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Co-designed Land-use Scenarios and their Implications for Storm Runoff and Streamflow in New England

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Abstract

Landscape and climate changes have the potential to create or exacerbate problems with stormwater management, high flows, and flooding. In New England, four plausible land-use scenarios were co-developed with stakeholders to give insight to the effects on ecosystem services of different trajectories of socio-economic connectedness and natural resource innovation. With respect to water, the service of greatest interest to New England stakeholders is the reduction of stormwater and flooding. To assess the effects of these land-use scenarios, we applied the Soil and Water Assessment Tool to two watersheds under two climates. Differences in land use had minimal effects on the water balance but did affect high flows and the contribution of storm runoff to streamflow. For most scenarios, the effect on high flows was small. For one scenario—envisioned to have global socio-economic connectedness and low levels of natural resource innovation—growth in impervious areas increased the annual maximum daily flow by 10%, similar to the 5–15% increase attributable to climate change. Under modest population growth, land-use decisions have little effect on storm runoff and high flows; however, for the two scenarios characterized by global socio-economic connectedness, differences in choices regarding land use and impervious area have a large impact on the potential for flooding. Results also indicate a potential interaction between climate and land use with a shift to more high flows resulting from heavy rains than from snowmelt. These results can help inform land use and development, especially when combined with assessments of effects on other ecosystem services.

Keywords Land-use change · Ecosystem services · Storm runoff · Streamflow · Landscape scenarios · New England

Introduction

Changes to the landscape will affect water-related ecosystem services, and planning and development must be informed by the range of potential effects to ensure resilient and sustainable water resources, especially under a changing climate. While climate and precipitation are the primary drivers of the hydrologic cycle, land use and land cover modulate those signals and can exacerbate or mitigate the impacts (Brauman et al. 2007). Watersheds concentrate precipitation inputs in space (regulating service), distribute them in time (regulating service), and remove water via evapotranspiration (provisioning service). Through modifications to infiltration capacity and vegetation, changes to land use and land cover will affect the partitioning of water between evapotranspiration and streamflow along with the timing of streamflows. An understanding of how plausible future landscapes might affect the water balance and streamflow can improve planning, infrastructure design, and policy decisions.

An increase in vegetation cover tends to increase both evapotranspiration, which reduces the provision of streamflow, and infiltration, which increases the temporal regulation of streamflow. Paired watershed and observational studies generally show that a reduction in vegetation cover leads to an increase in average streamflow due to the reduction in evapotranspiration (e.g., Andréassin 2004; Bosch and Hewlett 1982; Brown et al. 2005, 2013; Bruijnzeel 2004). In contrast, the effects of vegetation cover on low flows are less certain due to the competing effects on evapotranspiration and infiltration (e.g., Devito et al. 2005; Guswa et al. 2017; Homa et al. 2013; Jencso

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and McGlynn 2011; Laaha et al. 2013; Price 2011; Smahktin 2001). The direction of the effect on flooding and high flows is more certain, as vegetation increases evapotranspiration (reducing streamflow) and infiltration (reducing peak flows). The loss of vegetation, coupled with increases in impervious cover, increases peak flows. The magnitude and significance of those services are uncertain across environments and events, however. For example, in the UK, increases in vegetation were found to reduce peak flows for small to moderate rainfall events but had little effect for larger events (Dadson et al. 2017). When the land is saturated, the regulating effect of infiltration may be reduced, and some claim that landscape effects on flood reduction may be overestimated (Calder and Aylward 2006). In one case, authors even found the opposite effect, with increased impervious area correlated with decreased high flows, perhaps due to a concomitant increase in stormwater detention infrastructure (Homa et al. 2013).

Modeling studies have also been used to elucidate the effects of land use on streamflow. Karlsson et al. (2016) examined the combined effect of four land-use scenarios, four climate models, and three hydrological models on streamflows in Denmark and found that the climate model had more influence than land-use change. Ashagre et al. (2018) used the Soil and Water Assessment Tool (SWAT) to show that forests and woodlands, relative to agriculture, regulated both sediment loads and peak flows in Tanzania. Baker and Miller (2013) also used SWAT in East Africa and found that increases in urbanization resulted in greater surface runoff and reduced groundwater recharge. For the Songkhram River Basin in Thailand, Shrestha et al. (2018) employed SWAT to determine that the effects of climate change (20% decrease in streamflow) were greater than the effects due to potential land-use changes (5% increase in streamflow). Dennedy-Frank and Gorelick (2019) estimated the effects of 10% forest-cover change on streamflow for 29 watersheds across continents and climates using SWAT. They found that forest restoration resulted in a very slight decrease in water yield (on the order of 1–2%) for 96% of watersheds, a modest decrease (~4%) in high flows for all watersheds, and less clear results for low flows with 78% of watersheds indicating a reduction and 22% showing an increase (Dennedy-Frank and Gorelick 2019).

SWAT has also been applied to multiple watersheds in the United States. In the northeast, an increase in forest cover led to a decrease in the severity and duration of both high and low flows (Anh and Merwade 2017). In southern Alabama, Wang et al. (2014) showed that a near doubling of urban area from 26.4% of the landscape to 50.2% resulted in an increase of only 2.2% in the mean flow. Hantush and Kalin (2006) simulated urbanization in the Pocono Creek in Pennsylvania, and they found that increasing development from 5.8% of the landscape to 75.8% reduced average flows by 1.1% and increased the average annual maximum daily flow (AMDF) by 19.4%. Suttles et al. (2018) applied SWAT to a 17,000 km^2 watershed in North Carolina and found that land-use change affected the partitioning of streamflow between baseflow and storm runoff. Cheng (2013) used SWAT to simulate and compare four land-use scenarios and three climate scenarios with respect to streamflow and found that the effects of climate were greater than those due to land-use change. Building on that work, Cheng et al. (2017) used SWAT to investigate the ability of stormwater detention to mitigate the effects of climate change on high flows for the Charles River watershed in Massachusetts.

In this work, we use SWAT to examine the effects of plausible, future land-use scenarios on streamflow for two watersheds in New England under both a historical and potential future climate. The land-use scenarios were co-developed with scientists and a range of stakeholders as part of the New England Landscape Futures (NELF) project, a large research network designed to integrate diverse modes of knowledge and create a shared understanding of how the future may unfold (McBride et al. 2019; Thompson et al. 2020). Like all scenarios, the NELF scenarios are not intended as forecasts or predictions; instead, they explore multiple hypothetical futures in a way that recognizes the irreducible uncertainty and unpredictability of complex systems (Thompson et al. 2012). Co-designing scenarios increases the range of viewpoints included in the process and is widely credited with enhancing the relevance, credibility, and salience of outcomes (Cash et al. 2003). Participatory development of land-use scenarios is particularly useful in landscapes such as New England where change is driven by the behaviors and decisions of thousands of independent land owners rather than by a central decision-making authority. Throughout this paper, we use the term "scenarios" to refer to the stakeholder-informed future landscapes, and we use the term "simulations" to refer to the combinations of climate-watershed-landscape used in our analyses.

In New England, where precipitation is abundant and consistent throughout the year, stakeholders expressed that the primary water-quantity issues of concern are related to stormwater, peak streamflow, and flooding. Consequently, this work focuses on storm runoff and high flows to reveal the magnitude of potential effects due to plausible changes to the landscape. To examine the robustness of these landscape signals, we investigate two different watersheds and two different climates. Results can identify whether differences in land use across the scenarios may necessitate investments in infrastructure to mitigate increased high flows (as in Cheng et al. 2017). This work also provides one piece of a more holistic and comprehensive assessment of ecosystem services across these land-use scenarios (e.g., Thompson et al. 2014).

Methods

Land-cover Scenarios for New England in 2060

McBride et al. (2017, 2019) describe NELF's participatory process for co-developing scenarios of future land cover in New England in 2060. In brief, narrative land-use scenarios were co-designed using a scenario development process that engaged over 150 stakeholders (e.g., conservationists, planners, resource managers, land owners, and scientists) from throughout the region. The scenarios were created using the intuitive logics approach, a structured process in which participants develop plausible storylines describing a set of distinct alternative futures (Schwarz 1991) building off of a "Recent Trends" scenario. The NELF participants used this process to construct four scenarios—Go It Alone (GA), Connected Communities (CC), Yankee Cosmopolitan (YC), and Growing Global (GG)—in addition to historical land use and the Recent Trends scenario. The four scenarios are characterized by extreme states of two driver variables: (1) low to high natural resource planning and innovation and (2) local to global socio-economic connectedness (Table 1), which the stakeholders determined to be among the most uncertain and potentially impactful drivers for the region. Storylines for each scenario are provided in Table 1, which is adapted from the detailed narratives available in Fallon Lambert et al. (2018).

Land uses for the scenarios were simulated using the cellular land-cover-change model, Dinamica EGO v.2.4.1 (Soares-Filho et al. 2009, 2013), using a process that iterated between modelers and stakeholders to ensure that the resulting maps accurately represented the stakeholders' intent (Thompson et al. 2020). The 50-year scenarios have 30-m resolution and span the years 2010–2060 in 10-year time steps. Land cover varies across five classes: high-density development, low-density development, forest, agriculture, and legally protected land (e.g., conservation easements). Other land-cover classes, such as water, were held constant. For the Recent Trends scenario, the rate and spatial patterns of land-cover transitions were based on observed changes in classified Landsat data between 1990 and 2010 (Olofsson et al. 2016; Thompson et al. 2017).

Study Watersheds—Cocheco River and Charles River

To investigate the effects of these plausible landscape scenarios (Table 1) on storm runoff and streamflow, we selected the Cocheco River watershed, defined by USGS gage 01072800, and the Charles River watershed, defined by USGS gage 01104500 (Fig. 1). The Cocheco River watershed in southeastern New Hampshire is in one of the most rapidly urbanizing parts of New England. The watershed has an area of 207 km^2, and the main channel is 34 km in length and drops 170 m in elevation from the headwaters to the gage at an elevation of 36.2 m. Average annual precipitation is 1059 mm/year, and average streamflow is 3.14 cms, equivalent to 479 mm/year. A number of historic mill ponds and dams within the Cocheco River watershed are now breached and/or in ruins (Cocheco River Watershed Coalition 2008). The few that are active are maintained for recreation with no control of streamflow. The large reservoir in the southwest portion of the watershed, Baxter Lake, is also for recreation only and provides no flood control (FEMA 2008). Total water withdrawals for Farmington and Rochester combined average 2.4 million gallons per day (City of Rochester, NH 2020; Town of Farmington, NH 2020), with the vast majority of that water being returned to the Cocheco River via return flows.

The Charles River flows through some of the most densely populated parts of New England, and a SWAT model had previously been calibrated to study this watershed (Cheng et al. 2017). The watershed has an area of 648 km^2, and it is flatter and more developed than the Cocheco watershed (Fig. 1). The outlet elevation is 6.10 m, and the main channel drops only 101 m over its 108-km length. Average annual precipitation is 1111 mm/year, and average streamflow is 8.01 cms, equivalent to 389 mm/year. Net withdrawals for water supply (withdrawals minus return flows) average 4.4 million gallons per day (USGS 2016).

Figures 2 and 3 display the land uses across the Cocheco River and Charles River watersheds for the landscape scenarios described above. Table 2 reports the fraction of each soil and land-use type within the watersheds.

Streamflow Metrics of Interest

The Charles River has rarely experienced flood damage in the past five decades due to successful nature-based solutions, implemented when the US Army Corps of Engineers (USACE) purchased easements to 33 km^2 of low-lying land along the river in the 1970s and 1980s (USACE 2020a). However, increased urbanization in the lower basin may have aggravated flood damages in March 2010 (Rosenzweig et al. 2018). Throughout the twentieth century, the Cocheco River overflowed its banks, leading to damage to the surrounding towns. In response, the USACE constructed a number of levees to mitigate flood damage (USACE 2020b). More recently, flooding in May 2006 and April 2007 led to significant property damage, and President Bush declared disaster areas for much of central and southern New Hampshire after each (Olson 2007; FEMA 2008).

Table 1 Storylines for New England Landscape Futures in 2060

Local	Socio-economic connectedness	Global
High		
Connected Communities (CC) This is the story of how a shift toward living “local” and valuing regional self-sufficiency and local resource use increases the urgency to protect local resources. The New England population has increased slowly over the past 50 years and most communities are coping with climate change by anchoring in place rather than relocating, making local culture and the use and protection of local resources increasingly important to governments and communities. New England has been less affected by climate change than many other regions of the USA in this scenario. Concerns about global unrest and the environmental impacts of global trade have led New Englanders to strengthen their local ties and become more self-reliant. These factors combine with heightened community interest and public policies to strengthen local economies and fuel burgeoning markets for local food, local wood, and local recreation. Drivers: high natural resource planning and innovation; local socio-economic connectedness		Yankee Cosmopolitan (YC) This is the story of how we embrace change through experimentation and upfront investments. While environmental changes break records and urbanization continues to pressure natural systems, society responds with greater flexibility, ingenuity, and integration. In this scenario, New England has experienced substantial population growth spurred by climate and economic migrants who are seeking areas less vulnerable to heat waves, drought, and sea-level rise. Most migrants are international but some have relocated from more climate-affected regions in the USA. At the same time, a strong track record in research and technology has made New England a world leader in biotech and engineering, creating a large demand for skilled labor. The region’s relative resilience to climate change and growing employment opportunities has made New England a major economic and population growth center of the USA. Abundant forests remain a central part of New England’s identity, and they support increases in tourism, particularly in Vermont, Maine, and New Hampshire. Drivers: high natural resource planning and innovation; global socio-economic connectedness
Natural resource planning and innovation		
Go It Alone (GA) This is the story of a region challenged by shrinking economic opportunities paired with increasing costs to meet basic needs, yet innovation is stagnant and new technologies are not rising to increase efficiency or create new opportunities. With local self-reliance and survival as the primary objectives, natural resource protections are rolled-back and communities turn heavily to extractive industries.		Growing Global (GG) This is the story of an influx of climate change migrants seeking refuge in New England, and taking the region by surprise. New pressures on municipal services drive a trend toward privatization. Regional to national policies have promoted global trade but global agreements to address climate change have failed.
Low		
In this scenario, population growth in the region has remained fairly low and stable over the past 50 years as the lack of economic opportunity, high energy costs, and tightened national borders have deterred immigration and the relocation of people from within the USA to New England. The concurrent shrinking of national budgets and lack of global economic connections have left little leeway to deal with challenges such as high unemployment, demographic change, and climate resilience. Within New England this has resulted in the rolling back of natural resource protection policies and the drying up of investments in new technologies and ecosystem protections in response to a lack of regulatory drivers. Over the last 50 years, the region has seen the significant degradation of ecosystem services as a result of poor planning, increased pollution, and heavy extractive uses of local resources using conventional technologies. Drivers: low natural resource planning and innovation; local socio-economic connectedness		In this scenario, by 2060, a steady stream of migrants has driven up New England’s population, with newcomers seeking to live in areas with few natural hazards, ample clean air and water, and low vulnerability to climate change. This influx of people has taken the region by surprise and local planning efforts have failed to keep pace with development. The region has experienced increasing privatization of municipal services as state and local governments struggle to keep up with the needs of the burgeoning population. Trade barriers were lifted in the 2020s to counter economic stagnation and the volume of global trade has multiplied over the past 40 years as a result of increasing globalization. However, all attempts at global climate change negotiations and renewable energy commitments have failed in this globally divided world. Drivers: low natural resource planning and innovation; global socio-economic connectedness

Scenario icons and descriptions are adapted with permission from Fallon Lambert et al. (2018)

Consequently, high streamflows are of particular interest in these watersheds.

Across scenarios and climates, we consider two metrics of streamflow relevant to New England stakeholders. The first is the water balance—the partitioning of precipitation among evapotranspiration, storm runoff, and baseflow. Runoff and baseflow together constitute streamflow; storm runoff is the rapid response to precipitation events, whereas

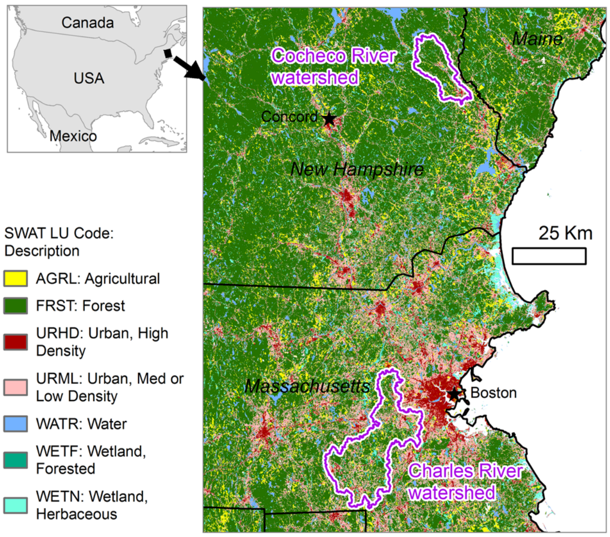

Fig. 1 Locations of the Cocheco River watershed and the Charles River watershed with land covers from 2010

baseflow represents the slower component of streamflow driven by seasonal and interannual variability. The second metric is the annual maximum daily flow (AMDF). While true peak flows may be short-lived phenomena—on the scale of minutes to hours—the AMDF nonetheless provides an indication of the potential for flooding and associated damage. To assess the differences in AMDF among land-use scenarios, we use paired comparisons, since the weather forcing across the scenarios is the same (see "Weather forcing"). For every pair of scenarios, the relative difference in AMDF is calculated for each year of simulation. Those yearly differences are resampled with replacement to create 10,000 bootstrap samples. An empirical 95% confidence interval for the true mean of the relative difference in AMDF is determined from those samples to indicate whether the relative difference is statistically different from 0.

Hydrologic Model—SWAT

This project employed SWAT (Arnold et al. 1998; Neitsch et al. 2011) to represent the effects of land-cover differences on hydrology. SWAT is a well-known and well-tested, process-based model that represents weather, hydrology, growth and seasonality of vegetation, and landscape management practices. It operates with a daily time step, and space is represented in a semi-distributed way. Within a watershed, subbasins are linked via a stream network, and each subbasin is represented by a collection of hydrologic response units (HRUs). Each HRU comprises a particular combination of soil, slope, land use, and land management. Within a subbasin, HRUs are not represented explicitly in space and do not interact with each other, and water-balance equations are solved within each HRU. Incoming precipitation is partitioned among canopy interception, storm runoff, and storage in the soil. Soil water then contributes to lateral subsurface flow, groundwater return flow, and deep recharge.

In SWAT, land use affects hydrology and streamflow via a few parameters, including:

(1) The curve number, the parameter in the curve number method for estimating storm runoff (USDA 2004), which depends on soil and land use;
(2) The fraction of impervious area and the fraction of impervious area that is directly connected to storm sewer infrastructure; these parameters affect the aggregated curve number for urban areas;
(3) Vegetation, which affects the seasonality and magnitude of evapotranspiration.

Across different landscape scenarios, the weather, topography, soils, and soil-related parameters are held constant.

Weather forcing

Simulations were run in SWAT for 19-year periods for both historical weather and a future climate. The first 3 years of all simulations were used as a spin-up period and were not used in subsequent analyses. The years were selected so that the final simulated years coincided with the years of the land cover datasets plus the 8 years before and the 7 years after (2002–2017 for the historical weather and 2052–2067 for the simulated future climate).

Data for the historical weather came from the National Oceanic and Atmospheric Administration's Climate Data Online Search webtool (NOAA 2018). The Rochester Skyhaven Airport (054791) weather station was used for the Cocheco River watershed, and the Boston (14739) weather station was used for the Charles River watershed. Precipitation and temperature data for a possible future climate were obtained from the USGS Geo Data Portal Bias Corrected Constructed Analogs V2 Daily Climate Projections dataset (USGS 2018). The spatially and temporally downscaled LOCA CMIP5 CCSM4 RCP 8.5 dataset has among the highest temperature correlations with observed data (Kumar et al. 2013) and performs well with comparisons to historical and paleo climate data (Sillmann et al. 2013).

Precipitation and temperature data were used with the weather generator in SWAT (using the WGEN_US_FirstOrder database) to simulate additional weather parameters, including relative humidity, wind speed, and solar radiation. The Penman–Monteith method was used to estimate potential evapotranspiration (Arnold et al. 2012). Table 3 presents precipitation statistics for the two climates across the two watersheds. While annual precipitation is greater for the future climate, precipitation extremes—e.g., the 5% and 1% exceedance depths—are less intense than for the historic weather.

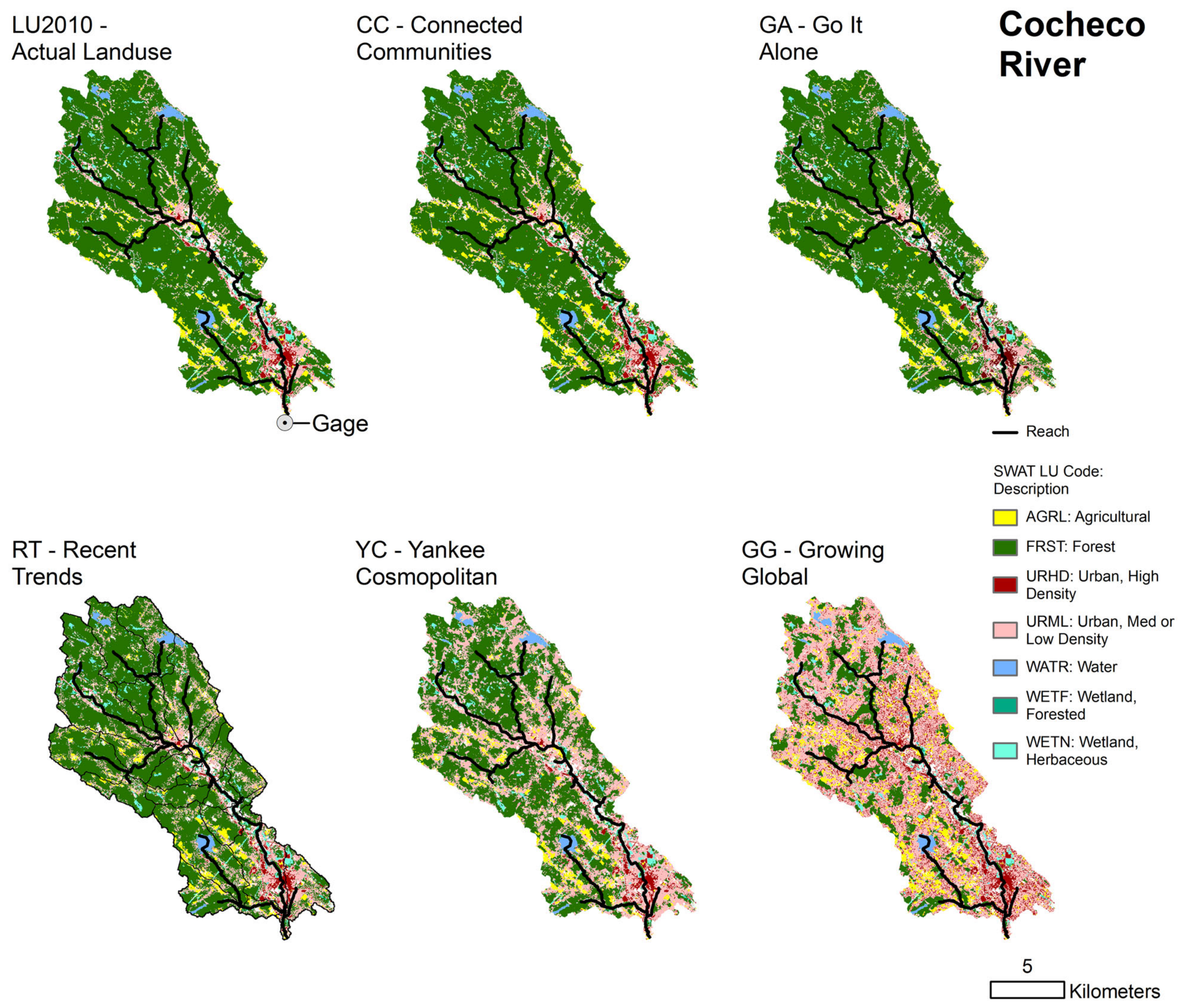

Fig. 2 Land use for the Cocheco River watershed. LU2010 indicates land use in 2010 from the NLCD. Recent Trends, Connected Communities, Yankee Cosmopolitan, Go It Alone, and Growing Global represent plausible land-use scenarios in 2060

Landscape features and watershed discretization

Land-cover maps were derived from the NELF scenarios (McBride et al. 2017, 2019; Plisinski et al. 2017; Thompson et al. 2020). While the NELF scenarios combined water with wetlands and considered swamps to be forests, we separated water and wetlands, and accounted for herbaceous wetlands and swamps explicitly by extracting those land-cover types from the National Land Cover Database (NLCD; Homer et al. 2015) and imposing them on the NELF scenarios. Soil data were obtained from the SSURGO database (USDA 2014). Three slope classes were calculated for each watershed using natural class breaks; breakpoints of 5.7 and 14.1% were used for the Cocheco River watershed and 4.6 and 11.5% for the Charles River watershed. To better represent the spatial heterogeneity and small land-use patches that are typical of the New England landscape, we did not merge smaller HRUs with larger neighbors, as is sometimes done. For land-use classes from 2010, the Cocheco River watershed is represented by 25 sub-watersheds and 4835 HRUs, and the Charles River watershed is represented by 40 sub-watersheds and 17631 HRUs. The numbers of HRUs range from 4835 to 5892 and 17,631 to 19,431, for the Cocheco and Charles, respectively, across all scenarios.

Land-cover differences in SWAT manifest predominantly as differences in plant growth and evapotranspiration and in the generation of storm runoff via the curve number (Arnold et al. 2012). We chose curve numbers (CN2) to reflect conditions in New England. Because there is very little woodland pasturing in New England, we changed the CN2 values for generic forest (FRST) from the default values in SWAT, which would be appropriate for forests subject to grazing by livestock ("fair" condition), to

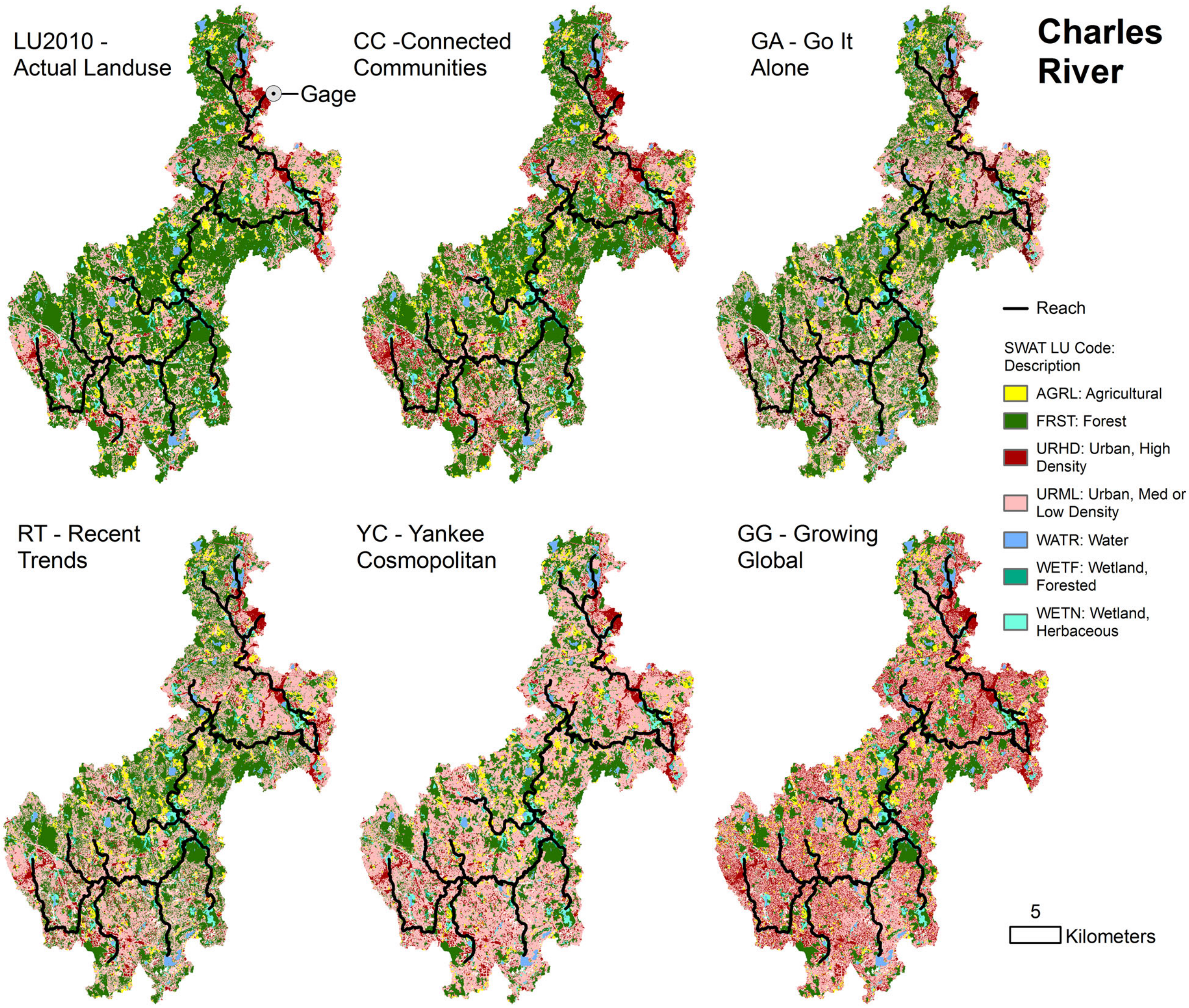

Fig. 3 Land use for the Charles River watershed. LU2010 indicates land use in 2010 from the NLCD. Recent Trends, Connected Communities, Yankee Cosmopolitan, Go It Alone, and Growing Global represent plausible land-use scenarios in 2060

Table 2 Soil hydric classes and fractional land use across scenarios and watersheds

Watershed and soil hydric class	Land-use scenario	% urban	% forest	% agriculture
Cocheco	2010	14.3	75.5	4.4
A—0%	RT	22.8	66.7	4.7
B—92%	GA	16.1	73.8	4.3
C—6%	CC	14.6	74.3	5.3
D—2%	YC	39.6	49.9	4.7
	GG	65.7	18.6	9.8
Charles	2010	35.2	50.6	6.2
A—20%	RT	50.7	35.2	6.1
B—39%	GA	47.7	38.4	5.8
C—24%	CC	41.8	43.3	6.9
D—17%	YC	63.8	22.8	5.4
	GG	68.9	16.2	6.8

those for forests without livestock grazing (“good” condition). CN2 values for forest were 5, 55, 70, 77 for soil hydric classes A–D, respectively.

The NELF scenarios group all agricultural land under a single designation. We do the same and modify the default curve number for the generic agriculture land cover (AGRL) in SWAT to better suit the region. The default for AGRL in SWAT is appropriate for farmland dominated by corn or row crops, while New England farms have a greater fraction of pasture and hay fields. County-level data from the United States Agricultural Census (USDA 2018) were used to determine the mix of agricultural types across New England. A representative curve number for our generic agricultural type was created by using an area-weighted average of curve numbers for the individual agricultural types. Resulting curve numbers are 42.3, 65.1, 76.2, and 82.1 for soil hydric classes A–D, respectively. Other

Table 3 Precipitation statistics for historic weather and the future climate

Watershed	Climate	Annual precipitation (mm)	Depth of precipitation on days with precipitation	
			5%—exceedance (mm)	1%—exceedance (mm)
Cocheco	HW	1059	30.0	51.5
	FC	1194	17.1	34.6
Charles	HW	1111	31.8	53.6
	FC	1345	22.9	45.4

parameters in SWAT's vegetation database (plant.dat) for the agriculture land cover were not changed.

Urban areas in the NELF scenarios are designated as either "high-density development" or "low-density development." We consider these two classes to be analogous to Urban Residential High Density (URHD) and Urban Residential Medium/Low Density (URML), respectively, in SWAT. We calculated the fraction of impervious surface for all of New England by overlaying the NLCD urban land-cover types (Homer et al. 2015) on the NLCD 2011 Percent Developed Imperviousness GIS layer (Xian et al. 2011) and calculating separate area-weighted averages for URHD (consisting of the NLCD "Developed, High Intensity") and URML (consisting of NLCD "Developed, Open Space," "Developed, Low Intensity," and "Developed Medium Intensity"). This resulted in 88.9% impervious for URHD and 27.5% impervious for URML in our simulations. For all scenarios except CC and YC, the fractions of connected impervious area (i.e., the impervious area that is directly connected to storm sewers) were left at SWAT's default values of 44% and 17%, respectively, for URHD and URML. For CC and YC, those numbers were halved to 22% and 8.5% to represent natural resource innovation (Table 1) and downspout disconnection (e.g., USEPA 2020). CN2 values for the pervious portions of these urban areas were set to 39, 61, 74, 80 for hydric classes A–D, respectively, since the pervious portions of New England's urban areas are usually grass-covered lawns with >75% grass cover (Arnold et al. 2012). No other values in the urban.dat file were changed.

Water withdrawals and return flows

Water use in New England is predominantly non-consumptive, and there is very little irrigated agriculture. While the dynamics of withdrawals and return flows may affect low flows (e.g., Desimone et al. 2002), they will have limited effect on the annual water balance and on the AMDF. In addition, the withdrawals in the Charles River and Cocheco River watersheds are modest. Conservatively, net withdrawals in the Charles River watershed are <0.2 cms or 2.5% of the mean streamflow in the Charles River and <0.5% of the average AMDF. Net withdrawals are even less in the Cocheco River watershed; with a conservative ratio of 75% for return flows, net withdrawals amount to <1% of mean streamflow. Because these withdrawals and return flows have only a very small effect on our streamflow metrics of interest, we reduced the complexity of our models by not representing these dynamics explicitly.

Calibration

To increase model performance and accuracy, parameters that were unrelated to land cover within the SWAT model were calibrated by matching simulated streamflow to observed streamflow under current land use. Model parameters were calibrated separately for each watershed using observed flow for the years 2002–2011 and validated using the observed flow from 2012 to 2017. Parameters that were explicitly related to land use, such as the curve number and vegetation parameters, were not included in calibration, since they were our driver variables of interest. We used a semi-automated approach with the SWAT Calibration and Uncertainty Program using the SUFI-2 optimization method (Abbaspour 2015). Starting values for our calibration were either the default values in SWAT or the calibrated results from an earlier study on the Charles River (Cheng et al. 2017). We calibrated the model to match daily streamflow, and we used the Nash–Sutcliffe efficiency (NSE), percent bias, and the ratio of the root-mean-square error to the standard deviation of the streamflow observations (RSR) as metrics of goodness of fit. Calibration continued until none of the metrics improved by more than 5% over the previous iteration. Moriasi et al. (2007) suggest that a hydrologic model can be viewed as satisfactory if the NSE value (based on monthly streamflow) is >0.50, the RSR is <0.70, and the percent bias is <25%.

Results

Model Performance under Historic Conditions

The final model for the Cocheco River had an NSE of 0.58, RSR of 0.64, and percent bias of −13.6% for daily streamflow during the calibration period. The model for the

Charles River had values of 0.74, 0.51, and 1.2%, respectively. For the validation period, the Cocheco River had an NSE of 0.49, RSR of 0.72, and percent bias of −19.5%, and the Charles River had values of 0.74, 0.51, and 23.3%, respectively. Consistent with these results, modeled average annual evapotranspiration from 2002 to 2017, under historical land use and climate, was within 20% of estimated long-term evapotranspiration from 2000 to 2013 (Reitz et al. 2017) for the Cocheco River watershed and within 10% for the Charles River watershed. Based on goodness-of-fit metrics, we deemed the models satisfactory (Moriasi et al. 2007); final model parameters and goodness-of-fit metrics are shown in Tables 4 and 5.

Water Balance

Across the simulations, land use has little effect on the average partitioning of precipitation between evapotranspiration and streamflow (Fig. 4). Under historic weather, simulated evapotranspiration is 44–45% of precipitation in the Cocheco River watershed and 46–48% of precipitation in the Charles River watershed with little variation among land-use scenarios (Fig. 4). For the future climate, annual precipitation increases from 1059 to 1194 mm in the Cocheco River watershed and 1111 to 1345 mm in the Charles River watershed, and evaporation decreases (Fig. 4). As a result, evaporation represents a smaller fraction (35–36%) of precipitation for the simulations with a future climate.

While total streamflow is nearly unchanged across the land-use scenarios, the partitioning of streamflow between baseflow and storm runoff does vary. In the Cocheco River watershed, baseflow is 90–94% of streamflow for all land-use scenarios, except GG, for both historic and future weather. For GG, baseflow is 74% and 78% of streamflow for historic weather and a future climate, respectively. In the more developed Charles River watershed, baseflow represents between 40 and 61% of streamflow under historic weather, with the lowest fraction associated with the GG scenario (Fig. 4). For the future climate, both storm runoff and baseflow increase. As a fraction of streamflow, the baseflow contribution increases by ~10% and shows variability across scenarios similar to that under historic weather.

Seasonal water balances exhibit behavior similar to the annual water balances. Differences in land use have little effect on the partitioning of water between streamflow and evapotranspiration; rather, the effect is in the separation of streamflow into baseflow and storm runoff (Fig. 5). The increases in streamflow associated with a future climate vary seasonally, with large increases in autumn and winter, moderate increases in spring, and little effect in summer

Table 4 Calibrated parameters for SWAT models of the Cocheco River and Charles River watersheds

Description	SWAT file	Cocheco	Charles
Soil evaporation compensation factor	.bsn	0.84	0.99
Surface runoff lag coefficient	.bsn	3.94	4.62
Fraction of transmission loss from main channel that enter deep aquifer	.bsn	0.01	0.01
Plant uptake compensation factor	.bsn	0.69	0.95
Baseflow alpha factor (1/days)	.gw	0.19	0.22
Groundwater delay time (days)	.gw	32.16	36.37
Threshold depth in the shallow aquifer required for return flow (mm H20)	.gw	972.19	1150.78
Groundwater “revap” coefficient	.gw	0.06	0.08
Deep aquifer percolation fraction	.gw	0.09	0.08
Threshold depth in the shallow aquifer for “revap” or percolation to the deep aquifer (mm H2O)	.gw	1027.11	534.91
Soil evaporation compensation factor for HRUs	.hru	0.98	1.00
Plant uptake compensation factor	.hru	0.78	0.09
Baseflow alpha factor for bank storage (days)	.rte	0.81	0.70
Effective hydraulic conductivity in main channel alluvium (mm/h)	.rte	242.34	405.11
Available water content of the soil (mm H2O/mm soil) for hydric class A	.sol	0.22	0.20
Available water content of the soil (mm H2O/mm soil) for hydric class B	.sol	0.30	0.30
Available water content of the soil (mm H2O/mm soil) for hydric class C	.sol	0.19	0.08
Available water content of the soil (mm H2O/mm soil) for hydric class D	.sol	0.15	0.16
Saturated hydraulic conductivity (mm/h) for hydric class A	.sol	236.58	65.47
Saturated hydraulic conductivity (mm/h) for hydric class B	.sol	391.94	492.62
Saturated hydraulic conductivity (mm/h) for hydric class C	.sol	259.36	252.56
Saturated hydraulic conductivity (mm/h) for hydric class D	.sol	321.95	343.35
Effective hydraulic conductivity in tributary channel alluvium (mm/h)	.sub	170.37	330.13

(Fig. 5). This results in a shift in the majority of streamflow from the spring–summer months to the autumn–winter months. For historic weather, streamflow during the fall and winter (September–February) represents 40–45% of annual streamflow for the Cocheco River and Charles River watersheds. Those fractions increase to 50–55% under the future climate (Fig. 5).

Annual Maximum Daily Flow

The AMDF exhibits significant year-to-year variability due to variability in weather and precipitation. Under historic weather and land use, simulated AMDFs range from 10.7 to 78.2 m^3/s (equivalent to 4.5–32.7 mm/day) for the Cocheco River watershed and 15.5–94.0 m^3/s (2.1–12.5 mm/day) for the Charles River watershed. To discriminate among the land-use scenarios, and to account for the year-to-year variability in precipitation forcing, a paired comparison was used to quantify the effect of land use on AMDF. While AMDF varies significantly from year-to-year, the relative differences in AMDF among scenarios are uncorrelated with the magnitude of AMDF; therefore, the mean relative difference is representative of the effect of land use. Figures 6 and 7 present the average relative differences between a given scenario and historic land use in 2010, along with the 95% confidence intervals for those means, determined via 10,000 bootstrap samples. Part of the reason for the large confidence interval for the GG scenario under historic weather in Fig. 6 is due to the extreme-value nature of the AMDF. For instance, in the Cocheco River watershed in 2007, the AMDF is less for GG than all other scenarios; however, when one looks at the total streamflow over 2 or 3 days, it is greatest for GG. This idiosyncrasy in timing leads to a negative difference in AMDF between GG and land use in 2010 for 2007 and the associated large confidence interval.

Analysis of the difference in these flows between land use in 2010 and future scenarios indicates that land-use change could have a moderate effect on the AMDF (Figs 6, 7 and Table 6). Under the GG scenario, the AMDFs are ~10%

Table 5 Goodness of fit for SWAT models of the Charles River and Cocheco River watersheds based on daily streamflow

Watershed	Description	Years	NSE	Bias	RSR
Cocheco	Calibration	2002–2011	0.58	−13.6%	0.64
	Validation	2012–2017	0.49	−19.5%	0.72
	Overall	2002–2017	0.58	−15.3%	0.65
Charles	Calibration	2002–2011	0.74	1.2%	0.51
	Validation	2012–2017	0.74	23.3%	0.51
	Overall	2002–2017	0.75	7.2%	0.5

NSE is the Nash–Sutcliffe efficiency, and RSR is the ratio of the root-mean-squared error to the standard deviation of the observations. All goodness-of-fit statistics were calculated in R with the hydroGOF package (Zambrano-Bigiarini 2017)

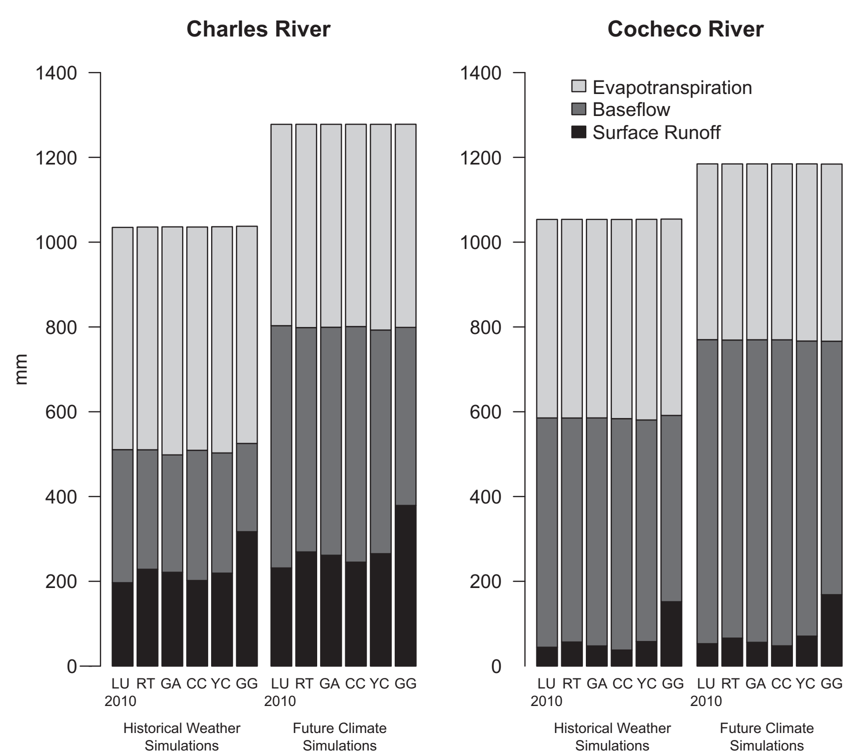

Fig. 4 Average water balances for the Charles River and Cocheco River watersheds across scenarios and climates

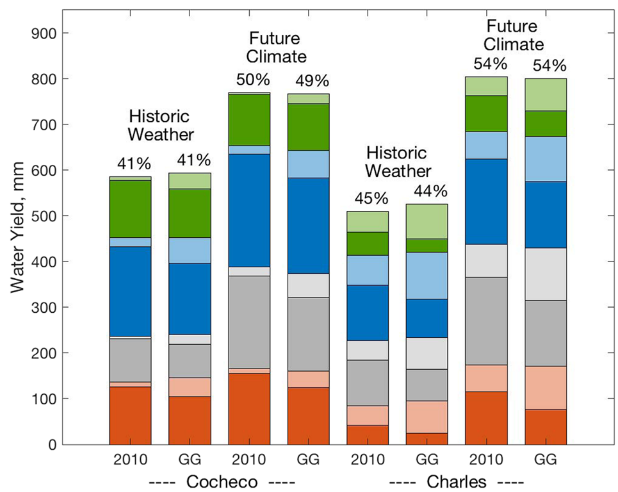

Fig. 5 Seasonal water yield for the Cocheco and Charles River watersheds for land use from 2010 and Growing Global (the two extremes) under both historic weather (HW) and a future climate (FC). Seasons are represented by colors, from the bottom: orange—autumn (SON); gray—winter (DJF); blue—spring (MAM); green—summer (JJA). Darker shades represent baseflow, and lighter shades represent storm runoff. Percentages at the top of each bar represent the fraction of total streamflow attributed to the autumn and winter months

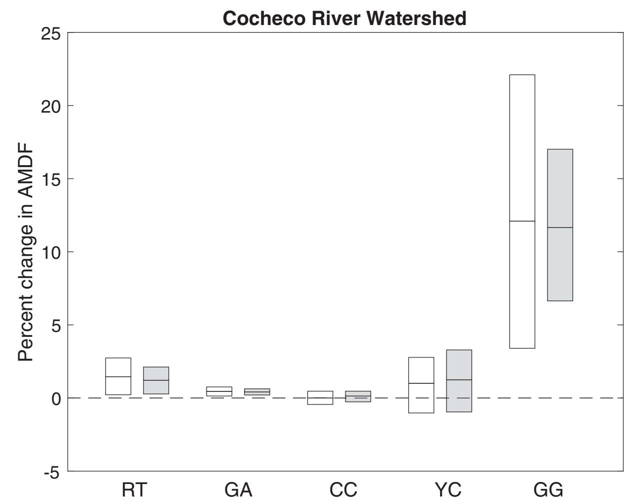

Fig. 6 Relative differences in annual maximum daily flows (AMDF) between land-use scenarios and historic land use in 2010 for the Charles River watershed. Bars represent 95% confidence limits determined via bootstrap, and the line in the middle represents the mean relative difference in AMDF between that scenario and land use in 2010. Scenarios are denoted as follows: RT Recent Trends, GA Go It Alone, CC Connected Communities, YC Yankee Cosmopolitan, GG Growing Global

larger than those under historic land use. This result is robust across both the Cocheco River and Charles River watersheds and both historic and future climates. Mean differences in AMDF between the GG scenario and all other scenarios are statistically significant at the 95% confidence level. While differences among the other pairs of scenarios are sometimes statistically significant and sometimes not (e.g., Table 6), none of them are functionally significant, with mean differences ranging from 0 to 3%.

While the AMDFs increase with increasing urbanization, the relationship depends on the nature of the urbanization—whether high density or medium/low density—as manifested through increases in the fraction of impervious area (Fig. 8). For example, while total urban area is greater for both the Recent Trends and GA scenarios than for CC (Table 2), the CC scenario has a higher proportion of high-density development, and a comparable fraction of total impervious area (Table 6 and Fig. 8). The lower fraction of directly connected impervious area in the YC and CC scenarios mitigates the effect of urbanization on AMDF only slightly.

Discussion

Differences among Land-use Scenarios

Variations in the future land-use scenarios have little effect on the overall water balance for the Cocheco River and Charles River watersheds. The dominant effect of land use is on the temporal regulating service: partitioning streamflow between faster storm runoff and slower baseflow (Figs 4, 5), consistent with other studies (e.g., Suttles et al. 2018; LaFontaine et al. (2015); Baker and Miller 2013). The effects are similar across the two climates and two watersheds. When comparing land use in 2010 with the GG scenario, the effect on AMDF reaches a maximum of ~10%, similar to what others have found. Dennedy-Frank and Gorelick (2019) report moderate increases (~5%) in high flows when 10% of forest land is converted to urban area. Cuo et al. (2009) found that annual maximum daily streamflows increased by 5% as urban areas increased from 0.4 to 6.5% of land area.

Our results show that a large change in impervious area is required to generate an effect on AMDF (Table 6). For the Cocheco River watershed, a fivefold increase in impervious cover (from 5 to 27% of land area, LU2010 versus GG, Table 6) produces an increase in AMDF of ~10% (for both historic weather and the future climate), giving a relative sensitivity of 2%. The relative sensitivity of AMDF to impervious area is 6% for the Charles River watershed (Table 6). These results are consistent with those of Hantush and Kalin (2006) who found a relative sensitivity of AMDF to developed area of 2% in Pennsylvania. Part of the reason for these limited sensitivities is that high flows in New England and the northeast occur predominantly in March and April when evapotranspiration is low, the ground is saturated, and snow is melting. Under such conditions, the regulating service associated with infiltration is reduced, resulting in smaller differences among land uses.

Sensitivity of AMDF to annual precipitation is much greater: 40–60% for the Cocheco River watershed and over 80% for the Charles River. High flows in the Charles River are more sensitive to increases in precipitation due to the nonlinear relationship between runoff and impervious cover. As impervious cover increases (i.e., as the curve number increases), the absolute sensitivity of runoff to rainfall approaches 1, the theoretical maximum. Since the Charles River watershed is more urbanized than the Cocheco River watershed, the sensitivity to precipitation is greater. Even though the relative sensitivities of AMDF to land use and precipitation are quite different, the effects on AMDF of plausible future changes in land use and climate in 2060 are comparable. Effects due to land-use change reach 10% and effects attributable to climate change are ~5% for the Cocheco River and 17% for the Charles River (Table 6). Those climate effects are similar to the 1.5–10.8% estimated increases for high flows for the Alabama–Coosa–Tallapoosa River Basin (Gangrade et al. 2020).

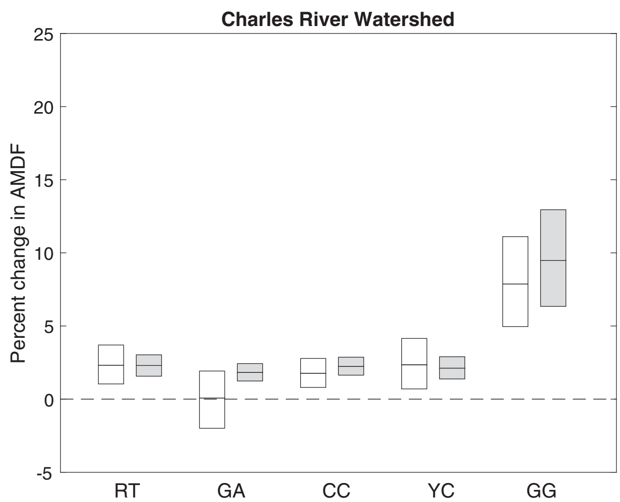

Fig. 7 Relative differences in annual maximum daily flows (AMDF) between land-use scenarios and historic land use in 2010 for the Cocheco River watershed. Bars represent 95% confidence limits determined via bootstrap, and the line in the middle represents the mean relative difference in AMDF between that scenario and land use in 2010. Scenarios are denoted as follows: RT Recent Trends, GA Go It Alone, CC Connected Communities, YC Yankee Cosmopolitan, GG Growing Global

Interactions of Land-use and Climate Changes

While this work focuses on the effects of plausible changes to land use on mean and high streamflows, it can also provide insight to the interactive and compounding effects of land-use and climate changes. As indicated above, the Cocecho and Charles River watersheds exhibit different degrees of sensitivity to changes in mean annual precipitation; this is due, at least in part, to the urbanized nature of the landscape in the Charles River watershed. Table 6 also indicates that, while the effects of climate and land use are largely additive, there is potentially a small exacerbation of the increase in AMDF due to climate under the GG scenario than under the historic land use. The additive effect of climate and land use seen in Table 6 is comparable to what others have reported in similar studies (e.g., Suttles et al. 2018; Martin et al. 2017; LaFontaine et al. 2015).

Table 6 High-density urban area (URHD), medium/low-density urban area (URML), impervious area, and average annual maximum daily flow (AMDF) across the simulations

Watershed	Land-use scenario	% URHD	% URML	% Impervious	Historic weather average max daily flow, cms	Future climate average max daily flow, cms
Cocheco	2010	2.2	12.1	5.3	32.0	33.6
	RT	2.5	20.3	7.8	32.7*	34.0*
	GA	2.4	13.7	5.9	32.2*	33.7*
	CC	2.9	11.7	5.8	32.1	33.7
	YC	3.4	36.2	13.0	32.5	34.0
	GG	14.6	51.1	27.0	34.7*	37.3*
Charles	2010	5.5	29.7	13.1	40.4	47.3
	RT	7.5	43.2	18.5	41.8*	48.5*
	GA	7.0	40.8	17.4	41.0	48.3*
	CC	11.0	30.8	18.3	41.4*	48.5*
	YC	10.0	53.9	23.7	41.9*	48.4*
	GG	24.4	44.5	34.0	44.2*	52.3*

Scenarios are denoted as follows: 2010 historic land use in 2010, *RT* Recent Trends, *GA* Go It Alone, *CC* Connected Communities, *YC* Yankee Cosmopolitan, *GG* Growing Global. AMDFs marked with an asterisk (*) indicate landscape scenarios for which the mean relative difference between the AMDF for that scenario and historic land use is statistically different from 0 (for that watershed and climate); see Figs 6 and 7

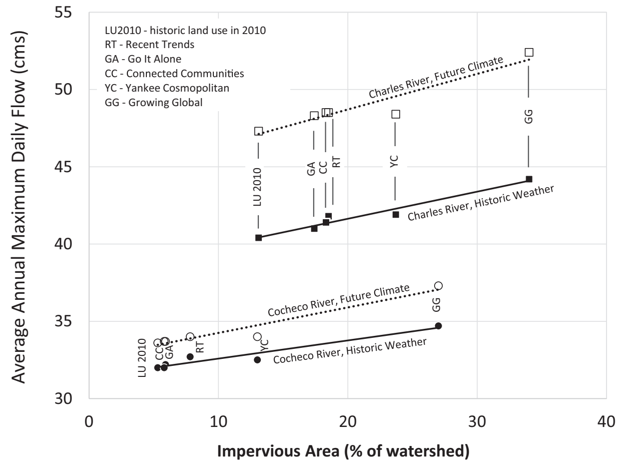

Fig. 8 Average annual maximum daily flow increases with impervious area. Land-use scenarios are indicated by letter codes. Open symbols indicate simulations for the future climate and filled symbols represent historic weather. Square symbols represent the Charles River watershed and circles represent the Cocheco River watershed. Regression lines are included for illustration of the increase of AMDF with impervious area

A warmer climate also results in a shift of streamflow to fall and winter months (Fig. 5). This result is consistent with Cuo et al. (2009), who found that temperature increases from 1915 to 2006 in northwestern Washington resulted in a shift of 20% of annual streamflow from summer months (JJA) to winter months (DJF). This shift affects not only mean flows, but peak flows as well. In New England, most annual maximum flows occur in the springtime as a result of a combination of rain, snowmelt, and wet soils. In the Cocheco River watershed, 75% of AMDFs occur between January and June, and the fraction is 88% for the Charles. Under the future climate, springtime maximum flows drop to 69% in the Cocheco watershed and to 63% in the Charles River watershed. This shift as a result of warmer temperatures also has the potential to exacerbate differences due to land use. In the Cocheco River watershed under historic weather—a simulation with significant snowmelt—the mean difference in springtime AMDFs between GG and historic land use is just 1%, while the mean difference for the four AMDFs occurring between July and December is 36%. This points to a potential additional interaction between climate and land-use changes as warmer temperatures lead to a greater fraction of high flows being attributed to heavy rain events rather than snowmelt.

Limitations of Approach

The utility of the results depends upon the appropriateness of the mathematical representations in SWAT; there are some inherent limitations of the model, and the results of this work should be interpreted within that context. First, some of the model parameters (such as available water content, hydraulic conductivity, and surface runoff lag) are determined by calibrating the model to existing conditions. Using the model to represent future land uses presumes that those parameters are unchanging across the scenarios. In most cases, we anticipate this to be true, as those parameters are functions of soil, topography, or other watershed characteristics that are generally unchanged as the land cover changes. Characteristics that do change with land use, such as the curve number and vegetation cover, are not calibrated but determined a priori. Second, the temporal resolution of this work is limited to the daily timescale. This precludes the representation of sub-daily dynamics of precipitation and streamflow. Therefore, instantaneous peak streamflows cannot be modeled, and this work is limited to daily discharge. Third, SWAT represents space in a semi-distributed way. While the model accounts for spatial variations among watershed characteristics, the HRU structure does not permit the representation of the spatial arrangement and connectedness of landscape elements. Therefore, feedbacks and interactions among different parts of the landscape cannot be represented explicitly. For example, increased runoff from one HRU cannot infiltrate in a different HRU. Such interactions can only be represented implicitly. Relatedly, storm runoff is represented with an approach that implicitly accounts for effects of soil, land cover, and land management through a single parameter. This is consistent with large-scale analyses and is not intended for small-scale green-infrastructure evaluation. Results from this work must be interpreted within the context of these modeling limitations.

Implications of Findings for Policy and Design

The results of this work indicate that the effects of climate and land use on runoff and high flows are largely additive (Table 6), and the combination of a wetter future climate and increased urbanization has the potential to exacerbate high flows and flooding. While the results imply that it would take a major reworking of the landscape to mitigate the effects of climate change, they also indicate that rapid growth and development could present significant challenges for stormwater management and existing infrastructure. If population growth is modest, land-use decisions and development patterns have little effect on storm runoff and high flows (compare scenarios CC and GA in Figs 4, 6, and 7). However, when the future is characterized by global socio-economic connectedness and increased population growth (YC and GG, Table 1), the results are substantively different from each other (Figs 4, 6, and 7). In this case, urban planning and choices regarding land use can have a large impact on regulating services and the potential for flooding. Planning for smart and sustainable growth while concomitantly investing in multi-functional landscapes and natural infrastructure could reduce flood damages (e.g., LaFontaine et al. 2015). In addition, with increased high flows, communities may need to increase the size and character of their water infrastructure and/or allow for short periods of inundation (Rosenzweig et al. 2018).

Next Steps

To more precisely elucidate the effects of changes in urban land use and land cover, one could refine the representation of urban hydrology and introduce and test potential infrastructure solutions. Models such as the Storm Water Management Model and HydroCAD are better equipped to represent the natural and engineered features of an urban landscape, the sub-daily dynamics of the runoff response to storm events, and the elements of green infrastructure at the site and local scales. These more detailed studies will necessarily be narrower in geographic scope, and continued engagement with stakeholders in the scenario-planning process can provide guidance to locations of interest. In addition, changes to nutrient and sediment loads, resulting from changes to the landscape, may be of interest to stakeholders in New England. Given the modest effects of landscape on streamflow, effects on water quality may be all the more important and significant.

Conclusions

Across the NELF scenarios, variations in land use have little effect on the overall water balance. Rather, the impact is on high flows and the partitioning of streamflow between storm runoff and baseflow. Those effects are correlated with the amount of impervious cover. For most of the scenarios (GA, CC, and YC), the effects are muted and less than the effects due to watershed or climate. For the GG scenario, however, the effects are large and comparable to or greater than the effects of climate. These responses to land-cover change are robust across the Cocheco River and Charles River watersheds. Results from this work can help inform designs and decisions related to infrastructure resiliency and can complement other studies to provide a comprehensive and integrated assessment of multiple ecosystem services across possible future landscapes.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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