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Development of Flood Regressions and Climate Change Scenarios To Explore Estimates of Future Peak Flows

Open-File Report 2015–1235

U.S. Department of the Interior
U.S. Geological Survey

Cover. Background photography; April 2, 2005 flood on the Rondout Creek near Napanoch New York. Photograph by James Porter, New York City Dept. of Environmental Protection.

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Conversion Factors

International System of Units to Inch/Pound

Multiply	By	To obtain
	Length	
kilometer (km)	0.6214	mile (mi)

Supplemental Information

An arc-second is a unit of angular measurement equal to 1/3,600 of 1 degree. The length of an arc-second on Earth depends on the latitude; at a mid-latitude location, such as New York State, 30 arc-seconds are approximately equal to 800 meters.

Abbreviations

USGS U.S. Geological Survey

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Abstract

A new Web-based application, titled "Application of Flood Regressions and Climate Change Scenarios To Explore Estimates of Future Peak Flows," has been developed by the U.S. Geological Survey, in cooperation with the New York State Department of Transportation, that allows a user to apply a set of regression equations to estimate the magnitude of future floods for any stream or river in New York State (exclusive of Long Island) and the Lake Champlain Basin in Vermont. The regression equations that are the basis of the current application were developed in previous investigations by the U.S. Geological Survey (USGS) and are described at the USGS StreamStats Web sites for New York (http://water.usgs.gov/osw/streamstats/new_york.html) and Vermont (http://water.usgs.gov/osw/streamstats/Vermont.html). These regression equations include several fixed landscape metrics that quantify aspects of watershed geomorphology, basin size, and land cover as well as a climate variable—either annual precipitation or annual runoff.

The application uses predictions of future annual precipitation from five climate models and two future greenhouse gas emissions scenarios and provides results that are averaged over three future periods—2025 to 2049, 2050 to 2074, and 2075 to 2099. Results are presented in ensemble form as the mean, median, maximum, and minimum values among the five climate models for each greenhouse gas emissions scenario and period. These predictions of future annual precipitation are substituted into either the precipitation variable or a water balance equation for runoff to calculate potential future peak flows. This application is intended to be used only as an exploratory tool because (1) the regression equations on which the application is based have not been adequately tested outside the range of the current climate and (2) forecasting future precipitation with climate models and downscaling these results to a fine spatial resolution have a high degree of uncertainty. This report includes a discussion of the assumptions, uncertainties, and appropriate use of this exploratory application.

Introduction

The U.S. Geological Survey (USGS), in cooperation with the New York State Department of Transportation, developed a Web-based application to estimate the magnitude of future floods for any stream or river in New York State (excluding Long Island) and the Lake Champlain Basin in Vermont. This report describes how annual precipitation data from climate models are applied to the peak flow regression equations implemented in the StreamStats Web application (http://water.usgs.gov/osw/streamstats/) to provide new estimates of peak flow magnitudes for three periods in the 21st century: from 2025 to 2049, 2050 to 2074, and 2075 to 2099.

The purpose of the new Web-based application, titled "Application of Flood Regressions and Climate Change Scenarios to Explore Estimates of Future Peak Flows," is to allow the user to apply regression equations that provide predictions of current peak flows in ungaged basins and to provide estimates of the magnitudes of future peak flows for any stream or river in New York State (exclusive of Long Island) and the Lake Champlain Basin of Vermont (Burns and others, 2015). The assumptions that were used in this Web application are described, as well as the sources of uncertainty in the future peak flow estimates. Guidance about how to use the application, metadata, or to download the underlying geodatabase is provided from within the Web application.

StreamStats Program

The existing set of peak flow magnitude regression equations for current conditions were developed by the USGS (Lumia and others, 2006; Olson, 2014) and are implemented in the Web-based stream analysis application titled, "The StreamStats Program," which provides information about streams and rivers in New York (http://water.usgs.gov/osw/streamstats/new_york.html) and Vermont (http://water.usgs.gov/osw/streamstats/Vermont.html), among other States. The StreamStats Program allows the user to delineate a watershed at any point on the stream channel within these two States and obtain information about the stream and watershed. The available peak flow information for New York includes the instantaneous magnitudes of flows with recurrence intervals of 1.25, 1.5, 2, 5, 10, 25, 50, 100, 200, and 500 years (annual exceedance probabilities of 87.5, 75, 50, 20, 10, 4, 2, 1, 0.5, and 0.2 percent, respectively). The available peak flow information for Vermont includes the instantaneous magnitudes of flows with recurrence intervals of 2, 5, 10, 25, 50, 100, 200, and 500 years (annual exceedance probabilities of 50, 20, 10, 4, 2, 1, 0.5, and 0.2 percent, respectively). New York is divided into six regions for the purposes of this analysis, and separate regression equations were developed for each of these regions (Lumia and others, 2006). A single set of peak flow regression equations was developed for Vermont (Olson, 2014).

Climate Change Application

In the application described in this report, the original regression equations are applied with a new climate variable (either precipitation or runoff) substituted into a given equation. To evaluate how future climate might affect peak flow magnitudes, data are applied from five climate models that were part of the most recent global climate assessment, the 5th Phase of the Coupled Model Intercomparison Project (CMIP5; Taylor and others, 2012). These models were selected based on discussions with climate scientists as to which of the CMIP5 climate models best represent past trends in precipitation in the Lake Champlain basin based on an analysis described in Guilbert and others (2014). Precipitation data from these climate models were obtained from downscaled projections at a spatial resolution of 30 arc-seconds that are available from the National Aeronautics and Space Administration, as described by Thrasher and others (2013). Precipitation data were evaluated for two future scenarios, termed "Representative Concentration Pathways" (RCP) in CMIP5, that provide estimates of the extent to which greenhouse-gas concentrations in the atmosphere are likely to change through the 21st-century. These scenarios, RCP 4.5 and RCP 8.5, were evaluated for each climate model in CMIP5 (Taylor and others, 2012). RCP refers to potential future emissions trajectories of greenhouse gases, such as carbon dioxide. RCP 4.5 is considered a midrange-emissions scenario, and RCP 8.5 is a high-emissions scenario.

Results were averaged for three future periods, from 2025 to 2049, 2050 to 2074, and 2075 to 2099, following the approach used in the USGS Climate Change Viewer (http://www.usgs.gov/climate_landuse/clu_rd/nccv.asp). The downscaled precipitation data for each model and RCP scenario averaged over these 25-year periods were obtained from the developers of the USGS Climate Change Viewer (Jay Alder, U.S. Geological Survey, written communication, 2015).

The new Web-based application calculates an ensemble of results based on all five climate models for any of the two greenhouse-gas scenarios and three time periods, and reports the results as summary statistics. These available results are meant to reflect a range of variation predicted from among the five models and two greenhouse-gas scenarios. Information on the models, greenhouse gas scenarios, and time periods is listed in table 1.

Table 1. Climate models, greenhouse-gas emissions scenarios, and time periods used for estimates of future peak-flow magnitudes for streams in New York.

Name/description	Abbreviation	Reference
Climate models		
Beijing Normal University Earth System Model	BNU–ESM	Ji and others (2014)
Community Earth System Model with Biogeochemical Cycling Model, Version 1.0	CESM1–BGC	Lindsay and others (2014)
Centre National de Recherches Météorologique Climatological Model 5	CNRM–CM5	Voldoire and others (2012)
Institut Pierre Simon Laplace Climate Model 5A, Low-Resolution	IPSL–CM5A–LR	Dufresne and others (2013)
Norwegian Earth System Model, Intermediate Resolution	NorESM1–M	Bentsen and others (2013)
Greenhouse-gas emissions scenarios		
Representative Concentration Pathway 4.5	RCP 4.5	Thomson and others (2011)
Representative Concentration Pathway 8.5	RCP 8.5	Riahi and others (2011)
Time periods		
Average from 2025 to 2049	2025–2049	USGS Climate Change Viewer (http://www.usgs.gov/climate_landuse/clu_rd/nccv.asp)
Average from 2050 to 2074	2050–2074	USGS Climate Change Viewer (http://www.usgs.gov/climate_landuse/clu_rd/nccv.asp)
Average from 2075 to 2099	2075–2099	USGS Climate Change Viewer (http://www.usgs.gov/climate_landuse/clu_rd/nccv.asp)

Assumptions

The application of these peak flow regression equations involves a space-for-time substitution approach because the regression equations were originally derived to account for spatial variation in flood peaks across each hydrologic region of New York and across Vermont. Extending spatial analyses of hydrologic responses through space-for-time substitution holds promise as an alternative approach to rainfall-runoff modeling for improving understanding of how climate change is likely to affect future hydrology (Sivapalan and others, 2011; Liu and Schwartz, 2012; Gyawali and others, 2015). The logic of applying these regression equations to describe how streams and rivers may respond to future changes in the precipitation regime is grounded in how basin characteristics, such as drainage area and slope, affect the magnitudes of peak flows. Here, a physical basis is assumed for the manner in which the geomorphic and land-cover independent variables in the regression equations affect peak flows. The user is cautioned, however, that these are statistical models based on association and that the independent variables in the regression equations may represent a variety of physical factors that are actually driving the peak flow response of basins. For example, the precipitation or runoff variable may in part represent the effects of elevation, which varies with these two measures.

According to this approach, the key variable that will govern the change in peak flows is the exponent of either precipitation or runoff in the regression equations. If this exponent is greater than one, then peak flows will increase by a relative amount that is greater than the relative increase in precipitation or runoff. The opposite will occur if the exponent is less than one. For example, if precipitation in region 1 of New York increases by 10 percent in a future climate scenario, then the 50-year recurrence-interval peak flow will increase by 11.38 percent because the exponent of the precipitation variable for this region and flow is 1.131 (table 1; Lumia and others, 2006).

Several additional simplifying assumptions were made in the development of this Web-based tool. A broad assumption is that the relation between annual precipitation or runoff and the magnitudes of peak flows will be the same in the future as these values were over the time periods for which the regression equations were developed. These relations were developed based on an analysis of all pertinent and available streamgage discharge data in New York through 1999 (Lumia and others, 2006) and in Vermont through 2011 (Olson, 2014). Discharge data from surrounding States and Canadian Provinces were also used in developing these relations. Several analyses of historical climate data and projections of future climate based on model output have indicated that the magnitude and frequency of large precipitation events is increasing (Groisman and others, 2005; Hodgkins and Dudley, 2011) and is likely to further increase in the future (Toreti and others, 2013; Jannssen and others, 2014). These and other analyses suggest that the relation between annual precipitation and runoff and the size and intensity of large precipitation events may change in the future (Silliman and others, 2013). The development of this Web-based application necessitated the use of the available regression equations, which consider only annual values of precipitation or runoff.

Another important assumption made in the development of this Web-based application is applicable to the peak flow regression equations developed for hydrologic regions 2, 3, 4, and 6 in New York, which use annual runoff as the climatological variable. These annual runoff values are based on the hydrologic analysis of Randall (1996) from 1951 to 1980. Annual runoff is the difference between annual precipitation and annual evapotranspiration (ET) in the absence of changes in water storage or major human alteration of the water cycle in a basin. Recent reports have indicated that ET is increasing in the Northern Hemisphere and that continued increases are likely during the 21st-century (Miralles and others, 2014); however, some conflicting evidence has shown that changes in ET are complex, of high spatial variability, and likely to be influenced by multi-decadal climate oscillations (Jung and others, 2010). In this Web-based application, the ET-to-precipitation ratio is held constant and future changes in annual runoff are governed by changes in precipitation and resulting changes in ET. The effects of future changes in ET on the magnitude of peak flows are not well known at present but are likely to be substantial based on analyses of the role of low soil moisture in moderating the hydrologic impact of past large precipitation events (Ivancic and Shaw, 2015).

A final assumption is pertinent only to the regression equations for region 3 in New York. In this region, the median maximum seasonal snow depth is one of the predictive variables in the regression (Lumia and others, 2006). Future snowfall and snowpack depth for region 3, which includes the Catskill Mountains, is expected to decrease during the 21st-century as the climate warms (Matonse and others, 2013). The effects of a decreasing snowpack on floods in this region are not well known and were not considered in the development of this Web-based application.

Limitations and Uncertainty

This application has several sources of uncertainty, which in total are difficult to quantify and are discussed below. The recommendation is to use this tool in an exploratory manner and to consider the results along with other sources of information to decide how future climate change may affect peak flow magnitudes. This field of investigation is evolving rapidly, and new and better applications and approaches are likely to emerge in the future.

Check Basin in Current StreamStats Before Using Climate Change Application

The peak flow regression equations implemented in StreamStats are not readily applicable to two types of watersheds: (1) those that are greatly affected by stream regulation such as reservoirs and (or) by withdrawals or additions for water supply or irrigation and (2) those where urban land use exceeds 15 percent of basin area (Lumia and others, 2006). None of the basins in Vermont are considered urbanized (Olson, 2014).

The user of this Web-based application is encouraged to first obtain a table of basin characteristics from StreamStats before considering how climate change may affect flood magnitudes. Note that the current application provides a percent urban land-area value for any delineated basin reported as “Percentage of land-use from NLCD 2011 classes 21-24.” Regression-based estimates of current peak flow magnitudes for any basin with substantial regulation or diversion or for urban land that covers more than 15 percent of basin area are considered to have unacceptably high uncertainty, indicating that estimates of future peak flow magnitudes in such basins will also have unacceptably high uncertainty. Methods for estimating peak flows in ungaged urban watersheds are described by Sauer and others (1983).

Another reason to explore a delineated basin in StreamStats before applying this new Web-based application is that some basins have geomorphic or land-cover characteristics, including basin drainage area, that are outside the linear range used to develop the peak flow regression equations in each region of New York or in Vermont. StreamStats provides a warning when an out-of-range basin has been delineated, and estimated flood magnitudes from such basins are considered to be poorly defined and should be used with extreme caution (Lumia and others, 2006). Lastly, the current climate explorer Web application requires that delineation points lie within hydrologic regions defined by Lumia and others (2006). For this reason, the stream delineation point (also termed “pourpoint”) cannot be in Pennsylvania, Canada, or offshore in the Great Lakes.

Sources of Uncertainty

There are several sources of uncertainty in the use of a regression-based approach to estimate peak flow magnitudes, especially when the role of future climate is being considered. The uncertainty of current [in this case, 1999 for New York and 2011 for Vermont] peak flow magnitude estimates can be obtained by using the standard error of prediction of the regression equations for each region of New York as described by Lumia and others (2006) and for Vermont as described by Olson (2014). Other sources of uncertainty in current peak flow estimates arise from inaccuracies in the basin delineation and in the predictive variables.

The application of regression equations derived from spatial analysis to climate change involves a space-for-time substitution. First, the regression equations indicate associations only and not physical processes, so changes in future hydrologic processes, such as runoff, may not be adequately represented in the set of predictive variables in each regression equation as used in this original version of the Web-based application. Second, the regression equations were developed for a 20th-century climate regime that may not adequately reflect the changes in temperature, precipitation, and snowfall patterns that are forecast for the 21st-century. These challenges to this statistical approach indicate a need to devise strategies for testing these regression equations in a climate-change context. At the time of development of the Web-based application, this approach had not yet been adequately tested or validated.

Considerable uncertainty also results from the assumptions and calculations embedded in each climate model and greenhouse-gas scenario. This source of uncertainty is difficult to evaluate; however, one approach has been to examine the ensemble of results available from various climate models and greenhouse-gas scenarios. This application has been designed to provide ensemble peak flow estimates reported as the mean, median, maximum, and minimum values for each selected combination of greenhouse-gas scenario and future 21st-century period for a given delineated basin. A final major source of uncertainty derives from the approach used for downscaling results from global climate models that have a spatial resolution of about 50 to 500 kilometers (Taylor and others, 2012) to the scale of 30 arc-seconds for the data used in this application. This source of uncertainty is potentially large but difficult to quantify (Mearns and others, 2014). The approach used to derive the NEX–DCP30 downscaled dataset can be broadly described as a statistical approach, as described by Thrasher and others (2013) and the National Aeronautics and Space Administration (2013).

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