**D_STREAMS**	Average distance to streams for the IDU
30	*Distance*	**RDSMAJ**	Average distance to major roads
31	*Distance*	**RDSMIN**	Average distance to minor roads
32	*Zoning*	**ZONE**	Generalized zoning class
33	*Population*	**POPDEN00**	Ca.2000 population density of this IDU
34	*Population*	**POPDENS**	Dynamic population density of this IDU
35	*Population*	**ALLOW_DENS**	Allowed population density
36	*Population*	**POP_CAP**	Population Capacity
37	*Population*	**POP_AVAIL**	Available Population Capacity
38	*Population*	**P_POP_AVAI**	% Population Available
39	*UGB*	**IN_UGB**	Specifies whether the majority of the IDU is inside an Urban Growth Boundary
40	*UGB*	**NEAREST_UG**	Nearest UGB
41	*UGB*	**D_UGB**	Distance to UGB
42	*UGB*	**U_EXPEVENT**	Specifies whether a UGB expansion event has happened
43	*UGB*	**U_PRIORITY**	UGB expansion priority
44	*Dwelling Units*	**NUMRS**	Ca. 2000 number of rural structures
45	*Dwelling Units*	**N_DU**	Number of dwelling units
46	*Dwelling Units*	**NEW_DU**	Number of new dwelling units
47	*Actor*	**ACTOR**	Type of actors
48	*Policy*	**POLICY**	Policy applied to this IDU
49	*Policy*	**POLICYAPPS**	Total number of policies applied to this IDU
50	*Policy*	**EXP_POLICY**	Type of expansion policy applied to this IDU
51	*management*	**CONSERVE**	Conservation Status
52	*management*	**LID**	Type of Low Impact Development strategies applied to this IDU

Table S6. Complete list of Envision policies.

ID	Policy Title	Scenarios				Brief Description
	Urban Development (UD)					The 3 UD policies apply to IDUs close to major roads, slope <20%, no wetlands or conservation/restoration opportunity areas (COA), not public, not in floodplain or riparian buffers.
UD1	Urban Densification (0-4 to 4-9 du/ac)	CnM	DnM	CM	DM	UD1 upgrades low- to med-density urban residential zones when IDU population density is approaching allowed density.
UD2	Urban Densification (4-9 to 9-16 du/ac)	CnM	DnM	CM	DM	UD2 upgrades med- to high-density urban residential zones when IDU population density is approaching allowed density.
UD3	Urban Densification (9-16 to >16 du/ac)	CnM	DnM	CM	DM	UD3 upgrades high- to very-high-density urban residential zone when IDU population density is approaching allowed density.
	Urban Conservation & Restoration (UC)					
UC1	Conservation at Strategic Locations within UGBs			CM	DM	Conserves undeveloped urban land with low development suitability (publands, floodplain, riparian, wetlands, & w/ high permeability soils), high habitat quality (natural vegetative patches>1ha), or high habitat potential (in COA).
	Rural Development (RD)					
RD1	Conversion of Agricultural Lands to Rural Residential	CnM	DnM	CM	DM	Allows new rural residential development in agriculture zones (<10% slope, not public, low agricultural productivity, no wetlands, close to transportation, outside 100-year floodplain).
RD2	Conversion of Agricultural Lands to Clustered Rural Residential		DnM	CM	DM	Allows new rural cluster development in agriculture zones (<10% slope, not public, low agricultural productivity, no wetlands, close to transportation, outside 100-year floodplain).
RD3	Conversion of Forest Lands to Rural Residential	CnM	DnM	CM	DM	Allows new rural residential development in forest zones (<20% slope, not public, close to transportation, outside 100-year floodplain).
RD4	Conversion of Forest Lands to Clustered Rural Residential		DnM	CM	DM	Allows new rural cluster development in forest zones (<20% slope, not public, close to transportation, outside 100-year floodplain).
RD5	Clustered Development in Rural Residential Zones			CM	DM	Encourages clustered development in rural residential zones.

Table S6. (continued).

ID	Policy Title	Scenarios				Brief Description
	Publands Conservation & Restoration (PC)					
PC1	Watershed Public Lands Rehabilitation	CnM	DnM	CM	DM	Converts non-forested upland public lands (exclude those with substantial infrastructure) to open forest, young conifer, or shrublands.
PC2	Riparian Buffers on Non-forested Public Lands	CnM	DnM	CM	DM	Converts non-forested riparian public lands (exclude those with substantial infrastructure) to open forest, young conifer, or shrublands.
	Rural Upland Conservation & Restoration (RC)					
RC1	Conservation within Low Suitability Rural Residential Zones			CM	DM	Protects low development suitability areas (wetlands, high agricultural productivity, w/ highly permeable soils, public, or inside 100-year floodplain) that were however designated by county zoning as Rural Residential Zones.
RC2	Rehabilitation of Upland Agricultural Lands with High Infiltration Capacity and Habitat Potential			CM	DM	Converts upland private agricultural lands with significant wetlands/highly permeable soils or inside COA into mixed open forest, young conifer forest, or shrublands.
RC3	Conservation Easement on Upland Forests with High Infiltration Capacity and Habitat Value			CM	DM	Establishes conservation easements on upland private forests with significant wetlands/highly permeable soils, or inside COA.
	Riparian Conservation & Restoration (RIP)					
RIP1	Conservation Easement on Private Riparian Vegetated Lands with Highly Permeable Soils			CM	DM	Establishes conservation easements on private riparian vegetative buffers with high permeability soils.

Table S6. (continued).

ID	Policy Title	Scenarios		Brief Description
RIP2	Conservation Easement on Private Riparian Vegetated Lands with low permeability soils	CM	DM	Establishes conservation easements on private riparian vegetative buffers with low permeability soils.
RIP3	Riparian Buffers on Rural Private Lands with Highly Permeable Soils	CM	DM	Establishes 120ft-wide riparian vegetative buffers on private lands with high permeability soils.
RIP4	Riparian Buffers on Rural Private Lands with Low Permeability Soils	CM	DM	Establishes 120ft-wide riparian vegetative buffers on private lands with low permeability soils.
	Low Impact Development (LID)			
LID1	LID on New Residential Developments	CM	DM	Applies LIDs (disconnection of streets, roofs, sidewalks, & parking/driveways, adding a rain garden, & 25% woodlands preservation) to new residential developments.
LID2	LID on New Commercial Developments	CM	DM	Applies LIDs (green roofs, porous pavements on parking lot, &10% woodland preservation) to new commercial developments.
LID3	Porous Pavements on Existing Low Traffic Roads	CM	DM	Rebuilds the secondary and light duty roads within 1000m to streams with porous pavements.
LID4	LID on Existing Residential Development	CM	DM	Applies LIDs (downspout disconnection, rain garden, & 25% woodlands rehabilitation) to existing residential developments within 1000m to the streams.
LID5	LID on Existing Commercial/Industrial Development	CM	DM	Applies LIDs (greenroofs, raingardens, & 10% woodland rehabilitation) to existing commercial/industrial developments within 1000m to streams.

Table S7. Population and land development characteristics of the present and future landscapes.

	Present	Future (Ca. 2050)			
	Ca. 2000	**CM**	**DM**	**CnM**	**DnM**
3-basin Total					
Total population (#)	11266	33797	37446	28588	33673
Total urban developed area (km^2)	11.52	21.41	21.47	16.85	15.32
Total rural residential area (km^2)	40.07	53.65	70.12	65.67	97.51
Total footprint (km^2)	51.60	75.06	91.59	82.52	112.84
Total imperviousness (%)	2.87%	4.72%	5.21%	4.40%	5.11%
Land uses (%):					
Urban	2.79%	5.74%	5.74%	4.54%	3.96%
Agriculture	18.54%	7.58%	6.32%	15.99%	14.43%
Forest	56.76%	68.69%	66.39%	57.94%	52.91%
Rural Residential	9.79%	13.16%	17.19%	16.13%	23.90%
Other Vegetation	11.62%	4.78%	4.32%	5.29%	4.70%
Basin A					
Total population (#)	3039	5541	6951	5782	6258
Urban developed area (km^2)	3.24	3.73	3.72	3.75	3.74
Rural residential area (km^2)	6.45	6.82	11.35	8.47	11.33
Total footprint (km^2)	9.70	10.55	15.07	12.22	15.07
Total imperviousness (%)	9.73%	10.93%	12.84%	11.68%	12.88%
Urban density (du/ac)	0.81	1.66	1.36	1.64	1.36
Rural density (du/ac)	0.60	0.63	0.66	0.56	0.55
Overall density (du/ac)	0.67	0.99	0.83	0.89	0.75
Basin B					
Total population (#)	3233	6575	8403	6975	9049
Urban developed area (km^2)	3.29	4.28	4.29	4.20	4.08
Rural residential area (km^2)	9.16	13.22	17.49	16.68	25.74
Total footprint (km^2)	12.44	17.50	21.78	20.87	29.83
Total imperviousness (%)	2.77%	3.75%	4.22%	4.08%	5.01%
Urban density (du/ac)	0.76	1.22	1.07	1.37	1.17
Rural density (du/ac)	0.47	0.52	0.59	0.41	0.42
Overall density (du/ac)	0.55	0.69	0.69	0.60	0.52
Basin C					
Total population (#)	4994	21680	22093	15831	18366
Urban developed area (km^2)	4.99	13.41	13.46	8.91	7.50
Rural residential area (km^2)	24.46	33.60	41.28	40.52	60.44
Total footprint (km^2)	29.46	47.01	54.74	49.43	67.94
Total imperviousness (%)	2.20%	4.47%	4.82%	3.78%	4.35%
Urban density (du/ac)	0.26	1.78	1.27	1.58	1.18
Rural density (du/ac)	0.48	0.53	0.59	0.42	0.44
Overall density (du/ac)	0.44	0.88	0.76	0.63	0.52

Table S8. Statistical results of the non-parametric repeated measures ANOVA (Friedman Test). N=30 for all comparisons. Development scenarios were ranked from smallest to largest according to median values of the corresponding flow metric. Post-hoc Wilcoxon test *p* values were adjusted with Bonferroni Correction. Although Wilcoxon tests were applied no matter the previous Friedman test turned out significant or not, *p* values were not reported for those with no significant differences in either group or pairwise comparisons.

Flow Metric	Bsn	Devel. Scenario	Median	Mean	Std. Dev.	Min.	Max.	Friedman Test Statistics		
								Group *p*	**Pairs**	**Adjusted Wilcoxon *p***
Qmean (cfs)	A	DM	17.398	17.907	7.446	1.291	34.840	0.000	DM vs. CM	0.221
		CM	17.498	17.946	7.419	1.413	34.732		DM vs. 1990	1.000
		1990	17.666	17.991	7.367	1.711	34.697		DM vs. CnM	0.000
		CnM	18.208	18.619	7.493	1.748	35.365		DM vs. DnM	0.000
		DnM	18.412	18.833	7.532	1.709	35.628		CM vs. 1990	1.000
									CM vs. CnM	0.000
									CM vs. DnM	0.000
									1990 vs. CnM	0.000
									1990 vs. DnM	0.000
									CnM vs. DnM	0.000
	B	CM	67.384	69.114	27.932	8.336	134.184	0.000	CM vs. DM	0.000
		DM	67.562	69.274	27.949	8.304	134.400		CM vs. 1990	0.000
		1990	68.016	69.662	27.901	8.961	134.211		CM vs. CnM	0.000
		CnM	70.504	71.894	28.367	9.634	137.385		CM vs. DnM	0.000
		DnM	71.409	72.630	28.555	9.608	138.471		DM vs. 1990	0.005
									DM vs. CnM	0.000
									DM vs. DnM	0.000
									1990 vs. CnM	0.000
									1990 vs. DnM	0.000
									CnM vs. DnM	0.000

Table S8. (continued).

Flow Metric	Bsn	Devel. Scenario	Median	Mean	Std. Dev.	Min.	Max.	Group *p*	Pairs	Adjusted Wilcoxon *p*
	C	1990	153.309	156.642	67.123	17.932	319.492	0.000	1990 vs. CM	0.001
		CM	153.418	157.769	67.837	16.332	320.798		1990 vs. DM	0.000
		DM	153.819	158.315	67.930	16.328	321.490		1990 vs. CnM	0.000
		CnM	159.510	164.180	68.686	18.872	327.198		1990 vs. DnM	0.000
		DnM	161.555	166.091	69.089	18.737	329.634		CM vs. DM	0.000
									CM vs. CnM	0.000
									CM vs. DnM	0.000
									DM vs. CnM	0.000
									DM vs. DnM	0.000
									CnM vs. DnM	0.000
1DMAX	A	1990	165.749	176.620	77.978	20.539	367.626	0.000	1990 vs. CM	0.000
(cfs)		CM	175.726	186.942	80.882	17.428	383.870		1990 vs. DM	0.000
		DM	188.863	200.972	87.437	15.037	411.416		1990 vs. CnM	0.000
		CnM	200.693	207.101	87.333	23.336	413.182		1990 vs. DnM	0.000
		DnM	215.190	220.669	92.173	21.493	434.724		CM vs. DM	0.000
									CM vs. CnM	0.000
									CM vs. DnM	0.000
									DM vs. CnM	0.000
									DM vs. DnM	0.000
									CnM vs. DnM	0.000

Table S8. (continued).

Flow Metric	Bsn	Devel. Scenario	Median	Mean	Std. Dev.	Min.	Max.	Group *p*	Pairs	Adjusted Wilcoxon *p*
	B	1990	676.452	733.593	354.043	84.614	1688.041	0.000	1990 vs. CM	0.000
		CM	689.342	750.687	362.241	77.057	1732.184		1990 vs. DM	0.000
		DM	702.056	763.725	367.840	76.703	1758.317		1990 vs. CnM	0.000
		CnM	797.758	844.859	396.056	103.295	1889.688		1990 vs. DnM	0.000
		DnM	848.788	894.171	416.610	103.119	1984.684		CM vs. DM	0.000
									CM vs. CnM	0.000
									CM vs. DnM	0.000
									DM vs. CnM	0.000
									DM vs. DnM	0.000
									CnM vs. DnM	0.000
	C	1990	1748.076	1914.687	976.649	182.577	4537.935	0.000	1990 vs. CM	0.000
		CM	1976.385	2089.284	1048.620	165.202	4852.235		1990 vs. DM	0.000
		DM	2012.053	2125.036	1062.273	163.895	4915.802		1990 vs. CnM	0.000
		CnM	2181.564	2289.545	1102.305	220.399	5131.221		1990 vs. DnM	0.000
		DnM	2294.217	2397.425	1141.649	216.338	5314.857		CM vs. DM	0.000
									CM vs. CnM	0.000
									CM vs. DnM	0.000
									DM vs. CnM	0.000
									DM vs. DnM	0.000
									CnM vs. DnM	0.000

Table S8. (continued).

Flow Metric	Bsn	Devel. Scenario	Median	Mean	Std. Dev.	Min.	Max.	Group *p*	Pairs	Adjusted Wilcoxon *p*
7DMIN (cfs)	A	DnM	0.004	0.009	0.015	0.000	0.074	<0.001	DnM vs. CnM	0.000
		CnM	0.005	0.010	0.017	0.000	0.083		DnM vs. DM	0.001
		DM	0.006	0.010	0.017	0.000	0.082		DnM vs. CM	0.000
		CM	0.006	0.012	0.017	0.000	0.079		DnM vs. 1990	0.000
		1990	0.042	0.047	0.032	0.003	0.125		CnM vs. DM	1.000
									CnM vs. CM	1.000
									CnM vs. 1990	0.000
									DM vs. CM	0.004
									DM vs. 1990	0.000
									CM vs. 1990	0.000
	B	DnM	0.000	0.022	0.087	0.000	0.454	0.691		
		CnM	0.000	0.026	0.098	0.000	0.510			
		CM	0.000	0.038	0.126	0.000	0.618			
		DM	0.000	0.038	0.126	0.000	0.612			
		1990	0.000	0.045	0.154	0.000	0.762			
	C	DnM	0.000	0.034	0.162	0.000	0.881	0.842		
		CnM	0.000	0.040	0.185	0.000	1.005			
		DM	0.000	0.059	0.224	0.000	1.178			
		1990	0.000	0.059	0.248	0.000	1.334			
		CM	0.000	0.059	0.228	0.000	1.207			

Table S8. (continued).

Metric	Bsn	Scenario	Median	Mean	Std. Dev.	Min.	Max.	Group *p*	Pairs	Adj. Wilcoxon *p*
LPC (Count)	A	1990	4.000	4.400	2.253	1.000	10.000	<0.001	1990 vs. CM	1.000
		CM	5.000	4.700	2.395	1.000	10.000		1990 vs. DM	0.015
		DM	5.000	5.133	2.193	2.000	10.000		1990 vs. CnM	0.002
		CnM	5.000	5.267	2.518	1.000	11.000		1990 vs. DnM	0.000
		DnM	6.000	5.767	2.300	1.000	11.000		CM vs. DM	0.258
									CM vs. CnM	0.082
									CM vs. DnM	0.000
									DM vs. CnM	1.000
									DM vs. DnM	0.023
									CnM vs. DnM	0.041
	B	DM	4.500	4.967	2.251	2.000	10.000	<0.001	DM vs. CM	1.000
		CM	5.000	5.033	2.220	2.000	10.000		DM vs. 1990	1.000
		1990	5.000	5.100	2.234	2.000	11.000		DM vs. CnM	0.000
		CnM	5.000	5.867	2.583	2.000	12.000		DM vs. DnM	0.000
		DnM	6.000	6.133	2.776	3.000	14.000		CM vs. 1990	1.000
									CM vs. CnM	0.001
									CM vs. DnM	0.000
									1990 vs. CnM	0.002
									1990 vs. DnM	0.000
									CnM vs. DnM	0.313
	C	1990	1.000	1.467	1.042	0.000	4.000	<0.001	1990 vs. CM	0.000
		CM	5.000	5.400	2.608	1.000	13.000		1990 vs. DM	0.000
		DM	6.000	5.633	2.512	2.000	11.000		1990 vs. CnM	0.000
		CnM	6.000	6.333	2.294	3.000	13.000		1990 vs. DnM	0.000
		DnM	7.000	6.933	2.504	4.000	12.000		CM vs. DM	1.000
									CnM vs. CM	0.259
									CM vs. DnM	0.015
									CnM vs. DM	0.010
									DM vs. DnM	0.000
									CnM vs. DnM	0.046

Table S8. (continued).

Flow Metric	Bsn	Devel. Scenario	Median	Mean	Std. Dev.	Min.	Max.	Group *p*	Pairs	Adjusted Wilcoxon *p*
HPC (Count)	A	1990	7.000	7.033	2.895	0.000	14.000	<0.001	1990 vs. CM	0.002
		CM	8.000	7.833	3.323	0.000	15.000		1990 vs. DM	0.000
		DM	8.500	8.267	3.403	0.000	15.000		1990 vs. CnM	0.000
		CnM	8.500	8.667	3.872	0.000	20.000		1990 vs. DnM	0.000
		DnM	8.500	8.833	3.752	0.000	19.000		CM vs. DM	0.005
									CM vs. CnM	0.003
									CM vs. DnM	0.000
									DM vs. CnM	1.000
									DM vs. DnM	0.086
									CnM vs. DnM	1.000
	B	CM	7.500	7.467	3.683	0.000	18.000	<0.001	CM vs. 1990	1.000
		1990	8.000	7.400	3.410	0.000	17.000		CM vs. DM	0.078
		DM	8.000	7.733	3.667	0.000	18.000		CM vs. CnM	0.004
		CnM	8.500	8.533	3.693	0.000	18.000		CM vs. DnM	0.001
		DnM	9.000	8.933	3.685	0.000	18.000		1990 vs. DM	0.745
									1990 vs. CnM	0.000
									1990 vs. DnM	0.000
									DM vs. CnM	0.047
									DM vs. DnM	0.004
									CnM vs. DnM	0.020

Table S8. (continued).

Flow Metric	Bsn	Devel. Scenario	Median	Mean	Std. Dev.	Min.	Max.	Group *p*	Pairs	Adjusted Wilcoxon *p*
	C	1990	7.000	7.500	3.256	0.000	14.000	<0.001	1990 vs. CM	0.000
		CM	8.000	8.467	3.739	0.000	19.000		1990 vs. DM	0.000
		DM	8.000	8.500	3.830	0.000	19.000		1990 vs. CnM	0.000
		CnM	10.000	9.633	4.098	0.000	20.000		1990 vs. DnM	0.000
		DnM	10.000	10.000	4.235	0.000	20.000		CM vs. DM	1.000
									CM vs. CnM	0.001
									CM vs. DnM	0.000
									DM vs. CnM	0.001
									DM vs. DnM	0.001
									CnM vs. DnM	0.359
N0D (days)	A	1990	0.000	0.100	0.548	0.000	3.000	<0.001	1990 vs. CM	0.002
		CM	0.000	7.467	11.723	0.000	45.000		1990 vs. DM	0.002
		DM	0.000	8.533	12.797	0.000	46.000		1990 vs. CnM	0.001
		CnM	0.000	9.067	13.321	0.000	48.000		1990 vs. DnM	0.001
		DnM	0.500	10.267	14.200	0.000	50.000		CM vs. DM	0.010
									CM vs. CnM	0.006
									CM vs. DnM	0.002
									DM vs. CnM	0.234
									DM vs. DnM	0.004
									CnM vs. DnM	0.002
	B	DnM	35.000	37.333	25.979	0.000	92.000	0.296		
		CnM	35.500	37.033	25.877	0.000	92.000			
		DM	36.000	36.200	26.637	0.000	91.000			
		CM	36.000	36.233	26.605	0.000	91.000			
		1990	37.500	36.700	26.562	0.000	91.000			

Table S8. (continued).

Flow Metric	Bsn	Devel. Scenario	Median	Mean	Std. Dev.	Min.	Max.	Group *p*	Pairs	Adjusted Wilcoxon *p*
	C	CnM	36.500	36.900	25.200	0.000	89.000	<0.001	CnM vs. DnM	0.078
		DnM	36.500	37.333	25.157	0.000	90.000		CnM vs. DM	0.027
		DM	37.000	35.000	25.354	0.000	87.000		CnM vs. CM	0.021
		CM	37.500	35.133	25.258	0.000	87.000		CnM vs. 1990	0.159
		1990	38.500	37.833	25.815	0.000	90.000		DnM vs. DM	0.007
									DnM vs. CM	0.005
									DnM vs. 1990	1.000
									DM vs. CM	1.000
									DM vs. 1990	0.000
									CM vs. 1990	0.000
LPD (days)	A	DnM	9.750	25.483	43.867	1.000	206.000	0.959		
		DM	10.000	27.600	39.165	1.000	134.000			
		CnM	11.750	37.633	59.165	1.000	205.000			
		CM	13.750	45.367	59.912	2.000	204.000			
		1990	14.000	39.983	55.131	1.000	203.000			
	B	CnM	7.750	13.517	15.787	3.000	88.000	0.038	CnM vs. DnM	1.000
		DnM	8.500	11.450	7.824	3.000	28.500		CnM vs. 1990	1.000
		1990	11.500	22.317	27.753	3.000	97.000		CnM vs. CM	1.000
		CM	15.000	24.100	28.326	3.000	98.500		CnM vs. DM	1.000
		DM	15.000	24.350	28.302	2.500	98.500		DnM vs. 1990	1.000
									DnM vs. CM	1.000
									DnM vs. DM	1.000
									1990 vs. CM	1.000
									1990 vs. DM	1.000
									CM vs. DM	1.000

Table S8. (continued).

Flow Metric	Bsn	Devel. Scenario	Median	Mean	Std. Dev.	Min.	Max.	Group *p*	Pairs	Adjusted Wilcoxon *p*
	C	DnM	7.750	11.500	10.713	1.000	45.000	0.081	DnM vs. CnM	0.108
		CnM	9.750	13.800	14.513	2.000	72.000		DnM vs. DM	0.282
		DM	10.250	23.817	33.555	2.500	132.500		DnM vs. CM	1.000
		CM	10.500	22.467	37.035	2.000	178.000		DnM vs. 1990	0.015
		1990	18.500	25.517	20.762	0.000	73.000		CnM vs. DM	1.000
									CnM vs. CM	1.000
									CnM vs. 1990	0.108
									DM vs. CM	1.000
									DM vs. 1990	1.000
									CM vs. 1990	1.000
HPD	A	DnM	3.750	4.800	3.274	0.000	14.000	0.034	DnM vs. CnM	1.000
(days)		CnM	4.000	4.950	3.354	0.000	14.000		DnM vs. DM	1.000
		DM	4.000	5.183	3.990	0.000	16.000		DnM vs. CM	1.000
		CM	4.000	5.650	4.459	0.000	15.500		DnM vs. 1990	0.119
		1990	5.000	6.217	4.437	0.000	16.000		CnM vs. DM	1.000
									CnM vs. CM	1.000
									CnM vs. 1990	0.202
									DM vs. CM	0.352
									DM vs. 1990	0.077
									CM vs. 1990	0.162

Table S8. (continued).

Flow Metric	Bsn	Devel. Scenario	Median	Mean	Std. Dev.	Min.	Max.	Group *p*	Pairs	Adjusted Wilcoxon *p*
	B	DnM	3.250	4.133	3.159	0.000	14.000	0.009	DnM vs. CnM	0.078
		CnM	4.000	4.467	3.118	0.000	14.000		DnM vs. DM	0.183
		DM	4.000	5.317	4.213	0.000	15.000		DnM vs. CM	0.122
		CM	4.000	5.583	4.233	0.000	15.000		DnM vs. 1990	0.014
		1990	4.500	5.550	4.149	0.000	15.000		CnM vs. DM	0.985
									CnM vs. CM	0.407
									CnM vs. 1990	0.090
									DM vs. CM	1.000
									DM vs. 1990	1.000
									CM vs. 1990	1.000
	C	CnM	2.750	3.650	3.023	0.000	15.000	0.103		
		DnM	3.000	3.667	2.922	0.000	15.000			
		CM	3.000	3.983	3.067	0.000	13.000			
		DM	3.000	4.117	3.446	0.000	15.000			
		1990	4.000	4.633	4.150	0.000	20.500			
TL1 (Julian date)	A	DnM	226.500	229.967	23.000	186.000	274.000	0.021	DnM vs. CnM	0.151
		CnM	228.000	231.667	22.538	190.000	270.000		DnM vs. DM	0.010
		DM	231.500	233.433	22.820	192.000	270.000		DnM vs. CM	0.001
		CM	234.500	234.900	24.390	192.000	293.000		DnM vs. 1990	0.007
		1990	239.500	244.167	21.890	209.000	293.000		CnM vs. DM	0.313
									CnM vs. CM	0.013
									CnM vs. 1990	0.014
									DM vs. CM	0.078
									DM vs. 1990	0.022
									CM vs. 1990	0.080

Table S8. (continued).

Flow Metric	Bsn	Devel. Scenario	Median	Mean	Std. Dev.	Min.	Max.	Group *p*	Pairs	Adjusted Wilcoxon *p*
	B	1990	215.000	224.800	34.645	178.000	280.000	0.411		
		DnM	215.000	227.333	35.914	180.000	282.000			
		CM	215.500	225.567	34.367	179.000	281.000			
		DM	215.500	225.633	34.546	179.000	281.000			
		CnM	218.500	228.267	35.496	180.000	282.000			
	C	DnM	215.000	229.267	35.183	181.000	283.000	<0.001	DnM vs. 1990	1.000
		1990	219.000	229.800	34.511	181.000	281.000		DnM vs. CnM	1.000
		CnM	220.000	230.267	34.683	181.000	283.000		DnM vs. CM	0.000
		CM	221.500	231.567	33.731	182.000	283.000		DnM vs. DM	0.000
		DM	221.500	231.633	33.682	183.000	283.000		1990 vs. CnM	0.230
									1990 vs. CM	0.000
									1990 vs. DM	0.000
									CnM vs. CM	0.004
									CnM vs. DM	0.004
									CM vs. DM	1.000
RBI (unitless)	A	1990	0.212	0.213	0.021	0.176	0.269	0.000	1990 vs. CM	0.000
		CM	0.236	0.239	0.024	0.197	0.313		1990 vs. DM	0.000
		DM	0.261	0.262	0.024	0.216	0.323		1990 vs. CnM	0.000
		CnM	0.265	0.268	0.024	0.222	0.326		1990 vs. DnM	0.000
		DnM	0.289	0.289	0.024	0.241	0.335		CM vs. DM	0.000
									CM vs. CnM	0.000
									CM vs. DnM	0.000
									DM vs. CnM	0.000
									DM vs. DnM	0.000
									CnM vs. DnM	0.000

Table S8. (continued).

Flow Metric	Bsn	Devel. Scenario	Median	Mean	Std. Dev.	Min.	Max.	Group *p*	Pairs	Adjusted Wilcoxon *p*
	B	1990	0.220	0.222	0.020	0.182	0.267	0.000	1990 vs. CM	0.000
		CM	0.234	0.235	0.021	0.194	0.282		1990 vs. DM	0.000
		DM	0.240	0.240	0.022	0.199	0.288		1990 vs. CnM	0.000
		CnM	0.267	0.268	0.024	0.221	0.320		1990 vs. DnM	0.000
		DnM	0.288	0.288	0.025	0.237	0.343		CM vs. DM	0.000
									CM vs. CnM	0.000
									CM vs. DnM	0.000
									DM vs. CnM	0.000
									DM vs. DnM	0.000
									CnM vs. DnM	0.000
	C	1990	0.256	0.257	0.028	0.202	0.319	0.000	1990 vs. CM	0.000
		CM	0.294	0.293	0.032	0.235	0.369		1990 vs. DM	0.000
		DM	0.301	0.299	0.032	0.240	0.375		1990 vs. CnM	0.000
		CnM	0.329	0.326	0.032	0.267	0.404		1990 vs. DnM	0.000
		DnM	0.347	0.344	0.034	0.279	0.422		CM vs. DM	0.000
									CM vs. CnM	0.000
									CM vs. DnM	0.000
									DM vs. CnM	0.000
									DM vs. DnM	0.000
									CnM vs. DnM	0.000

Table S9. Sum of the squares of the rank differences (SSrd) for each flow metric and the Equivalent Standard Deviation (ESD) for each future flow regime.

				SS (Rank Dif.)			
Bsn		**Flow Metric**	REF	CM	DM	CnM	DnM
A	1	Qmean	0	39	107	122	257
	2	1DMAX	0	30	120	265	465
	3	7DMIN	0	122	192	192	347
	4	LPC	0	94	117	112	187
	5	HPC	0	46	115	188	207
	6	N0D	0	70	206	26	104
	7	LPD	0	104	174	189	178
	8	HPD	0	114	163	173	211
	9	TL1	0	103	139	170	241
	10	RBI	0	30	120	270	480
	ESD=√(∑SS/(10*30))		**0**	**1.58**	**2.20**	**2.38**	**2.99**
			REF	CM	DM	CnM	DnM
B	1	Qmean	0	93	45	77	185
	2	1DMAX	0	42	102	223	403
	3	7DMIN	0	11	22	29	50
	4	LPC	0	80	80	113	131
	5	HPC	0	46	52	114	174
	6	N0D	0	62	81	117	135
	7	LPD	0	132	134	91	105
	8	HPD	0	74	79	113	161
	9	TL1	0	65	56	73	75
	10	RBI	0	30	120	270	480
	ESD=√(∑SS/(10*30))		**0**	**1.45**	**1.60**	**2.02**	**2.52**
			REF	CM	DM	CnM	DnM
C	1	Qmean	0	36	108	239	427
	2	1DMAX	0	30	120	265	465
	3	7DMIN	0	7	21	19	36
	4	LPC	0	142	133	216	301
	5	HPC	0	75	73	227	263
	6	N0D	0	169	173	99	109
	7	LPD	0	204	190	158	200
	8	HPD	0	131	119	159.75	167
	9	TL1	0	133	145	50	43
	10	RBI	0	30	120	270	480
	ESD=√(∑SS/(10*30))		**0**	**1.79**	**2.00**	**2.38**	**2.88**

Table S10. Characteristics of the MACAv2-LIVNEH data product.

	MACAv2-LIVNEH (http://maca.northwestknowledge.net/)
Training Dataset	Developed by Livneh et. al, (2013) Covering time period 1950-2011
Temporal Extent	1950-2100
Temporal Resolution	Daily
Resolution	4~6km (1/16-deg)
Spatial Extent	Contiguous USA (CONUS) and Columbia Basin into Canada
Downscaled Variables	Maximum daily temperature near surface Minimum daily temperature near surface Average daily precipitation amount at surface Average daily downward shortwave radiation at surface Average daily wind speed near surface Average daily specific humidity near surface (only one ensemble run, i.e., r1i1p1, was downscaled for each model even though some models had multiple ensemble runs)

Table S11. Precipitation comparison of future climate datasets. Nine climate variables were calculated for both historical climate records (1978-2007) and the four future climate datasets (2036-2065). Variable definitions are as follows.

Max-T: 30-yr average daily maximum temperature (℃).

Min-T: 30-yr average daily minimum temperature (℃).

Mean-P-Annual: 30-yr average annual precipitation (mm).

Max-P: 30-yr average daily maximum precipitation (mm).

Mean-P-*XXX* stands for 30-yr average seasonal precipitation (mm).

Season designation: DJF (December, January, and February), MAM (March, April, and May), JJA (June, July, and August), and SON (September, October, and November).

No. of Days w/ no Precipitation: Average number of days in a year without any precipitation.

Variables	**Historical**	**CanESM2 _RCP4.5**	**CanESM2 _RCP8.5**	**CNRM-CM5 _RCP4.5**	**CNRM-CM5 _RCP8.5**
Temperature:					
Max-T (℃)	38	40	42	39	39
Min-T (℃)	-9	-6	-6	-8	-9
Precipitation:					
Mean-P-Annual (mm)	1202	1239	1209	1128	1150
Dif% from historical		**3%**	1%	**-6%**	-4%
Max-P (mm)	68	77	74	70	75
Dif% from historical		**14%**	9%	**4%**	11%
Mean-P-DJF (mm)	528	594	559	537	532
Mean-P-MAM (mm)	284	253	270	244	259
Mean-P-JJA (mm)	70	52	46	53	53
Mean-P-SON (mm)	320	340	335	295	305
No. of Days w/ no Precipitation	225	226	231	228	218

Table S12. Similarity of flow metric loadings for the two separate NMDS ordinations for Basins B and C. Flow metric loadings for Basins B and C were sufficiently similar for each axis that a combined ordination was used. 7DMIN had no loadings for Basins B or C because median values for all scenarios were zero. Significance codes: <0.05 = *, < 0.01 = **, < 0.001 = ***, ns = ≥ 0.05.

	Basin	**MDS1**	**MDS2**	**Pr(>r)**
Qmean	B	0.83	-0.56	*
	C	0.77	-0.63	**
1DMAX	B	0.99	-0.13	***
	C	0.87	0.49	***
7DMIN	B	--	--	
	C	--	--	
LPC	B	-0.02	-1.00	*
	C	-0.02	-1.00	
HPC	B	0.38	-0.92	***
	C	0.92	-0.39	**
N0D	B	0.74	0.68	**
	C	0.48	0.88	***
LPD	B	-0.68	0.73	**
	C	-0.65	0.76	***
HPD	B	-0.80	-0.60	
	C	-0.71	-0.70	
TL1	B	-0.78	-0.63	**
	C	-0.67	-0.74	***
RBI	B	0.87	-0.49	***
	C	0.99	0.15	**

Table S13. Flow metric loadings for the two NMDS ordinations. Axis loading values ≥0.5 are in bold, and ≤ -0.5 are in bold and underlined. 7DMIN had no loadings for Basins B or C because median values for all scenarios were zero. Significance codes: <0.05 = *, < 0.01 = **, < 0.001 = ***, ns = ≥0.05.

Flow metrics		**Axis A1 loading**	**Axis A2 loading**	**Pr(>r)**	**Axis A1 (left to right)**	**Axis A2 (down to up)**
Basin A						
TL1	Date of Annual Minimum	**-0.97**	0.26	***	Earlier 1st annual minimum	
7DMIN	7-day Minimum	**-0.89**	-0.46	***	7-day minimum ↓	
LPD	Low Pulse Duration	**-0.68**	**-0.74**	*	Duration of low flows ↓	Duration of low flows ↓
HPD	High Pulse Duration	-0.21	**-0.98**	**		Duration of high pulses ↓
LPC	Low Pulse Count	-0.20	**0.98**	ns		No. of low-flow events ↑
Qmean	Annual Average Flow	0.46	**-0.89**	***		Annual average ↓
HPC	High Pulse Count	**0.73**	**-0.68**	ns	No. of high pulses ↑	No. of high pulses ↓
N0D	No. of Zero-flow Days	**0.81**	**0.58**	**	No. of dry days ↑	No. of dry days ↑
1DMAX	1-day Maximum	**0.90**	-0.44	***	Largest flood ↑	
RBI	R-B Index	**0.91**	0.42	**	Flashiness ↑	
Flow metrics		**Axis BC1 loading**	**Axis BC2 loading**	**Pr(>r)**	**Axis BC1 (left to right)**	**Axis BC2 (down to up)**
Basin B & C						
HPD	High Pulse Duration	**-0.99**	0.16	***	Duration of high pulses ↓	
LPD	Low Pulse Duration	**-0.94**	0.35	***	Duration of low flows ↓	
TL1	Date of Annual Minimum	-0.22	**-0.98**	***		Earlier 1st annual minimum
N0D	No. of Zero-flow Days	0.26	**0.97**	***		No. of dry days ↑
LPC	Low Pulse Count	0.41	**-0.91**	***		No. of low-flow events ↓
HPC	High Pulse Count	**0.95**	-0.31	***	No. of high pulses ↑	
1DMAX	1-day Maximum	**0.98**	0.18	***	Largest flood ↑	
Qmean	Annual Average Flow	**1.00**	-0.07	***	Annual average ↑	
RBI	R-B Index	**1.00**	-0.06	***	Flashiness ↑	
7DMIN	7-day Minimum	**--**	--	--		

Figure S1. The ca. 2000 landscape.

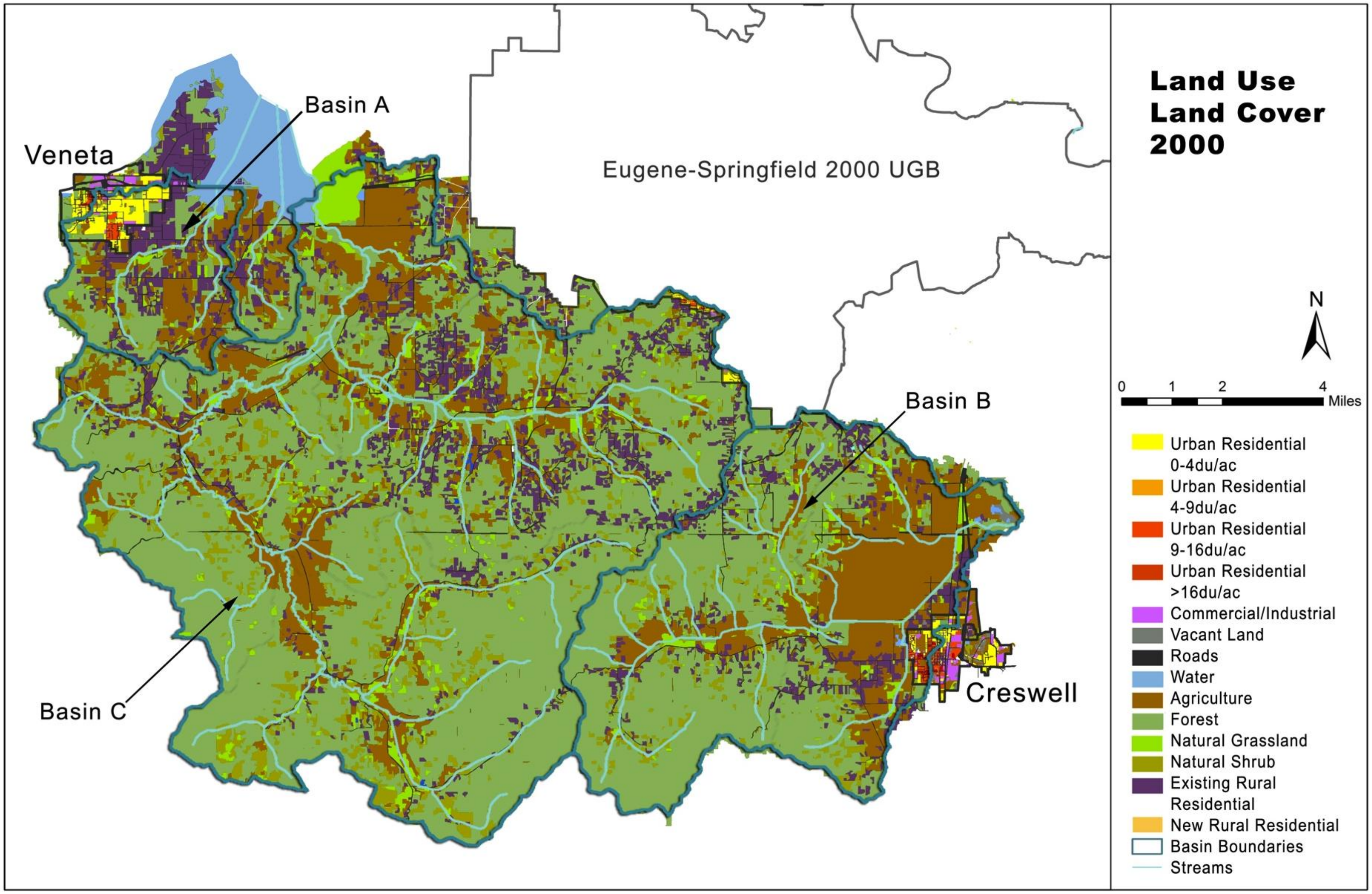
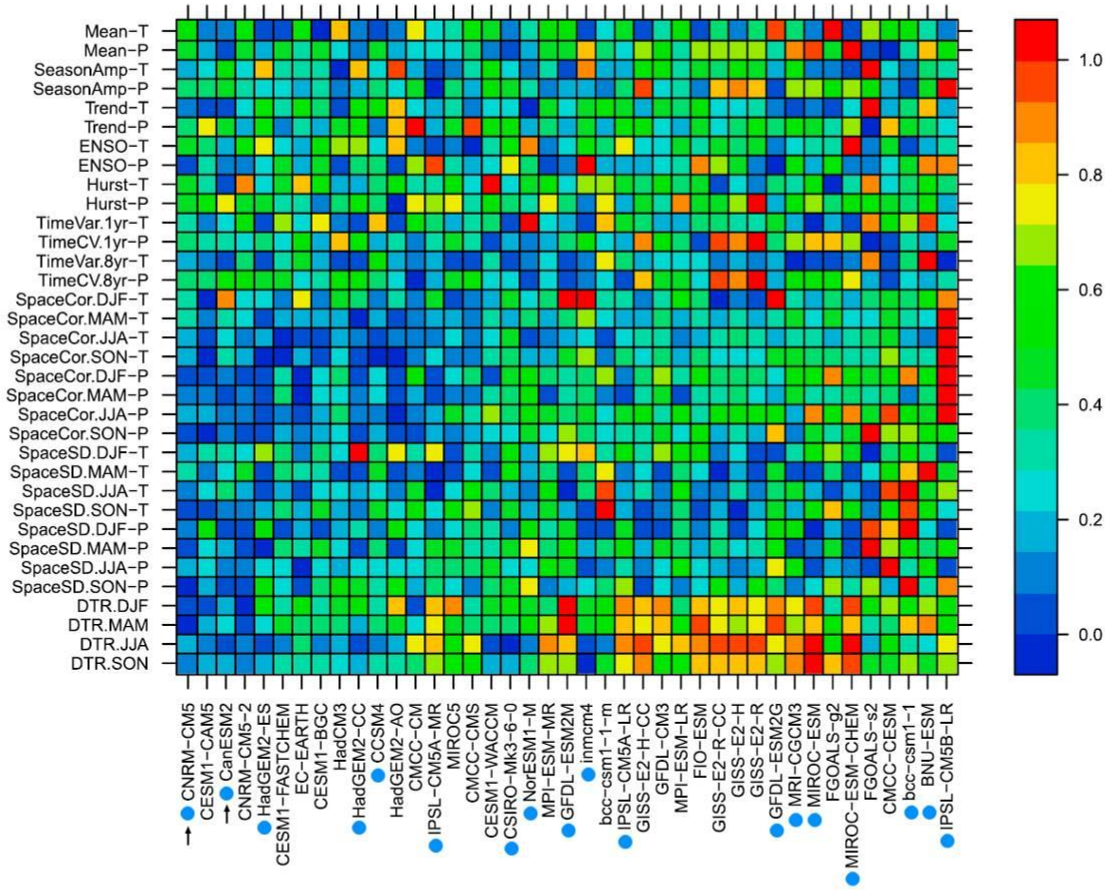


Figure S2. Flow metric responses under future development scenarios (organized by catchment basin). Central column "REF" indicates the reference scenario (1990 landscape, historical climate). Scenarios are ranked from minimum to maximum according to flow metric median values. Median values may be similar 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 not significantly different are bounded by a bold black outline.

No.	Flow Metric	MIN →								→ MAX
	Basin A									
1	Annual Average (Qmean)			DM -2%	CM -1%	REF	CnM 3%	DnM 4%		
2	1-Day Maximum (1DMAX)					REF	CM 6%	DM 14%	CnM 21%	DnM 30%
3	7-Day Minimum (7DMIN)	DnM -90%	CnM -88%	DM -87%	CM -85%	REF				
4	Low Pulse Count (LPC)					REF	CM 25%	DM 25%	CnM 25%	DnM 50%
5	High Pulse Count (HPC)					REF	CM 14%	DM 21%	CnM 21%	DnM 21%
6	Number of 0 Days (N0D)*⋆					REF	CM +7d	DM +9d	CnM +9d	DnM +10d
7	Low Pulse Duration (LPD)	DnM -30%	DM -29%	CnM -16%	CM -2%	REF				
8	High Pulse Duration (HPD)	DnM -20%	CnM -20%	DM -20%	CM -20%	REF				
9	Date of Annual Min. (TL1)*	DnM -13d	CnM -11.5d	DM -8d	CM -5d	REF				
10	Richards-Baker Index (RBI)					REF	CM 11%	DM 23%	CnM 25%	DnM 36%
	Basin B									
1	Annual Average (Qmean)			CM -1%	DM -1%	REF	CnM 4%	DnM 5%		
2	1-Day Maximum (1DMAX)					REF	CM 2%	DM 4%	CnM 18%	DnM 25%
3	7-Day Minimum (7DMIN)	DnM 0†	CnM 0†	CM 0†	DM 0†	REF				
4	Low Pulse Count (LPC)			DM -10%	CM 0%	REF	CnM 0%	DnM 20%		
5	High Pulse Count (HPC)				CM -6%	REF	DM 0%	CnM 6%	DnM 13%	
6	Number of 0 Days (N0D)*	DnM -2.5d	CnM -2d	DM -1.5d	CM -1.5d	REF				
7	Low Pulse Duration (LPD)			CnM -33%	DnM -26%	REF	CM 30%	DM 30%		
8	High Pulse Duration (HPD)	DnM -26%	CnM -16%	DM -16%	CM -11%	REF				
9	Date of Annual Min. (TL1)*					REF	DnM 0	CM +0.5d	DM +0.5d	CnM +3.5d
10	Richard-Baker Index (RBI)					REF	CM 6%	DM 9%	CnM 21%	DnM 31%
	Basin C									
1	Annual Average (Qmean)					REF	CM 0%	DM 0%	CnM 4%	DnM 5%
2	1-Day Maximum (1DMAX)					REF	CM 13%	DM 15%	CnM 25%	DnM 31%
3	7-Day Minimum (7DMIN)		DnM 0†	CnM 0†	DM 0†	REF	CM 0†			
4	Low Pulse Count (LPC)					REF	CM 400%	DM 500%	CnM 500%	DnM 600%
5	High Pulse Count (HPC)					REF	CM 14%	DM 14%	CnM 43%	DnM 43%
6	Number of 0 Days (N0D)*	CnM -2d	DnM -2d	DM -1.5d	CM -1d	REF				
7	Low Pulse Duration (LPD)	DnM -58%	CnM -47%	DM -45%	CM -43%	REF				
8	High Pulse Duration (HPD)	CnM -31%	DnM -25%	CM -25%	DM -25%	REF				
9	Date of Annual Min. (TL1)*				DnM -4d	REF	CnM +1d	CM +2.5d	DM +2.5d	
10	Richards-Baker Index (RBI)					REF	CM 15%	DM 18%	CnM 29%	DnM 36%

*: Number of Zero-flow Days (N0D) and Date of Annual Minimum (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.
★: Because stories told by means vs. medians were drastically different for N0D in Basin A, and comparison of means more appropriately represented the trend in this case (a unique situation among all flow metrics), means instead of medians are reported.)

Figure S3. CMIP5 GCM evaluation matrix (adapted from Rupp et al. 2013). This figure was adapted from Rupp et al. (2013), which assessed the performance of CMIP5 models in simulating the historical climate of the U.S. Pacific Northwest. Different colors indicate the magnitude of relative error in the ensemble mean of each metric in relation to historical data (blue = the smallest relative error/best performance, red = the largest relative error/worst performance). Models on the left showed smaller total relative error (sum of relative errors from all the metrics) than those on the right. The Blue dots underneath the model names indicate availability of downscaled data from the MACAv2-LIVNEH data product. The first two, the CNRM-CM5 and CanESM2, were chosen because they ranked the highest for general performance across all climate variables and were particularly good for precipitation-related variables.



APPENDIX B

METHOD FOR DEVELOPING A LANDSCAPE MAP THAT REPRESENTS THE CENTRAL TENDENCY OF EACH LAND DEVELOPMENT SCENARIO

Each land development scenario was run in Envision for 10 times. Because of the stochastic character of Envision, actual population allocation among simulation runs can be different from the targeted population. We then selected 5 of the 10 runs that showed the closest population allocation to the targets for further land cover inspections. For example, in Table B-1 below, runs 3, 4, 6, 8, and 9 of scenario DM were selected because of the relatively small differences in population outcomes from the targets. The land use land cover outcomes of runs 3, 4, 6, 8, and 9 were then examined. For each IDU, the LULC type that happened the most often during the 5 runs (i.e., the Mode) was identified, and the percentage of IDUs with the same LULC types as the Modes were calculated for each run.

The variability in land cover types among replicate runs turned out to be small according to Table B-2 below. For every scenario, I modeled the differences in hydrological outcomes between the two runs with the largest land cover contrasts in SWAT. For instance, 4.3% (the largest among the 4 scenarios, Table B-2) of the IDUs had different LULC outcomes between Run 2 and Run 4 in scenario DnM. Hydrological divergence caused by this 4.3% difference was then modeled in SWAT. The correlation coefficient between the two resulted hydrographs was equal to 0, as in all other 3 scenarios. Therefore, we concluded that Run 0 (CnM), Run 5 (CM), Run 4 (DnM), and

Run 9 (DM) sufficiently represented the central tendency in LULC and hydrological outcomes of its corresponding scenario.

Table B-1. Different population outcomes of the 10 runs for scenario DM.

	Popu. Targets	**Runs** 1	2	3	4	5	6	7	8	9	10
Creswell	2734	2927	2901	2662	2632	2834	2622	2800	2517	2560	2875
Dif.%		7%	6%	-3%	-4%	4%	-4%	2%	-8%	-6%	5%
Veneta	2239	2483	2455	2188	2172	2431	2112	2433	2102	2168	2445
Dif.%		11%	10%	-2%	-3%	9%	-6%	9%	-6%	-3%	9%
Rural	16290	17981	18320	16502	16397	18117	16455	17904	16590	16425	18083
Dif.%		10%	12%	1%	1%	11%	1%	10%	2%	1%	11%

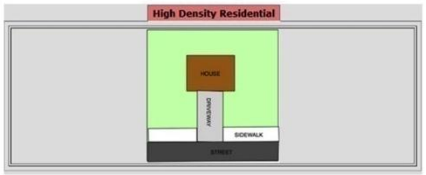
Table B-2. Percentages of IDUs with the same LULC types as the modes for each scenario run.

Scenario	**Run**	**Convergence toward Modes**	**Max.-Min.**
CnM	***Run 0***	***85.3% (max.)***	
	Run 2	83.0%	
	Run 3	82.1%	
	Run 4	81.8% (min.)	
	Run 7	82.4%	3.50%
CM	Run 1	82.2% (min.)	
	Run 3	82.6%	
	Run 5	***85.2% (max.)***	
	Run 6	83.3%	
	Run 9	82.8%	3.00%
DnM	Run 1	80.1%	
	Run 2	79.4% (min.)	
	Run 4	***83.7% (max.)***	
	Run 5	79.7%	
	Run 7	79.4%	4.30%
DM	Run 3	82.3% (min.)	
	Run 4	83.1%	
	Run 6	82.9%	
	Run 8	83.8%	
	Run 9	***85.5% (max.)***	3.20%

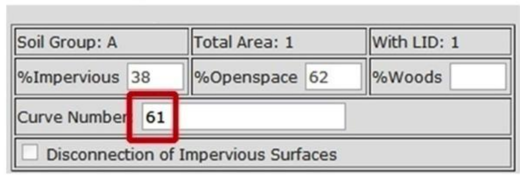
APPENDIX C

APPLYING L-THIA TO DEVELOP NEW CURVE NUMBERS

1/4 acre lot



Without any LIDs



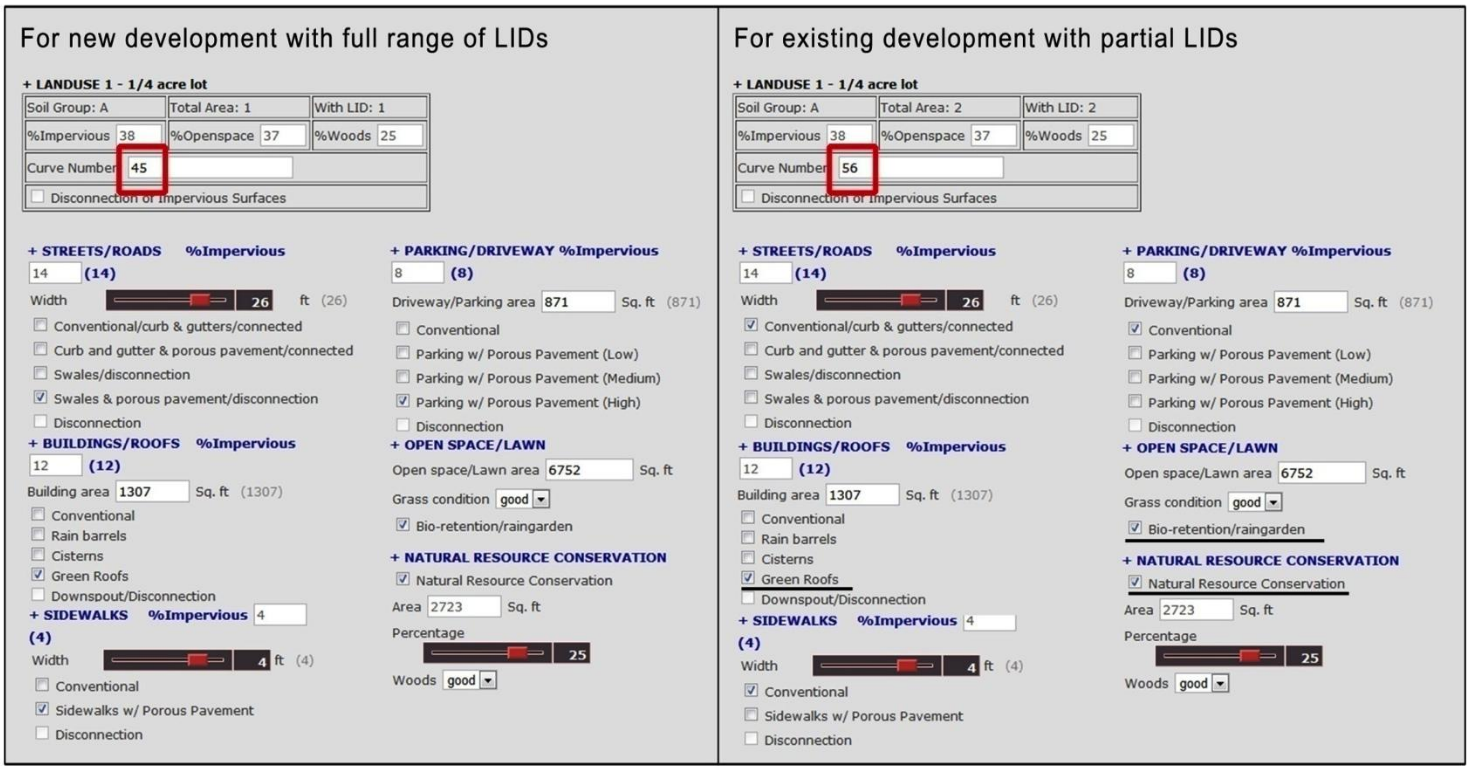


Table C-1. Curve numbers developed in L-THIA for new land cover types.

Category	Land Cover Type	Density	FIMP	Curve Numbers			
				HSG A	HSG B	HSG C	HSG D
Urban Residential	Residential-high density - w/out LID	8-24 du/ac	58%	70	80	87	90
	Residential-high density - new w/ full LID			50	65	74	79
	Residential-high density - existing w/ partial LID			67	76	82	85
	Residential-high/medium density - w/out LID	4-8 du/ac	48%	66	78	85	89
	Residential-high/medium density - new w/ full LID			48	63	73	78
	Residential-high/medium density - existing w/ partial LID			62	72	80	83
	Residential-medium density - w/out LID	2-4 du/ac	38%	61	75	83	87
	Residential-medium density - new w/ full LID			45	61	71	77
	Residential-medium density - existing w/ partial LID			56	68	77	81
	Residential-med/low density - w/out LID	0.5-2 du/ac	20%	51	68	79	84
	Residential-med/low density - new w/ full LID			40	57	68	75
	Residential-med/low density - existing w/ partial LID			44	60	71	76
Commercial/ Industrial	Commercial/Industrial - w/out LID		77%	84	89	92	94
	Commercial/industrial - new w/ full LID			48	63	72	76
	Commercial/Industrial - existing w/ partial LID			80	85	88	90
Transportation	Transportation - existing w/ porous pavement		/	85	87	87	87
Rural Residential	Rural Residential - 1 ac lot - w/out LID		18%	44	64	76	82
	Rural Residential - 1 ac lot - w/ LID			39	56	68	74
	Rural Residential - 2 ac lot - w/out LID		12%	43	64	76	81
	Rural Residential - 2 ac lot - w/ LID			21	29	35	38
	Rural Residential - 2.7 ac lot - w/out LID		14%	56	69	77	81
	Rural Residential - 2.7 ac lot - w/ LID			47	66	76	81

APPENDIX D

SCENARIO COMPARISONS TO EXPLORE THE IMPORTANCE OF INTEGRATED STORMWATER MANAGEMENT AND COMPACT REGIONAL GROWTH

The fact that the compact and ISM scenarios exceeded their counterparts in reducing flow alterations suggests that both compact regional growth and the application of ISM are effective approaches to protecting the hydrology of the catchment basins in question. However, due to the differences in population growth outcomes across scenarios and basins (Table S7), the story is more complicated. Here, I consider landscape outcomes and flow alterations in light of the population differences.

For each watershed, I further compared the compact scenarios with their dispersed counterparts (CM vs. DM, CnM vs. DnM), and the ISM scenarios with their no-ISM counterparts (CM vs. CnM, DM vs. DnM) to explore the relationship among regional population growth, ISM, and hydrologic outcome. Additionally, I searched for scenarios with equal or larger population growth that still generated less flow alterations. The eight development variables (Table S7) were carefully examined to explore generalizable implications for watershed planning.

First, comparisons between the best- (CM) and worst-case (DnM) scenarios across the entire study area suggest that dispersion of growth into the rural areas without any mitigation may incur substantial hydrological impacts. Scenarios CM and DnM resulted in almost identical total population for the study area as a whole. Despite the varied population distribution among the three basins, CM led to less flow alteration in every basin. This makes a strong case for the benefits of integrating compact growth and ISM for reducing development impacts.

Second, the importance of ISM was repeatedly demonstrated by paired comparisons between the ISM scenarios and their no-ISM counterparts. In the two dispersed scenarios (DM vs. DnM) in Basin A, urban population and urban developed area were almost identical. However, DM allocated 11% more people into the rural area without enlarging the rural footprint. Thus, with a higher rural density and an identical total development footprint, DM achieved a better hydrological outcome by application of ISM. Furthermore, comparisons of CM vs. CnM and DM vs. DnM in Basin C conveyed a similar message. Accommodating >20% more people than their no-ISM counterparts, the ISM scenarios resulted in smaller total development footprints accompanied by larger urban but smaller rural areas. Both urban and rural densities were higher in the ISM scenarios. This indicates that, in this case, the exacerbated hydrologic impacts from a more dispersed, larger, and unmanaged rural landscape was more overwhelming than that of a larger, denser, but managed urban area.

Additionally, limiting the development footprint may not be the absolute most important principle as long as ISM is applied. Comparisons between scenarios DM 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.

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