Journal of Hydrology 549 (2017) 194–207

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Framework for incorporating climate change on flood magnitude and frequency analysis in the upper Santa Cruz River

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ARTICLE INFO

Article history:
Received 18 December 2014
Received in revised form 16 March 2017
Accepted 22 March 2017
Available online 28 March 2017
This manuscript was handled by K. Georgakakos, Editor-in-Chief.

Keywords:
Hourly precipitation
Watershed model
Flood frequency
Flood intensity

ABSTRACT

Hourly precipitation for one historical (1991–2000) and two future periods (2031–2040 and 2071–2079) were generated using the Weather Research and Forecasting (WRF) Regional Climate Model (RCM). The climate simulations were conducted for the Southwest region of the United States using an hourly temporal and 10 km spatial resolution grid. The boundary forcing for the WRF model was developed by the Hadley Centre for Climate Prediction and Research/Met Office's HadCM3 model with A2 emission scenario. The precipitation from the RCM-WRF model was bias-corrected using the observed data, and then used to quantify the impact of climate change on the magnitude and frequency of flood flow in the upper Santa Cruz River watershed (USCRW) in southern Arizona. The Computational Hydraulics and River Engineering two-dimensional (CHRE2D) model, a two-dimensional hydrodynamic and sediment transport model, was adapted for surface flow routing. The CHRE2D model was first calibrated using a storm event on July 15th, 1999, and then applied to the watershed for three selected periods. The simulated annual maximum discharges in two future periods were added to the historical records to obtain the flood frequency curve. Results indicate the peak discharges of 100-year, 200-year, and 500-year flood only increased slightly, and the increase is within the 90% confidence interval limits. Therefore, the flood magnitude and frequency curve will not change with the inclusion of projected future climate data for the study watershed.

1. Introduction

Flood magnitude and frequency are essential for both hydraulic structures and flood risk management. The World Disaster Report (IFRCRCS, 2012) found that flooding is the leading disaster accounting for approximately 55% of all the natural disasters. Flood magnitude and frequency will change as climate changes. From the analysis of precipitation projections from eight Global Climate Models (GCMS) (Shamir et al., 2015), the Southwest US will see more dry summers and less wet ones. Dominguez et al. (2012) found a decrease in the mean winter precipitation of approximately 7.5% in the Southwestern US. However, the maximum area-averaged daily precipitation in the winter will increase 12.6% and 14.4% for the return periods of 20 years and 50-years, respectively. The precipitation changes require the re-analysis of flood frequency curve, which traditionally derived from the limited historical records.

Flood frequency studies (Booij, 2005; Chen and Grasby, 2014; Leonard et al., 2008; Mirza et al., 2003; Raff et al., 2009; Li et al., 2013) in different regions of the world showed that the impacts of climate change on flood magnitude and frequency vary regionally due to local climate and watershed characteristics (e.g., elevation, location). Estimated flood flows from hydro-climate models are often used together with historical records for flood risk analysis (Shamir et al., 2015; Booij, 2005; Chen and Grasby, 2014; Leonard et al., 2008; Mirza et al., 2003; Raff et al., 2009; Li et al., 2013). All of these studies used the precipitation output from climate models as the input to hydrologic models for surface flow routing. Either lumped or distributed hydrological models were chosen to compute surface runoff and stream flow and their spatial and temporal distributions.

To route surface flow in a watershed with complex terrains, a hydrodynamic model capable of simulating stream flow as well as overland flow is required (Yu and Duan, 2014, 2016). Many hydrological models for simulating stream flow are based on the solutions of kinematic wave (Vivoni et al., 2007) or diffusion wave (Qu and Duffy, 2007) equations. Both the kinematic and diffusion

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http://dx.doi.org/10.1016/j.jhydrol.2017.03.042
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wave equations are simplifications of the shallow water equations. Singh (2002) have studied the limits and accuracies of these equations. Recent research (Yu and Duan, 2014) showed that the simplified models can yield inaccurate predictions of peak flow in streams. Yu and Duan (2012, 2014, 2016) developed the CHRE2D model based on the solutions of shallow water equations and the kinematic wave approximation for surface flow routing in a watershed. The model takes the raw DEM data as the input, and is capable of simulating surface flow routing over complex irregular terrains. In this paper, the CHRE2D model was used to route the hourly precipitation data for the historical (1991–2000) and future periods (2031–2040, 2071–2079) in the USCRW.

The precipitation output from GCMs has commonly been used to investigate the impact of climate change on flood risk (Merritt et al., 2006; Dominguez et al., 2009; Geil et al., 2013). GCMs participating in phase 3 of the Coupled Model Intercomparison Project (CMIP3) typically have a resolution of approximately 103–455 km, while the newer CMIP5 models range between 68 and 342 km (Flato et al., 2013). Because of the coarse spatial resolution of GCMs and the uncertainty of their precipitation output at a fine temporal resolution, the results from GCMs are not suitable for direct flood modeling (Kay et al., 2006a,b). A high resolution RCM embedded within a GCM will provide the output at a finer scale resolution, which can be used to assess the impact of climate change on stream flow. Since HadCM3 provides the most realistic boundary conditions for simulating summer precipitation in the Southwest (Shamir et al., 2015), it is used as the forcing boundary to the RCM. WRF-RCM was then operated to predict future precipitation. WRF-HAD was found to have relatively large wet biases in the study area (Shamir et al., 2015), therefore, a bias-correction procedure was applied to remove these biases.

The common precipitation input data for hydrological models are the daily or monthly average precipitation, which result in the daily or monthly averaged flow in the river. However, the design of hydraulic structures requires the peak discharge, such as 100-year flood flow for bridge design. The daily averaged flow can be much less than the peak flow in the Southwest because of the short duration and high intensity of storm events. Hanel and Buishand (2010) found the increase in the large quantiles of the daily maxima was much smaller than that in the quantiles of the hourly maxima at the end of 21st century. Therefore, hourly precipitation from the RCM was used in this study. Hourly precipitation was bias corrected, and then used as input to the CHRE2D model to simulate surface flow.

The objective of this paper is to quantify the changes of flood magnitude and frequency caused by climate change in the USCRW. Instead of using a simplified hydrological model, an advanced hydrodynamic model, CHRE2D, was used. The precipitation generated from the WRF regional climate model was routed through the watershed. Three periods were simulated: the historical period of 1991–2000, the future periods of 2031–2040 and 2071–2079. In particular, we applied the event-based bias correction method to precipitation in all three periods, calibrated the CHRE2D model using a summer event, and verified the modeling results using 39 observed storm flows in the historical (1991–2000) period. The calibrated model was applied to simulate storm events in two future periods for developing the new flood magnitude and frequency curve.

2. Data source

2.1. The study site

The Santa Cruz River Watershed (SCRW), located in south central Arizona (Fig. 1), is a transboundary watershed at an elevation ranging from 668.12 to 2845.92 m. The Santa Cruz River (SCR) is an ephemeral river that drains into the Gila River, a tributary to the Colorado River (Shamir et al., 2007). The SCR flows to the South and makes one 40.22 km loop through Mexico before re-entering the United States at nearly 5 miles from Nogales, Arizona. Then, the river flows northward to its confluence with the Gila River. The study area is the upper Santa Cruz River watershed encompassing the reach of the SCR within the US, approximately 4000 square kilometers. The largest tributary to this reach is the Rillito River in Tucson, Arizona. The topographic data were from the LIDAR survey in 2005 by the Pima County Regional Flood Control District. Although the LIDAR data have a fine grid resolution, the computational cell was obtained by aggregating the LIDAR data to $100\,\mathrm{m} \times 100\,\mathrm{m}$ cell. The simulation domain is approximately $40,000\,\mathrm{m} \times 100,000\,\mathrm{m}$, so the total number of cells is 400,000.

In the SCRW, the mean monthly precipitation in the summer is greater than that in the winter (Wood et al., 1999). Winter and summer are the major sources of precipitation, and spring and fall are usually dry. The mean annual precipitation from 1914 to 2000 at the Nogales gauge located at the upper SCRW was 422 mm, consisting of an average 59% in the summer and 29% in the winter (Shamir et al., 2007). Fig. 2 shows the monthly averaged streamflow from 1940 to 2013 at the Cortaro gauge at the downstream of the study reach. The summer rainy season is typically from July to September, and sometimes extends to October. The winter rainy season is from November to March, and flow is much smaller than that in the summer. Fig. 3 shows the annual peak discharges at the Cortaro gauge, and the different symbols represent the season when the peak discharge was observed. One can find most of the peak flow events (about 81.25%) occurred in the summer, and only a few (about 15.63%) in the winter. In the past 74 years, only two annual peak flow events were observed in the fall, October 1973 and October 1983, respectively. In 2000, the second largest annual event occurred in October. Although a flood event in the study site most likely occur in the summer, several large events were seen in the fall. Therefore, we selected a typical rainfall event between 1991 and 2000 to calibrate the surface flow model. Then, the calibrated model was verified by selected events from all four seasons.

2.2. Climate data source

Historical and future climate projections at the global scale were used as the forcing data for the regional climate model. The forcing data was obtained from the HadCM3 (Gordon et al., 2000; Pope et al., 2000) model with A2 emission scenario for 43 vertical levels at an approximate horizontal resolution of 3.75° by 2.5°. The HadCM3 global data was used as forcing for the Advanced Research Version (ARV) of the WRF regional climate model (Skamarock et al., 2005). The model was run continuously for 111 years at 35 km resolution over a large domain that encompasses the United States and northern Mexico, and the model output was stored in every six hours. WRF single-moment three-class microphysics (Hong et al., 2004), Kain-Fritsch cumulus parameterization (Kain and Fritsch, 1993), Goddard shortwave radiation (Chou and Suarez, 1994), Rapid radiative transfer model (RRTM), longwave (Mlawer et al., 1997), Eta surface layer (Janjic, 1996, 2002, Mellor-Yamada-Janjić (MYJ) planetary boundary layer (Janjic, 1990, 1996, 2002), and the Noah land surface model Version 1.0 (Chen and Dudhia, 2001) were used. The WRF model (Skamarock et al., 2005) was used in a two-step downscaling simulation. The first step used 35 km and 6 h resolution over the contiguous U.S. Then, using the 35 km WRF data as the lateral boundary conditions, a second one-way downscaling was performed at 10 km and 1 h resolution over a smaller domain (28°–37° N, 105°–116° W) covering the State of Arizona (Fig. 1c) for