Climate change and land use impacts on hydrologic processes of watershed systems
Ammara Talib and Timothy O. Randhir

ABSTRACT

Land use, land cover and climate change (CC) can significantly influence the hydrologic balance and biogeochemical processes of watershed systems. These changes can alter interception, evapotranspiration (ET), infiltration, soil moisture, water balance, and biogeochemical cycling of carbon, nitrogen, and other elements. The need to evaluate the combined effect of land use change and CC of watershed systems is a focus of this study. We simulated watershed processes in the SuAsCo River watershed in MA, USA, using a calibrated and validated Hydrological Simulation Program Fortran model. Climatic scenarios included downscaled regional projections from Global Climate Model models. The Land Transformation Model was used to project land use. Combined change in land cover and climate cause 10% increase in peak volume with 7% increase in precipitation and 75% increase in effective impervious area. Climate and land use changes can intensify the water cycle and introduce seasonal changes in watershed systems. Understanding dynamic changes in watershed systems is critical for mitigation and adaptation options. We propose restoration strategies that can increase the resilience of watershed systems.

Key words | climate change, hydrologic processes, land use/land cover change, stormwater, watershed systems

INTRODUCTION

Inadequate water supplies and poor water quality are problems of increasing concern in watersheds, and climate and land cover change can exacerbate these issues. These impacts are observed as shocks to water balance that result in changes in evapotranspiration (ET), infiltration, and soil moisture (Kosmas et al. 1997; Santhi et al. 2006; Marshall & Randhir 2008a; Kim et al. 2013). This can lead to changes in runoff rate and volume, timing of spring and winter runoff events, groundwater recharge, baseflows, and intensity and frequency of floods and droughts (Pielke & Avissar 1990; Moscrip & Montgomery 1997). In addition to water balance and altered hydraulic conditions, climate change (CC) and human-induced landscape alteration can also affect water quality (Marshall & Randhir 2008a, 2008b). In the United States, for example, water quality of 35%, 45%, and 44% of assessed rivers, lakes, and estuaries, respectively, is impaired (US EPA 1999; IPCC 2014). Rate of evaporation is higher in forested areas because of higher leaf surface area, deeper roots than other vegetation, and higher surface aerodynamic roughness in forests (Farley et al. 2005; Calder 2007). Hence, reduction in forested land could lead to decrease in ET (Pielke & Avissar 1990; Lin et al. 2007; Fu et al. 2009), rate of interception, and water yield that governs soil moisture content, runoff, and baseflow patterns (Henderson-Sellers et al. 1995; Lin et al. 2007). These changes often result in more intense and frequent runoff
mainly caused by poor land use practices that compact soils and expose them to erosion, and decrease percolation into groundwater (Kosmas et al. 1997; Brath et al. 2006).

CC is another stressor to watershed systems. With continuation of the current emissions trajectory, the global mean surface temperatures would likely increase by 2.0 °C by mid-century and 3.7 °C by the end of the 21st century (IPCC 2014). In addition to increase in temperature, increase in precipitation is also expected in some regions (IPCC 2014). As a result, more runoff is expected in future for high-latitude regions, such as the north of Canada and the United States. When soil is saturated and rainfall rate exceeds the infiltration capacity of the soil, overland flow hydrographs may be intensified. Multiple lines of evidence have confirmed a trend towards reduced snowpack and earlier spring runoff in many parts of the United States (Milly et al. 2005; Milliman et al. 2008; Boyer et al. 2010; Vaze et al. 2010; Pederson et al. 2011; Schindler & Bruce 2012).

Watershed modeling (Albek et al. 2004; Dudula & Randhir 2016) remains an important tool in simulating processes to predict/or forecast stormwater flows for identifying adaptation practices. However, the complexities of watershed processes make it difficult to predict stormwater quality (Obropta & Kardos 2007). Hydrologic models such as ANSWERS (Beasley et al. 1980), AGNPS (Young et al. 1987), WEPP (Flanagan & Nearing 1995), PLOAD (Shen et al. 2011), EuroSEM (Morgan et al. 1998), Hydrological Simulation Program Fortran (HSPF; Bicknell et al. 1995; Albek et al. 2004), RUSLE (Renard et al. 1997) and SWAT (Santhi et al. 2006) are often used in combination with geographic information systems (GIS) for discharge simulations and sediment and nutrient transport studies. The HSPF Model is a robust, reliable, and comprehensive model commonly applied to flood forecasting and water quality modeling, as well as assessment of best management practices and sensitivity of streamflow to CC (Bicknell et al. 1993; Dudula & Randhir 2016).

An adequate amount of research has been conducted on the potential impacts of land use/land cover (LULC) change on hydrology (White & Greer 2006; Marshall & Randhir 2008a; Carey et al. 2011; De Girolamo & Lo Porto 2012) and of future CC on water resources (Marshall & Randhir 2008b). However, most of these studies do not integrate future land use configurations into their analysis. There are a very few studies that have analyzed the combined effects of climate and land use changes on water quality (Wilson & Weng 2011; Tong et al. 2012; Kim et al. 2013), but they extend only to 2030 (Wilson & Weng 2011) and to 2050 (Tong et al. 2012; Kim et al. 2013). As a result, the long-term synergistic impacts on surface water flows of future detailed urban land use configurations and trends, under various long-term climate emission scenarios, may be fuzzy (Wilson & Weng 2011; Cuo et al. 2013; Tran & O’Neill 2015). Integrated approaches are needed that are sensitive to LULC and CC to adequately represent hydrologic processes (Ewen & Parkin 1996; Choi & Deal 2008) in order to quantify impacts over longer time scales. Integrated models can provide information about watersheds that will be useful for making decisions regarding the development and management of water and land resources (Randhir & Tsvetkova 2011).

In this study, we use GIS and statistical and simulation modeling to assess the hydrologic response of a semi-urban watershed to combined influence of climate and land cover. The influence of LULC and CC on watershed systems was quantified under near and future scenarios. The Land Transformation Model (LTM) was used for future land use scenario; LTM estimates urban growth based on remote sensing data, artificial neural networks, and GIS (Pijanowski et al. 2006, 2014). Representative concentration pathways (RCPs), i.e., the scenarios based on the Fifth Assessment Report (AR5) of the IPCC (IPCC 2014), were used for CC modeling in this study. RCPs are a set of greenhouse gas concentration and emissions pathways designed to support research on the impacts of and potential policy responses to CC (Moss et al. 2010; Riahi et al. 2011; Van Vuuren et al. 2011).

This paper is unique in simulating combined influence of future climate and land use on watershed systems using the most recent land use and CC models. The general objective of this research is to evaluate the synergistic effects of LULC change and CC on water resources in a watershed system. Specific objectives are: (i) to calibrate and validate baseline stream discharge in the watershed system and (ii) to quantify the synergistic impacts of LULC and CC on runoff. Specific hypotheses are: (i) baseline simulations are significantly close to observed information (H0: $O_{Dկ} - S_{m} = 0$); (ii) combined impacts of
LULC change ($\Delta LULC$) and climate change ($\Delta CC$) on water quality and water quantity are significant (Ha: $\Delta WQ/ (\Delta CC + \Delta LULC) = \text{significant}$).

**METHODOLOGY**

**Study area**

The SuAsCo River watershed (Figure 1), combining the Sudbury, Assabet, and Concord tributaries, is a small semi-urban watershed in eastern Massachusetts and is one of the 27 major watersheds of the Commonwealth of Massachusetts, USA. It partially or wholly encompasses 36 Massachusetts towns. The total drainage area of the SuAsCo watershed is 1,012.69 km$^2$. The lower Concord River Basin is the portion of the basin that drains directly to the Concord River, which is at the confluence of the Sudbury and Assabet Rivers in the town of Concord. Mean annual streamflow from the basin at outlet NWIS gaging station, Concord River below River Meadow Brook (station no. 1099500), is about 421 Mgal/d.

The watershed has a humid continental climate, with warm summers and cold, snowy winters. Annual average precipitation is 1.21 meters. Mean annual temperature is 9.2 °C, with ET of 0.65 meters. The index of dryness, i.e. the ratio of potential ET to precipitation is 0.53. Predominant soil types in the watershed include fine sandy loam (34%), outcrop and urban land complex (24%), loamy sand (11%), and muck (10%). Soils of hydrologic groups A and D covers about 34.6% and 25.6% of the watershed respectively, while hydrologic groups C and B cover about 23.8% and 16.1%, respectively. Forest is the predominant land use in the watershed at 43% and 35% is in urban land uses. Wetlands, both forested and non-forested, constitute about 13% of the watershed. About 5% of the land use is for agriculture, pasture, and brush land.

**Conceptual model**

The conceptual model that represents the theory and data flows used in studying LULC and CC impacts is shown in Figure 2. Both abiotic (soil and topography, temperature, precipitation, moisture) and biotic factors (vegetation, population) contribute to environmental heterogeneity on the watershed scale. Changes in climate may cause changes in precipitation at the local scale; however, climate variability or human activities or both can cause changes in ET, surface runoff, infiltration, and active groundwater flow. All these variations in the hydrologic cycle have major implications for water resources management. Other than that, a range of variables, such as production and transportation costs, capital flows and investments, taxes, and subsidies, are defined by economic factors and policies. For example, better access to credit and markets as well as secure land tenure for farmers can encourage more deforestation instead of relieving pressure from deforestation.

To deal with disturbance in the hydrologic cycle, sustainable use of natural resources, a multi-sectoral approach to CC and LULC change, and transparency and accountability are necessary. Having said that, to study the impacts of stressors on the watershed scale, the HSPF model was chosen for this study to simulate watershed processes (Ribarova et al. 2008) and run at time-steps of less than a day (Bicknell et al. 2001). HSPF is a continuous simulation...
model based on the principle of conservation of water mass, that is, inflow equals outflow plus or minus any change in storage (Zarriello & Ries 2000).

**Data**

We used daily-flow data from the USGS gaging stations at four sites (Figure 1). The gaging station at the Concord River below River Meadow Brook in Lowell (station no. 01099500) was used for calibration for 1973–2008. Three other gaging stations were used for validation: Nashoba Brook near Acton (station no. 01097300) for 1973–2008, Assabet River at Maynard (station no. 01097000) for 1973–2008, and Sudbury River at Saxonville (station no. 01098530) for 1980–2008. Streamflows for all four gaging stations are in Data Set Number 1, 2, 5, 18 in the Watershed Data Management file.

Weather data are from three weather stations in and around the SuAsCo River watershed. The Worcester Weather Service Office Anomalous Propagation (Station no. MA 199923) weather station is located about 22 miles southwest from the center of the Sudbury and Assabet River Basins. Walpole 2 (Station no. 198757) is located about 19 miles southeast from the center of the Sudbury and Assabet River Basins. Bedford (Station no. MA 190535) is located about 5 miles to the southeast of the lower Concord river basin. Meteorological data, including precipitation, air temperature, dew-point temperature, solar radiation, and wind speed, were obtained from the National Climatic Data Center for three USGS stations: Bedford, Worcester WSO AP, and Walpole 2 from January 1973 to December 2008.

**Model calibration and validation**

The model was calibrated for a 36-year period from January 1, 1973, to December 31, 2008, by minimizing the differences between simulated and observed streamflow at the four stream gages in the model area. The range of calibrated parameters was comparable with the parameters from other calibrated models for neighboring watersheds, such as Ipswich (Zarriello & Ries 2000), Blackstone (Barbaro & Zarriello 2007), and Taunton River (Barbaro & Sorenson 2013), that share the similar land use type, and the study of the SuAsCo watershed by Zarriello et al. (2010).
We derived optimum parameter values using the calibration process with the HSPEXP tool (Lumb et al. 1994) using statistical criteria for daily, monthly, and yearly flows. Discharges measured at four gaging stations provided data for calibration and validation as described above under ‘Data’.

Calibration is done by adjusting relevant parameters to reduce differences between simulated and observed streamflow characteristics, such as volume error, highest flows and lowest flows, storm and seasonal volume error, low flow recession, summer and winter volume. $R^2$ and the Nash–Sutcliffe model efficiency coefficient ($E$) were used to measure the quality of the model fit. Hydrographs and flow-duration curves of the daily mean flow reflect climate, topography, and hydrogeologic conditions of the basin.

Statistical tests

Statistical tests were performed to compare simulated flow with observed flow from the gaging stations. Tests used were: (i) percentage flow difference (total model simulated flow – total observed flow)/total observed flow); (ii) regression coefficient, $R^2$; and (3) the Nash–Sutcliffe efficiency (NSE) (Nash & Sutcliffe 1970). The model efficiency or agreement between the observed and simulated daily discharge data series was measured by NSE: $\text{NSE} = 1 - \frac{\left( \sum_i^n (Q_{\text{sim}} - Q_{\text{obs}})^2 \right)}{\left( \sum_i^n (Q_{\text{obs}} - \bar{Q})^2 \right)}$, where $n$ is the number of time-steps, $Q_{\text{sim}}$ and $Q_{\text{obs}}$ the simulated and observed streamflow at time-step $i$, and $\bar{Q}$ the average observed streamflow over the simulation period.

LULC change and CC impacts

The LTM (Pijanowski et al. 2000, 2006) was used for predicting future land use. The LTM uses a set of spatial interaction rules and machine learning (artificial neural networks) to predict land use change at a township scale. Drivers such as transportation, urban infrastructure, and proximity to water bodies were used at spatially explicit scale, including historically contributing factors to land use change for 1300 townships, and stitched together in GIS. For CC, we use RCP scenarios (IPCC-AR5). To assess intermediate scenarios, we used RCP4.5 to assess the impacts of CC, using an estimated 2.7 °C increase of average annual temperature and 7% increase in precipitation in the watershed by the year 2100 (IPCC 2014).

RESULTS AND DISCUSSION

Baseline results

Results of calibration show that simulated streamflow measured at the gaging station in the Concord River below River Meadow Brook, Lowell, are in good agreement with observed flow over a wide range of flow conditions and seasons. The model fit for the daily, monthly, and yearly mean flows at this station have an $R^2$ of 0.79, 0.84, and 0.88, respectively, with NSE of 0.78, 0.83, and 0.71, respectively (Table 1). Simulated streamflow in the Sudbury River at the Saxonville stream gage is also in good agreement with observed flow over a wide range of flow conditions and seasons. The model fit for the daily, monthly, and yearly mean flows at this station have an $R^2$ of 0.75, 0.82, and 0.85 respectively, with NSE of 0.73, 0.79, and 0.54, respectively (Table 1). Simulated and observed flow-duration curves of streamflow at Nashoba stream gage are generally in close agreement. The model fit for the daily, monthly, and yearly mean flows at this station have an $R^2$ of 0.69, 0.76, and 0.62 respectively, and NSE of 0.67, 0.75, and 0.61 respectively (Table 1). Thus, the simulated model can represent the dynamics of the hydrograph well at daily, monthly, and yearly scales. Simulated streamflow in the Assabet River at the Maynard stream gage is in good agreement with the observed flow over a wide range of flow conditions and seasons. The model fit for the daily, monthly and yearly mean flows have an $R^2$ of 0.80, 0.84, and 0.78, respectively, and NSE of 0.78, 0.80, and 0.65, respectively (Table 1).

Combined influence of climate and land cover

To assess the combined impact of land cover change and CC, the model is run with LTM projected land cover (Table 2) and CC scenario (RCP 4.5) for periods 2035, 2065 and 2100. Figure 3(a) shows changes in annual average
water balance with future land cover and CC. Total runoff increased by 4%, 6%, and 7% by combined change in LULC and CC during 2035, 2065, and 2100, respectively (Figure 3(b)). In addition, surface runoff increased by 78% by the year 2100 (Table 3).

**Variation in ET, baseflow, interflow, and groundwater recharge**

Effective impervious area (EIA) is expected to increase by 26% in 2035 and 75% in 2100 from baseline levels. The increase in EIA, along with 50% decrease in forest area in 2100 caused increase in total discharge and surface runoff. Three percent reduction in ET could be attributed to anthropogenic land use changes and 2.7°C increase in temperature by 2100. Baseflow is expected to reduce by 6% by 2100 and interflow to increase by 8% in 2035 to 14% in 2100. With increases in direct runoff, a reduction in water available for soil moisture replenishment and for infiltration can be expected. Decrease in groundwater recharge and decrease in baseflow is expected in future because of increases in total runoff because of expected increase in impervious cover. The increased impervious cover in future has the potential to increase flood peaks during storm events and to decrease baseflows between storms.

**Table 1 | Calibration and validation statistics**

<table>
<thead>
<tr>
<th>Stream gage</th>
<th>R² (Daily)</th>
<th>NSE (Daily)</th>
<th>R² (Monthly)</th>
<th>NSE (Monthly)</th>
<th>R² (Yearly)</th>
<th>NSE (Yearly)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Calibration</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concord River below River Meadow Brook at Lowell</td>
<td>0.79</td>
<td>0.78</td>
<td>0.84</td>
<td>0.83</td>
<td>0.88</td>
<td>0.71</td>
</tr>
<tr>
<td><strong>Validation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sudbury River at Saxonville</td>
<td>0.75</td>
<td>0.73</td>
<td>0.82</td>
<td>0.79</td>
<td>0.85</td>
<td>0.54</td>
</tr>
<tr>
<td>Assabet River at Maynard</td>
<td>0.8</td>
<td>0.78</td>
<td>0.84</td>
<td>0.8</td>
<td>0.78</td>
<td>0.65</td>
</tr>
<tr>
<td>Assabet River at Nashoba Brook near Acton</td>
<td>0.69</td>
<td>0.67</td>
<td>0.76</td>
<td>0.75</td>
<td>0.62</td>
<td>0.61</td>
</tr>
</tbody>
</table>

NSE, Nash-Sutcliffe efficiency.

**Table 2 | Land use changes in the watershed**

<table>
<thead>
<tr>
<th>Land use</th>
<th>2035</th>
<th>2065</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area (acres)</td>
<td>Percent area (%)</td>
<td>Change from baseline (%)</td>
</tr>
<tr>
<td>Low density</td>
<td>37,850</td>
<td>15</td>
<td>22</td>
</tr>
<tr>
<td>Medium density</td>
<td>29,271</td>
<td>12</td>
<td>32</td>
</tr>
<tr>
<td>Public/transitional</td>
<td>16,559</td>
<td>7</td>
<td>24</td>
</tr>
<tr>
<td>Commercial/industrial</td>
<td>14,410</td>
<td>6</td>
<td>28</td>
</tr>
<tr>
<td>High density</td>
<td>13,432</td>
<td>5</td>
<td>27</td>
</tr>
<tr>
<td>Open water</td>
<td>8,078</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Agriculture/pasture</td>
<td>14,848</td>
<td>6</td>
<td>31</td>
</tr>
<tr>
<td>Wetlands</td>
<td>26,933</td>
<td>11</td>
<td>–18</td>
</tr>
<tr>
<td>Forest</td>
<td>88,263</td>
<td>35</td>
<td>–19</td>
</tr>
<tr>
<td>EIA</td>
<td>23,966</td>
<td>9.6</td>
<td>26.3</td>
</tr>
</tbody>
</table>

1 acre = 4046.86 m².
Monthly and seasonal changes in streamflows

Streamflow is expected to decrease during the months of April by 8% in 2035, 17% in 2065, and 19% in 2100 (Figure 4(a)). The highest decrease in streamflow is observed during April, which could be a result of 2.7 °C increase in temperature by 2100. On the other hand, streamflow was increased for the month of September by 13% in 2035, 23% in 2065, and 29% in 2100 (Figure 4(b)). A significant increase in streamflow is expected to occur between July and October because of the 7% increase in precipitation in 2100. A 2.7 °C rise in temperature would considerably reduce the snow storage reservoir during winter and thus largely contribute to a shift in flood events. For March and May, precipitation changes are compensated by changes in ET and thus streamflow may show insignificant change during the same period compared to other months. An increase in temperature could increase spring and summer ET and compensate for the increase in precipitation during summer resulting in minor changes in discharge. This increase in ET can be attributed to increase in daily

Table 3 | Predicted annual average streamflow values and percentage change for SuAsCo, MA, USA, in future land cover projections and CC scenario

<table>
<thead>
<tr>
<th>Streamflow</th>
<th>Units</th>
<th>2005</th>
<th>2035</th>
<th>Change from baseline (%)</th>
<th>2065</th>
<th>Change from baseline (%)</th>
<th>2100</th>
<th>Change from baseline (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total runoff</td>
<td>Inches</td>
<td>23</td>
<td>23.8</td>
<td>3.7</td>
<td>24.3</td>
<td>6</td>
<td>24.6</td>
<td>7.0</td>
</tr>
<tr>
<td>Surface runoff</td>
<td>Inches</td>
<td>3.2</td>
<td>4.2</td>
<td>28.4</td>
<td>4.9</td>
<td>51</td>
<td>5.8</td>
<td>78</td>
</tr>
<tr>
<td>Interflow</td>
<td>Inches</td>
<td>3.4</td>
<td>3.7</td>
<td>8</td>
<td>4.0</td>
<td>15</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>ET</td>
<td>Inches</td>
<td>20.1</td>
<td>19.9</td>
<td>-0.9</td>
<td>19.9</td>
<td>-1</td>
<td>19.4</td>
<td>-3.2</td>
</tr>
<tr>
<td>10% High flows</td>
<td>Inches</td>
<td>7.2</td>
<td>7.3</td>
<td>2.1</td>
<td>7.4</td>
<td>2.8</td>
<td>7.4</td>
<td>3.1</td>
</tr>
<tr>
<td>25% High flows</td>
<td>Inches</td>
<td>13.0</td>
<td>13.4</td>
<td>2.5</td>
<td>13.6</td>
<td>4.3</td>
<td>13.6</td>
<td>4.7</td>
</tr>
<tr>
<td>50% High flows</td>
<td>Inches</td>
<td>18.7</td>
<td>19.2</td>
<td>3.0</td>
<td>19.6</td>
<td>4.9</td>
<td>19.7</td>
<td>5.7</td>
</tr>
<tr>
<td>50% Low flows</td>
<td>Inches</td>
<td>4.3</td>
<td>4.6</td>
<td>6.5</td>
<td>4.7</td>
<td>9.9</td>
<td>4.9</td>
<td>12.7</td>
</tr>
<tr>
<td>25% Low flows</td>
<td>Inches</td>
<td>1.3</td>
<td>1.4</td>
<td>8</td>
<td>1.5</td>
<td>13</td>
<td>1.5</td>
<td>16.6</td>
</tr>
<tr>
<td>10% Low flows</td>
<td>Inches</td>
<td>0.3</td>
<td>0.4</td>
<td>8.2</td>
<td>0.4</td>
<td>13.7</td>
<td>0.4</td>
<td>17.4</td>
</tr>
<tr>
<td>Average storm peak volume</td>
<td>Cfs</td>
<td>2,045</td>
<td>2,163.6</td>
<td>6</td>
<td>2,218.5</td>
<td>8</td>
<td>2,257.6</td>
<td>10</td>
</tr>
<tr>
<td>Baseflow Recession rate</td>
<td>Inches</td>
<td>0.97</td>
<td>0.96</td>
<td>-0.4</td>
<td>0.96</td>
<td>-0.8</td>
<td>0.96</td>
<td>-0.1</td>
</tr>
<tr>
<td>Summer volume</td>
<td>Inches</td>
<td>3.2</td>
<td>3.5</td>
<td>8.2</td>
<td>3.72</td>
<td>14.5</td>
<td>3.84</td>
<td>18.4</td>
</tr>
<tr>
<td>Winter volume</td>
<td>Inches</td>
<td>6.8</td>
<td>7.37</td>
<td>8.4</td>
<td>7.8</td>
<td>14.8</td>
<td>7.9</td>
<td>15.8</td>
</tr>
<tr>
<td>Summer storms</td>
<td>Inches</td>
<td>0.51</td>
<td>0.56</td>
<td>9.2</td>
<td>0.59</td>
<td>16</td>
<td>0.61</td>
<td>20</td>
</tr>
<tr>
<td>Winter storms</td>
<td>Inches</td>
<td>1.79</td>
<td>1.85</td>
<td>3.4</td>
<td>1.87</td>
<td>4.8</td>
<td>1.87</td>
<td>5</td>
</tr>
</tbody>
</table>
mean air temperature, solar radiation, water vapor deficit, and decrease in humidity.

Overall, winter streamflow is increase by 5% of the baseline by 2100 in SuAsCo. Higher winter discharge is a result of intensified snowmelt and increased winter precipitation. The increase in siltation, crusting, and compaction of surface soil because of land cover change can lead to reduction in infiltration and to increase in stormwater runoff (Niehoff et al. 2002). When it comes to seasonal variation, increase in summer streamflow (about 20%) was higher than the winter storm. The expected increase in summer stormflow can be attributed to reduced potential ET in urbanizing areas compared to forested and agricultural areas. Thus, changing some of the forested land into urban land can result in increased runoff. There is a higher potential for infiltration in the summer than in the winter, especially, at the early phase of the storm event because storm events in the summer are generally preceded by dry soil conditions (Hundecha & Bárdossy 2004).

Changes in low flows and peak flows

Combined change in land cover and climate increased the frequency of 10% low flows (17.4%) more compared to 10% high flows (3.1%) (Table 3). These changes in high flows and low flows indicate potential increases in extremes in stormflows. This could be a result of variation in ET, resulting from changing temperature and increasing impervious cover, which accelerates hydrograph events. The variability can also be due to changes in snowmelt that increase winter and summer floods. Summer variability and winter volumes in flows increase by 18.4% and 15.8%, respectively (Table 3). Increase in winter floods may be because of increase in rainfall as snowfall and early melt contributing to melt water runoff contribution that could increase peak flows. Table 3 shows that mean peak discharge are expected to increase by 5.8% in 2035 and 10.4% in 2100 relative to baseline levels.

The increase in storm peak volume could be a result of the 7% increase in precipitation and 2.7 °C increase in temperature that is expected in 2100 and to a decrease in infiltration rate under future scenarios of land cover. It is clear that increase in precipitation and temperature in the near and far future has major effect on variability and timing of stormflows. In addition to climatic effects, land cover change with loss of vegetation cover and high rainfall intensities can increase siltation and reduce macropore connectivity (Niehoff et al. 2002). The runoff is expected to be higher because of reduced infiltration resulting from surface armoring in urban areas. This indicates an introduction of seasonal and overall variability in hydrologic processes needing investments and design of management practices that increase resilience of watershed systems.

General approaches to watershed-based restoration strategies

First, there is a need to develop an understanding of watershed components, processes, and water uses and users, and then to identify abiotic stressors (such as total phosphorus, total nitrogen, fish passage, altered hydrology) causing impairments or threats to water quality. The point sources for which a National Pollutant Discharge Elimination System (NPDES) is required need to be identified, as well
as the non-point sources not requiring an NPDES. It is cost effective to protect and restore watersheds based on problem ranking in sub-basins or priority areas. Then a list of management options can be developed, and some options can be eliminated that are not feasible on constraints and criterion. To achieve watershed restoration, it is helpful to set a timeline and interim milestones of protection implementation.

Altered hydrology (peak flow and low baseflow) in a watershed system can be managed by restored wetlands, conservation tillage, terraces, groundwater pumping reduction, and irrigation management. Strategies to reduce collapse of bluffs and erosion of streambanks by reducing peak flows include riparian forest buffers, livestock exclusion, and controlled stream crossings. Nitrogen load can be reduced by constructed wetlands, controlled drainage, woodchip bioreactors, and two-stage ditches. In addition, to reduce total phosphorus sewerage around lakes, elimination of straight pipes and surface seepages, injecting nutrients below the soil and hypolimnetic withdrawal can be helpful strategies. In addition to abiotic components of watersheds, there is a need for management plans for biotic components as well: examples include improving/increasing natural riparian habitat, two-stage ditches, dam operations to mimic natural conditions, restoration of natural meanders and complexity, and accurately size bridges and culverts to improve stream stability.

CONCLUSION

We evaluated stormwater runoff in the SuAsCo River watershed under future land use and CC scenarios. Combined future impacts of LULC and CC are likely to impact water resources and these impacts may be higher than their individual effects. CC and land cover change are expected to increase total runoff by about 4% by 2035, 6% by 2065, and 7% by 2100. Surface runoff may increase significantly from 28% of baseline in 2035 to 78% in 2100. This increase is because of a 75% increase in EIA and 50% reduction in forest area by the year 2100. There is need for reducing EIA through low impact development practices in urbanizing watersheds. Loss of forest cover is a critical issue that can be managed through forest conservation practices and use of zoning rules that regulate land use change in critical areas.

Combined change in land cover and climate are expected to cause 6% to 10% increase in average storm peak volume. A 7% increase in precipitation and 75% increase in EIA by 2100 are expected to increase average storm peak volume. Storm peak volume is expected to increase to 6% by 2035, 8% by 2065, and 10% by 2100. Increasing peak flow information needs to be a part of town planning and infrastructure design for stormwater. Town or city plans developed using historic data may not suit future impacts of land use and CC. In addition, old infrastructure designed may not be resilient to these peak volumes. The infrastructure includes stormwater systems, culverts, bridges, and flood channels, which need to be carefully evaluated and restored according to future emerging needs.

Winter streamflow is expected to increase by 5% from the baseline. Higher winter discharge can be a result of intensity of snowmelt and increased winter precipitation. However, the increase is summer stormflow (about 20%) is higher than winter stormflows. Streamflow is expected to decrease by 19% in April by 2100 and increase by 29% in September by 2100. The large decrease in streamflow occurred in April because of the 2.7°C increase in temperature. A significant increase in streamflow between July and October is because of 7% increased precipitation in 2100. For March and May, precipitation changes nearly compensated ET changes and streamflow showed minimal change during the same period compared to other months. Thus, increase in seasonal variation in hydrologic processes introduces uncertainty in watershed systems.

The results show that there is a need for adaptation plans to increase resilience of urbanizing watersheds under impending climate and land use change. Better comprehensive and sustainable watershed protection programs, including erosion and sediment control, stormwater management, and best management practices, could be designed to minimize future adverse impacts on flow and its implication on non-point source pollution (Randhir 2003). A comprehensive strategy of low impact developments, smart growth, and open space is critical to handle future changes to watershed systems. This needs a participatory approach as land use change impacts require
information sharing and cooperative approaches to implementing these strategies for sustaining watershed ecosystems.

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