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A web-based screening model for climate risk to water supply systems in the northeastern United States

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ABSTRACT

The aim of this study is to describe the development and application of a web-based decision support tool (ViRTUE) for performing climate risk evaluations of water supply systems. The tool is designed for small-scale water utilities in the northeastern United States that may lack the resources for detailed climate change risk investigations. Development of this tool demonstrates a relatively new approach to web application development using the Shiny framework for the R programming language to create an interactive environment for stakeholders and water managers to explore climate vulnerabilities. Using a decision-scaling framework, the tool allows the user to perform a climate stress test to evaluate the performance and vulnerability to water supply shortfalls of local reservoir systems over a wide range of potential climate change scenarios using a generic systems model. Probabilities of future climate conditions derived from climate projections then help inform utility operators of impending risk.

Software availability

Product Title: Vulnerability and Risk Assessment Tool for Water Utilities (ViRTUE)
Developer: Sarah Whateley
Contact Address: Dept. of Civil and Environmental Engineering, University of Massachusetts Amherst, 130 Natural Resources Rd. Amherst, MA 01003
Contact Email: swhatele@umass.edu
Available Since: 2013
Programming Language: R
Availability: https://virtue.shinyapps.io/myapp
Source Code: https://github.com/swhatele/ViRTUE
Cost: Free

1. Introduction

Water resource managers and decision-makers are faced with many uncertainties when planning and managing water systems including changes in future population, per capita water demands, regulatory requirements, environmental standards, and climate, among others. These uncertainties impact both short-term operational decisions (e.g. water allocation) and long-term adaptation decisions (e.g. infrastructure investment). Despite the inherent uncertainty in future conditions, water planners must decide how to plan and manage their water systems with the resources available to them. This study addresses these issues through a pragmatic framework for rapid assessment of climate change vulnerability for water utilities. The framework is implemented in a novel web-based tool called Vulnerability and Risk Assessment Tool for Water Utilities (ViRTUE), which is designed for small-scale water utilities that may lack the financial or technical resources to perform more detailed climate change risk investigations.

Developing effective management strategies and adaptation actions that reduce risk to water resources requires an assessment of regional climate hazards on existing system infrastructure and operations (Mastrandrea et al., 2010). Climate risk assessment of water resource systems is a process for identifying and evaluating vulnerabilities that may threaten existing infrastructure and system performance. The process often involves a series of climate/weather models, rainfall-runoff models, and systems models to evaluate the impacts of climate change and variability on system functioning. Yet, this process can be time and resource intensive, especially for smaller utilities that often lack the ability to conduct a

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full vulnerability analysis.

In general, the water resources literature focuses primarily on large systems, with relatively few applications for small-scale systems. Climate change studies are typically performed for large water resource systems that are capable of investing the time and resources necessary for such analyses (Horton et al., 2011; Kirshen et al., 2008; Lettenmaier et al., 1999). However, small water utilities may be most susceptible to climate change but do not have the means to assess system performance under future uncertainty. While potentially less equipped to perform computationally-intensive climate analyses, small systems may have more flexibility, less institutional complexity, and greater adaptive capacity to cope with climate change than larger systems (Hamlet, 2011). The development of an easily accessible (i.e. web-based) climate vulnerability tool, designed for rapid assessment of climate risks to water resources systems, would encourage smaller utilities to identify and prepare for potential vulnerabilities in the future.

The need for screening-level, computer-based models and tools to integrate knowledge and provide support in decision-making and management is supported by the scientific literature (Anderson et al., 2004; Borowski and Hare, 2006; Chapra, 1991; Welp, 2001). However, few software packages exist that are inexpensive, simple to use, and provide these services to small water utilities. One exception is the U.S. Environmental Protection Agency's (USEPA) Climate Resilience Evaluation and Awareness Tool (CREAT) designed to help the water sector assess regional and local climate-change impacts. This desktop-based tool leads utilities through a self-directed exploration of potential climate change related risks and adaptation options (Travers, 2010). In contrast, a simple, web-based tool for assessing climate vulnerabilities of water systems may provide advantages such as ease of use, accessibility, collaboration, instant modifications, and wide availability (Byrne et al., 2010). A web-based screening-level tool would also help narrow the persistent gap between knowledge production and tool use by removing software dependencies, simplifying scenario testing, and providing a user-friendly interface (Lemos et al., 2012). Finally, this tool is designed to employ the decision-scaling methodology (Brown, 2010; Brown et al., 2011, 2012; Whateley et al., 2014), a vulnerability-led alternative to the GCM projection-led assessment process employed in CREAT.

Recent advances in web standards, browser performance, and free and open-source software (FOSS) present a promising new avenue for developing web-based tools that are more user-friendly and accessible than traditional desktop software (Swain et al., 2015). These advances in web technologies have transformed the implementation, design, and deployment of decision support systems (DSS) (Bhargava et al., 2007; Booth et al., 2011; Sun, 2013). Decision support systems provide users with computer-based tools (i.e. models and data processing capabilities) that help support complex decision-making and encourage interactive problem solving (Salewicz and Nakayama, 2004). In the last decade, web-based approaches to DSS software have increased the accessibility of decision-making tools to individuals without extensive modeling experience.

The use of web applications for environmental modeling is becoming more common in the literature (Goodall et al., 2011; Walker and Chapra, 2014). For example, Walker and Chapra (2014) developed an interactive web application, WIRM, with a rapid screening model for investigating potential water quality impairments due to biochemical oxygen demand (BOD) discharges. The WIRM tool gives users the ability to interactively adjust parameters for rapid evaluation and visualization of the relationships between parameter values and model output. As another example, Goodall et al. (2011) present an application for a service-oriented computing (i.e. where software systems are interconnected to allow for community and multidisciplinary modeling) for modeling water resource systems using web services. Specifically, their study seeks to develop standards and procedures for data gathering, processing, and visualization of hydrologic simulation models on the web with the objective of more robust and effective implementation design. Yet, many modern web technologies such as these require prior knowledge of and experience with standard web languages (HTML, JavaScript, and CSS), making the web development process inaccessible to many researchers and practitioners.

In more recent years, the development of new web frameworks offers an opportunity to create web applications directly from common scientific languages such as R and Python. This further increases the accessibility of scientific research and modeling tools because researchers can create web applications based on programming languages they are already familiar with, and without needing to become experts in web development. This paper presents a web-based tool developed using the Shiny web application framework (RStudio, Inc) for the R statistical computing language (R. C. Team). Shiny allows users with no web development skills to create interactive and fully-featured web applications written entirely in the R language. Using Shiny, the application developer can write both the front-end (i.e. client-side) user interface and the back-end (i.e. server-side) computational engine using familiar R functions and syntax. Shiny automatically converts the user interface code into standard web languages (HTML, CSS, and JavaScript) that can be run in any modern web browser. Shiny also handles client–server communications for passing application inputs and outputs between the user and the server, facilitating rapid development of interactive user interfaces.

Recently, publications of Shiny web applications have appeared in a wide range of scientific fields, including a web-based mapping application for precision agriculture (Jahanshiri and Shariff, 2014), the development of a data exploration tool for microbial communities (Beck et al., 2014), an interactive web application to assist in knowledge elicitation about water requirements of floodplain and wetland vegetation (Guillaume and Fu, 2013), and a web server for predicting transcriptional regulatory modules (Liu and Miranda-Saavedra, 2014). The role of Shiny in all of these applications is to take complex scientific concepts and present them through an intuitive and user-friendly graphical interface. The Shiny web application framework thus offers a promising new method for developing decision support applications in the water resources community. In particular, the server side framework, which offers reactive expressions that automatically regenerate output data and figures when changes are made to the input (Wan and Hudak, 2000), allows developers to create interactive web applications that are well suited for self-directed climate risk assessment of water resource systems.

To the authors' knowledge, there are no web-based tools designed for exploring water supply system performance under climate change. This study addresses this gap by presenting a web-based tool that uses a vulnerability-based framework to rapidly assess climate change and other impacts on small water supply utilities (i.e. serving populations of 250,000 or less). This tool also demonstrates a new approach for enabling researchers and practitioners to create web-based modeling software that can be programmed entirely within the R programming language. Section 2 introduces traditional methods of assessing climate impacts on water supply systems and describes the vulnerability-based framework used in ViRTUE to allow water utilities to interactively evaluate risks to their systems. Section 3 describes the development approach, model theory, and workflow used in ViRTUE. Section 4 illustrates an application of the tool in a case study of a water supply system in the northeastern United States and compares the vulnerabilities identified using ViRTUE with output from an independent simulation model of the case study system. Section 5 describes outreach and feedback on the application and utility of the tool for small-scale water supply systems in the northeastern United States. Sections 6 and 7 end the paper with a discussion and conclusion of the tool's contributions to the water resource and environmental modeling communities.

2. Climate risk assessment methodologies

2.1. Scenario-based climate risk assessment

Traditionally, water supply impact studies evaluate system performance by combining downscaled Coupled Ocean-Atmosphere Global Climate Models (OA/GCM) with rainfall-runoff models and reservoir operations models to predict future climate risk (Rajagopalan et al., 2009; Wiley and Palmer, 2008; Wilby and Dessai, 2010). These top-down or scenario-based approaches use projected climate change scenarios to evaluate system performance.

Top-down approaches undertaken for the purposes of making adaptation or operational decisions tend to propagate significant errors, generating large uncertainty ranges in climate impacts and system risk (Dessai, 2009). For example, the inherent uncertainty in GCM projections related to initial condition ensembles (Deser et al., 2012), climate forcings (Stainforth et al., 2005), and model inadequacies due to poorly understood climate physics and computational complexity (New and Hulme, 2000) make it difficult to incorporate information from these scenarios into adaptation decisions (Stainforth et al., 2007).

Given these concerns, alternative methods of climate risk assessment have emerged that build from the concepts of decision theory and scenario planning. Rather than suggest a single, best-guess future, these methods attempt to incorporate the concept of robustness into water resources planning and design, selecting strategies that perform well across a range of generated scenarios (Lempert and Collins, 2007; Ray et al., 2013; Watkins and McKinney, 1997). These methods include Info-Gap Decision Theory (Ben-Haim, 2001), Robust Decision Making (RDM) (Lempert et al., 2006; Lempert and Groves, 2010), Robust Optimization (Ray et al., 2013; Watkins and McKinney, 1997), Real Option analysis (de Neufville et al., 2006), Decision-Scaling (Brown, 2010), and the scenario-neutral approach (Prudhomme et al., 2010). Such 'bottom-up' approaches are designed to identify system vulnerabilities over a range of plausible future conditions to aid in selecting robust adaptation strategies.

2.2. Decision-scaling: a vulnerability-based framework

Decision-scaling is a bottom-up methodological framework which inverts GCM-led approaches to climate risk assessment by evaluating system performance over a range of climate futures independent of any assumed probabilities (Brown et al., 2011). Rather than evaluate vulnerabilities among a small set of future climate projections as generated by the GCMs, the decision-scaling method involves systematically exploring a virtually unlimited number of future scenarios to reveal system vulnerabilities by using a stochastic weather generator. The process is generally referred to as a climate stress test (Brown and Wilby, 2012). Multiple sources of climate information (i.e. GCM projections, paleoclimate reconstructions, and subjective climate information) can be used to evaluate risks associated with the vulnerabilities identified (Brown, 2010; Brown et al., 2011). This methodology uses a decision analysis framework to characterize the future climate so that climate scenarios are derived from the decision at hand. Similar to other robustness-based approaches, decision-scaling defines robust adaptation strategies as those that perform acceptably over a range of future uncertainty (Steinschneider et al., 2014; Whateley et al., 2014; Moody and Brown, 2013).

In this study, the decision-scaling framework is embedded in a web-based tool designed for water utilities in the northeastern United States. In recognition of limitations in projecting the future climate, the tool uses decision-scaling to tailor the analysis to focus on the future climate states that pose the greatest threat to system performance and estimates probabilities associated with those decision-relevant climate states (Brown and Wilby, 2012). This reduces the computational time and resources necessary for analysis, and permits rapid identification of vulnerabilities to climate change. It is particularly well suited for small utilities, which comprise small spatial areas and thus are not well served by coarse resolution GCM projections.

3. ViRTUE: Vulnerability and Risk Assessment Tool for Water Utilities

The Vulnerability and Risk Assessment Tool for Water Utilities (ViRTUE) is a web application for assessing risks to small-scale water supply systems in the northeastern United States (available at https://virtue.shinyapps.io/myapp). While ViRTUE is currently designed for the Northeast U.S. in terms of data availability and vetted hydrologic models, in principle it is fully generalizable to other regions. The tool provides a mechanism to understand and explore individual water utilities climate risk exposure using a stress test, in which the performance of local reservoir systems is tested over a wide range of potential climate and socioeconomic changes. The components and workflow of the application are illustrated in Fig. 1. This section will describe the development approach, model theory, and interface/workflow of ViRTUE.

3.1. Development approach

ViRTUE was developed using the Shiny web application framework for the R programming language. R is a free and open source statistical programming language that is becoming increasingly popular among environmental modelers and scientists (Muenchen, 2013). Traditionally, converting a simulation model or statistical analysis to a web application required substantial knowledge of standard web languages (HTML, CSS, and JavaScript) in order to construct the user interface. This requirement presents a challenge for scientists and engineers who are not familiar with modern web languages or development practices. The Shiny web development package provides a powerful framework allowing researchers to write web applications using only R functions and syntax. Because Shiny converts the R source code into HTML/JS/CSS automatically, the developer can create an entire interactive web application in R (see Interactive Web Apps with shiny Cheat Sheet for a template of the software architecture[1]). Although knowledge of HTML, CSS, and JavaScript is not required, Shiny also provides the flexibility to incorporate these languages to create more advanced and innovative web features. For example, ViRTUE incorporates an open-source JavaScript library for interactive maps, called leaflet,[2] which enables the user to click on a map to define the location of their reservoir system.

[1] http://shiny.rstudio.com/images/shiny-cheatsheet.pdf.
[2] http://leafletjs.com, accessed December 15, 2014.

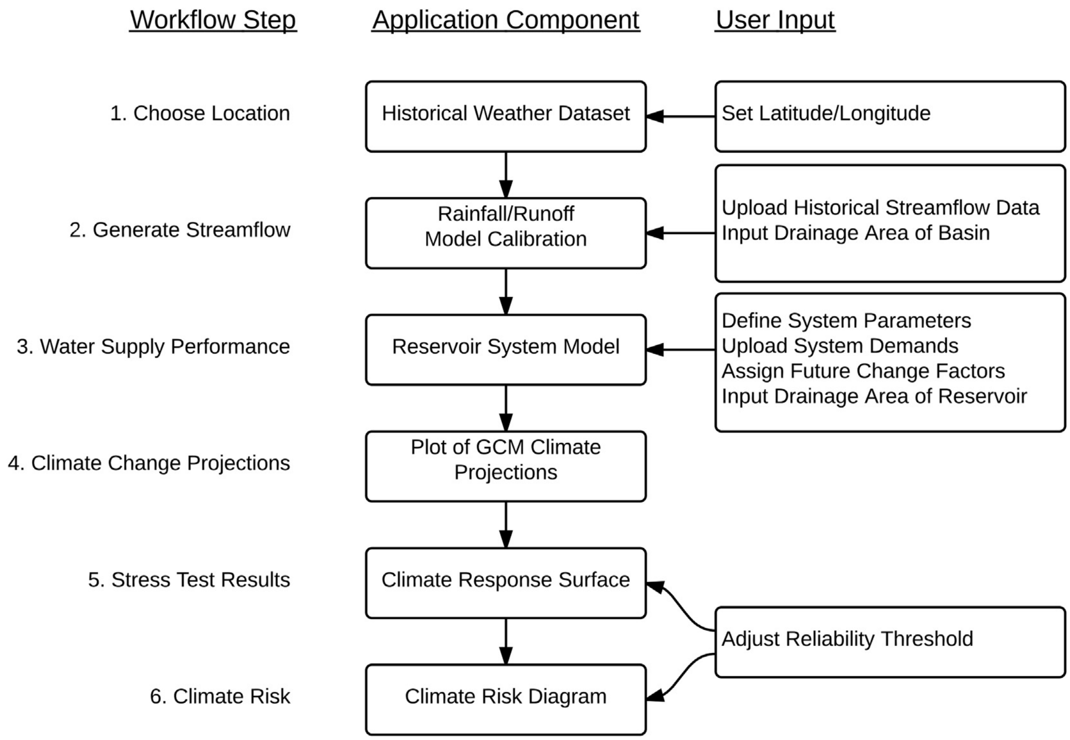

Fig. 1. Schematic diagram of the components and workflow of the ViRTUE application to assess climate risks to water supply systems.

3.2. Model theory

The stress test approach used in ViRTUE begins with the generation of monthly time series of precipitation and temperature using a stochastic weather generator. The weather generator is a stochastic model for generating synthetic time series of climate variables. It allows exploration of user defined climate changes, including changes in means and variability that are plausible yet not sampled by GCM projections (Steinschneider and Brown, 2013; Stainforth et al., 2007). While the use of climate change projections can reveal vulnerabilities to the projections that happen to be used, this approach reveals vulnerabilities to specific climate changes.

The monthly weather generator in ViRTUE couples a wavelet decomposition with an autoregressive model of annual precipitation to account for low frequency climate oscillations in the Northeast (Steinschneider and Brown, 2013). A k-nearest neighbor resampling approach is then used to disaggregate the stochastically generated annual precipitation time series to a monthly time step, preserving the covariance structure between weather variables. The weather generator is trained using historical data from a gridded observed meteorological dataset covering 1949–2010 (over a 1/8° grid cell space) (Maurer et al., 2002). Multiple climate realizations (i.e. fifty time series of monthly precipitation and temperature) are generated to account for internal climate variability (i.e. the natural fluctuations in the climate system that arise in the absence of external forcings).

Linear trends in temperature and precipitation are applied to each variability realization to simulate transient climate change. This approach allows plausible climate change space to be effectively and exhaustively explored. Currently the changes in climate that can be explored in the tool are limited to percent changes in mean annual precipitation and absolute changes in mean annual temperature from historic values for the region of interest (i.e. the latitude and longitude coordinates of the water supply reservoir). Exploration of variability changes are also possible but have not been incorporated yet.

The monthly weather variable time series, adjusted to represent climate changes, are then used as input to a lumped-parameter hydrologic model to estimate monthly streamflow. This hydrologic model is adapted from the 'abcd' model developed by Thomas (1981). The original 'abcd' model was modified to account for the influence of snow accumulation and melt on hydrologic processes in the northeastern United States, which introduces a fifth parameter (e) and is commonly referred to as the 'abcde' model (Steinschneider et al., 2012; Martinez and Gupta, 2010). The abcde model is calibrated to historic streamflows within ViRTUE using the shuffled complex evolutionary algorithm (SCE), a probabilistic global optimization method designed for parameter estimation in conceptual rainfall-runoff models (Thyer et al., 1999; Duan et al., 1992). This model was chosen for use in ViRTUE because of its parsimonious nature (i.e. few parameters) and geographic and hydrologic compatibility in the Northeast.

The output of the hydrologic model is then used as input for a simple, reservoir systems model that follows 'standard' operating policies (i.e. meet a release target if sufficient water is available, otherwise release all available water in the current time step) so that it is generalizable to any system (Loucks et al., 2000). The reservoir model is designed for the analysis of a single reservoir system, however, multiple reservoirs can be lumped together for a crude assessment of total system risk. In practice, standard operating policies are used primarily for planning purposes. Alternatively, the user can select a hedging option that imposes prespecified operating policies that reduce releases in times of drought (i.e. when reservoir levels drop below drought severity thresholds) to explore system performance under operational practice. Most operators adopt hedging policies to save water in the reservoir for future releases in case there is an extended period of low inflows (Loucks et al., 2000). In ViRTUE, hedging policies are adapted from the Springfield Water and Sewer Commission's (SWSC) drought severity index curves, which are typical of small systems (Dresser, 2005; Westphal et al., 2007).

3.3. Tool workflow

The decision-scaling framework embedded in ViRTUE leads a user through a self-guided, six-step process arranged as a series of tabbed panels on the user interface. In the first three steps of the process, the user performs a climate stress test of their system to identify vulnerabilities based on a wide range of potential climate change scenarios (as described above). After performing the stress test, the user is presented with additional information regarding the probabilities of these scenarios based on GCM output in order to assess the risk of not meeting water supply demands. Note that these GCM projections are best viewed as subjective probabilities of future climate change. Ultimately they categorize the climate change projections in terms of whether they indicate problems for the utility or not. A more formal approach for developing climate change probabilities is in development, although they will necessarily remain subjective probabilities (Steinschneider et al., 2015).

ViRTUE is designed to be used by stakeholders and water managers without the need for external support from scientists or engineers by providing guiding instructions through each step of the analysis. In addition, users can download the results of each step in the analysis and save key figures for their records and for use in climate reports. The following sub-sections describe each of the six steps of the analysis in detail.

3.3.1. Step 1: choose location

In the first step of ViRTUE, the user specifies the location of their reservoir system by clicking on an interactive map. The location information (i.e. latitude/longitude) is used to retrieve historical climate data for that location to create synthetic future climate time series using the weather generator described in Section 3.2. Climate changes are imposed on one of the stochastically generated weather realizations, chosen at random from the fifty total realizations created. As a result, for each iteration of the tool a slightly different result will emerge based on the randomly selected weather realization chosen for that analysis. After all climate change scenarios are created, time series of historic monthly precipitation (mm) and temperature (°C) from 1949 to 2010 are presented to the user.

3.3.2. Step 2: generate streamflow

In the second step, the user provides historical flow data to calibrate the rainfall-runoff model described in Section 3.2. The historical flow data can be provided as either direct inflows to the reservoir or measured streamflow from a nearby monitoring gage. If flows are taken from a nearby gage station (Q_{gagedt}), the tool uses a simple drainage area ratio method to scale the volume of water coming into the system (Archfield and Vogel, 2010).

$$Q_{ungaged_t} = \frac{A_u}{A_g} Q_{gaged_t} \qquad (1)$$

where Q_{gaged_t} are historic flows at a nearby gage, A_u is the drainage area of the ungaged site, A_g is the drainage area of the gaged site (required as input in Tab 2), and $Q_{ungaged_t}$ are the ungaged flows into the reservoir. The ability to estimate streamflow at an ungaged site ($Q_{ungaged_t}$) is particularly important for small reservoir systems that have short or no historic inflow records.

When the historical flow data are uploaded, the application uses the historical climate data retrieved in step 1 to calibrate the rainfall-runoff model using the SCE algorithm as described in Section 3.2. After this model is calibrated, the user interface displays hydrographs and flow duration curves of the historical and simulated flows for evaluating the calibration. The goodness-of-fit of the model calibration is indicated by the Nash–Sutcliffe efficiency (NSE) coefficient (Nash and Sutcliffe, 1970). For users unfamiliar with this metric, instructions on how to interpret its value are provided by clicking on the plot.

3.3.3. Step 3: water supply performance

In step 3, the calibrated rainfall-runoff model is coupled to the reservoir systems model described in Section 3.2. The user provides a series of inputs including reservoir capacity, drainage area of the reservoir (A_u), daily water supply demands, and the threshold for system reliability (i.e. 95%). The reliability threshold defines what is considered acceptable performance in terms of reliability (i.e. the acceptable number of shortfall months over the period of record) for the system (Hashimoto et al., 1982).

$$R = 1 - \frac{\sum_{t=1}^{T} Sh(t)}{T} \qquad (2)$$

where R is the difference between unity and the ratio of the total number of shortage months that occur and the total number of months in the record (T). The shortfall function, $Sh(t)$, is a binary variable that is set to one if releases are less than the water supply demand for month t, and zero otherwise.

After the inputs are specified, the application uses the climate-altered flow realizations generated from the calibrated rainfall-runoff model as input into the generic systems model to simulate system performance. The results are presented as a series of plots including annual reservoir storages as a percent of capacity, monthly storages for a particular month of choice (e.g. April storages from 2014 to 2075), average monthly inflows into the reservoir, and overall water supply reliability (R).

In addition to evaluating system performance based on historical climate conditions, the user can also interactively explore the impact of incremental changes in climate and other variables on system performance using slider bars on the user interface. Adjustments that can be made include changes in mean annual temperature (0–5 °C at 0.5° intervals), changes in mean annual precipitation (75–125% of the historic mean at 5% intervals), changes in mean annual demand (0–200% of the historic mean at 5% intervals), additional storage capacity (0–200% at 10% intervals), and additional minimum flow (0–300 MGM at 5 MGM intervals). Although most of this paper focuses on climate risks to water systems, the allocation of limited water supplies to meet both human and ecological needs remains a challenge for small utilities. As such, the capability to explore changes in population (demand) and regulatory policies (minimum flow requirements) is included in ViRTUE.

Lastly, there are two simple system alternatives that can be explored. The first alternative is increasing reservoir size by adjusting an additional storage capacity option. This alternative approach requires significant capital investment. The second alternative strategy is to alter operating policies, which requires much less investment by a utility. Clicking the 'Hedge' checkbox of ViRTUE imposes restrictions on water supply releases during droughts (see Section 3.2) beyond what the standard operating rules would predict. Implementing release rules provides a more realistic depiction of system performance since 'standard' operating policies are not often followed in practice.

3.3.4. Step 4: climate change projections

In step 4, ViRTUE provides information about the distributions of changes in mean precipitation (%) and mean temperature (°C) based on an ensemble of GCM projections (RCP emission scenario 4.5) from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model dataset. Gridded simulated data was downscaled to a monthly temporal resolution and 0.125°spatial resolution based on the bias-correction spatial disaggregation (BCSD) statistical downscaling method (Reclamation, 2013). This tab allows users to visualize the range of climate changes (centered around 2050) projected for the region where their reservoir system is located. The GCM output is specific to the location of the user's system as specified in step 1. The GCM projections allow utilities to better assess the likelihood of climate risks identified through the stress test. The projected changes are displayed as a histogram reflecting the range and frequency of the climate changes represented by the ensemble of climate change projections. The purpose of this step is to illustrate the kinds of climate changes that a representative set of projections indicates for their location.

3.3.5. Step 5: stress test results

In step 5, an overview of the results from the climate risk assessment is presented to the user. This overview is shown as a climate response surface of water supply reliability. A climate response surface is a representation of system performance (i.e. contours of system reliability) across climate change space (e.g. changes in annual mean temperature and precipitation). In this display the climate response surface is divided into regions of 'acceptable' and 'unacceptable' system performance according to a user-specified reliability threshold level. The climate change space encompasses the full range of mean changes in precipitation and temperature that can be explored in step 3.

The user can adjust the reliability threshold, which changes the areas defined as acceptable and unacceptable. Additionally, GCM projections are superimposed on the climate response surface to illustrate the distribution and range of the projections relative to the impacts (in terms of reliability) that such changes would have. In this way the projections are put into the context of their implications for the system. However, rather than simply learning whether projections indicate risks or not, this visualization allows the user to determine which climate changes cause hazards, whether those changes are sampled by the projections or not. For instance, if a water utility only has trouble meeting demands when mean precipitation decreases and the GCM projections show only increases in mean precipitation in the future, they may conclude that their system is at low risk of failure.

3.3.6. Step 6: climate risk

In the final step, the overall risk in terms of acceptable/

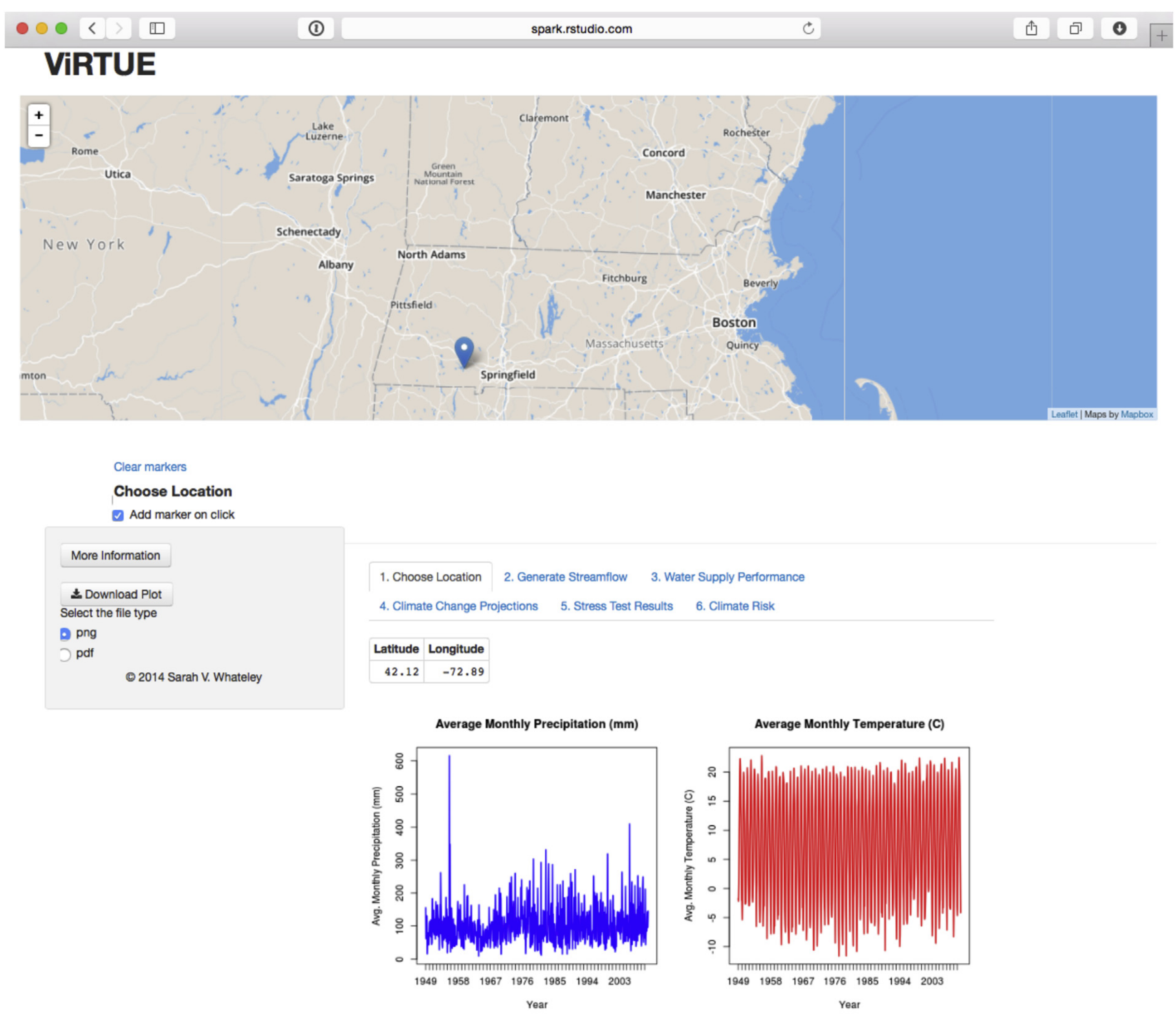

Fig. 2. Screen shot of the 'Choose Location' tab of ViRTUE. Climate altered time series of monthly precipitation and monthly temperature are generated in this step by clicking on the map near the reservoir system of interest. Time series of historic average monthly precipitation (left) and temperature (right) appear on the user interface.

unacceptable system performance is presented. Here risk is defined as the fraction of projections that fall below the reliability threshold level. The results are shown in the form of a bar chart with one bar illustrating the fraction of GCM projections that fall above the threshold of reliability (acceptable) and the other bar showing the fraction of GCM projections that fall below the threshold of reliability (unacceptable).

4. Case study: Springfield water and sewer commission

To demonstrate an application of ViRTUE, we present a case study using the Springfield Water and Sewer Commission's (SWSC) water supply system. The reservoir system, located in the Westfield River Basin in Central Massachusetts, consists of three major reservoirs: Cobble Mountain Reservoir (total storage at max elevation is 22,829 MG), Borden Brook Reservoir (2500 MG), and Littleville Reservoir (10,560 MG). The SWSC serves a population of approximately 250,000 people in Massachusetts, including the municipalities of Agawam, East Longmeadow, Ludlow, Westfield, and Springfield. For the purposes of this analysis, Cobble Mountain Reservoir was treated as the system's major storage reservoir, with inflows from surface runoff, direct precipitation, and the Borden Brook Reservoir located upstream. The Borden Brook Reservoir was excluded from the analysis because it has minimal active operation and primarily functions as a run-of-river facility.

4.1. Model application

Fig. 2 shows a screen shot of ViRTUE after the first step of analysis is complete. In this case, the marker is placed at the base of the Cobble Mountain Reservoir and time series of historical average monthly precipitation (mm) and temperature (°C) from 1949 to 2010 are generated and displayed on the user interface.

Fig. 3 illustrates output from the second step of ViRTUE, in which the abcde model is calibrated to historic flows at the West Branch Westfield River station at Huntington, MA (USGS 01181000). Since flows in this case are taken from a nearby gage station (Q_{gaged_t}), the tool uses the drainage area ratio method described earlier. Calibration of the model in this case yielded a Nash–Sutcliffe efficiency of 0.58, which is acceptable for a water supply system with no flood risk concerns.

Fig. 4 shows a screen shot of performance results generated from the tool's systems model under base case conditions (i.e. no change in mean climate or demands). Under base case conditions the water supply reliability over the period of record is 100% (top left plot in Fig. 4). In addition, the storage as a percent of capacity fluctuates between 80% and 100% (top right), and the April storage remains near capacity for all future years (bottom left). The hydrograph (bottom right) peaks in April for both the base case flows (blue line) and all climate altered flows (grey polygon), which is expected in a region where the wintertime snowpack persists into the late spring. In addition, flows are the lowest in the hot summer months.

Fig. 5 illustrates the distributions of changes in mean precipitation (%) and mean temperature (°C) based on an ensemble of GCM projections from the WCRP's CMIP5 multi-model dataset. The GCM projections suggest mean temperature increases of 2.4 °C and mean precipitation increases of 7.5% by the year 2050.

The climate response surface of water supply reliability for the Springfield water supply system is illustrated in Fig. 6. Regions in blue are considered ‘acceptable’ system performance according to a user-specified reliability threshold level (i.e. the black contour line represents a water supply reliability of 95%). Regions in red are considered ‘unacceptable’ system performance. Additionally, the ensemble of GCM projections are plotted as black points on the climate surface. An analysis done strictly with GCM projections would suggest Springfield's system will perform acceptably in the future. However, if projections are wrong and mean precipitation decreases (by approximately 15%), water supply reliability would drop below the 95% threshold.

Results from Fig. 7 illustrate that 100% of the GCM projections in Fig. 6 fall above the reliability threshold. Therefore, the Springfield system performs adequately across all future climate projections and the fraction of climate projections that suggest acceptable performance is 1 (fraction of climate projections that suggest unacceptable performance is 0).

4.2. Validation

A comparison of the generic system simulator embedded in ViRTUE with a more detailed simulation model of Springfield's reservoir operating policies (outside of the tool) was conducted.

Fig. 8 compares the climate response surfaces of reliability using output from ViRTUE (left) and a reservoir model of Springfield's water supply system (right). The Springfield simulation model that incorporates more realistic reservoir-operating policies exhibits modest differences with the ViRTUE results. For

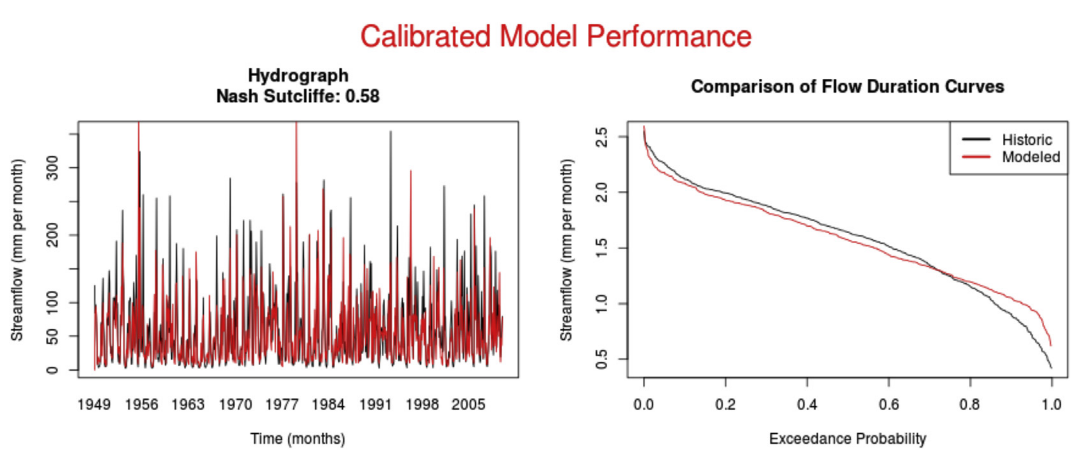

Fig. 3. A hydrograph (left) and flow duration curve (right) produced in the ‘Generate streamflow’ tab of ViRTUE. The black lines illustrate historic flows and the red lines illustrate modeled flows. The Nash–Sutcliffe efficiency value of 0.58 quantifies the performance of the abcde hydrologic model calibration. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

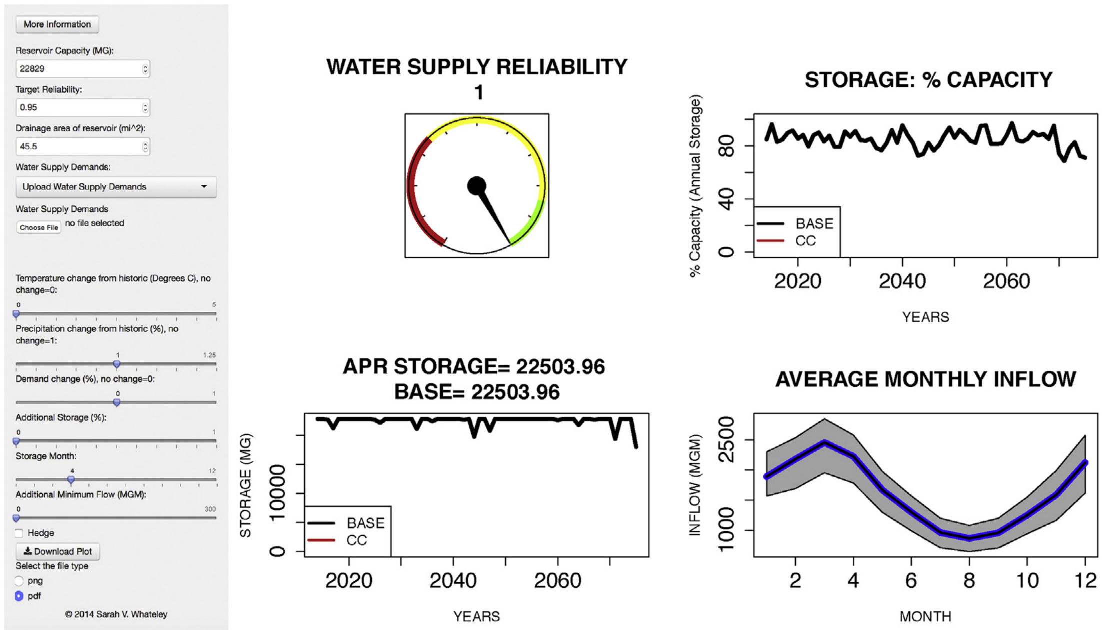

Fig. 4. System diagnostics of ViRTUE: Period of record water supply reliability (top left), reservoir storage as a percent of capacity (top right), annual storage for a particular month (bottom left), and monthly inflows into the system (bottom right). The left panel illustrates climatic and socioeconomic changes (slider bars) that can be explored to test system performance. Storage capacity, drainage area of the reservoir, a target reliability, and daily water supply demands are the inputs required.

example, the system specific model yields unacceptable system performance when mean precipitation is reduced by ~6% whereas the ViRTUE simulator reports vulnerability beginning at a reduction of ~15%. However, the results are generally consistent and provide the same message regarding climate risk to this system.

Output from the system simulator was also compared with historical data to assess the tool's ability to capture known risks from the past. For example, during the period between 1964 and 1967, the northeast United States experienced a severe drought and the Cobble Mountain Reservoir dropped down to approximately 30% of capacity. This was the most severe draw-down on record. During this period of time, there was a 20–25% drop in total precipitation for a few years. Validation results demonstrated the tool's ability to reproduce the Cobble Mountain Reservoir's drop in storage during this period of time (i.e., reservoir storage dropped to 25% of capacity between 1965 and 1966).

5. User feedback

In addition to evaluating the tool by comparing its performance with output from a simulation model specific to the system, the application and utility of the web-based tool to water supply systems in the Northeast was assessed through interviews with water managers and stakeholders. Development of the tool has involved significant outreach efforts throughout the Northeast, including meetings, webinars and phone conversations with several water utilities and companies in the region (e.g. Springfield Water and Sewer Commission, Amherst Public Works, Scituate Water

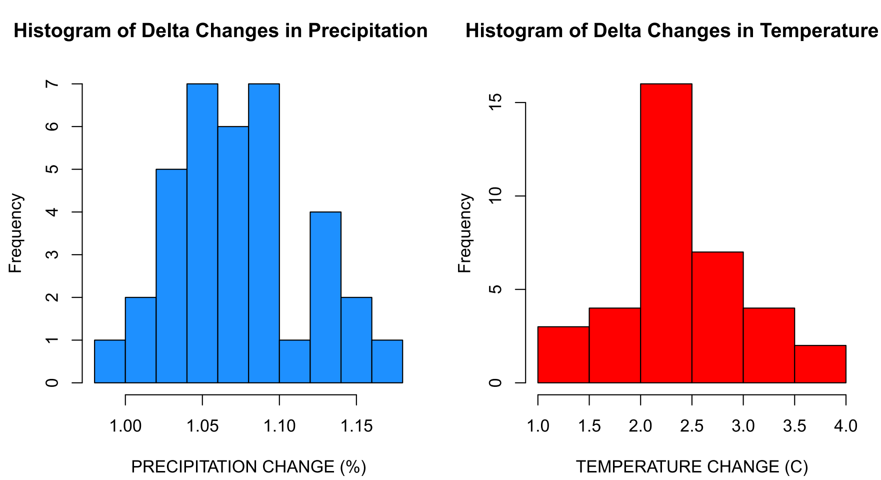

Fig. 5. Distribution of changes in mean precipitation (%) and mean temperature (°C) based on an ensemble of GCM projections (RCP emission scenario 4.5 from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model dataset.

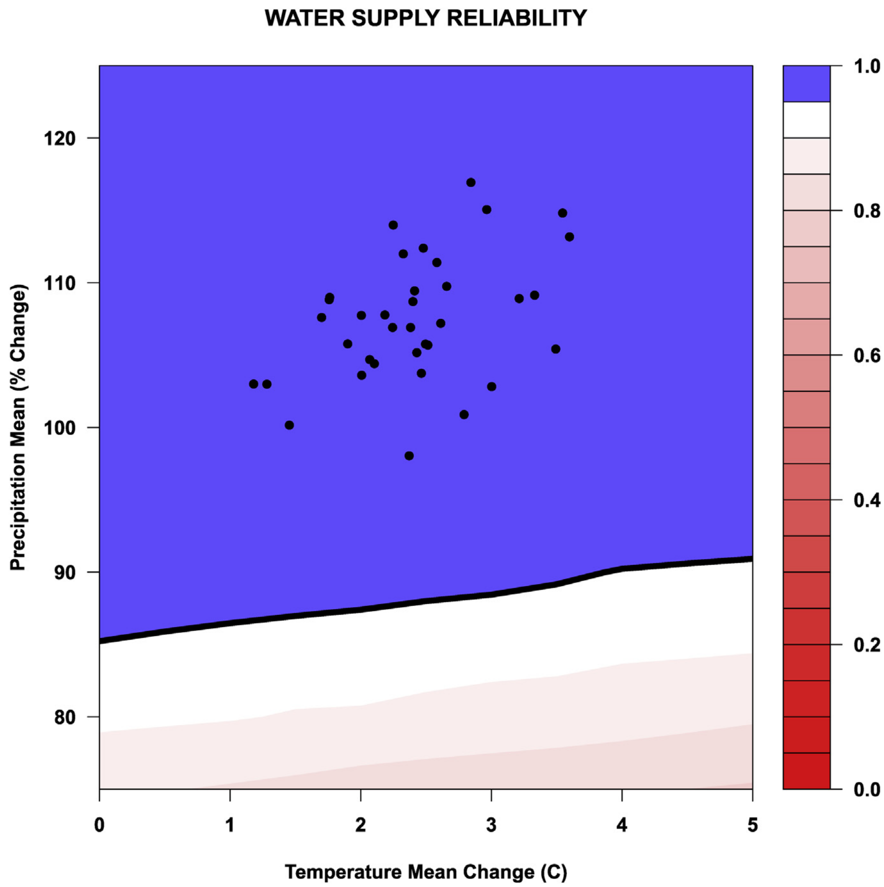

Fig. 6. Climate response surface of water supply reliability for the Springfield water supply system. Regions in blue are considered 'acceptable' system performance according to a user-specified reliability threshold level. Regions in red are considered 'unacceptable' system performance. Additionally, an ensemble of GCM projections are plotted as points on the climate surface. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Department, and United Water), attendance at local water conferences (e.g. New Hampshire Department of Environmental Service's (DES's) Annual Drinking Water Source Protection Conference in Concord, NH and NEWWA Spring Conference and Exposition in Worcester, MA), and demonstrations for representatives at regulatory agencies and governmental organizations (e.g. Massachusetts Division of Ecological Restoration, Massachusetts Water Works Association (MWWA), Executive Office of Energy and Environmental Affairs in Boston, MA, and the Environmental Protection Agency (EPA)).

This outreach has helped shape the various components of the tool and the design of its interactive interface. For example, water supply operators at the SWSC requested that monthly storages for a particular month of choice (e.g. April storages across time) appear on the tool's interface, since monthly storage variations impact both reservoir operations and system performance. Other utilities suggested the tool output (i.e., historical climate plots, hydrologic model calibration and reservoir performance plots, etc.) be downloadable for use in annual reports. In addition, several small utilities at the DES's Annual Drinking Water Source Protection Conference in Concord, NH emphasized the importance of being able to use measured flows at a nearby gage station instead of direct inflows to their reservoir because they either had no inflow data or only a short record of streamflow measurements. Lastly, a number of users of the tool (e.g., Amherst Public Works) indicated a need for a groundwater component, as the tool is currently designed only for surface water utilities. As such, we aim to expand the tool to groundwater-sourced utilities in the future.

6. Discussion

Two key findings emerge from this analysis. First, a new web-based tool, ViRTUE, was successfully created using the Shiny web framework for small-scale water supply utilities to assess risks to their systems, where ordinarily such analyses would not be feasible. With very few inputs (see Fig. 1) the simple, screening level vulnerability assessment in ViRTUE yields time series of historic climate, system reliability, storages, and inflows for a range of climatic and demand conditions. In addition, an ensemble of climate projections are provided, with results showing where in climate change space a system is vulnerable and the fraction of climate projections that suggest acceptable/unacceptable system performance according to a threshold of reliability. From these results, a water supply manager may choose to take action to better prepare for potential future changes that pose a risk to system performance, whether those changes include climate change, changes in demand, or additional minimum flow requirements. If their system exhibits significant vulnerabilities, a more in depth analysis of risks may be warranted.

The performance of ViRTUE was evaluated by application to a representative water supply system in the Northeast, the Springfield Water and Sewer Commission's (SWSC) water supply system. The results from the screening-level analysis of ViRTUE provide the same message regarding climate risk to the system as the results found using the system-specific simulation model of the Springfield system (Fig. 8), and thus demonstrate the value of the tool for a vulnerability assessment of small systems. Future versions of the

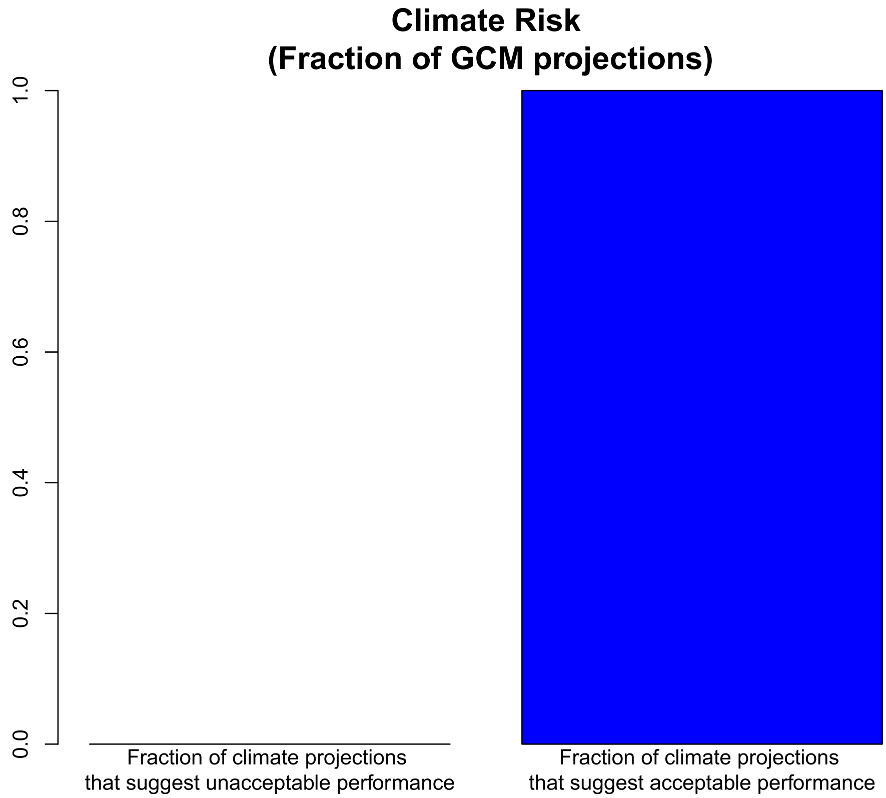

Fig. 7. Fraction of climate projections that suggest acceptable/unacceptable system performance.

tool will also illustrate changes in internal variability within the same iteration.

While this study presents an application of ViRTUE to a water supply system in the Northeast, the components of the tool can be adjusted for use in other regions of the world. To do so would require some minor adjustments, i.e., adjusting the parameters of the weather generator to account for low frequency variability in the region, uploading historical climate data for the region to the server, evaluating the performance of the 'abcd' hydrologic model to ensure it is a suitable structure for many catchments in the region (if not, it could be replaced with a new hydrologic model), and uploading GCM projections for the specific region of interest to the server. It is important to note, however, that using ViRTUE in regions that are data-sparse may be more difficult because of the need for long annual precipitation time series in estimating parameters in the wavelet decomposition. While the tool is

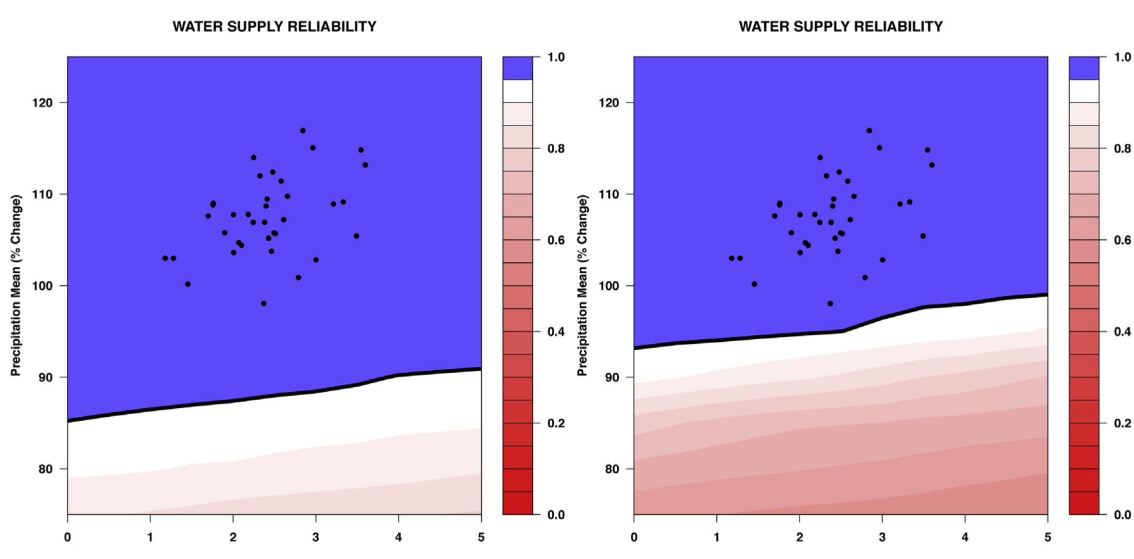

Fig. 8. Climate response surface for Springfield's water supply reliability using ViRTUE's system simulator (left) and a systems model that accounts for Springfield's reservoir rule curves (right).

generalizable to other regions, it should be tested on a case-by-case basis.

The second finding is that the Shiny web framework, as demonstrated by ViRTUE, introduces a relatively new approach to web application development that allows modelers to focus less on specific web technologies, and instead focus on converting their existing models and analyses into interactive web applications. As such, it is a valuable resource for individuals with limited web development skills looking to make models and tools more accessible to the water resources community. There is demand for more decision-making tools in water resources, however, they are often difficult to come by because of the divergent skill sets of scientists, engineers, web developers and decision makers. This paper demonstrates the use of the Shiny web framework to bridge that gap, allowing for collaborative development of web tools that can be coded in the widely-used and free R statistical computing language. Web-based tools of this nature offer opportunity for more dynamic and collaborative water resource management.

7. Conclusion

The study was motivated by the belief that small water utilities may be vulnerable to climate change but lack the resources to assess their risks. A web-based climate risk assessment tool, ViRTUE, was designed to help water utilities, particularly small-scale operators with less time and resources to invest in such studies, to identify vulnerabilities to changes in climate, demand, and environmental flow regulations. ViRTUE provides utilities the opportunity to perform a self-directed vulnerability analysis through an easy-to-use and widely-accessible platform. A web-based platform offers many advantages, such as wide availability, user accessibility, instant modifications, and the removal of software dependencies. There are also some disadvantages of using the web for such analyses including security vulnerabilities (i.e. concern for putting sensitive system specifications online), over simplification of system attributes made to support web-based simulation, and slower analyses than desktop tools due to network traffic and downloading time (Byrne et al., 2010). Overcoming these potential challenges with web-based simulation is vital for widespread use and acceptance of web-based tools in the water resources community.

The tool presented in this study is designed to assist water managers confronted with the potential challenges of climate impacts through a screening level risk assessment of water supply systems. Ultimately, decision-makers must address water resources management under uncertain future climate and socioeconomic changes. With no financial consequences and minimal time investment, utilities can interactively explore the vulnerabilities of their system and begin to assess the potential investments they may need to make in the future. The application of this tool will be particularly potent in developing countries, where utilities often lack alternative modeling tools. For small-scale water supply systems, a web-based tool may be the only option to assess system vulnerabilities under future uncertainty for their planning and management.

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