Modeling the impacts of climate change and future land use variation on microbial transport

Rory Coffey, Brian Benham, Karen Kline, Mary Leigh Wolfe and Enda Cummins

ABSTRACT

The impact of waterborne micro-organisms (potentially pathogenic) on public health may be exacerbated by the combined effects of climate and land use change. We used watershed modeling to assess the potential effects of climate change and future land management scenarios on microbial water quality in the Pigg River watershed, located in southwest Virginia, USA. The hydrologic simulation program in Fortran, climate forecasts from the Consortium for Atlantic Regional Assessment, future projections for land management, and current watershed data were used to simulate a range of potential future scenarios for the period 2040–2069. Results indicate that changes in climate will have the most significant impact on microbial fate and transport, with increased loading driven by trends in seasonal and annual precipitation. High flow and low flow periods represent periods of greatest uncertainty. As climate factors are to an extent uncontrollable, adaptation measures targeting land based source loads will be required to maintain water quality within existing regulatory standards. In addition, new initiatives may need to be identified and incorporated into water policy. This is likely to have repercussions for all watershed inhabitants and stakeholders, but will assist in sustaining water quality standards and protecting human health.

Key words | climate change, land management, microbial transport, watershed modeling

INTRODUCTION

Based on current literature, no studies presently exist that utilize watershed modeling to directly assess potential effects of climate change and land use evolution on microbial fate and transport. This study represents an initial approach to assess future impacts on microbial loading in watersheds using readily available climate and land management data.

There is growing concern about the potential effects of climate change on water resources globally (Patz et al. 2005; Jennings et al. 2009; Whitehead et al. 2009; Vermeulen & Hofstra 2014). Emerging health threats associated with climate change are being linked to decline in global freshwater resources, chiefly as a result of increased water extraction and microbial contamination (Delpla et al. 2009; Balbus et al. 2013). The World Health Organization estimates that warming and precipitation trends due to anthropogenic climate change over the past 30 years already claim over 150,000 lives annually (Patz et al. 2005) and incidence in waterborne morbidity are expected to rise over the next century (El-Fadel et al. 2012). Although there is consensus about temperature increases, there is less certainty about the likely impacts on water quality due to changes in regional precipitation, particularly from extreme events (Whitehead et al. 2009; Benítez-Gilabert et al. 2010). To date, few research studies exist on possible impacts of climate change on microbial water quality (Boxall et al. 2009; Hofstra 2011; Coffey et al. 2013a; Vermeulen & Hofstra 2014).

Changes in water quality during storms or drought periods can cause conditions that exceed thresholds of ecosystem tolerance and, thus, lead to water-quality degradation (Murdoch et al. 2000; Whitehead et al. 2009; Delpla et al. 2011; Taner et al. 2011; Stuart et al. 2011; Coffey et al. 2013a).
In the USA, variable changes in temperature and the amount/intensity of precipitation have been observed during the last century (Groisman et al. 2005; Imhoff et al. 2007). Water temperatures are increasing in streams throughout the USA and more intense precipitation is causing increased microbial contamination in water sources (Kaushal et al. 2010; Hofstra 2011; Coffey et al. 2013a). For the mid-Atlantic region, increases in both temperature and precipitation are predicted to occur in future years (Najjar et al. 2010; Ning et al. 2012; Pitchford et al. 2012). These changes in climate will present additional risk of microbial contamination for water resources and watershed stakeholders in the region (Imhoff et al. 2007; Delpla et al. 2009). Increases in stream flow will ultimately affect the mobility and dilution of micro-organisms (Whitehead et al. 2009). In addition, simultaneous future changes in land use, population increase, and the evolution of agricultural production systems may also contribute to increased microbial contamination of surface waters (Tong & Chen 2002; Hampson et al. 2010; Hofstra 2011; Coffey et al. 2013a). The current level of scientific understanding in the area is limited, meaning the scale to which climate change will affect water quality and accompanying public and/or ecological health risk is uncertain (Delpla et al. 2009; Coffey et al. 2013a).

The need for a watershed-scale modeling approach to freshwater environmental change is recognized in many studies, reports and legislative frameworks (Wilby et al. 2006; Boxall et al. 2009; Delpla et al. 2009; Jennings et al. 2009; Parajuli 2010; Hofstra 2011; Chien et al. 2013; Coffey et al. 2013a). Investigative studies in this area are difficult and comprehensive analysis may only be achievable through the use of watershed-scale water-quality modeling applications that possess the capabilities to predict the effects of future climate scenarios efficiently (Boxall et al. 2009; Hofstra 2011; Coffey et al. 2013a). Modeling the effects of past and current land use composition and climatic patterns on surface water quality can provide valuable information for environmental and land planning (Tong & Chen 2002; Wilson & Weng 2011). However, gaining knowledge of possible climate change impacts on water resources is a complex process which depends on outputs from a variety of numerical models capable of describing processes in quantitative terms (Johnson & Weaver 2009; Candela et al. 2012; Coffey et al. 2013a). Simulating effects on hydrology is associated with large uncertainty from both climate projections and hydrologic modeling approaches (Murdoch et al. 2000; Wu et al. 2012; Luo et al. 2013; Coffey et al. 2013a). In addition, simulating microbial fate and transport utilizing watershed modeling applications is complex with many areas of ambiguity (Coffey et al. 2013a).

From the literature reviewed, key climate factors that should be considered when simulating climate change effects on surface water quantity and quality were found to be: increase in extreme events, flooding and rainfall totals; drought periods; higher air and surface water temperatures; and increased evapotranspiration. Extreme precipitation events are a key component of climate change and an important driver of water-quality episodes (Wilby et al. 2006; Whitehead et al. 2009; Boxall et al. 2009; Hofstra 2011). Future climate scenarios suggest increases in precipitation volume in larger events, while the smaller ones remained constant or decrease (Johnson & Weaver 2009; Johnson et al. 2011; Coffey et al. 2013a). Parallel future changes in land use, human population and agricultural production also need to be accounted for in model development (Boxall et al. 2009; Hofstra 2011; Coffey et al. 2013a). It was concluded that these scenarios would have significant impacts on the fate and transport of bacteria and needed to be included in any modeling effort. A scenario-based model development approach focusing on land use, climate variation and flow conditions was adopted as it was considered to represent the most viable means of evaluating impacts on microbial water quality in future years (Johnson & Weaver 2009; Coffey et al. 2013a). Hence, the objective of this study is to use watershed-scale modeling to assess the potential impacts of climate change and future land management scenarios on simulated in-stream microbial load.

**Study area**

Pigg River is a tributary of the Roanoke River in southwestern Virginia with a drainage area of 1,015 km² (see Figure 1). Story creek, Snow creek, and Big Chestnut creek are the main tributaries of Pigg River. The land use distribution in the watershed is mainly composed of forest (72%) but with a significant portion of agricultural land (26%). Residential areas compose a small portion of the
watershed (2%) and are clustered primarily around the towns of Rocky Mount and Ferrum, both located in the western part of the watershed. Pigg River flows east and discharges into Leesville Lake. Leesville Lake discharges to the Roanoke River, which flows into the Albemarle Sound; the Albemarle Sound discharges to the Atlantic Ocean.

The majority of the Pigg River watershed is in the Piedmont physiographic region and is composed of hills, irregular plains, and isolated ridges and mountains. Forests in this region are dominated by loblolly-short leaf pine, with some chestnut oak. Soils in the region are mainly ultisols, clayey and acidic. The dominant State Soil Geographic soil group in Pigg River is Cecil-Madison-Enon, characterized by deep and well-drained soils on varying slopes with clayey or loamy subsoil. These soils are moderately permeable.

The climate of the watershed was characterized based on the meteorological observations acquired at ‘nearby’ weather stations, including Rocky Mount, Chatham, Roanoke Regional Airport, and Lynchburg Airport. Data were drawn from Rocky Mount (located in sub watershed 19 - see Figure 1) where available; holes in the data or missing types of data were gathered from the remaining stations, in preferential order as listed above. Long-term climate records for the Rocky Mount area show an average annual precipitation of 1,132 mm, with 54% of the precipitation occurring during the cropping season (May–October). Average annual snowfall at Rocky Mount is 424 mm, with the highest snowfall occurring during January. Average annual daily temperature is 13.1 °C. The highest average daily temperature of 24 °C occurs in July, while the lowest average daily temperature of 2.1 °C occurs in January.

Potential fecal coliform sources in the Pigg River watershed were assessed using information from the following sources: Virginia Department of Environmental Quality (VADEQ), Virginia Department of Conservation and Recreation, Virginia Department of Game and Inland Fisheries, Virginia Department of Agricultural and Consumer Services, Virginia Cooperative Extension (VCE), Natural Resources Conservation Service, Soil and Water Conservation Districts, watershed reconnaissance and monitoring, published information, and professional judgment (Benham et al. 2006b). Livestock, manure application, wildlife, pets and failing septic systems are the main sources of non-point source fecal pollution (transported to water channel
via surface runoff). The estimated human population in the watershed was 22,129 people in 2006, with an average of 2.43 people per household (Benham et al. 2006b). Pastures receive the greatest portion of microbial load, at around 80% for the watershed. Factors such as precipitation amount and pattern, die-off rates, manure application activities, type of waste, and proximity to the streams impact the amount of fecal coliform from upland areas that reaches the streams. The amounts of bacteria produced in different locations (e.g., confinement, pasture, forest) were estimated on a monthly basis to account for seasonal variability in wildlife behavior, and livestock production and practices. Livestock management and production factors, such as the fraction of time cattle spend in confinement, pastures, or streams; the amount of manure storage; and spreading schedules for manure application, were considered on a monthly basis. One poultry operation exists in the Pigg River watershed (located in the lower Pigg watershed) with birds raised entirely in confinement. Professional judgment was used in estimating wildlife species contributions (point and non-point sources) in the watershed (Benham et al. 2006b).

A summary of this data is given in Table 1. There were an estimated 7,328 dairy cattle and 6,218 beef cattle in the watershed in 2006. Key point sources of contamination (deposited directly to streams) in the watershed include wastewater treatment plants (WWTPs) (2), straight pipes from residential housing (14) and direct deposits from cattle and wildlife defecating in the stream (point load per sub-watershed). Direct deposits due to both dairy and beef cattle increases during the warmer months, when cattle spend more time in water (Benham et al. 2006b). This time allocated per month is displayed in Table 6. Owing to their nature, direct point source loadings to streams are not modified before transmission to the stream.

### METHODS

#### Initial model development and calibration

The hydrological simulation program – Fortran (HSPF) (Bicknell et al. 2001) was used to simulate the fate and transport of fecal coliform bacteria in the Pigg River. The HSPF model simulates non-point source runoff and pollutant loadings, performs flow routing through streams, and simulates in-stream water-quality processes. HSPF estimates runoff from both pervious and impervious parts of the watershed and stream flow in the channel network. To identify localized sources of fecal coliform within the watershed, the Pigg River watershed was divided into 23 sub-watersheds based on homogeneity of land use, stream network connectivity, and monitoring station locations.

#### Hydrology

The hydrological component of HSPF was calibrated using weather data (at Rocky Mount) and flow data from 1 September 1989 to 31 December 1995; it was validated using data from 1 June 1984 to 31 August 1989. The output from the HSPF model for both calibration and validation was daily average flow in meters cubed per second (m$^3$·s$^{-1}$). Hydrologic parameters within HSPF were refined during model calibration and adjusted within the recommended ranges (USEPA 2000). The expert system for the calibration of HSPF (HSPEXP) was used to aid calibration. It uses over 55 rules involving over 80 conditions to recommend parameter adjustments. The rules are divided into four phases: annual volumes, low flows, storm flows, and seasonal flows. Criteria in subsequent phases are not tested until all rules in the previous phase are passed (Benham et al. 2006b).

For both calibration and validation time periods, summary statistics compared modeled and observed flow for

<table>
<thead>
<tr>
<th>Wildlife type</th>
<th>Population density</th>
<th>Direct fecal deposition in streams (%) (larger streams; smaller streams)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deer</td>
<td>1,1793</td>
<td>0.5%; 0.25%</td>
</tr>
<tr>
<td>Raccoon</td>
<td>8,665</td>
<td>5%; 2.5%</td>
</tr>
<tr>
<td>Muskrat</td>
<td>1,262</td>
<td>12.5%; 6.25%</td>
</tr>
<tr>
<td>Beaver</td>
<td>1,378</td>
<td>25%; 12.5%</td>
</tr>
<tr>
<td>Geese</td>
<td>3,658 – off season</td>
<td>12.5%; 6.25%</td>
</tr>
<tr>
<td></td>
<td>5,123 – peak season</td>
<td></td>
</tr>
<tr>
<td>Wood duck</td>
<td>2,927 – off season</td>
<td>12.5%; 6.25%</td>
</tr>
<tr>
<td></td>
<td>4,392 – peak season</td>
<td></td>
</tr>
<tr>
<td>Wild turkey</td>
<td>3,095</td>
<td>0%</td>
</tr>
</tbody>
</table>
total annual runoff, total of highest 10% flows, total of lowest 50% flows, total winter (December–February) runoff, total summer (June–August) runoff (all in inches). Error statistics for these criteria were calculated and compared with the quality criteria specified in HSPEXP (Benham et al. 2006b). Achieving these recommended HSPEXP error metrics is the main hydrological requirement by VADEQ for the development of bacteria total maximum daily loads models using HSPF. It is also suggested that the coefficient of determination ($R^2$ value) and Nash Sutcliffe efficiency (NSE) for observed versus modeled flow be calculated for both calibration and verification simulation periods subsequent to meeting HSPEXP criteria. The $R^2$ value indicates how consistently observed versus predicted values follow a best fit line (a value of 1 is a perfect linear relationship). The NSE indicates how consistently observed values match predicted values (range $-\infty$ to 1; 1 is the optimum) (Moriasi et al. 2007).

After calibration of the Pigg River watershed, the default criteria in HSPEXP were met for both the calibration and validation periods. A summary of the main hydrology calibration and validation statistics is displayed in Table 2. The simulated flow for both the calibration and validation matched the observed flow well (Figure 2). For the calibration period, the NSE was 0.44 and the $R^2$ was 0.46 for daily flow. The NSE was 0.57 and the $R^2$ was 0.57 for the validation period. Overall the calibration met all the acceptance criteria (HSPEXP, NSE, and $R^2$) in both the calibration and the validation period. This indicates that the developed hydrologic model provides an acceptable prediction of Pigg River flows.

### Bacteria

For the water-quality simulation, bacteria inputs from loads applied to the land surface were distributed monthly using the bacteria source load calculator (BSLC) (Zeckoski et al. 2005). The BSLC was also used to generate hourly direct deposit loads to streams. HSPF allows input of land loads as a monthly variable and direct deposit loads as an hourly variable. The HSPF water-quality calibration was performed at an hourly time step using the HSPF model. Observed water-quality data for Pigg River and its tributaries were available for many stations throughout the watershed. Data from water-quality station 4APG003.29 (collected by VADEQ) located near the watershed outlet (Figure 1) were the focus of bacteria calibration and validation.

The die-off rates of fecal coliforms and *Escherichia coli* in soil are affected by many factors including moisture content, and soil pH. Bacteria die-off on the land surface is considered to follow an exponential decay and will reach an asymptotic limit. This is represented via a limit on surface accumulation of bacteria. In each phase and landscape location, bacteria decay is exponentially derived with time as:

$$Bacteria(t) = bacteria(t-1) \cdot \exp(-K)$$ (1)

where bacteria($t$) is the bacteria count of a bacteria population in one phase at one location on day $t$, and $K$ is the decay rate ($d^{-1}$). The rate is a function of the temperature and the decay rate at 20°C (Benham et al. 2006a; Baffaut & Sadeghi 2010; Coffey et al. 2010, 2013b). In-stream die-off is

| Table 2 | Summary statistics for the calibration and validation for the Pigg River |
|---------|------------------|------------------|------------------|
|         | Simulated        | Observed         | Error (±10%)     |
|         | Cal   | Val   | Cal   | Val   | Cal   | Val   |
| Total runoff (mm) | 2,667 | 2,150 | 2,744 | 2,009 | -2.8  | +7.1  |
| Average annual total runoff (mm) | 444  | 410   | 457   | 383   | -2.7  | +7.1  |
| Total of highest 10% of flows (mm) | 1,014 | 865   | 1,041 | 845   | -2.6  | +2.4  |
| Total of lowest 50% of flows (mm) | 602   | 475  | 660   | 463   | -8.74 | +2.4  |
| Coefficient of determination, $R^2$ | Daily: cal = 0.46; val = 0.57 | Monthly: cal = 0.79; val = 0.85 |
| NSE    | Daily: cal = 0.44; val = 0.57 | Monthly: cal = 0.75; val = 0.83 |

Cal = calibration; Val = validation.
Figure 2 | Observed and simulated flows and precipitation for the Pigg River during the (a) calibration period, and (b) validation period.
modeled using a temperature-corrected first-order decay function. In HSPF and other watershed modeling applications (e.g., SWAT), temperature is the only environmental variable that is used to modify die-off. The rate of decay \( K \) is as follows (Mancini 1978):

\[
K(T) = K(20) \theta (T - 20)
\]

(2)

where \( K(20) \) = die-off rate at 20 °C (h\(^{-1}\)) (user specified), \( T = \) temperature (°C), and \( \theta = \) unitless temperature adjustment factor for first-order decay (user specified). This value is relatively constant at 1.07 in manure, soil and water.

The calibration period was 1994–1998; with the dates of the calibration period selected according to the period of observed record available. The initial execution of the Pigg River model showed very high bacteria concentrations across the watershed. Several input parameters were altered during the calibration process, i.e., wildlife direct deposits, cattle direct deposits, interflow/groundwater concentrations, wash off factor, and decay rates were adjusted prudently to meet the calibration. After adjusting selected input parameters, the observed and simulated data matched well for the calibration period (see Figure 3(a)).

The validation period was 1999–2005; again, the dates of validation were selected based on available data. The results of the validation are presented graphically in Figure 3(b). Because in-stream bacteria concentrations are typically sampled infrequently (on a monthly basis, at best) and represent only an instant in time, it is not reasonable to expect any model to simulate a daily average concentration equal to an observed value on a particular day (Kim et al. 2007). For this reason, a temporal-window statistic uses simulated hourly-concentrations over a period of 5 days to calculate the minimum–maximum range that is compared to observed in-stream bacteria concentrations. Each temporal window is centered on the day the observed data was collected. Thus, this measure of model calibration determines how frequently the observed data falls within the range of simulated data during a time period that extends 2 days before and after the observation. The reported calibration statistics and criteria (Table 3) are used to guide the water-quality model calibration process for simulation of in-stream bacteria concentration.

**Conceptual climate change and watershed modeling framework**

Modeling bacteria fate and transport using global circulation model (GCM) data at watershed scale is a complex process with many potential approaches. The methods used here are based on an approach by Johnson & Weaver (2009) and address three characteristics—linkages across both spatial and temporal scales, and across scientific and management disciplines. Variations in precipitation, temperature, evapotranspiration, and land management were identified as key future drivers influencing water-quality endpoints. Seasonal variability and precipitation volume/intensity/frequency were considered as vital components in driving non-point and point sources of bacteria loading. Figure 4 illustrates the framework that is used for model development.

**Development of climate change scenarios**

Climate modeling data are available from a variety of sources (e.g., the Intergovernmental Panel on Climate Change (IPCC) Data Distribution Center) (IPCC 2001). GCMs, provide credible temperature and precipitation projections for regions as large as North America, but are less suitable for distinguishing differences in climate within regions. In this study, climate modeling data available through Penn State University’s Consortium of Atlantic Regional Assessments project (CARA) (http://www.cara.psu.edu/) is used (Dempsey & Fisher 2005). This northeastern USA dataset provides information that can help decision makers understand how outcomes of future decisions could be affected by potential changes in both climate and land use (Dempsey & Fisher 2005). The CARA dataset is derived from GCM experiments archived by the IPCC but distributed in an accessible summary form. It emphasizes the uncertainty about future climate by showing the wide differences in temperature and precipitation projections from models that climate scientists find most credible seven models endorsed by the IPCC (IPCC 2001): (1) CCCM – Canadian Centre for Climate Modeling and Analysis; (2) CSIRO – Australia’s Commonwealth Scientific and Industrial Research Organisation; (3) ECHM – German High Performance Computing Centre for Climate and Earth System Research; (4) GFDL – Geophysical Fluid Dynamics Laboratory; (5) HadCM – Hadley Centre for
Figure 3 | Observed water quality data at station 4APGG003.29 plotted with the daily minimum, maximum, and average simulated values for the (a) calibration, and (b) validation periods.
Climate Prediction and Research; (6) NCAR – National Center for Atmospheric Research; (7) CCSR – University of Tokyo, Center for Climate System Research/National Institute for Environmental Studies.

Following Hewitson (2003), CARA smoothed the model output to obtain a coarse resolution dataset that more closely matches the skill resolution of the models. The data were then fit with a splined surface at 1/8° resolution for

Table 3 | Comparison of in-stream fecal coliform model calibration and validation statistics for the Pigg River outlet

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Criteria</th>
<th>Calibration (%)</th>
<th>Validation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>± 100%</td>
<td>− 71</td>
<td>− 70</td>
</tr>
<tr>
<td>Median</td>
<td>± 100%</td>
<td>− 23</td>
<td>− 1</td>
</tr>
<tr>
<td>Geometric mean</td>
<td>± 100%</td>
<td>− 47</td>
<td>1</td>
</tr>
<tr>
<td>% of observed (obs) values within 5 day min.-max. range</td>
<td>&gt; 70%</td>
<td>48</td>
<td>45</td>
</tr>
<tr>
<td>% of obs values &gt; 5 day max.</td>
<td>~ equal to % of obs values &lt;5-day min.</td>
<td>38</td>
<td>35</td>
</tr>
<tr>
<td>% of obs values &gt; 5 day min.</td>
<td>~ equal to % of obs values &gt;5-day max.</td>
<td>14</td>
<td>21</td>
</tr>
</tbody>
</table>

Source: (Kim et al. 2007).

Figure 4 | Methodology to simulate bacteria fate and transport in future climate and land management scenarios.

Greenhouse gases data
B2 Emissions Scenario
Assumes moderate population growth/energy use, moderate technological progress and a local focus

Climate Change data
Variations in temperature and precipitation

SOURCE
Consortium for Atlantic Regional Assessment (CARA)
- 7 Global Climate Model (GCM) outputs-average
- Interpolated to 1/8 degree resolution for Rocky Mount station
- Historical data – 1971 to 2000; Future data – 2013 to 2099

Future Land management data
Human population and agricultural production

SOFTWARE
BASINS Climate Assessment Tool (BASINS CAT) & MS Excel
Perturb existing weather data based on CARA data downscaled for Rocky Mount (2040 – 2069):
- Increases in rainfall totals
- Increase in extreme events
- Incorporate drought periods
- Account for seasonal variation

SOFTWARE
Bacteria Source Load Calculator (BSLC)
Update current statistics on human population & agricultural production for Pigg river watershed (2040 -2069):
- Increased livestock densities + manure production
- Increase in human population + wastewater production
- Adjust land use area for residential and agriculture

Simulation of potential scenarios and future microbial loads
mapping (Hewitson 2003) and to obtain model output at the historical climate network (HCN) stations in the northeastern United States region. The approach used provides a simple but effective form of spatial and temporal downscaling, whereby GCM data of coarse spatial resolution were interpolated to a particular HCN. For the entire region, CARA provides historical climate records as well as future projections. Seasonal and annual observations covering the past 100 years are provided for 114 HCN stations within the region, plus 67 neighboring stations (Dempsey & Fisher 2005). Data are provided for each HCN station (including Rocky Mount, located within the study watershed), comparing observations with projections for past time periods (1911–1940, 1941–1970, and 1971–2000), as well as showing projections for three future time periods (2010–2039, 2040–2069, and 2070–2099) (Dempsey & Fisher 2005). The data averaged for each season of the year, and interpolated spatially from the original GCM grid resolution to 1/8° resolution (Johnson & Weaver 2009).

For this study, the downscaled CARA projections for precipitation and temperature at Rocky Mount HCN weather station (National Climatic Data Center station: COOP-447338), within Pigg River watershed were used. Simulated future changes in temperature and precipitation totals were examined for the period 2040–2069 from GCM data, downscaled by CARA. One IPCC future greenhouse gas emission storyline, B2 [moderate population growth and energy use, moderate technological progress, and a local focus; (IPCC 2003)] was used as it was considered to be the most prospective scenario for the location, considering population density and economic forecasts for the region. Seasonal climate change statistics were calculated using the difference in the 2040–2069 and 1971–2000 climate model simulation periods at Rocky Mount. This was based on the ensemble average of the seven GCMs for seasonal projections of temperature and precipitation; thus creating one climate scenario. The approach is similar to methods used by Christensen & Lattenmaier (2006) to assess hydrology impacts by considering ensemble averages of numerous GCMs. The data reflect climate impacts forecasted by the CARA dataset, and is used to perturb existing records of hourly observed precipitation and temperature (the historical time series 1985–2005) at Rocky Mount HCN used for model calibration and validation (hydrology: 1985–1995; bacteria: 1994–2005). Creating a climate change scenario in this way, by modifying historical records, permitted any spatial variability in climate change to be captured while maintaining the existing spatial correlation structure.

**Future temperature and precipitation trends**

Climate change impacts on the Pigg River watershed were assessed using GCM-produced, downscaled precipitation and temperature from CARA at Rocky Mount HCN station. For temperature, the existing time series used in model calibration/validation (1985–2005: hourly average hourly temperature in °C) is adjusted (addition/subtraction) to reflect projected seasonal and annual variations estimated in GCM projections. Future potential evapotranspiration (PET) was computed using updated temperature projections. These future temperature forecasts were input to the watershed data management utility software to create realizations based on hourly statistics conditional to the temperature series (Hummel et al. 2001). Two types of evaporation/evapotranspiration are required for input to HSPF: potential evaporation from a reach or reservoir surface (EVAP), represented as Penman pan evaporation; and potential evapotranspiration (PEVT), represented as Hamon potential evapotranspiration.

It is generally expected that as climate changes, a greater proportion of annual precipitation will occur in larger magnitude events (IPCC 2007). More intense precipitation will contribute a greater fraction to direct runoff and may also cause a non-linear increase in sediment erosion and pollutant loading (Groisman et al. 2005; Kundzewicz et al. 2007). The CARA dataset, however, did not provide information about which events would be most affected. To address this and capture a range of plausible changes in event intensity, climate change adjustments are made separately to precipitation events ≥70th percentile and events <70th percentile, while maintaining the precipitation mass balance (Johnson & Weaver 2009; Johnson et al. 2011). The net effect of this is an increase in the proportion of annual precipitation coming from larger events. These assumptions, about which events will be most affected by future changes, capture a range consistent with observed trends during the 20th century. During this period, there was a general trend throughout the USA toward increases
in the proportion of annual precipitation occurring in roughly the largest 50% magnitude events (Groisman et al. 2005).

To assess impacts on water quality, ensemble GCM projections (annual and seasonal) were used to update existing weather data used for initial model calibration and validation. The mean change in temperature was 2–42% over different seasons. Mean variations in precipitations were –3–51% for different seasons. A summary of ensemble precipitation and temperature changes (annual and seasonal-based on the B2 emissions scenario) considering the seven GCMs is shown in Table 4. Existing weather data were subsequently modified to reflect the data and to account for an increase in the frequency and intensity of extreme events.

Development of land management scenarios

The impacts of land use change on watersheds are pervasive and widespread across the USA; residential and urban development is a growing concern (Walsh et al. 2005; Walsh et al. 2005; Franklin County 2007; UVaWCCPS 2013). Future changes in agricultural production, ecosystem dynamics, and the management of point source contamination are also important factors affecting bacteria fate and transport. Furthermore, because climate change and land use variation may have similar impact profiles in certain locations (e.g., changes could lead to higher peaks and lower low-flow conditions), the management of land use impacts is a potentially important adaptive strategy for increasing resilience to climate change (Johnson et al. 2011). To explore the potential interaction of land use and climate change in the Pigg River watershed, the effects of future residential development and agricultural production are assessed in modeling scenarios.

Table 4 | Predicted potential annual and seasonal changes in temperature and precipitation in Pigg River watershed based on ensemble data from the CARA

<table>
<thead>
<tr>
<th>Variable</th>
<th>Predicted annual and seasonal change for the period 2040–2069</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annual (%)</td>
</tr>
<tr>
<td>Temperature</td>
<td>12</td>
</tr>
<tr>
<td>Precipitation</td>
<td>13</td>
</tr>
</tbody>
</table>

Urban and residential development scenarios for the Pigg River watersheds are derived from the University of Virginia-Demographics Research Group, (Dempsey & Fisher 2005; Franklin County 2007; UVaWCCPS 2013). Future variations in agricultural production and land use are based on United States Department of Agriculture projections (Franklin County 2007; Westcott & Trostle 2013). Future bacteria source data for human populations and agricultural production will be updated and incorporated into the BSLC. The BSLC uses externally generated inputs, such as land use distribution and livestock and human population estimates, to calculate monthly bacterial land loadings and hourly bacterial stream loadings. This aids in source characterization and scenario development; and produces source load data for bacteria in a format that can be utilized by HSPF to simulate the fate and transport of bacteria in tandem with future climate change projections from the CARA data. To be consistent with the climate change scenarios, data utilized were considered representative of the period 2040–2069.

To estimate changes in human population for the Pigg River watershed, data from the demographics Research Group in the Weldon Cooper Center for Public Service at the University of Virginia was assessed (UVaWCCPS 2013). In Franklin county, the human population is expected to increase by approximately 32% by 2050, and in Pittsylvania county the human population is projected to increase by 3% (UVaWCCPS 2013). The area of residential land use in the study location was subsequently increased to reflect the higher future human population. An area-weighted reduction in other land uses (forest, cropland, and pasture) was estimated to account for the increase in residential land use (32 or 5%) in each sub-watershed. It is assumed that the septic system failure rate will remain constant over time. Two WWTPs are located in the watershed at Ferrum and Rocky Mount. Analysis of current discharge data indicates that neither WWTP would exceed their permitted discharge rate despite increases in human population. The maximum permitted discharge rate was used for simulations. It is also assumed that no straight pipes will exist in the watershed by 2050 (due to the implementation of the TMDL program).

Limited data were available on potential changes in agricultural production up to 2050 and estimates used were
based on available data, and best judgment. Future changes in livestock and crop production were derived from the USDA agricultural projections to 2022 (Westcott & Trostle 2013). This data reflected the USA nationally and no specific data for the state of Virginia was available. It was assumed that the trends projected up to 2022 would continue to 2050 (i.e. if there was an increase of 2% up 2022, then by 2050 there would be an increase of ~4% – double the 2022 projection). From available information, it was estimated that there would be an 18% increase in beef cows by 2050. For dairy cows, it was calculated that there would be a 6% decrease in numbers (due to continuously increasing milk yields per cow). Poultry numbers are projected to increase by approximately 12%. The area of crops grown is expected to decrease by 5%. Area reductions in cropland were added to pasture (based on land uses in each sub-watershed) to compensate for an increase in the number of beef cows. A summary of potential future changes in bacteria sources and future land use scenarios for the watershed is detailed in Table 5.

As increased air temperatures are predicted to occur in future years, it is expected that cattle will consume higher quantities of water and spend more time in unrestricted surface waters to reduce thermal stress (Nardone et al. 2010). This will elevate the probability of fecal matter being deposited directly to streams (Coffey et al. 2013a). To account for this scenario, existing data from the BSCLC on hours spent by livestock in streams (Zeckoski et al. 2005) was updated to reflect future increases in temperature for individual seasons. The data used in existing (baseline) and future simulations are given in Table 6. Owing to the uncertainty and lack of prudent data on current wildlife populations in Table 5

<table>
<thead>
<tr>
<th>Bacteria source</th>
<th>Change in population 2010–2050</th>
<th>Literature source</th>
<th>Assumptions</th>
<th>Land use</th>
<th>Land use scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human</td>
<td>32%; 3%</td>
<td>UVaWCCPS (2015)</td>
<td>No straight pipes; wastewater treatment plant discharge unchanged</td>
<td>Residential</td>
<td>Increase in residential land use correlated to population rise</td>
</tr>
<tr>
<td>Beef cows</td>
<td>18%</td>
<td>Westcott &amp; Trostle (2013)</td>
<td>Livestock direct deposits adjusted based on future temperature rise</td>
<td>Pasture</td>
<td>Increase in pasture land from reduction in cropland</td>
</tr>
<tr>
<td>Dairy cows</td>
<td>– 6%</td>
<td>Westcott &amp; Trostle (2013)</td>
<td>Trend to 2022 used to estimate 2050 changes</td>
<td>Confined</td>
<td>–</td>
</tr>
<tr>
<td>Poultry</td>
<td>12%</td>
<td>Westcott &amp; Trostle (2013)</td>
<td>Trend to 2022 used to estimate 2050 changes</td>
<td>Cropland</td>
<td>Cropland area decreased and added to pasture in each sub watershed</td>
</tr>
<tr>
<td>Crops</td>
<td>– 5%</td>
<td>Westcott &amp; Trostle (2013)</td>
<td>Trend to 2022 used to estimate 2050 changes</td>
<td>Forestry</td>
<td>Forest area reduced to account for residential area increase</td>
</tr>
</tbody>
</table>

*Increase from area weighted decrease in other land uses (forest, cropland, and pasture).

Table 6 | Current and future estimates of hours per day spent in stream by livestock

<table>
<thead>
<tr>
<th>Livestock direct deposits: hours/day spent in stream</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing (baseline)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.8</td>
<td>1.0</td>
<td>1.5</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>1.5</td>
<td>1.0</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>Future</td>
<td>0.7</td>
<td>0.7</td>
<td>0.9</td>
<td>1.2</td>
<td>1.7</td>
<td>3.6</td>
<td>3.6</td>
<td>3.6</td>
<td>1.6</td>
<td>1.1</td>
<td>0.8</td>
<td>0.7</td>
</tr>
</tbody>
</table>
the watershed, it was assumed that numbers remain constant (as per calibration) for simulation of future scenarios in this study.

RESULTS

The results presented here examine changes in future stream flow and microbial load (based on projected variations in climate and land use for the 2040–2069) for an equivalent existing period from model calibration, referred to as the ‘baseline period’. For stream flow, the baseline simulation period represents the calibrated and validated model hydrology from 1985 to 1996. For bacteria, the baseline period represents the calibrated and validated water-quality model from 1994 to 2005. In this section, the variations in daily stream flow and the total daily microbial load (seasonally and annually) are assessed.

Future hydrological assessment with HSPF

Using HSPF, we assessed the impact of the selected environmental change scenarios on hydrology and fecal coliform loading in the Pigg River watershed. As a result of the increased annual precipitation and temperature forecast (Table 3), annual stream flows were expected to increase. Seasonal climate projections suggested an increase in stream flow in winter and fall. For spring and summer, future climate data indicated a slight reduction in flow. The mean daily flow for Pigg River increased from 13.16 to 13.74 m$^3$ s$^{-1}$ (+4%) at the outlet when precipitation data was updated to reflect future projections. Average annual runoff increased by 14% (418–478 mm). The rate of evapotranspiration increased by 18% and reflects the seasonal increases in temperature projected by the CARA dataset. Details of potential changes in the hydrology are given in Table 7. A breakdown of changes in monthly flow is given in Table 8. Increases in monthly runoff are evident in winter and fall. For spring and summer, there is a decrease in monthly runoff. This data are in line with seasonal projections in precipitation.

A cumulative frequency curve comparing simulated future flow with simulated baseline flow is displayed in Figure 5. Peak flows increased by 20–21% for high flows. For low flows, there was a decrease of 18–31%. Seasonal adjustments to rainfall are also replicated in the time series hydrograph (Figure 6), with less intense events in Spring/Summer (due to the forecasted slight reduction in precipitation and an increase in ET) and more precipitation in Fall/Winter. Overall, the hydrology results reflect the seasonal and annual trends that are associated with future precipitation and temperature increase based on the CARA dataset.

![Figure 5](https://iwaponline.com/jwcc/article-pdf/6/3/449/374292/jwc0060449.pdf)
Figure 5 | Cumulative frequency curves for simulated baseline and future flow at the Pigg River.

Figure 6 | Simulated change in flow for the Pigg River based on existing baseline hydrological simulation and future hydrological simulation.
Impacts of future climate and land management variation on microbial transport

Future microbial land and stream loadings data (from human populations, agricultural production, and land use) was estimated using the BSLC. Generated output files were utilized by HSPF to simulate the fate and transport of bacteria. Initially source loads from the BSLC were examined to identify variations in loading, contribution from non-point sources and point sources (Zeckoski et al. 2005). Baseline (existing) and future annual fecal coliform loadings to the stream and from the various species and source categories for the watershed are detailed in Table 9. Higher point source loadings were a result of increases in direct stream deposits from cattle. Pasture land was responsible for the highest annual microbial load out of all land uses. An increase in microbial die-off for stored manure was also evident (due to an increase in manure volume). Livestock bacterial sources, from both pasture and manure applied to cropland, were identified as the key source of bacteria loads for the watershed. An increase of 53% in annual load was estimated for livestock in the future scenario. The percent increase in human load for the watershed was 47%. From the data presented in Table 9, it is apparent that the key contributor to water-quality degradation in the future will still be livestock manure (88.58% contribution). This suggests that remediation efforts within Pigg River should target a reduction in load from agricultural sources. Reductions from other sources may also be necessary but would have minimal influence on overall loading. Focusing on restricting contributions from point sources should be the primary target for any future restoration efforts as direct inputs to streams do not receive any natural filtering prior to discharge to streams.

Modeling of future bacteria scenarios with HSPF

Combining the future bacteria source data together with future climate data in the HSPF modeling structure provided the capacity to assess the impact of potential scenarios on microbial loading in the Pigg River watershed. Simulated model results generated by HSPF were subsequently compared to the baseline period (encompassing water-quality calibration and validation period). To account for varying flow conditions, three different flow scenarios were considered when assessing microbial loading in the watershed: (1) low flow conditions: average annual flow less than $7.6 \text{ m}^3 \text{s}^{-1}$ (<25th percentile), three flow years

<table>
<thead>
<tr>
<th>Source</th>
<th>Percent contribution (%)</th>
<th>Load breakdown (cfu/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td>Future</td>
</tr>
<tr>
<td>PS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Streams</td>
<td>1.16</td>
<td>0.91</td>
</tr>
<tr>
<td>NPS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crops</td>
<td>0.82</td>
<td>0.75</td>
</tr>
<tr>
<td>Pasture</td>
<td>67.34</td>
<td>66.58</td>
</tr>
<tr>
<td>Residential</td>
<td>6.46</td>
<td>6.39</td>
</tr>
<tr>
<td>Forest</td>
<td>5.26</td>
<td>3.51</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Die-off</td>
<td>18.97</td>
<td>21.85</td>
</tr>
<tr>
<td>Species</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Livestock</td>
<td>85.98</td>
<td>88.58</td>
</tr>
<tr>
<td>Wildlife</td>
<td>7.65</td>
<td>5.14</td>
</tr>
<tr>
<td>Humans</td>
<td>4.55</td>
<td>4.49</td>
</tr>
<tr>
<td>Pets</td>
<td>1.82</td>
<td>1.79</td>
</tr>
</tbody>
</table>

*Pet loads based on human population.
(1999, 2000, and 2001) fulfilled these criteria; (2) average flow conditions: average annual flow between 7.6 and 12.3 m$^3$/s (25th–75th percentile), three flow years (1995, 1997, and 2005) fulfilled these criteria; (3) high flow conditions: average annual flow greater than 12.3 m$^3$/s (>75th percentile), 3 years (1996, 2003, and 2004) fulfilled these criteria.

Flow records and statistics (50-year historical period up to January 2013), for hydro station 02058400 (used in hydrology calibration) from the United States Geological Survey (USGS) were used to categorize flow conditions (USGS 2013). Annual and seasonal changes in microbial loads were considered in all simulation scenarios. HSPF generates outputs of average daily bacteria concentrations in colony forming units (cfu) 100 ml$^{-1}$. For the purposes of assessing impacts on bacteria, the total daily microbial load was calculated (average daily concentration $\times$ average daily flow). Bacteria loadings were also assessed for three individual future scenarios: (a) the impact of changes in ‘climate only’; (b) the impact of changes in ‘land use only’; and (c) the impact of changes in ‘land use and climate’.

Results for the simulation of three low flow years are displayed in Figure 7. The figure displays the percentage change in total fecal loading compared to the baseline and corresponding changes in stream flow. Changes in climate, i.e., ‘climate only’, are identified as a driver of increased loads for winter (41%), summer (10%), fall (212%), and annually (49%). For spring, there is a 33% reduction in microbial load. Future land use variation, i.e., ‘land use only’, accounts for a decrease in microbial load in winter (−9%), spring (−1%), fall (−14%), and annually (−2%). Increases in microbial load (14%) during the summer for ‘land use only’ are likely to be caused by increased deposits/time spent by cattle in stream and a reduction in flow. Combined impacts of climate and land use variation, i.e., ‘land use and climate’ cause a 47% increase in microbial loading for winter (31%), summer (14%), fall (199%), and annually (47%). In spring, a decrease in microbial load (−36%) is evident under the ‘land use and climate’ scenario. This decrease may be a consequence of reduced transport in runoff and stream flow. Given that impacts of ‘land use only’ result in lower microbial loading fluxes (±14%) compared to climate changes (which are uncontrollable),

![Figure 7](https://iwaponline.com/jwcc/article-pdf/6/3/449/374292/jwc0060449.pdf)
low flow periods are considered to be high-risk periods for microbial water quality under future conditions; in particular during winter and fall in below average flow years. Efforts to reduce microbial contamination focusing on direct discharges are therefore more likely to improve water quality, as streams are more sensitive to the impacts of point sources during low flow conditions.

A graph displaying changes in microbial loads for various scenarios under average annual flow ranges is displayed in Figure 8. The impacts of ‘climate only’ indicated higher microbial loads annually (4%), and in winter (22%) and fall (106%). Reductions in microbial load were apparent during spring (−26%) and summer (−22%) for the ‘climate only’ scenario. For the ‘land use only’ scenario, there were increases in microbial load annually (5%), and for spring (3%) and summer (11%). These increases are likely caused by additional direct deposits to streams by cattle (corresponding to temperature rise). There was no change for fall under the ‘land use only’ scenario; for winter, there was a minor reduction in microbial load (−1%). ‘Land use and climate’ simulations resulted in increased microbial load for winter, fall and annually; reductions were apparent for spring (−25%) and summer (−16%). Seasonally, results suggest that changes in load were indicative of future seasonal rainfall projections. The results again suggest that changes in climate will have a greater influence on microbial loading than land use change (considering seasonal variation). Given that results for this scenario represent what is considered to be ‘average annual flow conditions’, the changes typify the most prevalent situation for microbial water quality under simulated future conditions.

Impacts of future climate and land use variation for high flow years are presented in Figure 9. ‘Climate only’ contributed to increases in microbial load for winter (21%), fall (50%) and annually (21%). Decreased loads are seen in spring (−17%) and summer (−14%) under the climate scenario. Changes in ‘land use only’ indicated increased microbial load in for all periods (annual: 8%; spring: 9%; summer: 11%; fall: 8%) except winter (−3%). The combined ‘land use and climate’ scenario resulted in higher microbial loads annually, and for winter and fall. Reduced loading is apparent for spring (−10%) and summer (−5%). For high flow periods, seasonal changes in microbial load typically follow rainfall patterns for the ‘climate only’ and ‘land use

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**Figure 8** | Future changes in flow and microbial load for average flow years.
and climate’ scenarios. It is also apparent that climate change is the main driver of microbial transport and total loads under these conditions. The effects of variations in land use management on microbial loading are not as significant (~3 to 11%). Risk periods are associated with increased rainfall in both winter and fall. A combination of more runoff and additional microbial loads on land surfaces (non-point source contamination) is a plausible explanation for increased transport micro-organisms to surface waters.

**DISCUSSION**

Overall, trends in microbial load reflect the seasonal and annual variations in precipitation (Table 3). Similar trends have been reported in other studies examining the influence of climate variation on microbial transport (Vermeulen & Hofstra 2014). Our results concur with existing literature on the influence of climate change on waterborne pollutants (Whitehead et al. 2009; Vano et al. 2010; Hofstra 2011; Delpla et al. 2011; Coffey et al. 2013a) and indicate that future changes in climate and land use will influence the levels of microbial contamination in surface water. High flow and low flow conditions represent risk periods, based on model results. Efforts to maintain and improve water quality in future years need to target these risk periods to reduce contamination. Current pollution prevention plans, e.g., TMDL Implementation Plans focus on low and high flow as risk periods (Kline et al. 2009); however, integration of more stringent adaption measures may be required to negate the impacts of imminent climate and land use variation. This would have implications for stakeholders in efforts to maintain current remediation strategies and implement policy controls aimed at meeting water-quality standards.

We urge caution when interpreting the results of the study as significant uncertainty surrounds the use of watershed models to simulate microbial transport and the rationality of available future watershed data. There is a wide deviation in potential future climate conditions and consequently we stress that although it is almost certain
that climate change impacts will transpire, and effect microbial water quality, it is also apparent that the severity of impacts are directly under anthropological control. In this study, we used the most readily available downscaled climate data (from CARA) which could be easily incorporated into the existing HSPF framework. We also focused on projections for the B2 emissions scenario only, as it was perceived that this was the most credible situation in future years. Possible limitations in the modeling framework are detailed below:

(a) Watershed and water-quality simulation: uncertainty exists on the ability to accurately simulate hydrology during extreme low flow/high flow events and the re-suspension of bacteria in bed sediment (Coffey et al. 2010, 2013a; Kim et al. 2010; Pandey et al. 2012). Additional uncertainty surrounds many transport parameters, including decay (Benham et al. 2006a). Inaccuracies in simulating such circumstances can compromise prediction of in-stream bacteria (Coffey et al. 2013b).

(b) Future climate data: a variety of GCM projections and datasets are accessible for world regions to evaluate future climatic conditions. However, there is no consensus in the climate modeling community that any of these are explicitly better or more accurate than others for all relevant variables (Johnson et al. 2011). Several methodologies also exist that can be used to downscale GCM data to more detailed localized scales. Furthermore, a variety of different emission pathways can be simulated by GCMs which produce alternative climate projections.

(c) Future land use data: limited data availability on future land management scenarios also contributes to uncertainty in model development; in particular, detailed projections on livestock densities and crop production are vague beyond current data. Furthermore, obtainable agricultural projections do not exist at a local scale. Quantifiable bacteria source data on current wildlife populations is also unclear and future estimates do not presently exist.

These uncertainties highlight the complexities in the model approach to simulate future microbial transport scenarios. Other alternative approaches and scenarios have been used previously (Tong & Chen 2002; Christensen & Lettenmaier 2006; Ficklin et al. 2009, 2010; Jennings et al. 2009; Mango et al. 2010; Onuṣluel Gül & Rosbjerg 2010; Chung et al. 2011; Candela et al. 2012; Chien et al. 2013; Luo et al. 2013) and could potentially be adopted; however, it should be noted that no individual approach has been suggested to be distinctly better or worse than others in current peer reviewed literature. We consider the methods outlined in this study do represent an effective initial approach to assess future impacts on microbial transport using readily available data. As enhanced model refinements and more consistent state of the art data become available to users, the model developed here could be updated to address some of the uncertainties. In spite of possible limitations, the model provides an indication of potential changes in microbial fate/transport from future climate/land use change and confirms the potential deterioration in water quality that may occur in watersheds.

When various climate and land use scenarios from this study are examined, it is apparent that climate changes have the most significant impact on microbial fate and transport. This will present significant challenges for those charged with environmental planning and ecosystems protection, as even if land use remains unchanged, it is likely that the impacts of climate change alone will present a significant threat to microbial water quality. Negating the impacts will be difficult as climate factors are to an extent uncontrollable; it is proven that climate change is already happening (IPCC 2001, 2007; Kundzewicz et al. 2007; Whitehead et al. 2009). The ensuing climate variation will have serious implications for authorities, stakeholders and those tasked with regulation. At present it is difficult to forecast the extent to which land management will evolve. However, it is likely that an increased focus on controlling microbial transport from land sources will be required to meet regulatory standards and maintain ecological status for surface waters. Johnson et al. (2011) also suggest that land use management will be an important adaptive strategy to improve robustness of surface water to climate change driven contamination. Until feasible adaptation measures are initiated to counteract the impending effects of changing climate, the threat caused by micro-organisms (potentially pathogenic) in water sources will undoubtedly intensify. Measures need to be identified and derived through interdisciplinary collaboration involving regulators, the farming community, government departments and scientists. The
impact on watersheds and valued water resources could be severe; influencing both ecological condition and human health via water supply and recreational use.

**CONCLUSIONS**

The model and associated climate inputs developed here represent an initial step toward addressing concerns associated with multi-decadal climate change, land use variation and microbial fate/transport in watersheds. This will require the attention of climate change research, watershed management and the regulated communities over the long term. To date, limited research has been carried out in the area. Results of the work indicate that microbial loads will increase in future years, with low and high flow conditions highlighted as periods of increased risk of microbial contamination of surface waters. Increases in microbial load are symptomatic of projected precipitation patterns. Winter and fall are expected to be periods when increases in microbial loading will be greatest. Meteorological variability associated with climate change had much greater impacts than variations in land management. The work suggests that the risk of human exposure to waterborne pathogenic micro-organisms via recreational use of surface waters and insufﬁcient treated water supplies will be ampliﬁed in future years. Unless mitigation efforts to reduce greenhouse gas emissions (and moderate predicted changes in climate) are accelerated, adaptation measures will be required to reduce microbial source loads in watersheds. New policy actions and participative mechanisms to raise awareness and educate communities on future water-quality concerns as a result of climate change are also desirable. These could provide a solid basis to initiate and promote new adaptation efforts to sustain microbial water-quality standards and protect human health.

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