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

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Landscape scenarios and implications for streamflow in New England

1 **Co-designed land-use scenarios and their implications for storm runoff and streamflow in**
2 **New England**

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19 Keywords: land-use change; ecosystem services; storm runoff; streamflow; landscape scenarios;
20 New England

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25 **Research highlights**

- 26
27 1. Stakeholder-engaged scenarios provide meaningful and plausible futures for the New
28 England landscape and assessment of effects of land-use change on storm runoff and
29 streamflow
- 30 2. Effects of land use on the overall water balance are small across the landscape scenarios
- 31 3. Future land-use change has the potential to affect storm runoff and high flows to a degree
32 that is comparable to the effects due to changes in climate in 2060
- 33 4. The degree of natural resource innovation affects storm runoff and high flows when
34 population growth is large and has a negligible effect when population growth is low

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36

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37 **Abstract**

38

39 Future changes in both landscape and climate have the potential to create or exacerbate problems

40 with stormwater management, high flows, and flooding. In New England, four plausible land-

41 use scenarios were co-developed with stakeholders to give insight to the effects on ecosystem

42 services of different trajectories of socio-economic connectedness and natural resource

43 innovation. To assess the effects of these land-use scenarios on water-related ecosystem

44 services, we applied the Soil and Water Assessment Tool to two watersheds under two climates.

45 Differences in land use had minimal effects on the overall water balance but did affect high

46 flows and the relative contribution of storm runoff to streamflow. For most of the scenarios, the

47 effect was small and less than the effect due to climate change. For one scenario – envisioned to

48 have global socio-economic connectedness and low levels of natural-resource innovation – the

49 effects of land-use changes were comparable to the effects due to climate. For that scenario,

50 changes to the landscape increased the annual maximum daily flow by 10%, similar to the 5-15%

51 increase attributable to climate change. These results, which were consistent across both

52 watersheds, can help inform planning and policies regarding land use, development, and

53 maintenance of hydrologic ecosystem services.

54

55 **1 Introduction**

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

68 An increase in vegetation cover tends to increase both evapotranspiration, which reduces
69 the provision of streamflow, and infiltration, which increases the temporal regulation of
70 streamflow. Paired watershed and observational studies generally show that a reduction in
71 vegetation cover leads to an increase in average streamflow due to the reduction in
72 evapotranspiration (e.g., Andréassin, 2004; Bosch & Hewlett, 1982; Brown et al., 2005; Brown
73 et al., 2013; Bruijnzeel, 2004). In contrast, the effects of vegetation cover on low flows are less
74 certain due to the competing effects on evapotranspiration and infiltration (e.g., Devito et al.,
75 2005; Guswa et al., 2017; Homa et al., 2013; Jencso & McGlynn, 2011; Laaha et al., 2013; Price,
76 2011; Smakhtin, 2001). The direction of the effect on flooding and high flows is more certain, as
77 vegetation increases evapotranspiration (reducing streamflow) and infiltration (reducing peak

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78 flows). The loss of vegetation, coupled with increases in impervious cover, increases peak
79 flows. The magnitude and significance of those services are uncertain across environments and
80 events, however. For example, in the UK, increases in vegetation were found to reduce peak
81 flows for small to moderate rainfall events but had little effect for larger events (Dadson et al.,
82 2017). When the land is saturated, the regulating effect of infiltration may be reduced, and some
83 claim that landscape effects on flood reduction may be overestimated (Calder & Aylward, 2006).
84 In one case, authors even found the opposite effect, with increased impervious area correlated
85 with decreased high flows, perhaps due to a concomitant increase in stormwater detention
86 infrastructure (Homa et al., 2013).

87 Investigators have also used modeling studies to elucidate the effects of land use on
88 hydrologic ecosystem services. Karlsson et al. (2016) examined the combined effect of four
89 land-use scenarios, four climate models, and three hydrological models on streamflows in
90 Denmark and found that the climate model had more influence than land-use change. Ashage et
91 al. (2018) used the Soil and Water Assessment Tool (SWAT) to show that forests and
92 woodlands, relative to agriculture, regulated both sediment loads and peak flows in Tanzania.
93 Baker & Miller (2013) also used SWAT in East Africa and found that increases in urbanization
94 resulted in greater surface runoff and reduced groundwater recharge. For the Songkhram River
95 Basin in Thailand, Shrestha et al. (2018) employed SWAT to determine that the effects of
96 climate change (20% decrease in streamflow) were greater than the effects due to potential land-
97 use changes (5% increase in streamflow). SWAT has also been applied to multiple watersheds
98 in the United States. In the northeast, an increase in forest cover led to a decrease in the severity
99 and duration of both high and low flows (Ahn & Merwade, 2017). In southern Alabama, Wang
100 et al. (2014) showed that a near doubling of urban area from 26.4% of the landscape to 50.2%

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101 resulted in an increase of only 2.2% in the average daily flow. Hantush & Kalin (2006)
102 simulated urbanization in the Pocono Creek in Pennsylvania, and they found that increasing
103 development from 5.8% of the landscape to 75.8% reduced average flows by 1.1% and increased
104 the average annual maximum daily flow by 19.4%. Cheng (2013) used SWAT to simulate and
105 compare four land-use scenarios and three climate scenarios with respect to streamflow and
106 found that the effects of climate were greater than those due to land-use change. Building on that
107 work, Cheng et al. (2017) used SWAT to investigate the ability of stormwater detention to
108 mitigate the effects of climate change on high flows for the Charles River watershed in
109 Massachusetts.

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

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124 stakeholder-informed future landscapes, and we use the term “simulations” to refer to the
125 combinations of climate-watershed-landscape used in our analyses.

126 In New England, where precipitation is abundant and consistent throughout the year,
127 stakeholders expressed that the primary water-quantity issues of concern are related to
128 stormwater, peak streamflow, and flooding. Consequently, this work focuses on effects of land
129 use on storm runoff and high flows. The intent is to reveal the magnitude and robustness of
130 potential effects due to plausible changes to the landscape. This work can provide one piece of a
131 more holistic and comprehensive assessment of ecosystem services across these land-use
132 scenarios (e.g., Thompson et al., 2014).

133 **2 Methods**

134 **2.1 Land-cover scenarios for New England in 2060**

135 McBride et al. (2017) and McBride et al. (2019) describe NELF’s participatory process
136 for co-developing scenarios of future land cover in New England in 2060. In brief, four narrative
137 land-use scenarios were co-designed in context with a “Recent Trends” scenario using a scenario
138 development process that engaged over 150 stakeholders (e.g., conservationists, planners,
139 resource managers, land owners, scientists, etc.) from throughout the region. The scenarios were
140 created using the Intuitive Logics approach, a structured process in which participants develop
141 plausible storylines describing a set of distinct alternative futures (Schwarz, 1991). The NELF
142 participants used this process to construct four scenarios – Go It Alone (GA), Connected
143 Communities (CC), Yankee Cosmopolitan (YC), and Growing Global (GG) – characterized by
144 extreme states of two driver variables: (1) low to high natural resource planning and innovation
145 and (2) local to global socio-economic connectedness (Table 1), which they determined to be
146 among the most uncertain and potentially impactful for the region. Storylines for each scenario

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147 are provided in Table 1, which is adapted from the detailed narratives available in Fallon
148 Lambert et al. (2018).

149 Land uses for the scenarios were simulated using the cellular land-cover-change model,
150 Dinamica EGO v.2.4.1 (Soares-Filho et al. 2009; Soares-Filho et al., 2013), using a process that
151 iterated between modelers and stakeholders to ensure that the resulting maps accurately
152 represented the stakeholders' intent (Thompson et al., 2017). The 50-year simulations have 30-
153 m resolution and span the years 2010 to 2060 in ten-year time steps. Land cover varies across
154 five classes: High Density Development, Low Density Development, Forest, Agriculture, and
155 Legally Protected Land (e.g., conservation easements). Other land-cover classes, such as water,
156 were held constant throughout the simulations. For the Recent Trends scenario, the rate and
157 spatial patterns of land-cover transitions were based on observed changes in classified Landsat
158 data between 1990 and 2010 (Olofsson et al. 2016; Thompson et al., 2017).

159 **2.2 Study watersheds – Cocheco River and Charles River**

160 To investigate the effects of these plausible landscape scenarios (Table 1) on streamflow,
161 we selected the Cocheco River watershed, defined by USGS gage 01072800, and the Charles
162 River watershed, defined by USGS gage 01104500 (Figure 1). The Cocheco River watershed in
163 southeastern New Hampshire was selected because it is in one of the most rapidly urbanizing
164 parts of New England. The watershed has an area of 207 km², and the main channel is 34 km in
165 length and drops 170 m in elevation from the headwaters to the gage at an elevation of 36.2 m.
166 Average annual precipitation is 1059 mm/year, and average streamflow is 3.14 cms, equivalent
167 to 479 mm/year. The Charles River flows through some of the most densely populated parts of
168 New England, and a SWAT model had previously been calibrated to study this watershed
169 (Cheng et al., 2017). The watershed has an area of 648 km², and it is flatter and more developed

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170 than the Cocheco watershed (Figure 1). The outlet elevation is 6.10 m, and the main channel
171 drops only 101 m over its 108-km length. Average annual precipitation is 1111 mm/year, and
172 average streamflow is 8.01 cms, equivalent to 389 mm/year. Figures 2 and 3 display the land
173 uses across the Cocheco River and Charles River watersheds for the landscape scenarios
174 described above. Table 2 reports the fraction of each land-use type within the watersheds.

175 **2.3 Hydrologic model – SWAT**

176 This project employed the Soil and Water Assessment Tool (SWAT; Arnold et al., 1998;
177 Nietsch et al., 2011) to represent the effects of land-cover differences on hydrology. SWAT is a
178 well-known and proven process-based model that represents weather, hydrology, growth and
179 seasonality of vegetation, and landscape management practices. It operates with a daily time
180 step, and space is represented in a semi-distributed way. Within a watershed, sub-basins are
181 linked via a stream network, and each sub-basin is represented by a collection of Hydrologic
182 Response Units (HRUs). Each HRU comprises a particular combination of soil, slope, land use,
183 and land management. Within a sub-basin, HRUs are not represented explicitly in space and do
184 not interact with each other, and water-balance equations are solved within each HRU. Incoming
185 precipitation is partitioned among canopy interception, storm runoff, and storage in the soil. Soil
186 water then contributes to lateral subsurface flow, groundwater return flow, and deep recharge.

187 In SWAT, ecosystem services related to hydrology and streamflow are affected by a few
188 parameters related to land use, including

- 189 • The curve number, the parameter in the Curve Number Method for estimating storm
190 runoff (USDA, 2004), which depends on soil and land use;

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191 • The fraction of impervious area and the fraction of impervious area that is directly
192 connected to storm sewer infrastructure; these parameters affect the aggregated curve
193 number for urban areas;

194 • Vegetation, which affects the seasonality and magnitude of evapotranspiration.

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

197 **2.3.1 Weather forcing**

198 Simulations were run in SWAT for twenty-year periods for both historical weather and a
199 future climate. The first three years of all simulations were used as a warm-up period and were
200 not used in subsequent analyses. The years were selected so that the final simulated years
201 coincided with the years of the landcover datasets plus the eight years before and the eight years
202 after (2002-2017 for the historical weather and 2052-2067 for the simulated future climate).

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

212 Precipitation and temperature data were used with the weather generator in SWAT (using
213 the WGEN_US_FirstOrder database) to simulate additional weather parameters, including

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214 relative humidity, wind speed, and solar radiation. The Penman-Monteith method was used to
215 estimate potential evapotranspiration (Arnold et al., 2012).

216 **2.3.2 Landscape features and watershed discretization**

217 Land-cover maps were derived from the NELF scenarios (McBride et al., 2017; McBride
218 et al., 2019; Plisinski et al., 2017). While the NELF scenarios combined water with wetlands
219 and considered swamps to be forests, we separated water and wetlands, and accounted for
220 herbaceous wetlands and swamps explicitly by extracting those land-cover types from the
221 National Land Cover Database (NLCD; Homer et al., 2015) and imposing them on the NELF
222 scenarios. Soil data were obtained from the SSURGO database (USDA, 2014). Three slope
223 classes were calculated for each watershed using natural class breaks; breakpoints of 5.7% and
224 14.1% were used for the Cocheco River watershed and 4.6% and 11.5% for the Charles River
225 watershed. To better represent the small land-use patches that are typical of the New England
226 landscape, we did not merge smaller HRUs with larger neighbors, as is sometimes done.

227 Land-cover differences in SWAT manifest predominantly as differences in plant growth
228 and evapotranspiration and in the generation of storm runoff via the curve number (Arnold et al.,
229 2012). We chose curve numbers (CN2) to reflect conditions in New England. Because there is
230 very little woodland pasturing in New England, we changed the CN2 values for generic forest
231 (FRST) from the default values in SWAT, which would be appropriate in forests subject to
232 grazing by livestock (“fair” condition), to those for forests without livestock grazing (“good”
233 condition). CN2 values for forest were 5, 55, 70, 77 for soil hydric classes A through D,
234 respectively.

235 The New England Landscape Futures use a single designation for all agricultural land,
236 and we do the same by using the generic agriculture land-cover (AGRL). The default curve

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237 numbers for AGRL in SWAT are appropriate for farmland dominated by corn or row crops,
238 while New England farms are primarily pasture and hay fields. Therefore, we updated this
239 parameter by using county-level data from the United States Agricultural Census (USDA, 2018)
240 to determine an area-weighted curve number based on the actual agricultural types. Resulting
241 curve numbers for our agricultural land use are 42.3, 65.1, 76.2, and 82.1 for soil hydric classes
242 A through D, respectively. Other parameters in SWAT's vegetation database (plant.dat) were
243 not changed.

244 Urban areas in the NELF scenarios are designated as either "high-density development"
245 or "low-density development." We consider these two classes to be analogous to Urban
246 Residential High Density (URHD) and Urban Residential Medium/Low Density (URML),
247 respectively, in SWAT. We calculated the fraction of impervious surface for all of New England
248 by overlaying the NLCD urban landcover types (Homer et al., 2015) on the NLCD 2011 Percent
249 Developed Imperviousness GIS layer (Xian et al., 2011) and calculating separate area-weighted
250 averages for URHD (consisting of the NLCD "Developed, High Intensity") and URML
251 (consisting of NLCD "Developed, Open Space", "Developed, Low Intensity", and "Developed
252 Medium Intensity"). This resulted in 88.9% impervious for URHD and 27.5% impervious for
253 URML in our simulations. For all scenarios except Connected Communities and Yankee
254 Cosmopolitan, the fractions of connected impervious area (i.e., the impervious area that is
255 directly connected to storm sewers) were left at SWAT's default values of 44% and 17%,
256 respectively, for URHD and URML. For Connected Communities and Yankee Cosmopolitan,
257 those numbers were halved to 22% and 8.5% to represent natural-resource innovation (Table 1)
258 and the implementation of green infrastructure, such as bioswales and rain gardens. CN2 values
259 for the pervious portions of these urban areas were set to 39, 61, 74, 80 for hydric classes A

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260 through D, respectively, since the pervious portions of New England's urban areas are usually
261 grass-covered lawns with greater than 75% grass cover (Arnold et al., 2012). No other values in
262 the urban.dat file were changed.

263 **2.3.3 Calibration and model performance under historic conditions**

264 To increase model performance and accuracy, parameters that were unrelated to land
265 cover within the SWAT model were calibrated by matching simulated streamflow to observed
266 streamflow under current land use. Model parameters were calibrated separately for each
267 watershed using observed flow for the years 2002-2011 and validated using the observed flow
268 from 2012-2017. Parameters that were explicitly related to land use, such as the curve number
269 and vegetation-related parameters, were not included in calibration, since they were our driver
270 variables of interest. We used a semi-automated approach with the SWAT Calibration and
271 Uncertainty Program (SWAT-CUP) using the SUFI-2 optimization method (Abbaspour, 2015).
272 Starting values for our calibration were either the default values in SWAT or the calibrated
273 results from an earlier study on the Charles River (Cheng, et al., 2017). We used the Nash-
274 Sutcliffe efficiency, percent bias, and the ratio of the root-mean-square error to the standard
275 deviation of the streamflow observations (RSR) as metrics of goodness-of-fit. Calibration
276 continued until none of the metrics improved by more than 5% over the previous iteration.

277 The final model for the Cocheco River had a NSE of 0.58, RSR of 0.64, and percent bias
278 of -13.6% for the calibration period. The model for the Charles River had values of 0.74, 0.51,
279 and 1.2%, respectively. Moriasi et al. (2007) suggest that a model can be viewed as satisfactory
280 if the NSE value is greater than 0.50, the RSR is less than 0.70, and the percent bias is less than
281 plus or minus 25%; the calibrated models for both rivers were deemed satisfactory. For the
282 validation period, the Cocheco River had a NSE of 0.49, RSR of 0.72, and percent bias of -

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283 19.5%, and the Charles River had values of 0.74, 0.51, and 23.3% respectively. Final parameters
284 and goodness-of-fit metrics are shown in Table 3.

285 **2.4 Streamflow metrics of interest**

286 Across scenarios and climates, we consider two metrics of hydrologic regulation. The
287 first is the water balance – the partitioning of precipitation among evapotranspiration, storm
288 runoff, and baseflow. Runoff and baseflow together constitute streamflow; storm runoff is the
289 rapid response to precipitation events, whereas baseflow represents the slower component of
290 streamflow driven by seasonal and interannual variability. The second metric is the annual
291 maximum daily flow. While true peak flows may be short-lived phenomena – on the scale of
292 minutes to hours – the annual maximum daily flow nonetheless provides an indication of the
293 potential for flooding and associated damage.

294 **3 Results**

295 **3.1 Water balance**

296 Across the simulations, land use has little effect on the average partitioning of
297 precipitation between evapotranspiration and streamflow (Figure 4). Under historic weather,
298 simulated evapotranspiration is 44-45% of precipitation in the Cocheco River watershed and 46-
299 48% of precipitation in the Charles River watershed with little variation among land-use
300 scenarios (Table 5). For the future climate, annual precipitation increases from 1059 mm to
301 1194 mm in the Cocheco River watershed and 1111 mm to 1345 mm in the Charles River
302 watershed, and potential evaporation decreases (Table 5). As a result, evaporation represents a
303 smaller fraction (35%-36%) of precipitation for the simulations with a future climate.

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304 While total streamflow is nearly unchanged across the land-use scenarios, the partitioning
305 of streamflow between baseflow and storm runoff does vary. In the Cocheco River watershed,
306 baseflow is 90-94% of streamflow for all land-use scenarios, except Growing Global, for both
307 historic and future weather. For Growing Global, baseflow is 74% and 78% of streamflow for
308 historic weather and a future climate, respectively. In the more developed Charles River
309 watershed, baseflow represents between 40% and 61% of streamflow under historic weather,
310 with the lowest fraction associated with the Growing Global scenario (Table 5). For the future
311 climate, both storm runoff and baseflow increase. As a fraction of streamflow, the baseflow
312 contribution increases by approximately 10% and shows variability across scenarios similar to
313 that under historic weather.

314 Seasonal water balances exhibit behavior similar to the annual water balances.
315 Differences in land use have little effect on the partitioning of water between streamflow and
316 evapotranspiration; rather, the effect is in the separation of streamflow into baseflow and storm
317 runoff (Table 6 and 7). The increases in streamflow associated with a future climate vary
318 seasonally, with large increases in autumn and winter, moderate increases in spring, and little
319 effect in summer (Figure 5). For historic weather, streamflow during the fall and winter
320 represents 40% and 44% of annual streamflow for the Cocheco River and Charles River
321 watersheds, respectively. Those fractions increase to 51% and 55% under a future climate
322 (Figure 5).

323 **3.2 Changes in magnitude of annual maximum daily flow**

324 The annual maximum daily flow (AMDF) exhibits significant year-to-year variability due
325 to variability in weather and precipitation. Under historic weather and land use, simulated
326 AMDFs range from 10.7 to 78.2 m³/s (equivalent to 4.5 to 32.7 mm/day) for the Cocheco River

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327 watershed and 15.5 to 94.0 m³/s (2.1 to 12.5 mm/day) for the Charles River watershed. Due to
328 this year-to-year variability, a paired comparison was used to quantify the effect of land use on
329 AMDF. For each year of simulation, the difference in AMDF between each future land-use
330 scenario and the land use from 2010 indicates the effect of land-use change on high flows.
331 Figures 6 and 7 present the average differences, along with their 95%-confidence intervals
332 determined via 10,000 bootstrap samples, expressed as a percent of the average AMDF under
333 land use in 2010.

334 Analysis of the difference in these flows between land use in 2010 and future scenarios
335 indicates that land-use change could have a moderate effect on the annual maximum daily flow
336 (Figures 6 and 7 and Table 8). Under the Growing Global scenario, the annual maximum daily
337 flows are approximately 10% larger than those under the historic land-use scenario. This result
338 is robust across both the Cocheco River and Charles River watersheds and both historic and
339 future climates. Effects under other land-use scenarios are more modest, with mean values
340 ranging from 0-4%.

341 While the AMDFs increase with increasing urbanization, the relationship depends on the
342 nature of the urbanization – whether high density or medium or low density – and the associated
343 increases in the fraction of impervious area (Figure 8). For example, while total urban area is
344 greater for both the Recent Trends and Go-It-Alone scenarios than for Connected Communities
345 (Table 2), the Connected Communities scenario has a higher proportion of high-density
346 development, and a comparable fraction of total impervious area (Table 8 and Figure 8). The
347 incorporation of green infrastructure, manifest as a lower fraction of directly connected
348 impervious area in the Yankee Cosmopolitan and Connected Communities scenarios, mitigates
349 the effect of urbanization on AMDF only slightly.

350 **4 Discussion**

351 **4.1 Differences among land-use scenarios**

352 Variations in the future land-use scenarios have little effect on the overall water balance
353 and provisioning of streamflow. The dominant effect of land-use is on the temporal regulating
354 service: partitioning streamflow between faster storm runoff and slower baseflow (Table 5 and
355 Figure 4). The effects on these services are similar across the two climates and two watersheds.
356 Increases in urban areas lead to more water moving quickly to the streams, which increases the
357 magnitude of the annual maximum daily discharge. This effect reaches a maximum of
358 approximately 10% for both the Cocheco and Charles River watersheds when comparing land
359 use in 2010 with the Growing Global scenario.

360 The relative sensitivity of AMDF to impervious area is 2% for the Cocheco River
361 watershed and 6% for the Charles River watershed (for both historic weather and a future
362 climate). Thus, a large change in impervious area is required to generate a noticeable effect on
363 the annual maximum daily flow (Table 8). These results are consistent with those of Hantush
364 and Kalin (2006) who found a relative sensitivity of AMDF to developed area of 2% in
365 Pennsylvania. Part of the reason for these limited sensitivities may be that high flows in New
366 England and the northeast occur predominantly in March and April when evapotranspiration is
367 low and the ground is saturated. Under such conditions, the regulating service associated with
368 infiltration is reduced. Sensitivity of AMDF to precipitation is much greater: 40-60% for the
369 Cocheco River watershed and over 80% for the Charles River. Even though the sensitivities are
370 quite different, the effects on AMDF of plausible future changes in land use or climate in 2060
371 are comparable, with effects due to land-use change reaching 10% and effects attributable to

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372 climate change of approximately 5% for the Cocheco River and 17% for the Charles River
373 (Table 8).

374 **4.2 Implications of findings for policy and design**

375 The results of this work indicate that the effects of climate and land use on runoff and
376 high flows are additive (Table 8). The combination of a wetter future climate and increased
377 urbanization has the potential to exacerbate high flows and flooding. While the results imply
378 that it would take a major reworking of the landscape to mitigate the effects of climate change,
379 they also indicate that rapid growth and development could present significant challenges for
380 stormwater management and existing infrastructure. If population growth is modest, land-use
381 decisions and development patterns have little effect on storm runoff and high flows (compare
382 scenarios CC and GA in Table 5 and Figures 6 and 7). However, when the future is
383 characterized by global socio-economic connectedness and increased population growth (Table
384 1), the results from the Yankee Cosmopolitan and Growing Global scenarios are substantively
385 different (Table 5 and Figures 6 and 7). In this case, urban planning and choices regarding land
386 use can have a large impact on regulating services and the potential for flooding. Planning for
387 smart and sustainable growth while concomitantly investing in multi-functional landscapes and
388 natural infrastructure could reduce flood damages. Additionally, with increased high flows,
389 communities may need to increase the size of their water infrastructure and/or allow for short
390 periods of inundation (Rosenzweig et al., 2018).

391 **4.3 Limitations of approach**

392 This study employs a hydrologic model to investigate the potential impacts of future
393 land-use scenarios on streamflow. As such, the utility of the results depends upon the

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394 appropriateness of the mathematical representation of watershed characteristics and processes.
395 SWAT is a well-established model, suitable for watershed applications, that has been and
396 continues to be employed in a number of studies and investigations. Nonetheless, there are some
397 inherent limitations of the model, and the results of this work should be interpreted within that
398 context.

399 First, some of the model parameters (such as available water content, hydraulic
400 conductivity, and surface runoff lag) are determined by calibrating the model to existing
401 conditions. Using the model to represent future land use presumes that those parameters are
402 unchanging across the scenarios. In most cases, we anticipate this to be true, as those parameters
403 are functions of soil, topography, or other watershed characteristics that are generally unchanged
404 as the land cover changes. Characteristics that do change with land use, such as the curve
405 number and vegetation cover, are not calibrated but determined a priori. Second, the temporal
406 resolution of this work is limited to the daily timescale. This precludes the representation of sub-
407 daily dynamics of precipitation and streamflow. Therefore, instantaneous peak streamflows
408 cannot be modeled, and this work is limited to daily discharge. Third, SWAT represents space in
409 a semi-distributed way. While the model accounts for spatial variations among watershed
410 characteristics, the HRU structure does not permit the representation of the spatial arrangement
411 and connectedness of landscape elements. Therefore, feedbacks and interactions among
412 different parts of the landscape cannot be represented explicitly. For example, increased runoff
413 from one HRU cannot infiltrate in a different HRU. Such interactions can only be represented
414 implicitly. Relatedly, storm runoff is represented with an approach that implicitly accounts for
415 effects of soil, land cover, and land management through a single parameter. This is consistent

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416 with large-scale analyses and is not intended for small-scale green-infrastructure evaluation.

417 Results from this work must be interpreted within the context of these modeling limitations.

418 **4.4 Next steps**

419 Our results reveal that potential changes to high flows are strongly connected to increases
420 in urban land uses in New England. To more precisely elucidate the effects of such changes in
421 land use and land cover, one could refine the representation of urban hydrology. Models such as
422 the Storm Water Management Model (SWMM) and HydroCAD are better equipped to represent
423 the natural and engineered features of an urban landscape, the sub-daily dynamics of the runoff
424 response to storm events, and the elements of green infrastructure at the site and local scales.
425 Such site-scale and sub-daily simulations of hydrological responses can further inform policy
426 and practice, and these more detailed studies will necessarily be narrower in geographic scope.
427 Continued engagement with stakeholders in the scenario-planning process can provide guidance
428 to locations of interest along with the level of risk and types of landscape and infrastructure
429 interventions that communities are willing to accept.

430 Finally, changes to nutrient and sediment loads are additional effects of changes to the
431 landscape that may be of interest to stakeholders in New England. SWAT could be employed
432 (for the Charles River, Cocheco River, or other watersheds) to investigate the effects of the
433 landscape scenarios on the export of nitrogen, phosphorus, and sediment. The effects on water
434 quality could be combined with our results on high flows to create a more complete picture of
435 the effects of landscape futures on water-related services.

436 **5 Conclusions**

437 Application of a hydrologic model to stakeholder-developed scenarios can provide
438 meaningful insight to the effects of plausible land-use changes on water-related ecosystem
439 services. The combination of land use and climate change on storm runoff, high flows, and
440 flooding are issues of concern, not only in New England but worldwide. Across the NELF
441 scenarios, variations in land use had little effect on the overall water balance. Rather, the impact
442 was on high flows and the partitioning of streamflow between storm runoff and baseflow. Those
443 effects were correlated with the amount of impervious cover. For most of the scenarios (GA,
444 CC, YC), the effects were muted and less than the effects due to climate change. For the
445 Growing Global scenario, however, the effects were large and comparable to or greater than the
446 effects of climate. These responses to land-cover change were similar across the Cocheco River
447 and Charles River watersheds. Results from this work can help inform designs and decisions
448 related to infrastructure resiliency and can complement other studies to provide a comprehensive
449 assessment of ecosystem services across possible future landscapes.

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8 Tables

Table 1. Storylines for New England Landscape Futures in 2060. Scenario icons and descriptions are adapted with permission from Fallon Lambert et al. (2018).

Table 2. Fractional land use across scenarios and watersheds.

Table 3. Calibrated parameters for SWAT models of the Cocheco River and Charles River watersheds.

Table 4. Goodness-of-fit for SWAT models of the Charles River and Cocheco River watersheds. 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).

Table 5. Average annual fluxes across simulations. HW and FC indicate simulations under historic weather and a future climate, respectively. 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.





Table 6. Seasonal evapotranspiration (ET), storm runoff (SR), and baseflow (BF), in mm, for the Cocheco River watershed.

Table 7. Seasonal evapotranspiration (ET), storm runoff (SR), and baseflow (BF), in mm, for the Charles River watershed.

Table 8. High-density urban area (URHD), medium/low density urban area (URML), impervious area, and average annual maximum daily flow across the simulations. 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.

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Table 1. Storylines for New England Landscape Futures in 2060. Scenario icons and descriptions are adapted with permission from Fallon Lambert et al. (2018).

	Local	Socio-economic connectedness	Global	
High	 <p>Connected Communities (CC)</p> <p>This is the story of how a shift towards 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 fifty 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 U.S. 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.</p> <p>Drivers: high natural resource planning and innovation; local socio-economic connectedness</p>	 <p>Yankee Cosmopolitan (YC)</p> <p>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 U.S. 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 U.S. Abundant forests remain a central part of New England's identity, and support increases in tourism, particularly in Vermont, Maine, and New Hampshire.</p> <p>Drivers: high natural resource planning and innovation; global socio-economic connectedness</p>		
	Natural resource planning and innovation	 <p>Go It Alone (GA)</p> <p>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.</p>	 <p>Growing Global (GG)</p> <p>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 towards privatization. Regional to national policies have promoted global trade but global agreements to address climate change have failed.</p> <p>In this scenario, by 2060, a steady stream of migrants has driven up New England's</p>	

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<p>Low</p>	<p>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 U.S. 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.</p> <p>Drivers: low natural resource planning and innovation; local socio-economic connectedness</p>	<p>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.</p> <p>Drivers: low natural resource planning and innovation; global socio-economic connectedness</p>
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Table 2. Fractional land use across scenarios and watersheds.

Watershed	Land-use scenario	% Urban	% Forest	% Agriculture
Cocheco	2010	14.3	75.5	4.4
	RT	22.8	66.7	4.7
	GA	16.1	73.8	4.3
	CC	14.6	74.3	5.3
	YC	39.6	49.9	4.7
	GG	65.7	18.6	9.8
Charles	2010	35.2	50.6	6.2
	RT	50.7	35.2	6.1
	GA	47.7	38.4	5.8
	CC	41.8	43.3	6.9
	YC	63.8	22.8	5.4
	GG	68.9	16.2	6.8

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Table 3. 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 H2O)	.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/hr)	.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/hr) for hydric class A	.sol	236.58	65.47
Saturated hydraulic conductivity (mm/hr) for hydric class B	.sol	391.94	492.62
Saturated hydraulic conductivity (mm/hr) for hydric class C	.sol	259.36	252.56
Saturated hydraulic conductivity (mm/hr) for hydric class D	.sol	321.95	343.35
Effective hydraulic conductivity in tributary channel alluvium (mm/hr)	.sub	170.37	330.13

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Table 4. Goodness-of-fit for SWAT models of the Charles River and Cocheco River watersheds. 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).

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

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Table 5. Average annual fluxes across simulations. HW and FC indicate simulations under historic weather and a future climate, respectively. 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.

Simulation			Precip mm	ET		Runoff		Baseflow ³	
Weather	Scenario	Watershed		mm	% ¹	mm	% ²	mm	% ²
HW	2010	Cocheco	1059	468	44%	44	8%	541	92%
HW	RT	Cocheco	1059	469	44%	57	10%	528	90%
HW	GA	Cocheco	1059	468	44%	48	8%	538	92%
HW	CC	Cocheco	1059	470	44%	38	6%	546	94%
HW	YC	Cocheco	1059	473	45%	58	10%	523	90%
HW	GG	Cocheco	1059	463	44%	152	26%	439	74%
HW	2010	Charles	1111	524	47%	197	39%	314	61%
HW	RT	Charles	1111	525	47%	228	45%	282	55%
HW	GA	Charles	1111	538	48%	221	44%	277	56%
HW	CC	Charles	1111	527	47%	202	40%	307	60%
HW	YC	Charles	1111	534	48%	219	44%	284	56%
HW	GG	Charles	1111	512	46%	317	60%	208	40%
FC	2010	Cocheco	1194	415	35%	53	7%	717	93%
FC	RT	Cocheco	1194	415	35%	66	9%	703	91%
FC	GA	Cocheco	1194	415	35%	56	7%	714	93%
FC	CC	Cocheco	1194	415	35%	48	6%	722	94%
FC	YC	Cocheco	1194	418	35%	71	9%	696	91%
FC	GG	Cocheco	1194	418	35%	168	22%	598	78%
FC	2010	Charles	1345	475	35%	231	29%	572	71%
FC	RT	Charles	1345	480	36%	269	34%	529	66%
FC	GA	Charles	1345	479	36%	261	33%	538	67%
FC	CC	Charles	1345	477	35%	245	31%	556	69%
FC	YC	Charles	1345	485	36%	265	33%	528	67%
FC	GG	Charles	1345	479	36%	379	47%	420	53%

¹ percentage of precipitation. ²percentage of total streamflow

³Baseflow calculated as Water Yield – Storm Runoff

Landscape scenarios and implications for streamflow in New England

Table 6. Seasonal evapotranspiration (ET), storm runoff (SR), and baseflow (BF), in mm, for the Cocheco River watershed.

	Historic Weather						Future Climate					
	2010 Land Use			Growing Global			2010 Land Use			Growing Global		
	ET	SR	BF	ET	SR	BF	ET	SR	BF	ET	SR	BF
Fall	93	11	126	92	41	105	84	11	155	82	36	125
Winter	29	6	94	27	22	73	20	19	203	18	52	161
Spring	129	19	196	122	56	155	118	18	247	112	60	209
Summer	218	8	125	222	34	107	193	5	112	206	21	103

Landscape scenarios and implications for streamflow in New England

Table 7. Seasonal evapotranspiration (ET), storm runoff (SR), and baseflow (BF), in mm, for the Charles River watershed.

	Historic Weather						Future Climate					
	2010 Land Use			Growing Global			2010 Land Use			Growing Global		
	ET	SR	BF	ET	SR	BF	ET	SR	BF	ET	SR	BF
Fall	113	42	42	115	70	25	94	59	115	96	95	76
Winter	43	43	100	42	69	70	34	72	192	34	115	144
Spring	129	66	121	124	102	84	130	60	186	128	99	145
Summer	239	45	51	232	76	30	217	41	79	221	71	55

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Table 8. High-density urban area (URHD), medium/low density urban area (URML), impervious area, and average annual maximum daily flows across the simulations. 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.

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

9 Figure Captions

Figure 1. Locations of the Cocheco River watershed and the Charles River watershed with land covers from 2010. [color]

Figure 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. [color]

Figure 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. [color]

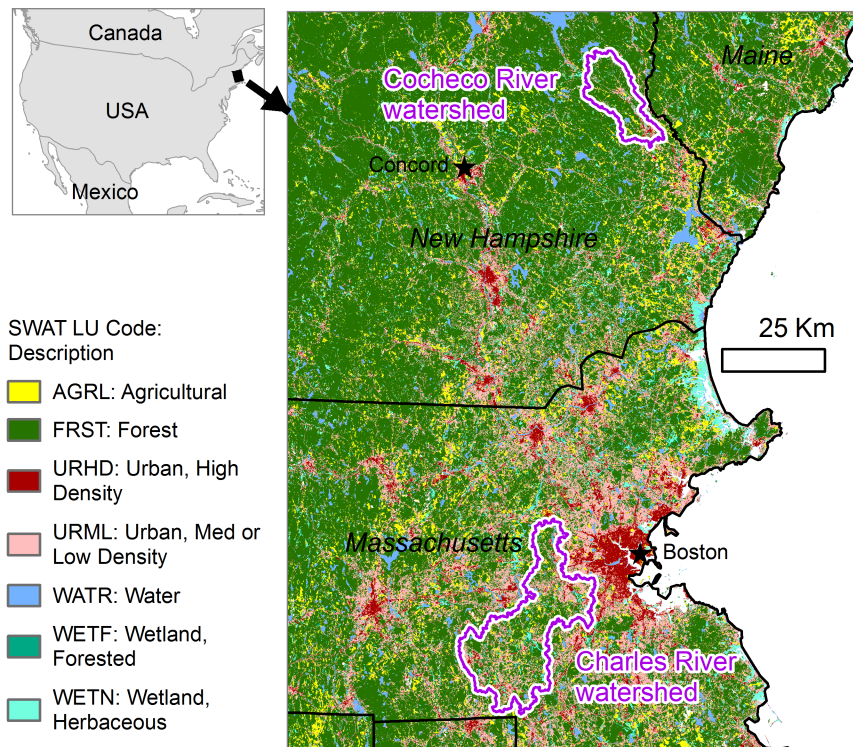
Figure 4. Average water balances for the Charles River and Cocheco River watersheds across scenarios and climates.

Figure 5. Seasonal water yield for the Cocheco and Charles River watersheds under for land use from 2010 and 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). [color]

Figure 6. Difference in annual maximum daily flow (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 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.

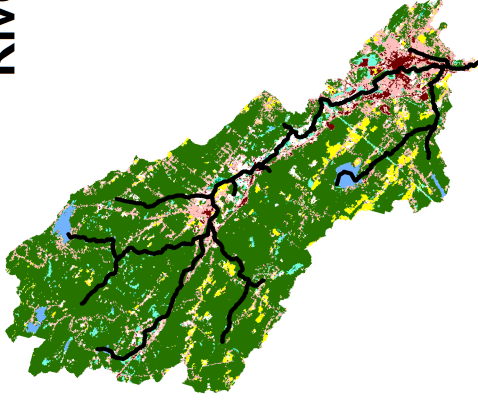
Figure 7. Difference in annual maximum daily flow (AMDF) between land-use scenarios and historic land use in 2010 for the Cocheco River watershed. Bars represent 95%-confidence limits determined via bootstrap, and the line in the middle represents the mean difference in AMDF between that scenario and 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.

Figure 8. Average annual maximum daily flow increases with impervious area. Land-use scenarios are indicated by letter codes: 2010 – historic land use in 2010, RT – Recent Trends, GA – Go It Alone, CC – Connected Communities, YC – Yankee Cosmopolitan, GG – Growing Global. Bold indicates simulations for a future climate and normal font represents historic weather. The larger font (and higher magnitude flows) are for the Charles River watershed, and the smaller font is for the Cocheco River watershed. For the Charles River watershed, results for Go It Alone, Connected Communities, and Recent Trends are very similar and plot on top of each other. For the Cocheco River watershed, results for Go It Alone, Connected Communities, and land use in 2010 are very similar and plot on top of each other.

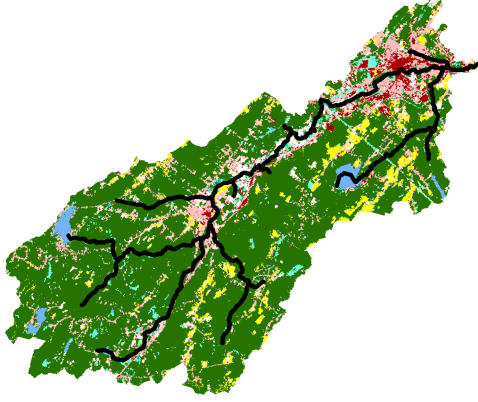


Cocheco River

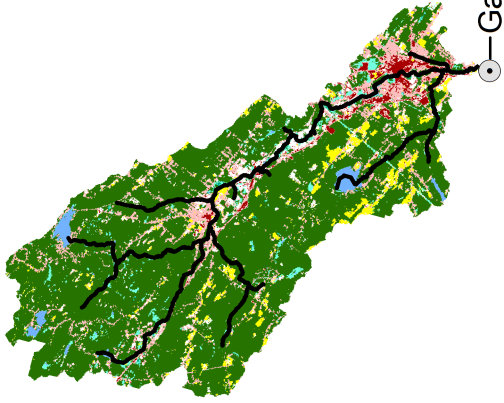
GA - Go It Alone



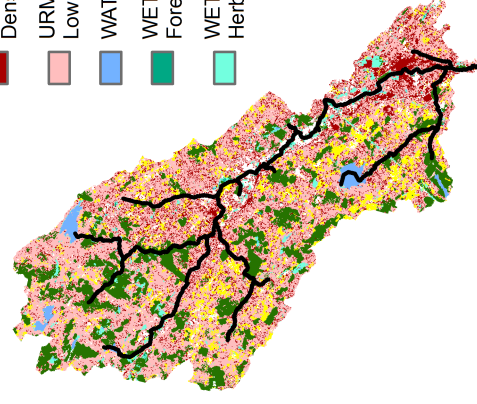
CC - Connected Communities



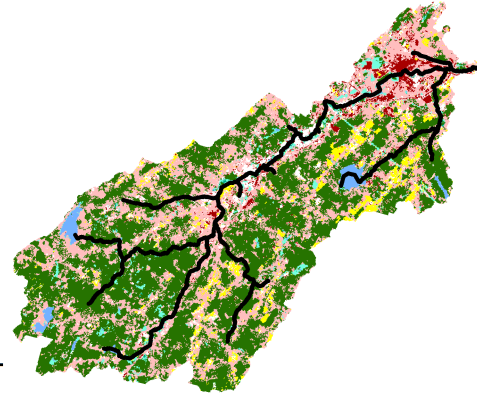
LU2010 - Actual Landuse



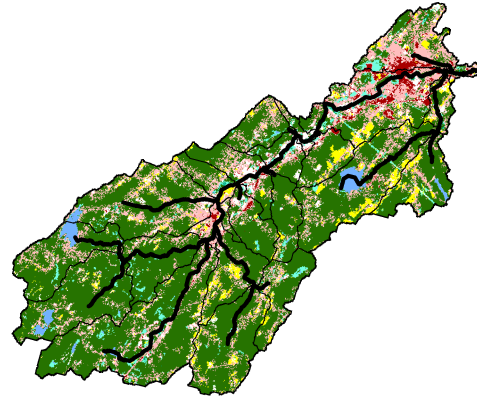
GG - Growing Global



YC - Yankee Cosmopolitan

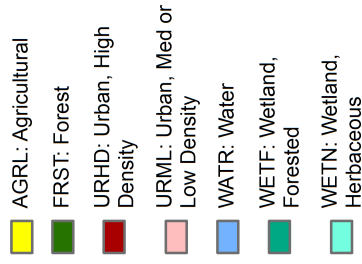



RT - Recent Trends



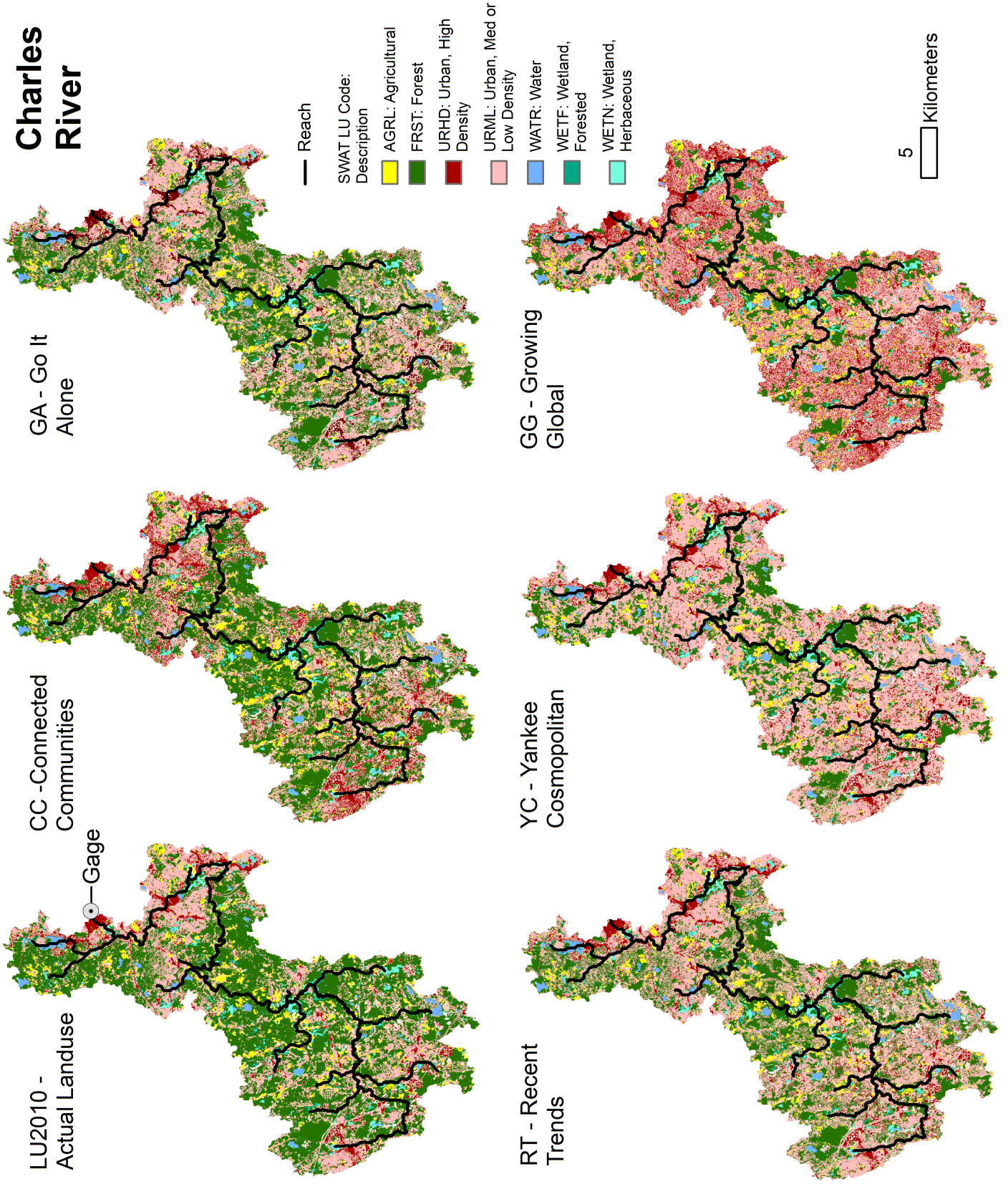
— Reach

SWAT LU Code:
Description

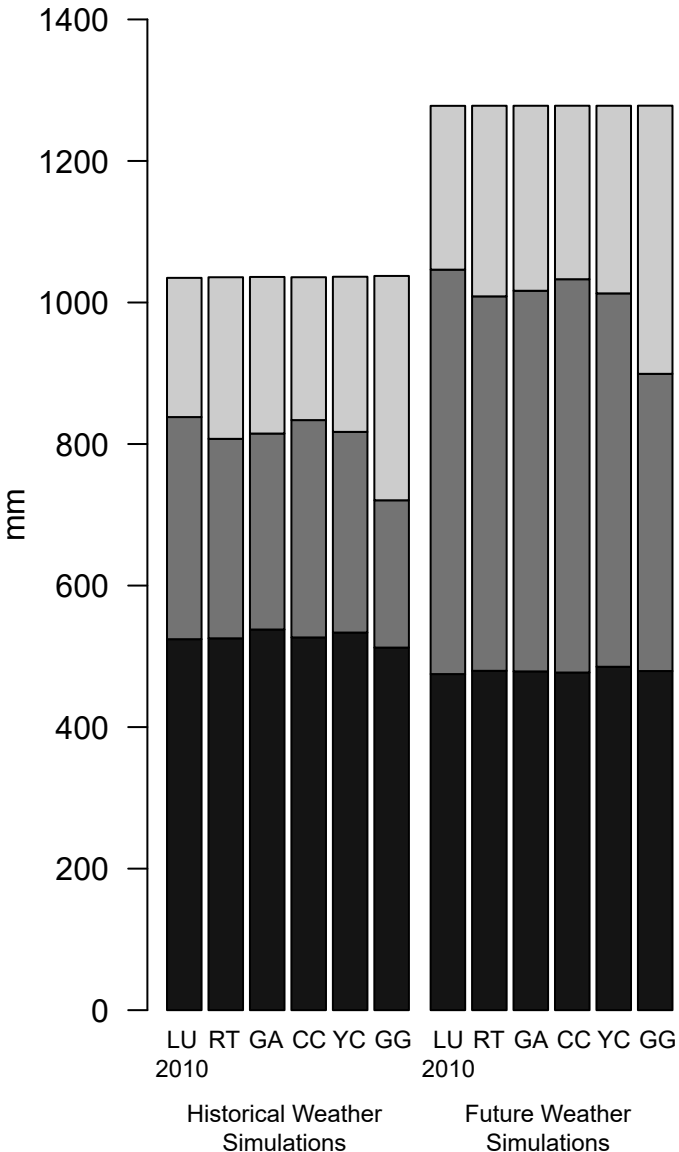


5  Kilometers

Charles River



Charles River



Cocheco River

