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Research Paper

Modeling the impact of development policies and climate on suburban watershed hydrology near Portland, Oregon

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HIGHLIGHTS

- We co-developed 50-year suburban growth scenarios with stakeholders and simulated watershed response.
- Development reduced evapotranspiration and increased streamflow in all scenarios.
- Condensed development patterns that preserved forests had the least hydrologic impact.
- LID controls increased infiltration but had minimal effect on watershed hydrology.
- Effects of development overwhelmed effects of a warming climate on watershed hydrology.

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ABSTRACT

We simulated watershed hydrologic response to land use scenarios representing different sets of policies for suburban development and watershed management in an urbanizing watershed near Portland, Oregon. We asked (1) Can watershed-scale planning and development policies reduce the hydrologic impacts of urbanization? (2) How effective are different policies (including “green” neighborhood design, riparian protection, and representative Low Impact Development (LID) stormwater controls) in maintaining the pre-development hydrologic regime? and (3) Does climate change influence these results? We co-developed 50-year land and water management scenarios with a stakeholder advisory committee and used a spatially-explicit natural and human systems model to evaluate changes in water balance and streamflow characteristics under each scenario. We also used a factorial analysis to explore the influence of individual scenario elements on watershed hydrology. Results indicate that the biggest driver of change for this watershed was the spatial extent of development, followed by the nature of the development pattern, climate, forest harvest, and use of LID controls. Stormwater runoff increased as developed area increased, as did stream discharge for both periods of high and low flow. Increases in evapotranspiration (ET) with climate warming were offset by reductions in ET with development. Designs that condensed development and preserved upland and riparian forest showed the greatest potential for maintaining pre-development water balance and streamflow regimes, thereby reducing impacts of urbanization. These results bridge spatial and temporal scales important to decision-makers, highlighting the importance of considering impacts over time of neighborhood-scale development decisions on watershed-scale hydrology.

1. Introduction

Urbanization degrades stream ecosystems by altering flow regimes, modifying channel morphology, and impairing water quality (Leopold, 1964). In undeveloped watersheds, most rainfall infiltrates into soils, or returns to the atmosphere as evapotranspiration (ET), but in urban watersheds, impervious surfaces and artificial drainage networks divert

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rainfall to overland flow paths and accelerate surface runoff to streams. Even when stormwater control measures (SCMs) are implemented, they may not prevent changes in watershed hydrology, channel morphology, and resulting impacts on aquatic ecosystems (Booth, Hartley, & Jackson, 2002; Jefferson et al., 2017; Walsh et al., 2016).

Both the goals and design of stormwater management systems have changed dramatically over the past century. For much of the 20th century, stormwater management focused on quickly removing rainfall from buildings and roads, without regard to downstream effects (Brown, Keath, & Wong, 2009). By the 1970s, growing concerns about flooding and erosion led to new rules and designs intended to slow the release of stormwater into natural waterbodies using detention basins (National Research Council. (2009), 2009). But research showed that streams and aquatic ecosystems responded not just to the rapid runoff and larger peak flows created by urbanization, but also to flow duration and sequence, sediment supply, water quality, and a host of other stream processes altered by urbanization (Walsh et al., 2005).

As a result, in recent decades the emphasis in stormwater management has shifted to reducing the volume of stormwater produced by minimizing impervious surfaces and incorporating low impact development (LID) technologies that promote infiltration and evaporation (Askarizadeh et al., 2015). For example, innovative water managers in the Portland, Oregon region are promoting an integrated approach combining: 1) planning and zoning rules that concentrate development and protect farmland and natural areas, 2) collaborative partnerships to support watershed management in the undeveloped areas of urbanizing watersheds and 3) new design and construction standards intended to minimize impervious surfaces, protect riparian areas and open space, and incorporate LID (Clean Water Services, 2019).

Climate change and population growth will compound existing challenges to urban water management. Urban planners, decision-makers, and water utility managers need to anticipate how their actions and policies will play out in a changing world. They must also communicate the logic behind their choices to developers, residents, and rate payers. The design and modeling of alternative future scenarios for land management is a useful approach for both investigating landscape response to alternative management options and communicating those results.

We implemented an iterative, stakeholder-guided process (Hulse, Branscomb, & Payne, 2004; Santelmann et al., 2019; Steinitz, 2012) to develop, test, and evaluate alternative future scenarios for Chicken Creek Watershed, a 4240 ha urbanizing watershed, located ~ 15 km southwest of Portland, Oregon (Fig. 1). We asked:

1. To what extent can watershed-scale planning and development policies reduce the hydrologic impacts of urbanization?
2. What is the relative effectiveness of different policies in maintaining pre-development hydrologic regimes?
3. To what extent might climate change influence these results?

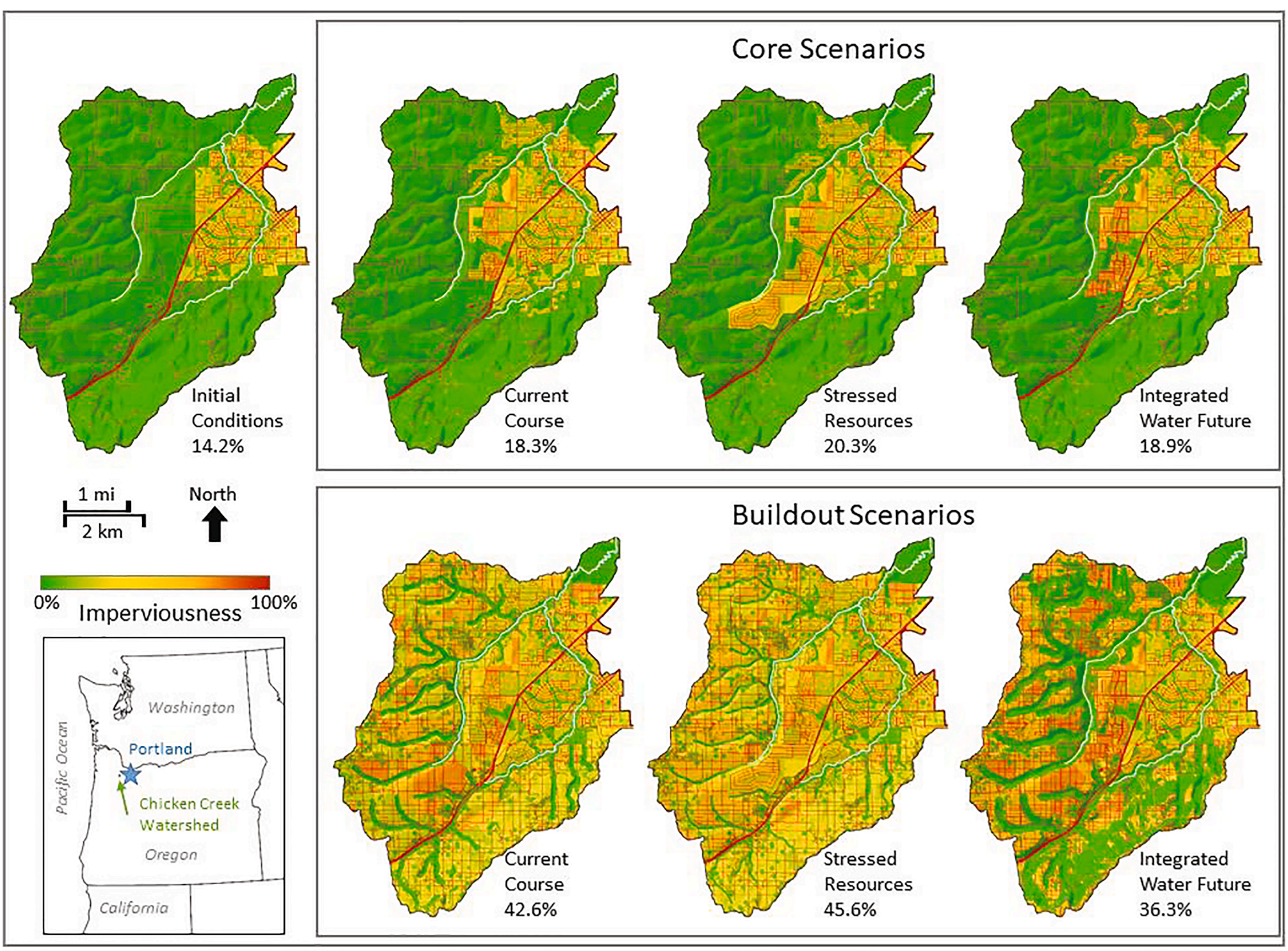

Fig. 1. Maps of Chicken Creek Watershed showing imperviousness for the Core and Buildout scenarios. Imperviousness was derived from land use/land cover maps developed for each scenario. The inset map shows the location of the study watershed on the outskirts of the Portland, Oregon metropolitan area in the USA Pacific Northwest.

To address the first question, we used the Envision modeling framework (Bolte, Hulse, Gregory, & Smith, 2007; Bolte, 2020; Guzy, Smith, Bolte, Hulse, & Gregory, 2008) to simulate the trajectory of urban development, climate change, and hydrologic response for the existing landscape and three alternative future scenarios representing plausible sets of policies for urban development and watershed management in the next 50 years: the Current Course, Stressed Resources, and the Integrated Water Future. The stakeholder process used for scenario development is described in Santelmann et al., 2019, thus, the emphasis of this work is on simulation modeling and results. We ran each simulation with daily weather inputs for a 50-year period of landscape change (2010–2060) followed by a 30-year evaluative period (2060–2090) with stable landscape conditions. We compared simulation output to assess the extent to which elements of the scenarios (e.g., development pattern, riparian protection, and LID features) changed the watershed hydrologic regime.

To address questions two and three, we also explored a wider range of hydrologic responses by comparing 48 scenarios in a $3 \times 2 \times 2 \times 2 \times 2$ factorial design of scenario elements: three hypothetical development patterns (implemented at two spatial extents), two forest harvest scenarios, two LID scenarios, and two climate scenarios. We compared these 48 scenarios to four versions of a no-development reference landscape (with and without forest harvest, under the two climate scenarios), for a total of 52 simulations.

While other studies (Bolson, Sukop, Arabi, Pivo, & Lanier, 2018; Groves, Knopman, Berg, Bond, Syme, & Lempert, 2018; Lin et al., 2007; Wu, Bolte, Hulse, & Johnson, 2015) have considered the effect of land use policies on watershed hydrology, this study differs in several important ways, including (1) co-development of multi-scale land and water management scenarios with a stakeholder advisory committee (SAC), (2) scenario evaluation with a spatially-explicit natural and human systems model, and (3) use of a factorial study design to systematically compare the influence of different scenario elements.

The work presented here attempts to bridge the gap between the spatial and temporal resolution of modeling approaches used to simulate hydrologic processes at urban neighborhood and watershed scales. Others (Bach, Rauch, Mikkelsen, McCarthy, & Deletic, 2014; Urich & Rauch, 2014) have reviewed the state of the science, highlighting the need for integrated urban water system models, and noted the utility of modular, process-based approaches (here, exemplified by the incorporation of SWMM5 as a plug-in to Envision) that are adaptable (Salvadore, Bronders, & Batelaan, 2015). The simulation results presented here highlight the utility of this type of integrated modeling for evaluating the effectiveness of multiple land and water management policies applied over different spatial extents.

2. Methods

2.1. Study area

The Chicken Creek Watershed (4240 ha) is located ~ 15 km southwest of Portland, Oregon, USA and includes ~ 60% of the suburban city of Sherwood (2010 population ~ 18,000). Sherwood is rapidly expanding and in 2010 ~ 680 ha of the watershed fell within urban reserves, areas designated by the regional planning agency, Portland Metro, to accommodate urban expansion over the next 50 years. Circa 2010, the primary land cover types within Chicken Creek Watershed were forest (38%), agriculture and rural residential (35%), urban (24%), and water/wetland (3%). The region has a maritime climate characterized by moderate, wet winters and warm, dry summers. Average annual temperature is 11.3 °C, and annual precipitation averages 99.5 cm.

2.2. Scenario development

Between 2015 and 2019, we convened a Stakeholder Advisory Committee (SAC) of regional water managers and agency professionals to develop alternative future scenarios representing combinations of climate, population growth, and land and water management policies (Hulse et al., 2004; Santelmann et al., 2019; Steinitz, 2012). Together, we developed three scenarios (hereafter referred to as "Core scenarios") representing a 50-year planning horizon, from initial landscape conditions in 2010 through the year 2060:

1. Current Course (hereafter CC) — Population growth is moderate and the current regulatory regime remains in force; leadership responds to but does not anticipate climate change.
2. Stressed Resources (hereafter SR) — Water treatment and conveyance system are stressed by rapid population growth and climate change; policies and action lag behind rapidly changing environments; resources for adaptation are limited.
3. Integrated Water Future (hereafter IWF) — Water quality and quantity are managed at the watershed scale. Pro-active, informed leadership employs anticipatory policies and actions to adapt to changes in climate and rapid population growth; public support provides resources for adaptation.

Each scenario varied assumptions about (1) population growth, and (2) development patterns, and (3) assumptions about water systems management practices judged to be plausible by the SAC. The research team converted scenario narratives into visualizations and spatially-specific input for models using watershed scale maps and descriptions that were iteratively reviewed by the SAC and paired with neighborhood designs showing more detail regarding housing patterns, lot size, street design and civic spaces for a ~ 100-hectare neighborhood within the larger watershed (Santelmann et al., 2019). Table 1 describes key attributes of the scenarios at the watershed scale.

The variation in spatial extent of development among the three scenarios was relatively small compared to watershed area, with corresponding differences in hydrologic response. While environmental planners and designers commonly employ alternative scenarios to depict and explore plausible policy options for the future of a place (Hulse et al., 2004; Steinitz, 2012; Wu et al., 2015), biophysical science modelers often use scenarios to test the outer performance bounds of the focal elements of the system in question, in our case, key hydrologic responses in a 4000 + ha watershed. After seeing the limited differences in hydrologic response among the three initial scenarios, the SAC encouraged us to also explore hydrologic response to more extensive change in the watershed. The SAC members specifically wanted to know, "What would happen if the development patterns of the three Core scenarios were extended to the whole watershed?"

With this guidance, the research team created three additional scenarios that expanded the patterns of development over the entire watershed, but in ways less constrained by political, economic and social assumptions about how the future will unfold in the coming 50 years. We called these scenarios the "Buildout scenarios" and created representations of watershed development patterns that assumed the ratios of low/medium/high density development and natural area protection in the initial "Core scenarios" were extended until all buildable land in the watershed was developed. We also added a "No Development" scenario as a reference scenario. The result was a total of seven landscape scenarios (Table 2 *and* Fig. 1); three *Core* scenarios developed in the stakeholder engagement process, three *Buildout* scenarios, and a *No Development* scenario based on the landscape circa 2010. The Core scenarios represent the most plausible trajectories of change for the Chicken Creek watershed through 2060. The No Development and Buildout scenarios represent extreme conditions, included to explore outer bounds of system response.

2.3. Model design

For our simulations, we modified a version of the Envision modeling framework developed for the Willamette River Basin, Oregon (Jaeger et al., 2017; Turner, Conklin, & Bolte, 2015). Envision integrates a GIS with an interface for connecting and sharing data between hydrological,

Table 1
Land and water management practices in the Core alternative future scenarios co-developed with the stakeholder advisory group.

Scenario Element	Current Course	Stressed Resources	Integrated Water Future
Theme	Current regulatory regime remains in force. Leadership and public support respond but do not anticipate change.	Water treatment and conveyance system are stressed. Policies and actions lag behind rapidly changing environments.	Water quality and quantity are managed at the watershed scale. Pro-active leadership employs anticipatory policies to adapt to climate change and population growth.
New housing types (% of new housing that is very low/ low/med/high density)[1]	Predominantly single-family homes with large yards. Some townhomes and apartments. (59%/24%/12%/ 5%)	Predominantly single-family homes with large or moderate sized yards. (51%/ 42%/4%/4%)	Mix of single-family homes with moderate yards, townhomes, and low-rise apartment buildings. (0%/ 58%/23%/20%)
Riparian protection	Current regional guidelines apply; no development in areas designated as high priority riparian zones[2]. In Buildout scenario, no development within 60 m of streams.	10% of high priority protection zones become developed. In Buildout scenario, no development within 30 m of streams.	High, medium and low priority riparian zones protected. In Buildout scenario, no development within 100 m of streams.
Slope restrictions applied in buildout scenarios	Following regional guidelines, no development on slopes > 40%.[3]	No restrictions.	No development on slopes > 20%.
Forest management	No forest harvest.	Annual target harvest rate of 20 ha of mature forest (stand age > 40 years).	No forest harvest.
Low Impact Development (LID) stormwater control measures	Bioretention cells in newly developed areas capture 29% of runoff from impervious surfaces during WQ design storm.[4]	Bioretention cells in newly developed areas capture 11% of runoff from impervious surfaces during WQ design storm.[4]	Bioretention cells in newly developed areas capture 37% of runoff from impervious surfaces during WQ design storm.[4]

[1] Density classes are very low = 0–4 DU/ac, low = 4–9 DU/ac, med = 9–16 DU/ac, high = >16 DU/acre
[2] Based on METRO regional government guidelines, Title 13, Class I zones protected in Current Course, and Title 13 Class I, II, III protected in Integrated Water Future (Portland Metro, 2018)
[3] Based on Washington County guidelines (Washington County, 2017)
[4] Design storm from (Clean Water Services, 2019)

ecological and socio-economic process models. Simulation of vegetation and land use changes (e.g., urban expansion and forest growth) run at an annual timestep, while hydrologic processes operate at a daily timestep. The hydrologic components of Envision share data with each other via FLOW, a modeling framework within the Envision platform (Fig. 2).

Model plugins to FLOW include a rainfall-runoff hydrologic model based on algorithms from HBV (Bergström & Lindström, 2015), and EvapTrans, a library providing access to a variety of ET algorithms. The ET models used here include both crop growth state (Jaeger et al., 2017) and forest characteristics such as leaf area index (LAI) (Turner et al., 2016). FLOW also simulates agricultural irrigation by moving water between HBV layers and stream reaches, and represents water transported into and out of the watershed as municipal water supply and wastewater. Municipal water demand is modeled in aggregate for the developed area and is a function of population, population density, household income, and water price (Jaeger et al., 2017).

For this project, we developed a new plug-in for FLOW called SWMM-lite, based on the Storm Water Management Model (SWMM) version 5.1.010 (US EPA, 2017). Within FLOW, SWMM-lite is used to model runoff, evaporation and infiltration in urbanized areas of the watershed, while HBV is used to model surface hydrologic process in exurban areas, as well as water fluxes through the subsurface, and in streams. As a simulation runs, the spatial modeling units within Envision can transition from an undeveloped to a developed state, with modeling of surface hydrology shifting from HBV to SWMM-lite. We developed this split-model approach to leverage the strengths of each model. HBV and EvapTrans simulate daily changes in soil moisture and ET as they respond to crop growth state and forest leaf area. Meanwhile, SWMM-lite represents urban subcatchment characteristics such as impervious surfaces, and the implementation of constructed LID. To simplify the implementation of the model at this relatively large spatial extent of an entire watershed, we used bioretention cells as a proxy for a variety of constructed LID features incorporated in neighborhood scale designs of the three Core scenarios (Santelmann et al., 2019). A set of parameters determine the rate of flux between storage "layers" in HBV. We selected this parameter set using an automated calibration process that compared modeled streamflow to daily historical streamflow records for Chicken Creek (Appendix A).

2.4. Model inputs

2.4.1. Landscape representation and hydrologic modeling

Representations of ca. 2060 conditions for the Core scenarios were first developed as land use-land cover (LULC) rasters with a 10 m resolution and 35 land cover classes (Santelmann et al., 2019). Areas were delineated for four density development classes and located according to proximity to the Sherwood UGB and to roads. Selected development sites also followed regional guidelines for housing types and density, environmental protection areas, and local planning efforts (Table 1). Once created, rasters were reviewed and approved by the SAC. We developed similar 10 m LULC rasters for the Buildout scenarios by extending the ratio of low/medium/high density development and natural area protection until all buildable land in the watershed was developed. The Buildout scenarios represent extreme conditions and were included to test model sensitivity and directions of change. In contrast to the Core scenarios, they do not represent plausible growth trajectories for the Chicken Creek watershed.

> We created 10 m rasters of watershed imperviousness by assigning an imperviousness value to each LULC class (Appendix B) based on a comparison between our LULC classes under initial conditions (ca. 2010), and imperviousness reported for Chicken Creek Watershed in 2011 National Land Cover Data (U.S. Geological Survey, 2014). These derived imperviousness values were similar to imperviousness values suggested for different zoning classes in the NRCS TR-55 urban hydrology manual (USDA Natural Resources Conservation Service. (1986), 1986). The LULC and imperviousness raster data became inputs for modeling.

In Envision the landscape is divided into Integrated Decision Units (IDUs) – polygons with similar land and water use characteristics that are nested within Hydrologic Response Units (HRUs). The HRUs are catchments whose boundaries are defined by physiography, based on a 30 m digital elevation model. Polygon boundaries for most of the Chicken Creek watershed were derived from IDUs created for the Willamette Water 2100 project (Jaeger et al., 2017). Polygon boundaries within the Urban Growth Boundary (UGB) were modified so that IDU boundaries aligned with 2010 census blocks. There are 476 IDUs in the Chicken Creek watershed, ranging

Table 2
Landscape characteristics of the Core, Buildout, and No Development landscape scenarios. The modeled area in Chicken Creek Watershed was 4240 ha. All scenarios include 115 ha of wetlands.

Scenario	Major Land Use/Land Cover Types (ha)			Protected Lands (ha)[2]	Dwelling Units	Watershed Imperviousness
	Developed[1]	Agriculture	Forest			
No Development Scenario	1007	1504	1613	431	5030	14.0%
Core Scenarios						
Current Course (CC)	1370	1145	1611	649	8659	18.3%
Stressed Resources (SR)	1558	1012	1559	390	11,137	20.3%
Integrated Water Future (IWF)	1376	1108	1642	1332	10,949	18.9%
Buildout Scenarios						
Current Course (CCBO)	3394	91	642	654	31,220	42.6%
Stressed Resources (SRBO)	3623	46	462	502	36,828	45.6%
Integrated Water Future (IWFBO)	2563	271	1292	1677	34,003	36.3%

[1] Developed lands include residential, commercial, industrial, civic, and transportation land use classes and excludes forested urban riparian areas.
[2] Protected lands includes riparian, wetland or steeply sloping areas excluded from development, as described in scenario assumptions (Table 1).

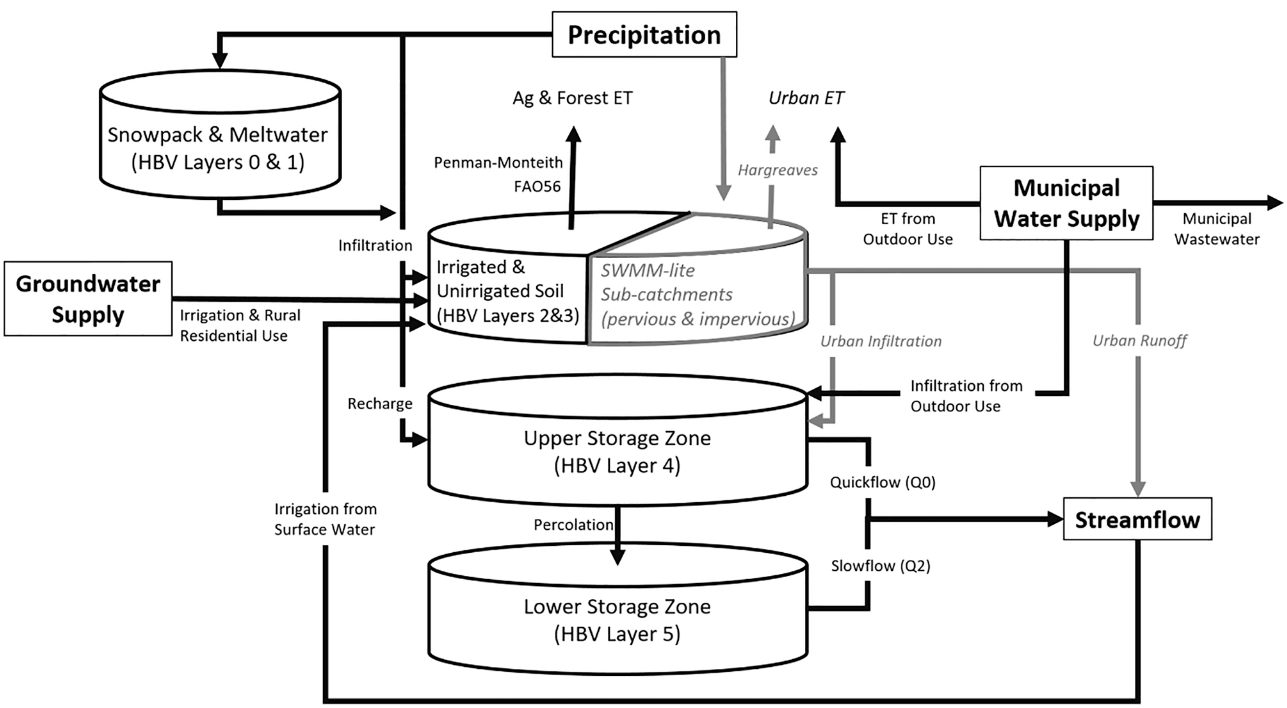

Fig. 2. Diagram of water fluxes and storage in the hydrologic modeling components of Envision. Urban stormwater processes (shown in grey italics) are modeled with "SWMM-lite", a model plug-in derived from USEPA's Storm Water Management Model (version 5.1.010; EPA, 2017). Other watershed processes including municipal water use, agricultural irrigation and subsurface hydrology are modeled within the modeling framework called FLOW. FLOW incorporates algorithms derived from the hydrologic model HBV (Bergström & Lindström, 2015).

in size from 0.04 ha to 130 ha (median 4.6 ha). The stream network and HRUs were also derived from the Willamette Water 2100 project based on NHD + V2 hydrology (US EPA, 2012). Each IDU was assigned attributes based on the majority class of LULC types within the IDU and a weighted average of imperviousness. Developed IDU polygons with 25% or greater imperviousness were represented as SWMM subcatchments with attributes derived from the IDUs and from SWMM models developed for the ~ 100-hectare neighborhood-scale scenario designs (Santelmann et al., 2019). We represented LID stormwater controls as bioretention cells implemented in SWMM subcatchments at different rates in each scenario (Table 1).

Land use change could occur during a simulation through several mechanisms including annual forest and crop growth, forest harvest, and urban development. Forest change was simulated using a forest state and transition model (Turner et al., 2015). Each forested IDU was assigned a forest class and age that changes over time and can be reset to age zero by a "harvest" event. Canopy characteristics and ET rates changed with forest age. Most forested lands in the study watershed occur in riparian areas and steeper slopes in the southeast portion of the watershed. The SR scenario assumed limited protection for forested areas with a target harvest rate each year (Table 1).

Over a simulation, IDUs transitioned from undeveloped to developed land use types using a set of prescribed transitions, until the pre-defined full development conditions for each scenario were reached. We identified polygons that would undergo this transition by comparing the initial condition, Core and Buildout scenario rasters. The IDUs that changed development type between 2010 and 2060 were manually assigned a transition year using the following rules:

1. IDUs are developed in five-year increments starting in 2011
2. IDUs closer to 2010 developed lands transitioned earlier in the scenario than those further from the 2010 developed lands
3. IDUs transitioned in adjacent groups – to simulate development patterns following infrastructure investments

2.4.2. Meteorological inputs

Daily meteorological inputs (temperature, precipitation, humidity, wind, radiation) are from downscaled climate projections (MACAv1) from the HadGEM-ES Global Climate Model and the RCP 8.5 greenhouse gas concentration pathway (Abatzoglou, 2013). This data set was among the warmer climate projections for the Pacific Northwest (Rupp, Abatzoglou, Hegewisch, & Mote, 2013; Vano, Kim, Rupp, & Mote, 2015). We ran simulations using daily data from this projection for the years 2010–2090.

Fig. 3 shows differences in annual temperature and annual precipitation from the mean for 1950–1999 for comparison to the future climate. Between 2010 and 2060, the period of landscape change in simulations, mean annual temperature rises ~ 4 °C with little change in mean annual precipitation. During the landscape evaluation period when no additional development occurs (2060–2090), mean annual temperature increases ~ 2 °C and mean annual precipitation is slightly lower compared to 2010–2060. The climate conditions shown here represent projections from a single GCM downscaled to a 4-km resolution. As with the landscape change depicted in the Core scenarios, this projection should be considered one plausible trajectory, not a precise prediction of the magnitude of climate change in the Chicken Creek Watershed.

To explore the relative importance of climate vs. different management choices, we also ran a set of "stationary climate" simulations as a reference to the future climate scenario. In these runs, meteorological inputs for each year over the scenario were drawn at random from the period 1950–1999, to represent a climate with no trend in temperature or precipitation from the recent past.

2.5. Simulations and analysis periods

Initial analyses compared the seven landscape scenarios including: the three Core scenarios developed with the SAC to represent plausible growth patterns through 2060, a No Development scenario, and the three Buildout scenarios, that extended development patterns across the entire watershed. To better understand the influence of individual scenario elements, we then ran additional simulations in a 3 × 2 × 2 × 2 × 2 factorial design (Fig. 4). Five scenario elements varied in these simulations including: development pattern (CC, SR, IWF), development extent (Core, Buildout), forest harvest (Harvest, No Harvest), constructed LID features (LID, No LID), and climate (Future, Stationary). In addition, we compared these 48 scenarios to four versions of the no-development reference landscape (with and without forest harvest, under the two climate scenarios), for a total of 52 simulations. Since the No Development scenarios had no new housing development and thus, also had no possible variations in development extent or LID features, we could not execute a complete factorial design for these simulations.

The length of each simulation was 80 years (2010–2090), including a period of landscape change (2010–2060) when development expanded and forest harvest occurred, and a post-development, evaluative period (2061–2090), when meteorological inputs varied, but no additional landscape change occurred. We included the evaluative period in the simulations as a way to compare hydrologic performance of the fully developed landscapes for a range of meteorological conditions (wet and dry weather years). Summary statistics reported for each simulation are derived from this period. The simulations were deterministic – meteorological inputs for each day were consistent across runs with the same climate scenario and multiple runs of each landscape scenario produced the same development pattern.

2.6. Response metrics

Model output tracked landscape change at an annual timestep, and water inputs, outputs, and fluxes between HBV layers and stream reaches at a daily timestep. We compared differences between water balance and

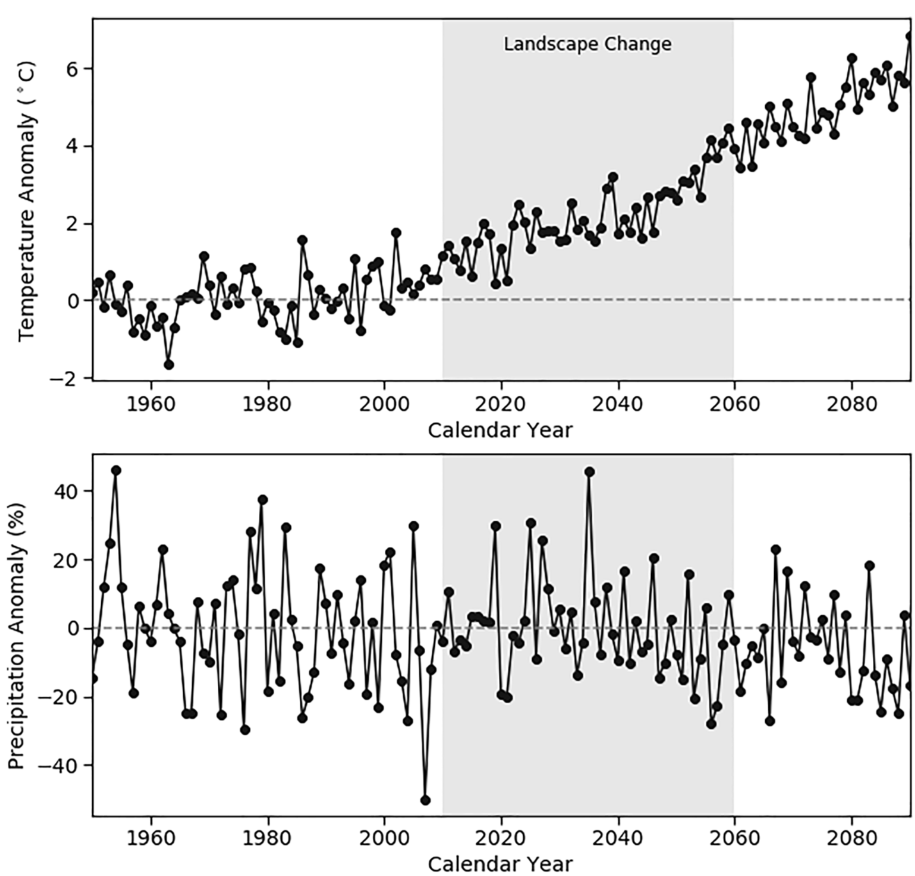

Fig. 3. The source of weather inputs for simulations was downscaled climate data from the HadGEM-ES Global Climate Model and the RCP 8.5 greenhouse gas concentration pathway (MACAv1; Abatzoglou et al., 2013). Plots show differences in annual temperature and annual precipitation from the mean for 1950–1999. Simulations were run from 2010 to 2090 with landscape change occurring between 2010 and 2060, then held constant from 2061 to 2090. Weather inputs for Stationary Climate runs were drawn at random from weather years 1950–1999.

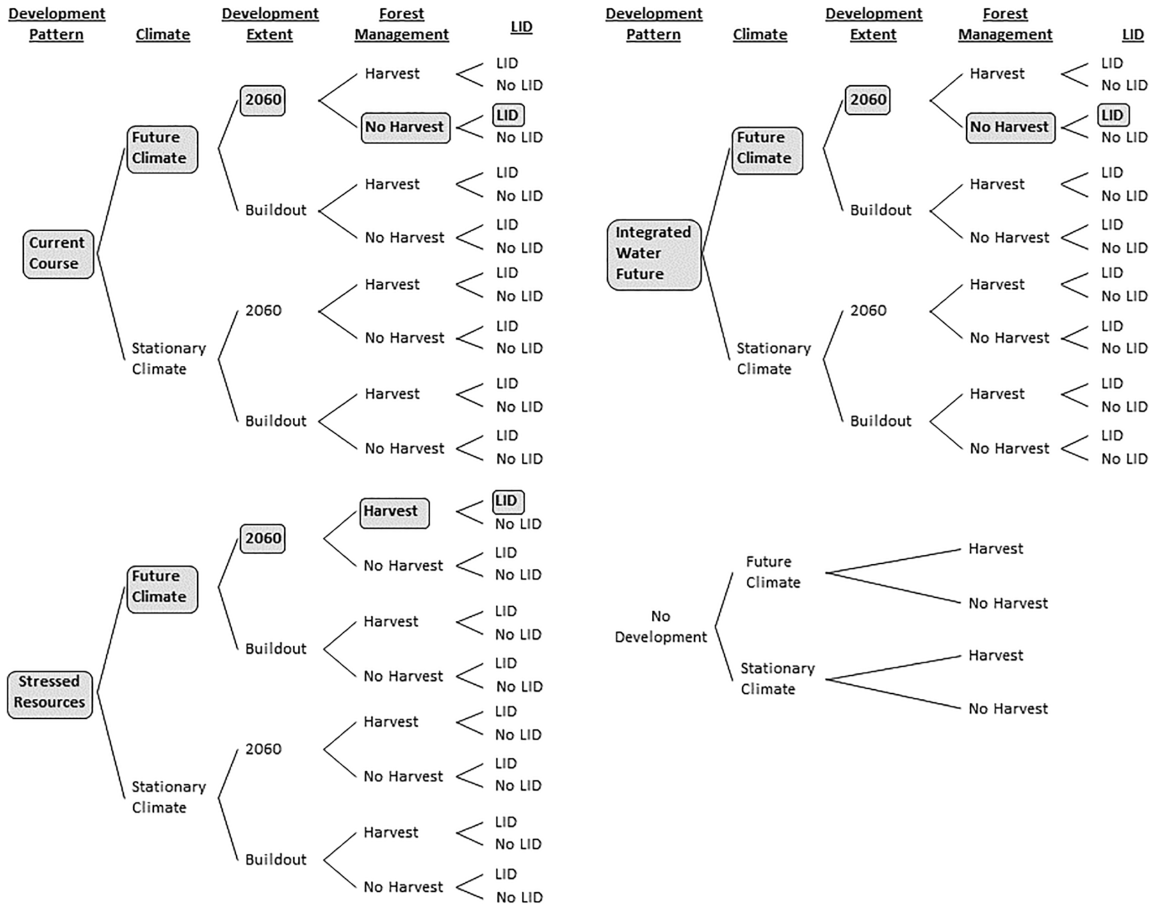

Fig. 4. Diagram of the factorial study design. Boxes denote combinations of scenario elements that were present in the Core scenarios developed with the stakeholder advisory group. Refer to Table 1 for detailed descriptions of the land and water management practices in these scenarios.

streamflow metrics between the No Development landscape and the development scenarios to determine the degree to which hydrology in the future scenarios differed from ca. 2010 conditions.

Average annual water balance for the evaluative period, water years (WY) 2061–2090, are reported as the volumes of water moving into, through, and out of the watershed over a year. Inputs included precipitation, groundwater pumping for agricultural irrigation and rural residential use, and municipal water supply from sources outside the basin (Fig. 2). Fluxes within the watershed included stormwater runoff, infiltration, subsurface flow to streams, and surface water irrigation. Water balance outputs include ET, wastewater flows to municipal treatment, and stream discharge at the watershed outlet.

We compared streamflow statistics derived from simulated daily stream discharge at the watershed outlet as integrative indicators influenced by all changes in the upstream water balance. Metrics compared include measurements of flow magnitude (mean flow and the 1%, 50%, and 99% flow exceedance levels), a measure of the frequency of high flows (high pulse count), and a measure of streamflow variability (Richardson-Baker Flashiness index (Baker, Richards, Loftus, & Kramer, 2004). The average annual high pulse count is calculated as the average number of days each year when streamflow was greater than twice the daily average flow for the WY2061-2090 period in the scenario with no development, no harvest and weather inputs from simulated historical conditions. We calculated the annual average Richardson-Baker flashiness index as the sum of the absolute values of day to day changes in flow volume, divided by the sum of the daily flow volumes for each water year.

2.7. *Statistical analysis of model results*

For the analysis of the 52 different scenarios representing elements of the futures in a factorial design, plus the four No Development comparators, we generated the same landscape metrics and water balance statistics as in the previous section, for the evaluative period (WY2061-2090). Model output was analyzed in PC-ORD ® (McCune & Grace, 2002) using detrended correspondence analysis (DCA). The matrix produced from the metrics of hydrologic response for each model run was standardized (Z-score standardization) and a constant value (3) was added to each matrix element so that all entries were positive. These standardized data were then used as the main matrix, and scenario attributes (Impervious Cover %, Mature Forest %, and Dwelling Units) were used as explanatory variables (second matrix) in the DCA.

3. Results

3.1. *Watershed response to future landscape conditions*

3.1.1. *Landscape characteristics and stormwater*

Representations of the landscape ca. 2010 and the three Core scenarios circa 2060 are shown in Fig. 1, along with the three Buildout scenarios that extend development throughout the entire watershed. Table 2 shows landscape characteristics for the seven landscape scenarios.

The No Development scenario maintains 2010 conditions with 24% of the Chicken Creek watershed in developed land uses, predominantly low and moderate density single family homes. Development in the three Core scenarios increases at rates the stakeholders thought plausible. The number of dwelling units increases by 170% in the CC scenario, and by 220% in the SR and IWF scenarios. Because the IWF includes more multifamily dwellings, it could accommodate almost as many dwelling units as the SR scenario, while maintaining wider forested riparian buffers, and protecting over twice as much land from development. Under 2010 conditions (No Development scenario), impervious surfaces covered 14% of the watershed, rising to 18–20% in the Core scenarios and 36–43% in the Buildout scenarios (Table 2, Fig. 1).

Fig. 5 shows the change in landscape characteristics and stormwater in simulations for the Core and Buildout scenarios and future climate conditions during the landscape change period (2010–2060). In all scenarios, urbanization results in loss of forest cover, increases in developed land, impervious cover, and stormwater runoff. However, scenarios differed with respect to their ability to accommodate population growth while maintaining the pre-development hydrologic regime (Table 2, Table 3). The IWF accommodated high population growth while minimizing stormwater runoff. By emphasizing multifamily dwelling units in moderate and high-density neighborhoods with constructed LID, the IWF maximized open space and minimized developed land area, imperviousness, and stormwater runoff (Fig. 5). In contrast, the SR scenario, while accommodating a similar population increase, produced more stormwater runoff relative to precipitation inputs. Whereas the CC scenario had the fewest dwelling units, the dispersed development pattern in this scenario resulted in stormwater runoff volume comparable to the IWF Core scenario and the SR Buildout scenario (Fig. 5c).

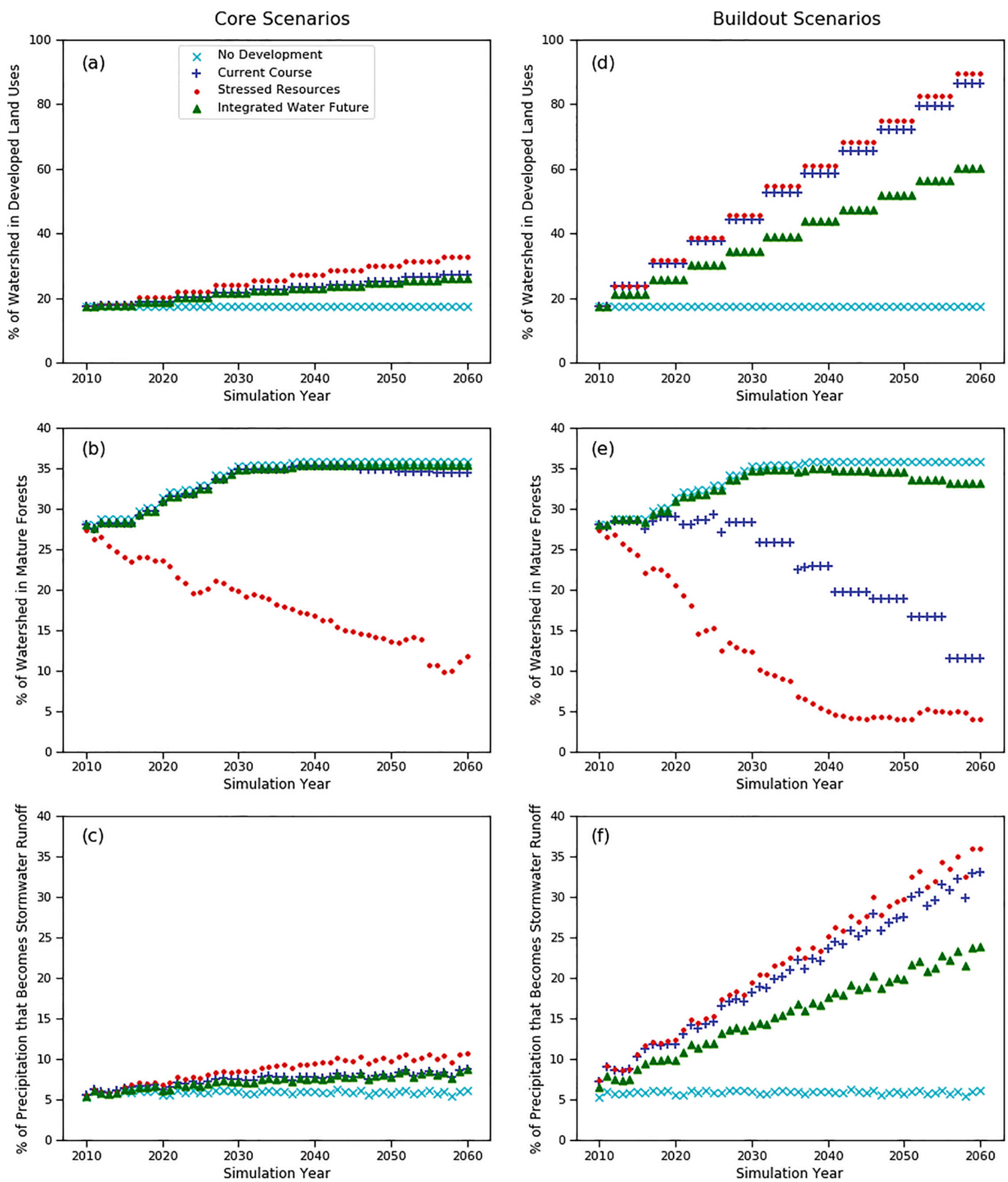

Fig. 5. Landscape change and stormwater runoff between 2010 and 2060 for the Core (a-c) and Buildout scenarios (d-f). The Core scenarios represent development rates the stakeholder advisory group thought plausible while the Buildout scenarios expanded development over the entire watershed. In simulations, undeveloped lands transitioned to developed every five years (a,d) and mature forests were harvested in the Stressed Resources scenarios (b,e). Stormwater runoff increased as impervious surfaces expanded in all scenarios (c,f).

Table 3
Flow duration and annual flow statistics for the seven landscape scenarios and HadGEM-ES future climate conditions. Values reported are for the evaluative period of simulations (WY2061-2090).

Scenario	Mean Flow (cms)	Flow Exceedence (cms)			Avg. Annual High Pulse Count[1]	Avg. Annual Richardson-Baker Flashiness Index[2]
		1%	50%	99%	(days)	
No Development	0.75	5.6	0.34	0.018	51	0.154
Core Scenarios						
Current Course	0.80	5.7	0.36	0.026	55	0.156
Stressed Resources	0.87	5.9	0.40	0.032	62	0.159
Integrated Water Future	0.79	5.6	0.37	0.027	54	0.156
Buildout Scenarios						
Current Course	1.2	7.6	0.50	0.049	93	0.187
Stressed Resources	1.3	7.8	0.49	0.046	95	0.198
Integrated Water Future	0.99	6.4	0.44	0.031	74	0.175

[1] Days when flow exceeds 1.62 cms (twice the mean annual flow for the no change scenario (no development, no harvest and weather inputs from simulated historical conditions)

[2] A measure of day-to-day change in flow volume divided by total annual flow volume (Baker et al., 2004)

3.1.2. Streamflow characteristics

In our modeling (at a daily timestep) development increases both high and low flows in the stream (Fig. 6). This result coincided with a loss of ET and soil water storage that occurred as imperviousness increased. The higher streamflows in the more developed scenarios also lead to more high flow days (high pulse count) and greater variability in streamflow (flashiness) (Table 3). Peak flows increased the most in the autumn and spring (Fig. 6), especially in the SR scenario. In winter, when the soil reservoir is saturated, most precipitation becomes streamflow in the No Development scenario as well as the alternative future scenarios. Among the Core scenarios, CC and IWF have similar developed land area and similar flow distributions.

The Buildout versions of each alternative future scenario represent extreme conditions, unlikely to occur, but useful because they magnify differences between scenarios and make it easier to visualize hydrologic response to development patterns. The Buildout scenarios show that if the entire watershed were developed with the IWF policies, fewer dwelling units could be accommodated than in the SR scenario. However, they also show that the development pattern that characterizes the IWF scenario leads to a lower watershed imperviousness for the number of dwellings accommodated, and streamflow characteristics more similar to the No Development scenario. Among the Buildout scenarios, CC and SR have similar developed land area and flow distributions.

3.1.3. Water balance

Simulation results of the Core, Buildout, and No Development scenarios were compared by developing water budgets from model results, an accounting of inputs, outputs, and fluxes within the watershed and urban water system (Table 4). Fig. 7 compares the relative magnitude of different elements of the annual water budget for the No Development, SR Buildout, and IWF Buildout scenarios for the evaluative period (WY2061-2090). The thickness of the lines in the diagram corresponds to the quantity of water for a specific input, output or movement of water through the watershed, starting with precipitation inputs (at the left of the diagram) and ending with outputs from the watershed (at right). Inputs (bars at far left) are first partitioned into the proportion entering developed and undeveloped land in the watershed (second bar from left), and then partitioned by the proportion going to different parts of the hydrologic cycle; ET, infiltration, stormwater, municipal wastewater, and streamflow from the watershed.

The diagrams illustrate the primary impact of urbanization on the hydrologic cycle: reductions in ET and corresponding increases in streamflow. Development, even with substantial land area dedicated to nature-based stormwater management and constructed LID, alters watershed hydrology. Both the SR and IWF scenarios include LIDs designed to increase infiltration, and model outputs do show an increase in infiltration in those scenarios relative to the No Development scenario. However, most of the water that infiltrates the subsurface eventually flows to the stream, thus increasing streamflow, although the increase is much larger for the SR Buildout scenario than for the IWF Buildout scenario. The CC Buildout scenario is not shown here, but is similar to the SR Buildout scenario.

Conservation of upland forests and protection of forested riparian areas in the IWF decreases the loss of ET relative to the SR or CC. As a result, the IWF shows the lowest increase in streamflow of any of the Buildout scenarios. In contrast, in the SR and CC Buildout scenarios, the loss of forest to both urbanization and forest harvest reduced ET and increased streamflow. Policies that protected forest were better able to maintain ET and minimize the increase in streamflow resulting from urbanization. These policies required denser development patterns and aggressive riparian and forest protection. While forested areas regrow after harvest, and ET recovers until the next harvest, the reduction of ET that comes from development is permanent.

As the watershed became fully urbanized (Buildout scenarios), imported water for domestic water use and urban irrigation became increasingly important, with a concomitant increase in wastewater production and export from the watershed. The IWF Buildout scenario, that retains more forest cover and public open space, mimics the original hydrology more closely than either the CC or SR Buildout scenarios.

3.2. Relative impacts of neighborhood design, riparian protection, climate, and constructed LID

Deconstructing the alternative future scenarios into their key components in a factorial design allowed us to explore the relative magnitude of the different factors influencing the hydrologic regime in the alternative futures individually. Fig. 8 shows a DCA ordination of the water balance metrics from simulations run for all 48 scenarios in the factorial design, as well as the four No Development scenarios (data in Appendix C). The ordination groups the 52 different model runs in multivariate space, using both explanatory variables and model run output. Both model runs and explanatory variables are associated with the axes. Runs that are most similar based on the hydrologic metrics plot closest together in the graph, while those that are less similar plot further apart.

The multivariate analyses shown in Fig. 8 compare all the different simulations against each other, and identify the relationships between the attributes of all simulations (such as development pattern, climate, presence/absence of mature forest) and the axes along which the individual model runs are separated. The more similar the hydrologic response is between different simulation runs, the closer the runs are in the multivariate space defined by the axes.

In Fig. 8*a*, the No Development scenarios (filled diamond symbols at right) and the Core scenarios (open symbols) are clearly distinguished from the three Buildout Scenarios (at left) in the ordination. Since impervious cover (IMPER), and dwelling units (DU) are negatively correlated ($r >$ 0.50) with Axis 1, the four No Development scenario runs load high on Axis 1 (at the far right), whereas runs for the Buildout scenarios load low

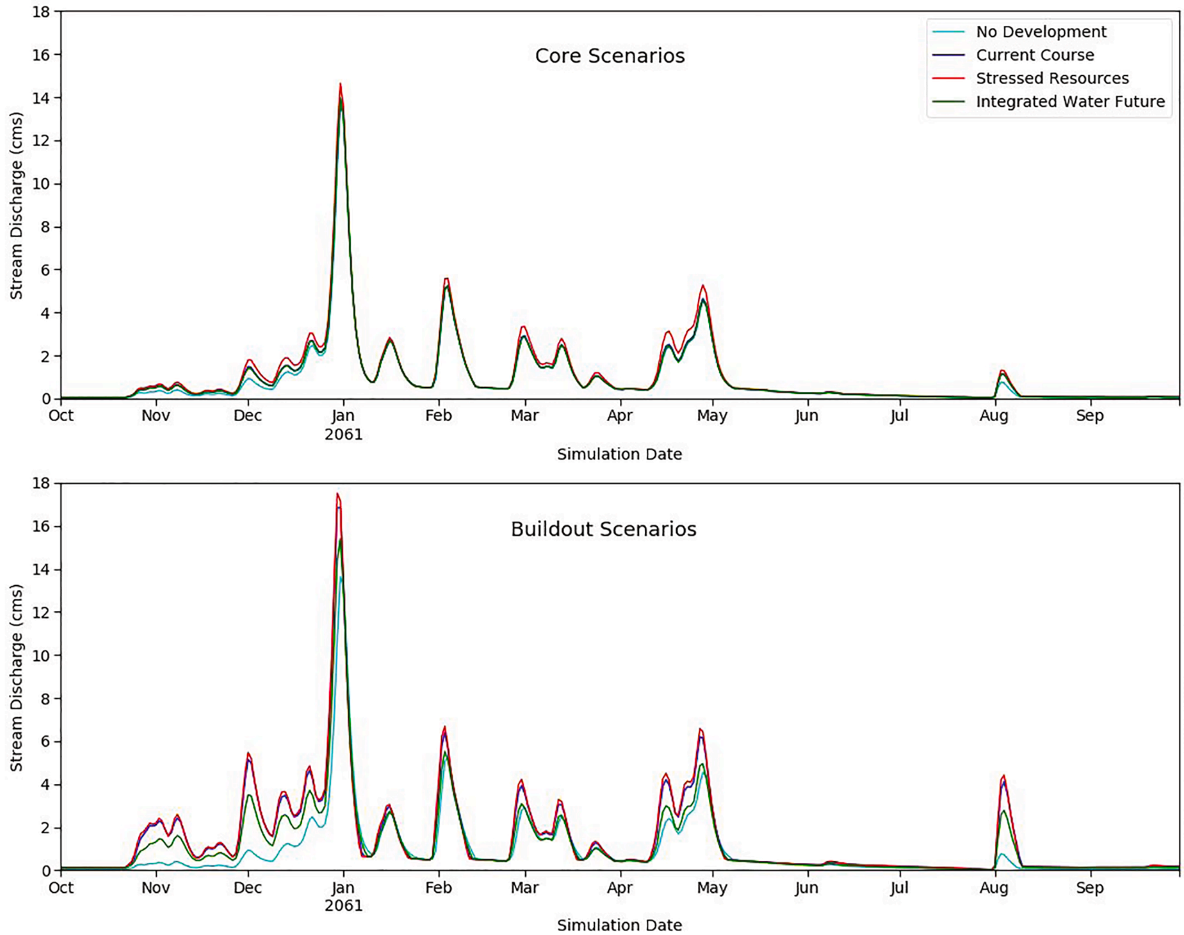

Fig. 6. Hydrographs for water year 2061 for the Core and Buildout scenarios.

Table 4
Major components of the watershed water balance for the seven landscape scenarios and the HadGEM-ES future climate. Values reported are means and standard deviations for the evaluative period of simulations (WY2061-2090), when urban development is no longer increasing. Units shown are mm3/mm2/year (abbreviated as mm), volume divided by watershed area.

	Inputs			Outputs			Fluxes within Watershed	
Scenario	Precipitation	Groundwater	Imported (Municipal)	ET	Streamflow	Exported (Wastewater)	Stormwater Runoff	Infiltration
	Mean (SD)	*Mean (SD)*	*Mean (SD)*	*Mean (SD)*	*Mean (SD)*	*Mean (SD)*	*Mean (SD)*	*Mean (SD)*
No Development	1131 (176)	9 (2)	35 (0)	571 (48)	580 (180)	29 (0)	66 (12)	497 (166)
Core Scenarios								
Current Course	1131 (176)	10 (1)	63 (0)	533 (46)	622 (178)	53 (0)	94 (18)	510 (158)
Stressed Resources	1131 (176)	11 (1)	82 (1)	483 (39)	673 (181)	68 (0)	116 (22)	524 (154)
Integrated Water Future	1131 (176)	11 (1)	81 (1)	545 (47)	613 (178)	67 (0)	93 (18)	495 (157)
Buildout Scenarios								
Current Course	1131 (176)	6 (0)	262 (2)	238 (21)	943 (171)	219 (2)	304 (60)	634 (106)
Stressed Resources	1131 (176)	5 (0)	263 (2)	212 (18)	968 (173)	219 (2)	368 (70)	589 (96)
Integrated Water Future	1131 (176)	8 (0)	259 (2)	422 (39)	760 (168)	216 (2)	211 (43)	539 (121)

on Axis 1. Among the Buildout scenarios, from left to right in Fig. 8*a*, the convex hulls link the runs for SR Buildout, CC Buildout, and IWF Buildout scenarios.

Runs with and without LID show almost no separation for the Core scenarios; however, in the Buildout scenarios, LID has more influence. In the Buildout scenarios, runs with LID load higher on Axis 2 than those without. The runs also show strong separation with climate (Fig. 8*b*); runs with the future climate load low on Axis 2, while runs with the simulated historical climate load high on Axis 2. Because Mature Forest cover is negatively associated with Axis 2 ($r > 0.30$), runs with no harvest occur closer to the origin than the corresponding point with harvest on Axis 2 (Fig. 8*c*).

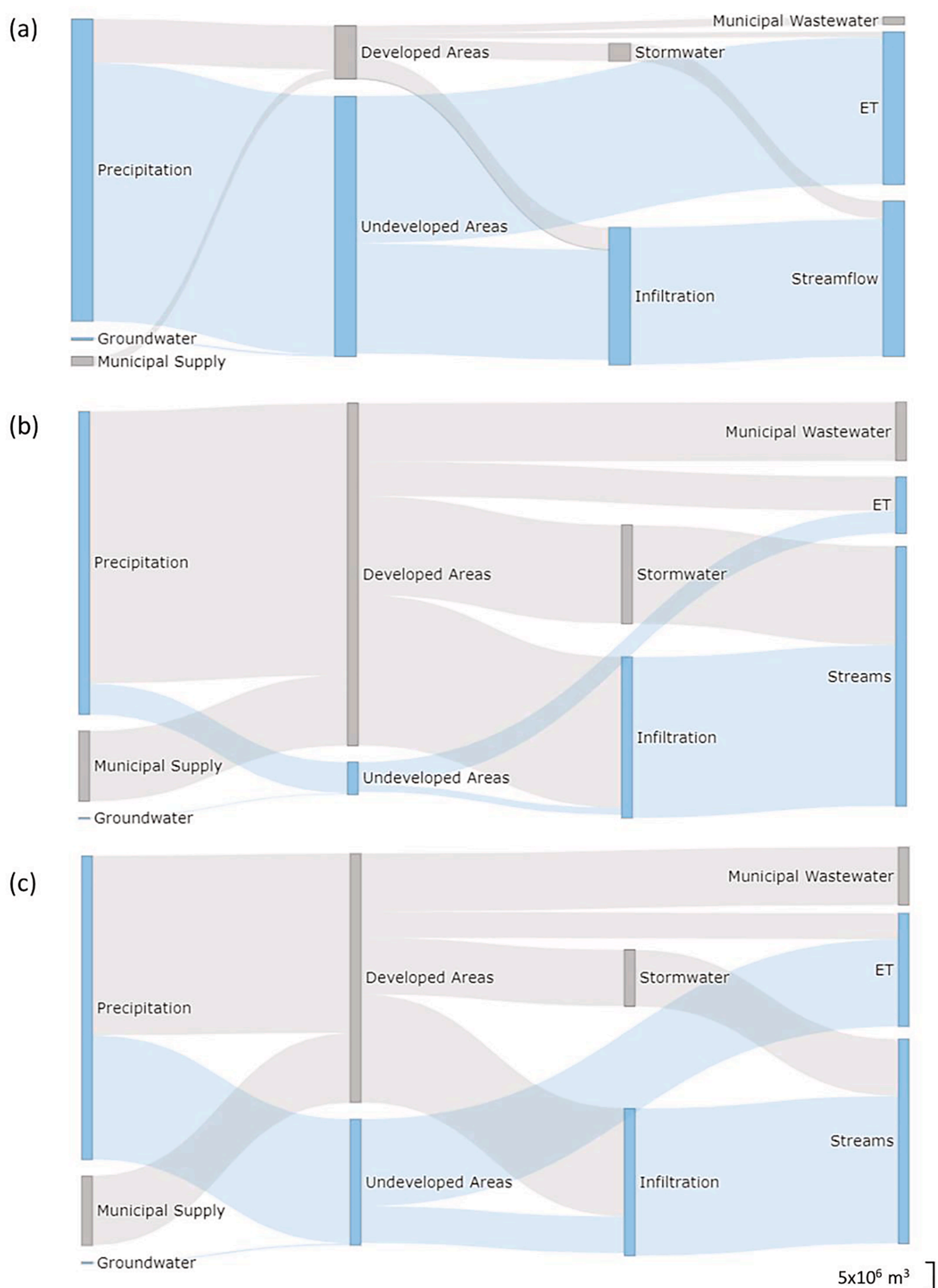

Fig. 7. Diagrams of the Chicken Creek water balance for the (a) No Development, (b) Stressed Resources Buildout, and (c) Integrated Water Future Buildout scenarios. The thickness of the lines corresponds to mean annual flux in m^3 for the evaluative period (WY2061-2090). The bars at left show water inputs (precipitation, municipal water supply from outside the basin, and rural groundwater pumping), the second-from-left bars show the proportion of those inputs in the developed and undeveloped portions of the watershed. Bars at the center-right of the figure show water fluxes within the watershed (stormwater and infiltration) and bars at the far right show outputs from the watershed (municipal wastewater, ET, and streamflow).

The LIDs initially captured runoff from impervious surfaces and redirected it to infiltration, especially in the Buildout scenarios. However, neighborhood design made a much greater difference. As shown in Fig. 2, the main effect of LIDs is to redirect some stormwater to the subsurface (HBV layer 4), from which it moves to the stream. While infiltration delays movement of water to the stream in a storm, it does not change the highly-altered water balance in the developed landscape. Water formerly removed from the watershed as ET is converted to runoff in the developed landscape, and LIDs have little effect on ET. Designs that incorporate open space and retain forest cover, as in the IWF, mimic the original water balance better than those with constructed LID features that focus on stormwater management through infiltration.

4. Discussion

The simulation results presented here provide useful insights for urban water managers, developers, and policy-makers. These results contrast the watershed hydrologic response to different approaches to mitigating the impacts of urban development; those which rely on constructed LID features such as bioretention cells to treat stormwater onsite as compared to development designs that explicitly incorporate policy goals of riparian protection and preservation of open space as part of stormwater management.

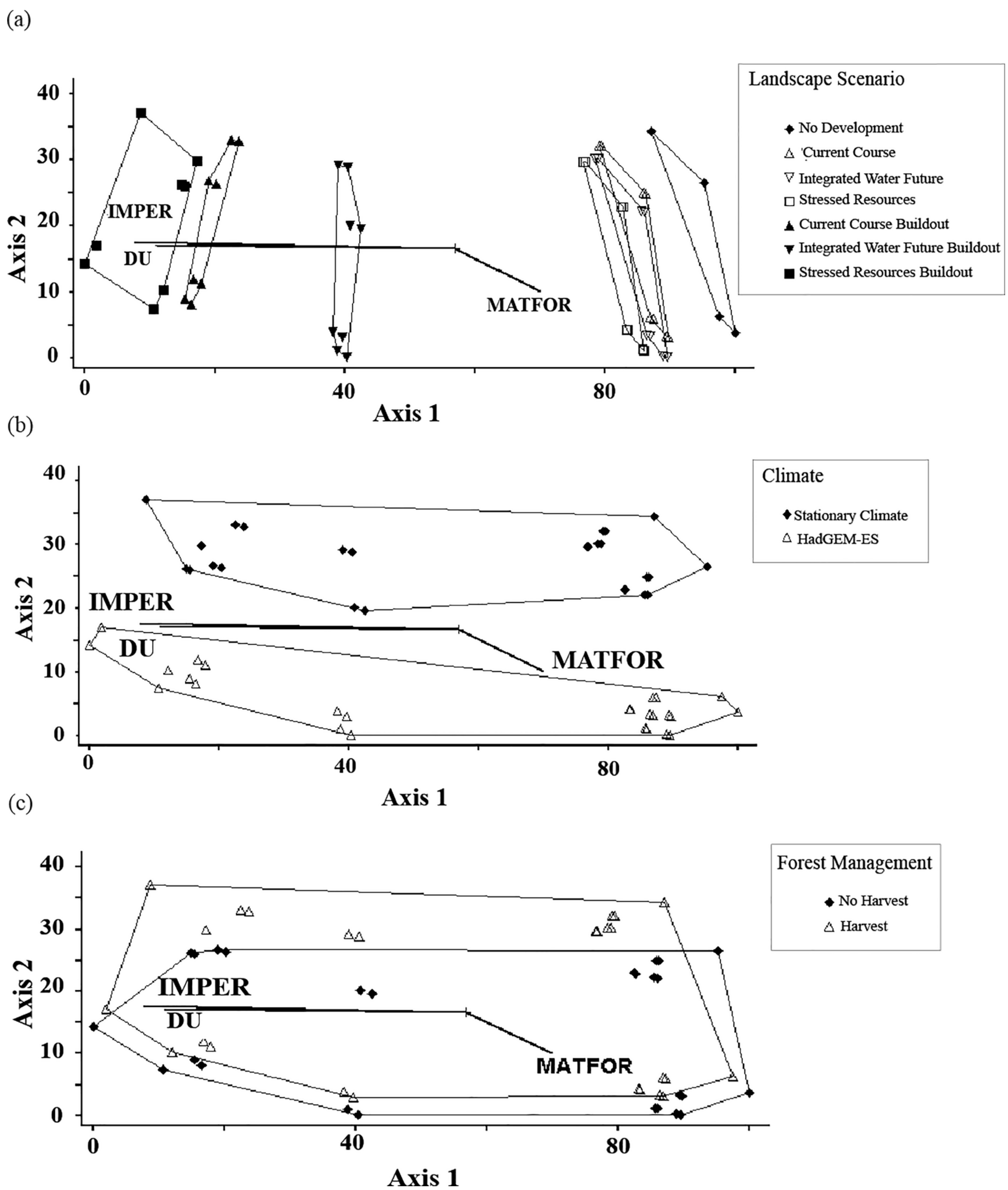

Fig. 8. Graph of ordination results. The same points, representing individual model runs, are shown in each figure. The three figures show the degree of separation among model runs according to three different grouping variables: a) development scenario, b) climate scenario, and c) forest harvest scenario. Grouping with or without LIDs is not shown, since except for the Stressed Resources Buildout scenario, these points plot on top of or next to each other.

4.1. Extent to which watershed-scale planning and development policies may reduce hydrologic impacts of urbanization

The results for the IWF scenario indicated that policies that condense development footprint and preserve upland and riparian forest show the greatest potential for maintaining the pre-development water balance and streamflow regimes while providing homes for a growing population. However, even the measures incorporated into the IWF scenario did not completely offset the effects of climate change and urbanization. Importantly, we note that the Core scenarios represent the most plausible trajectories of change for the Chicken Creek watershed. Growth rates in these scenarios were informed by the SAC, and include both dynamic landscape and climate conditions, as occur in the real world. In contrast, The No Development and Buildout scenarios represent extreme conditions included to explore watershed sensitivity and directions of change. All scenarios that included urban development diverged from the No Development baseline. This divergence increased as the spatial extent of development increased (Fig. 8). Divergence from pre-development conditions was greatest for the SR Buildout future, although that future was best able to accommodate population increases. What we found surprising was the degree to which the impacts of development in the IWF and CC scenarios were similar in the Core scenarios (Fig. 5, Fig. 6, Table 3), despite the fact that the IWF accommodated many more dwellings. The higher proportion of single-family dwelling units in the CC meant that this scenario had a higher imperviousness for the number of people housed in the 2060 future (Table 1, Table 2), a pattern exacerbated in the Buildout scenarios.

4.2. Effectiveness of policies intended to reduce the hydrologic impacts of urbanization

The ordination results indicate that the biggest driver of the hydrologic response in this watershed is the spatial extent of development (Buildout vs Core scenarios), followed by the nature of the development pattern (CC, IWF, or SR), effect of climate, and then forest harvest. The presence of constructed LID, represented as bioretention cells, had the least impact on watershed hydrology.

The influence of climate interacted with the effects of forest harvest and extent of development. The warmer future climate increased ET and decreased streamflow, but had less effect in model runs with forest harvest or extensive development, since these runs had less vegetation contributing to ET. Similarly, the spatial extent of development interacted strongly with the presence of LID for stormwater management. The scenarios with and without LID were indistinguishable in the Core scenarios, but were separated in the Buildout scenarios where developed land area (and LID) were much more extensive.

Several recent studies have investigated the relative importance of infiltration and stormwater harvesting for irrigation (returning harvested stormwater to ET over the annual timestep), noting that infiltration alone cannot mitigate alterations to the hydrologic regime produced by urbanization (Askarizadeh et al., 2015; Walsh et al., 2016). Our simulations indicate that incorporating natural vegetation (including open space, riparian and upland forest) into development is key to maintaining higher levels of ET (Fig. 7), highlighting the critical role of vegetation in maintaining the pre-development watershed balance and minimizing the impacts of urban development.

While it was beyond the scope of this effort to model rainwater harvesting and water re-use in these simulations, application of the IUWM model (Sharvelle, Dozier, Arabi, & Reichel, 2017) for the IWF Core scenario indicated that rainwater harvesting in residential areas could reduce urban water demand by 10%. Using harvested rainwater for outdoor irrigation could increase ET, reduce the need for imported water, and further decrease annual flows to streams. The gap between the IWF Buildout and the pre-development hydrologic regime could thus be narrowed even more through the addition of rainwater harvesting for use in outdoor irrigation, and by more extensive use of green infrastructure elements that increase ET, such as green roofs.

Constructed features such as bioretention cells that promote infiltration can improve water quality and reduce the amount of stormwater that must be conveyed through the stormwater system, but in watersheds such as Chicken Creek, where there is low vertical hydraulic conductivity and minimal movement of water into the deep sub-surface, water removed from the stormwater system through infiltration may still eventually reach the stream. To maintain the overall pre-development flow regime, approaches are needed that restore ET lost when development removes vegetation and increases impervious surfaces, or "harvest" stormwater in other ways (cisterns, rain gardens, green roofs) that allow the captured water to eventually leave the system as ET. In this study, we used bioretention cells as the only LID feature to simplify the modeling at this large spatial extent. Neighborhood scale studies of harvest focused LID, for example green roofs, suggest that they can help restore evapotranspiration, and reduce divergence from the pre-development water balance (Askarizadeh et al., 2015; Feng, Burian, & Pomeroy, 2016).

Development design (CC, IWF, SR), and the spatial extent at which those designs are implemented (Core scenarios vs Buildout), had the greatest effect on the hydrologic impacts of urbanization. The IWF, characterized by a mix of moderate- and high-density housing along with preservation of public open space and forest, provides the best example of a development pattern that approaches the ambitious goal of maintaining the predevelopment hydrologic regime. Comparisons of the various permutations of the SR, CC, and IWF Buildout scenarios in the factorial design, and the relatively small effect of LIDs, highlight the fact that even extensive deployment of SCMs that focus on infiltration alone will not suffice to mitigate the impacts of increased imperviousness.

The analysis of scenario elements in a factorial design also identified patterns that were not discernible in simulations of the Core scenarios alone. For example, as the watershed became fully urbanized, imported water became increasingly important to the water balance. In addition, LID had little impact in the Core scenarios, but had a discernible impact once they were employed at the spatial extent of the Buildout scenarios.

4.3. Limitations

As noted by Bach et al. (2014) and Seppelt, Müller, Schröder, and Volk (2009), integrated environmental models like Envision are best suited for exploration, theory building, and scenario testing for participatory planning. The analysis presented here is not meant to provide design criteria or to evaluate mitigation effectiveness, but rather to explore potential watershed-scale response to multiple changes that accrue over time. Within this context, we note here some sources of uncertainty.

First, the model is a simplification of a complex system. It does not fully represent the spatial and temporal heterogeneity of hydrologic processes, nor does it represent all processes that might operate to control watershed response to urbanization. For example, we did not model stormwater conveyance or detention basins that might change the timing of stormwater release to the stream. In addition, because the Envision model uses a daily timestep, we used a daily timestep in the SWMM-lite model plug-in rather than the sub-hourly and hourly timesteps more typical of infrastructure design and evaluation studies. As other studies have noted, a daily timestep is appropriate when the focus is on the urban water balance (Mitchell, McMahon, & Mein, 2003) and watershed level trends and patterns (Jovanovic, Sun, Mahjabin, & Mejia, 2018).

Like many hydrologic models, FLOW is a parameterized model calibrated by comparing simulated and historical streamflow. There is uncertainty associated with model parameters, as well as with the structure of the model, and the observations. And in this case, there is also uncertainty around the projections of growth and development. We have not attempted to quantify the level of uncertainty and its potential impact on any particular simulation result. Instead, we view any particular result as one possibility from among the wide range of possible future conditions. While not a formal exploratory model analysis, which might involve additional model structures, parameterizations, or stochasticity, the targeted exploration of a range of potential future conditions provides a useful mechanism to explore the questions of interest.

Another area of potential uncertainty is in the modeling of ET in SWMM-lite, which uses a temperature index model of reference crop ET (Hargreaves & Samani, 1985). The model estimates ET under well-watered conditions, but we recognize that actual ET values in urban areas will be limited, except for irrigated portions of the landscape. We did not attempt to capture the differences in ET under irrigated versus unirrigated conditions. The SWMM-based estimates of ET in the urban areas range from 148 mm yr^{-1} for the SR Buildout scenario to 175 mm yr^{-1} for the No Development scenario, within the ranges reported in other studies. In unrelated work, and using observed data, House-Peters and Chang (2011) estimated a range of suburban ET from 117 to 312 mm yr^{-1} based on 'external' water consumption data. Their estimates, for a watershed near Chicken Creek, compare favorably to the SWMM-based ET estimates presented here, suggesting that the magnitude of the SWMM-based ET estimates are reasonable.

4.4. Implications for urban water managers

Through most of the 20th century, urban stormwater management focused on reducing peak flows and improving the quality of water entering streams through stormwater filtration technologies. One of the key principles in the "next generation" of urban stormwater management is that the post-development water balance should match the predevelopment water balance, so that a similar proportion of rainfall reaches the stream. One of the biggest challenges to applying this principle to real-world landscapes is finding ways to eliminate the excess volume of runoff generated by loss of ET on impervious surfaces (Walsh et al., 2016). Based on our results, which are comparable to the estimated mean annual ET losses of 40–60% from undeveloped catchments in forested temperate regions (Zhang, Dawes, & Walker, 2001), maintaining forested areas and open space, and rainwater harvesting, will both be needed in water-smart cities of the future.

5. Conclusions

Few studies have investigated the impact of development on the water balance of an urbanizing watershed (Mitchell et al., 2003; Walsh et al., 2016), and of those, even fewer have explored the additional impact of projected changes in climate (e.g., Kalantari, Ferreira, Walsh, Ferreira, & Destouni, 2017). Here, we have used simulation modeling to explore alternative scenarios of development and their impact on the hydrologic response of a watershed in which urbanization is guided by three different sets of priorities. The simulations explored the combined effect of the specific sets of policies illustrated by the three Core scenarios, as well as specific elements of the scenarios in a factorial design, with climate change as one of the factors. By quantifying the potential impacts of urbanization, and the points at which development changes the overall water balance of the watershed, our simulations provide both examples of development patterns that can best maintain the pre-development hydrologic regime, and an illustration of the magnitude of rainwater harvest-focused LID that would be needed to offset development. There is a cost to implementing practices such as rainwater harvest and green roofs, including the need to convince and work with private property owners to install and maintain these facilities (Jarden, Jefferson, & Grieser, 2016). Alternative future scenarios can help illustrate the extent to which neighborhood design can mitigate the impacts of increased imperviousness that come with development, and the magnitude of additional efforts needed to maintain pre-development hydrologic regimes. Location-specific data on urban water systems combined with spatially-specific neighborhood designs can provide the information needed to analyze relative costs, benefits, and co-benefits of the different strategies, and identify the blend of solutions that meet the needs of regional stakeholders.

CRediT authorship contribution statement

Maria S.P. Wright: Conceptualization, Methodology, Investigation, Visualization. **Mary V. Santelmann:** Conceptualization, Methodology, Investigation, Supervision, Project administration. **Kellie B. Vaché:** Software, Validation. **David W. Hulse:** Conceptualization, Investigation.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2021.104133.

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