CLIMATE CHANGE AND URBAN WATERWAYS: ALTERATIONS IN THE FLOW REGIME UNDER MULTIPLE ENSEMBLES

Muhammad Saleem Akhter, Asaad Yahia Shamseldin, Bruce William Melville (The University of Auckland)

ABSTRACT

Adverse effects of urbanization on urban waterways have been established, however little is known about the anticipated impacts of climate change on hydrological flow regime and aquatic ecosystem. The present study focuses on the investigation of climate change impacts on the flow regime in the Lucas Creek catchment located in the Auckland region. Statistically and dynamically downscaled climatic variables from seven Global Climate Models (GCMs) are adopted under three Representative Concentration Pathway (RCP 2.6, RCP 4.5 and RCP 8.5) scenarios. Personal Computer Stormwater Management Model (PCSWMM) was calibrated and validated using the observed streamflow data. The performance of PCSWMM during calibration and validation was assessed using the Nash-Sutcliffe (NS) coefficient, the Root Mean Square Error (RMSE), and the coefficient of determination (R^2). Additionally, low flow (Q_{90}) and high flow (Q_{10}) indices were compared during calibration and validation using Percentage BIAS (PBIAS) criteria to verify the trends in discharge simulations. The model showed a good match between the observed and the simulated data indicating a good calibration. Following this, the model was used to simulate flow time series under the climate change scenarios. Alterations in the flow regime were assessed through flow duration curves and indicators of hydrological alteration. The results show a significant rise in peak flow in the 2090s (2081-2100) in comparison to baseline (1985-2005) however, low flow mainly decreases under RCP 2.6. Monthly streamflow increases over the annual cycle, but minimal changes are observed in January, March and November. The extreme minimum conditions observe higher positive changes under RCP 2.6 and RCP 4.5 compared to RCP 8.5. Similarly, the magnitudes of maximum flow conditions have observed a diverse pattern. The base flow index has shown variations ranging from -18% to 18% for most of the GCMs. Annual extremes' timings, duration of high pulses, rise rate and low pulse count observe a decreasing pattern. However, the duration of low pulses, fall rate, number of high pulse count and number of reversals follow a rising trend. The changes in the flow regime could have some advantages nevertheless, the aquatic ecosystem would observe severe adverse effects in the end.

KEYWORDS

Climate change, urban waterways, flow regime, FDC, IHA, urban ecosystem

PRESENTER PROFILE

Muhammad Saleem Akhter is a PhD Candidate at The University of Auckland. He holds Master of Water Resources Management from the University of South Australia. He has previously worked at International Water Management Institute (IWMI), Pakistan and Government of Punjab, Pakistan for more than five years. He has experience in climate change, hydrological and hydraulic modelling, stormwater and irrigation water management.

1 INTRODUCTION

Many studies have shown that natural waterways are deteriorated as a result of urbanization of their catchments (Akhter and Hewa, 2016, Lee et al., 2008, Hamel and Fletcher, 2014). The altered properties of urban catchments result in increased peak flow and runoff volumes, decreased base flow and deteriorated water quality. Nevertheless, climate change has become another big issue that would extensively alter the rainfall patterns in the future. The magnitudes of extreme storm events would be exacerbated and their frequencies would be elevated leading towards more severe and frequent floods (IPCC, 2013). Global Climate Models (GCMs) provide climate change information to assess the climate change impacts at the global and regional scale. However, the information available from GCMs is available at high spatial scale that is not directly useable for the hydrological models. In order to overcome this constraint, downscaling methods such as statistical downscaling and dynamical downscaling are used to obtain the climate data at the catchment or the station level. Extensive details about the downscaling methods are available in Rummukainen (2010), IPCC (2013) and Wilby et al. (2004). Several studies have assessed the climate change impacts using a single GCM (Hashmi et al., 2011) however, the application of multiple GCMs is considered to be more realistic to forecast the variability of climate. An ensemble of three GCMs was used by Cui et al. (2018) and they found that mean of all the GCMs provided better downscaling of current climatic variables. Similarly, Da Silva et al. (2018) stated that a variety of uncertainties are associated with GCMs therefore, application of multiple GCMs could address this issue and provide a better understanding of long term projections.

The altered hydrological cycle in the urban catchments adversely affects the biodiversity of the urban waterways. However, several studies have established that aquatic ecosystem would be further vulnerable under climate change. The urban heat island of the urban catchments would be further exaggerated under climate change resulting in more warm environments and increased rainfall intensity and frequency (Wilby, 2007). Lorrey et al. (2017) pointed out that increased rainfall intensities and frequencies would increase high flows in the future however, average rainfall would decrease leading towards prolonged low flows in the streams. Similarly, a study conducted by Da Silva et al. (2018) used design storms updated under climate change that resulted in higher flood hazards in the urban catchment. Even their proposed distributed storage units were not found to be adequate to mitigate the climate change effects. Climate change would substantially increase the mean annual runoff however, flow in the summer would be significantly decreased (Franczyk and Chang, 2008). Urban waterways are more vulnerable to climate change therefore, proper investigation of variations in the flow regime is needed to address this issue at the regional level.

Different rainfall-runoff models are employed to study the impacts of climate change on urban runoff and floods in the urban catchments. Stormwater Management Model (SWMM) developed by the United States Environmental Protection Agency (US EPA) is amongst the most widely used models in the urban areas. SWMM can be applied for both event-based and continuous simulation at various temporal and spatial scales. Numerous studies have used SWMM for the rainfall-runoff simulations around the globe (Zahmatkesh et al., 2014, Metcalf et al., 2017, Alamdari et al., 2017, Lee et al., 2008). The applicability of SWMM in the urban catchments has been verified from the results of these studies. Although the US EPA SWMM is freely available, however, it lacks in several functionalities such as Geographic Information System (GIS) and auto calibration tool. Therefore, several commercial versions are available with many advanced tools and functionalities including Personal Computer Stormwater Management (PCSWMM) developed by Computational Hydraulics International (CHI), Canada (CHI, 2018). Consequently, PCSWMM has been used in this paper to quantify climate change impacts through continuous simulations.

The alterations in the regime can be analyzed using many hydrological indices based on the available data and information needed (Butchart-Kuhlmann et al., 2018, Lee et al., 2008). The changes in the shape of a hydrograph and Flow Duration Curve (FDC) at pre and post management levels could simply reveal the variations in the flow regime. However, different indices of the FDC are used in urban catchments such as for high flow 10th percentile (Q_{10}) and low flow 95th percentile (Q_{95}) (Hamel and Fletcher, 2014). On the other hand, a comprehensive set of hydrological indices termed as Indicators of Hydrological Alteration (IHA) was developed by Richter et al. (1996) that has been extensively used in the riverine studies (Cui et al., 2018, Butchart-Kuhlmann et al., 2018). The IHA involves 32 indices that completely covers the different components of the flow regime (Richter et al., 1996). Various researchers have applied various combinations of different indices from the FDC and the IHA method to investigate urbanization effects on flow regime (Akhter and Hewa, 2016, Hamel and Fletcher, 2014, Clausen and Biggs, 1997), but studies using all of them in the urban catchments under climate change are still lacking. Therefore, the evaluation of both the methods to assess the alterations in the flow regime under climate change is necessary.

The present study is focused on assessing the climate change impacts on the flow regime of an urbanized catchment using multiple ensembles of Coupled Model Intercomparison Project 5 (CMIP5). To do this, PCSWMM using the input data from seven GCMs is used to simulate the flow time series. The alterations in flow regime are measured using the FDC and the IHA methods. The hydrological indices of both methods are directly related to the biodiversity and eco-system in the waterways. However, the application of both of the methods has not been evaluated under climate change at an urban catchment scale.

2 METHODOLOGY

2.1 STUDY AREA AND DATA

The Lucas Creek catchment is selected for the present study and the catchment map is shown in Figure 1. The total drainage area of the catchment is 626.35 ha and land has been developed for residential and commercial purposes in the last few decades. Currently, 55% of the catchment area is urbanized (AC, 2017) and a well-maintained drainage network exists. However, all the stormwater is eventually released to an open channel; the Lucas stream. Some issues related to flooding, erosion, fish barriers, riparian margins, land instability, stormwater contaminants, habitat and community protection have already been found as the major challenges within the catchment (NSC, 2010). According to Moores et al. (2016), deteriorated stormwater quality has already adversely affected the ecological life of the stream and low-lying areas are under higher risks of frequent flooding. They further warned that stormwater quality and quantity related issues would be further exacerbated in the catchment under dense urbanization and climate change. Subsequently, in the latest Auckland Unitary Plan (AUP) of the Auckland Council (AC), the Lucas Creek catchment has been put in Stormwater Management Area-control Flow-1 (SMAF-1) highlighting that the catchment is of high significance and is discharging to a sensitive channel (AC, 2017).

Figure 1: The Lucas Creek catchment boundary and hydro-meteorological stations

In order to record rainfall, evaporation and stormwater quantity and quality, the AC and the National Institute of Water and Atmospheric Research (NIWA) have installed several meteorological stations in the surroundings of the Lucas Creek catchment. Three nearby stations named Albany, Torbay and Oteha were chosen (Figure 1) and the Thiessen polygon method was applied to calculate mean areal rainfall over the catchment. The mean annual rainfall and evaporation in the Lucas Creek catchment vary from 1104 mm to 1155 mm and 848 mm to 1017 mm, respectively. Observed flow data from 2007 to 2016 is available at a gauge located at the outlet of the Lucas stream for calibration and validation. The mean annual flow of the catchment is between 36 m^3/s and 73 m^3/s. Spatial datasets such as Digital Elevation Model (DEM), land use and soil types were also acquired from the AC (Figure 2). The resolution of DEM is 1 m x 1 m.

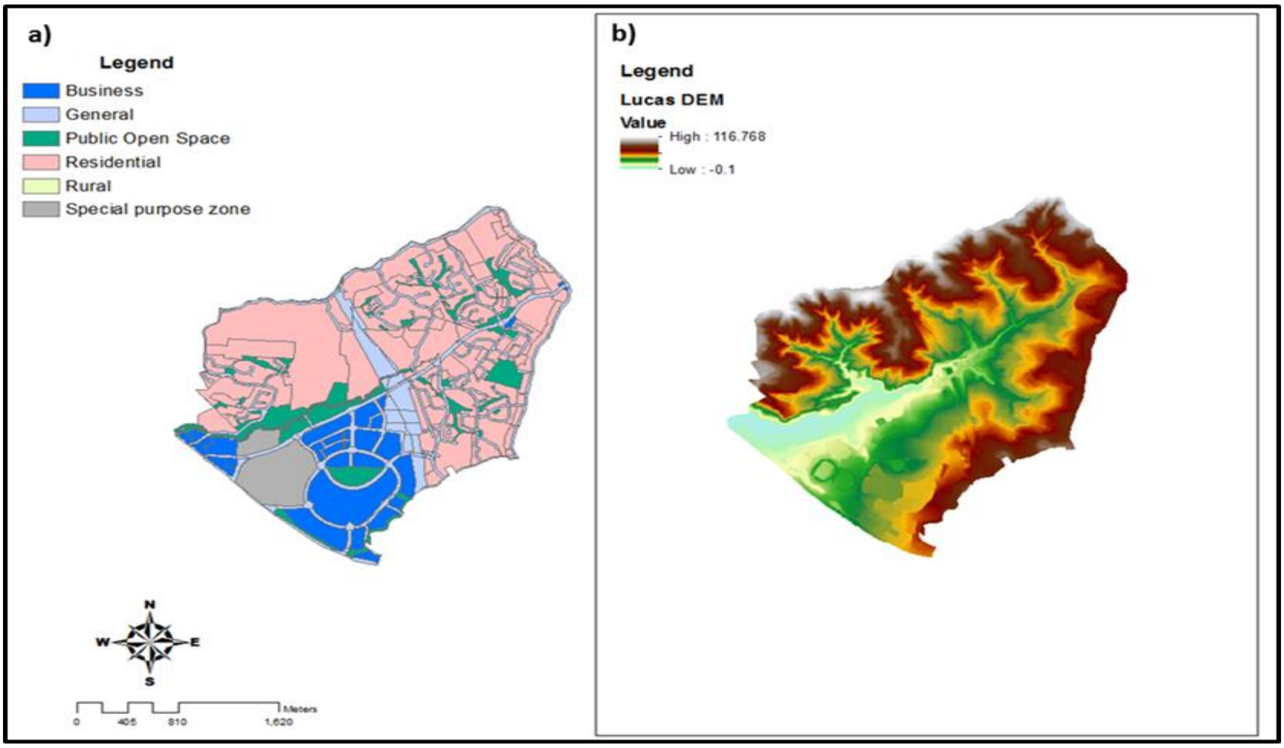

Figure 2: Description of the study catchment: a) land-use b) digital elevation model

Future projections of climate change were prepared using the data of GCMs from the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). In the AR5, future projections are driven by emission or concentration scenarios that consist of Representative Concentration Pathways (RCPs) called RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5. Further details can be found in (IPCC, 2013). Three outputs of the CMIP5 ensembles under RCP 2.6, RCP 4.5 and RCP 8.5 were selected for this study. RCP 2.6 is the lowest emission scenario that leads Radiative Forcing (RF) to 3.1 W/m^2 by 2035 and drops to 2.6 W/m^2 by 2100. RCP 4.5 is a medium scenario, which leads RF to 4.2 W/m^2 beyond 2100, and RCP 8.5 is the highest emission scenario that leads RF to 8.5 W/m^2 by 2100.

Dynamically downscaled and biased corrected rainfall and potential evapotranspiration data were obtained from the NIWA, New Zealand for six GCMs. A Regional Climate Model (RCM) named Hadley Centre Regional Climate Model, version 3 (HadRM3P) is used at the NIWA to downscale data at 5 km grid. The list of the six GCMs used at the NIWA is presented in Table 1. These GCMs would be named with their GCM numbers in the table such as GCM1, GCM2, GCM3, GCM4, GCM5 and GCM6 in the rest of the paper. Further details about these GCMs and the dynamical downscaling method are available in the report of the Ministry for the Environment (ME, 2016). For statistical downscaling, Statistical Downscaling Model (SDSM) was applied to downscale rainfall data from GCM7 (Table 1) at daily time step. The detailed process of statistical downscaling is discussed in Akhter et al. (2017).

Table 1: List of GCMs and their downscaling methods

GCM No.	GCM abbreviation	GCM Name	Downscaling method
1	CESM1.CAM5	Community Earth System Model-Community Atmosphere Model	RCM

2	BCC.CSM1.1	Beijing Climate Centre Climate System Model	
3	GFDL.CM3	Geophysical Fluid Dynamics Laboratory coupled climate model	
4	GISS.E2.R	Goddard Institute for Space Studies-Model E/Russell	
5	HadGEM2-ES	Hadley Global Environment Model 2-Earth System	
6	NorESM1.M	The Norwegian Earth System Model	
7	CanESM2	Second Generation Canadian Earth System Model	SDSM

2.2 MODEL CONCEPTUALIZATION, CALIBRATION, AND VALIDATION

PCSWMM can be used for event-based modeling or continuous simulation of the stormwater quantity and quality. Rainfall-runoff process in PCSWMM is completed through four algorithms; atmospheric, surface, water transport and groundwater (James et al., 2010). For the atmospheric algorithm, rainfall and evaporation data was directly obtained from the AC and the NIWA. Land-use and soil type data for the surface algorithm was extracted from the spatial data sets available from the AC. Water transport algorithm required data such as conduits, their cross-sections and junctions were retrieved from DEM using the available tools in PCSWMM. Likewise, groundwater and aquifer related information needed for the groundwater algorithm was not readily available. Therefore, initially most of the default values were applied taking deep aquifer in the catchment and model was set up. The Lucas Creek catchment was also discretized into twenty-two sub-catchments that were connected through junctions, conduits and storages as shown in Figure 3. An outfall is used to represent the flow gauge in the model. Two major storage units are included in the model and their storage rating curves were generated using PCSWMM tools. Land-use and sub-catchment layers were used to measure the percentage of imperviousness considering buildings, roads and paved areas as impervious areas.

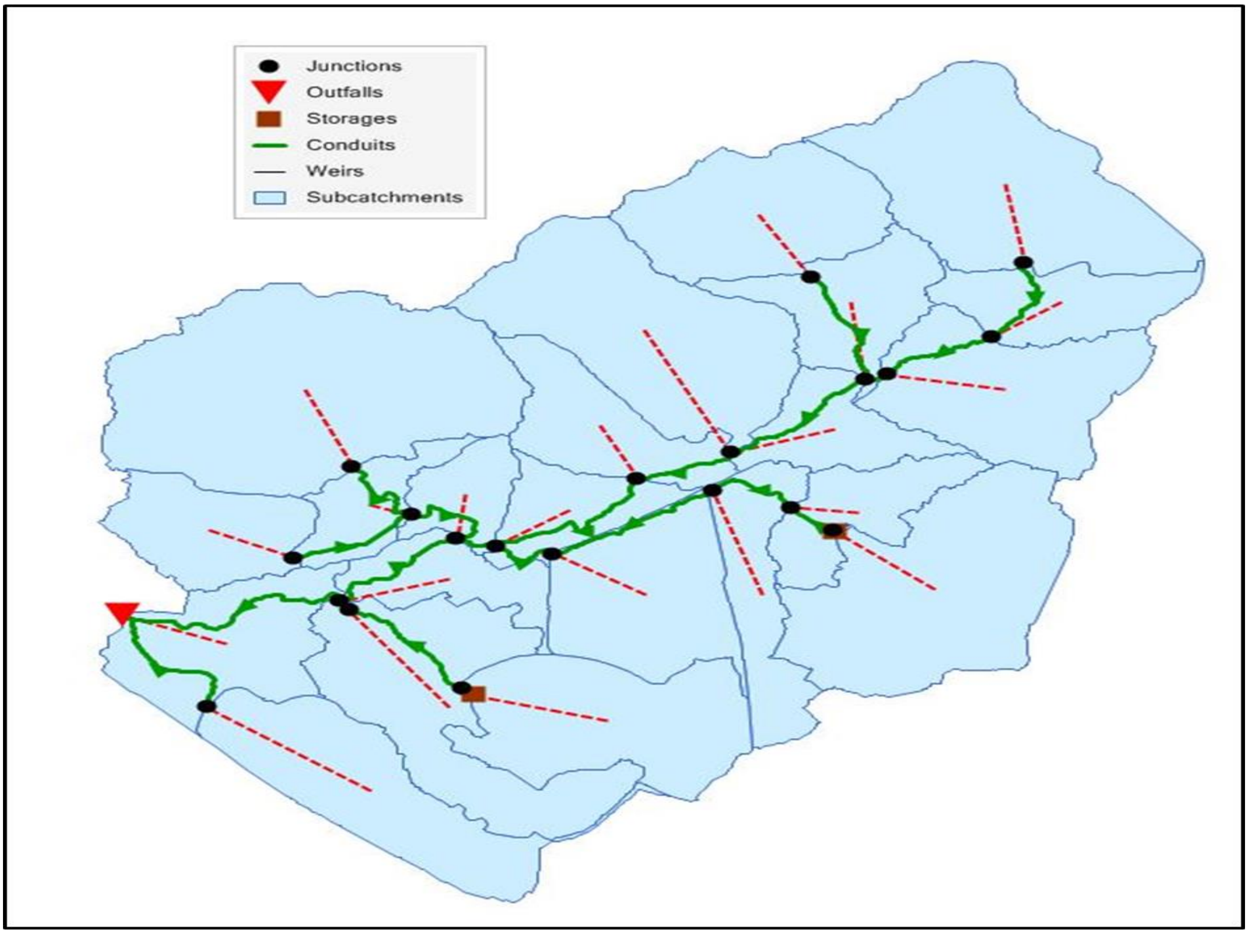

Figure 3: The Lucas Creek catchment discretization into sub-catchments

Calibration of the model is an important step and in PCSWMM, a tool called Sensitivity-based Radio Tunning Calibration (SRTC) is available for automatic calibration. SRTC tool operates using the sensitivity values assigned to different parameters based on their data sources. The method adopted by James (2005) was followed to assign the sensitivity values to impervious percentage, sub-catchment width, Manning's roughness for conduits, impervious and previous area, depression storage for the impervious and pervious area, minimum and maximum infiltration rate, decay constant, dry time and groundwater flow coefficients and exponents. Beside the SRTC tool, the trial and error method was also used to adjust parameters of groundwater algorithm related to aquifer properties. Calibration and validation were performed from 2007 to 2013 and 2014 to 2016, respectively. The Nash-Sutcliffe (NS) coefficient, the coefficient of determination (R^2) and Root Mean Square Error (RMSE) were used to evaluate the performance of the model during calibration and validation. Furthermore, Percentage BIAS (PBIAS) criteria was used to compare low flow (Q_{90}) and high flow (Q_{10}) indices during calibration and validation. NS, R^2, RMSE, and PBIAS are measured as:

$$NS = 1 - \frac{\sum_{i=1}^{n}(X_{obs,i} - X_{sim,i})^2}{\sum_{i=1}^{n}(X_{obs,i} - X_{avg})^2} \quad (1)$$

$$R^2 = \frac{\sum_{i=1}^{n}(X_{obs,i} - \bar{X}_{obs})(X_{sim,i} - \bar{X}_{sim})}{\sqrt{\sum_{i=1}^{n}(X_{obs,i} - \bar{X}_{obs})^2 \sum_{i=1}^{n}(X_{sim,i} - \bar{X}_{sim})^2}} \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_{obs,i} - X_{sim,i})^2}{n}} \quad (3)$$

$$PBIAS = \frac{\sum_{i=1}^{n}(X_{obs,i} - X_{sim,i})}{\sum_{i=1}^{n}(X_{obs,i})} X100 \qquad (4)$$

where n is the number of time steps; $X_{obs,i}$ and $X_{sim,i}$ are the observed and simulated values at time step i respectively and X_{avg} is average daily value over the simulation year.

2.3 FLOW REGIME VARIATIONS UNDER CLIMATE CHANGE

The alterations in the flow regime of the Lucas Creek catchment were examined using two different methods; the FDC method and the IHA method. In the FDC method, Flow Duration Curves (FDCs) quantify the changes in flow regime regarding the relative amount of time a particular magnitude of flow can exceed or becomes equal. Different events and their flow magnitudes can be extracted from FDCs. High point areas in the shape of FDCs relate to high flows or flooding and low point areas indicate low flows or base flow that is available during summer season or dry months. On the other hand, the IHA method of Richter et al. (1996) consists of 32 hydrological parameters that are used to investigate variations in the flow regime. All these parameters are usually classified into five different groups based on frequency, magnitude, duration, timing, and rate of change as presented in Table 2. The values of all the IHA parameters were calculated based on single period non-parametric analysis considering the skewed nature of hydrological data. For non-parametric analysis, the median is taken as 50th percentile and 25th percentile, and 75th percentiles were taken as the threshold for calculating upper and lower pulses, respectively. Version 7.1 of the IHA software was used in the present study.

Table 2: Classification of IHA parameters

IHA parameter group	Hydrological parameters
Group 1: Monthly streamflow magnitudes	Median discharge for each calendar month
Group 2: Magnitude of annual extremes over different durations	Annual 1-, 3-, 7-, 30-, 90-day maximum flow
	Annual 1-, 3-, 7-, 30-, 90-day minimum flow
	Base-flow index
Group 3: Timing of extreme annual flow	Julian data of annual 1-day maximum
	Julian data of annual 1-day minimum
Group 4: Frequency and duration of high/low pulses	Number of high pulses each year
	Number of low pulses each year
	Mean duration of high pulses
	Mean duration of low pulses
Group 5: Rate/frequency of flow condition changes	Fall rate
	Rise rate
	Number of reversals

The discharge time series produced by PCSWMM for all the GCMs were used in the IHA software for the baseline and future scenario analysis. In this analysis, the baseline is taken from 1985 to 2005 and future scenario analysis is performed in the 2090s (2081-2100) to assess the variations in the flow regime.

3 RESULTS AND DISCUSSIONS

3.1 PCSWMM PERFORMANCE DURING CALIBRATION AND VALIDATION

The SRTC tool was run to assess the sensitivity of all selected the parameters within their assigned sensitivity values. During this process, depression storage pervious, groundwater exponents and Manning's roughness of conduits were found to be insensitive and were left to their initial values. All the remaining sensitive parameters were tuned to obtain the best match between the observed and simulated flows. Further details about the working of the SRTC tool for calibration process can be found in CHI (2018) and Finney and Gharabaghi (2011). The low flows were found to be sensitive to the aquifer properties. Therefore, a sensitivity analysis was performed using the manual trial and error method to the highly sensitive aquifer parameters such as upper evaporation fraction, upper zone moisture, lower groundwater loss rate, water table elevation, tension slope, conductivity and conductivity slope. The sensitivity analysis of the aquifer properties on the total groundwater inflow is presented in Table 3. All the remaining parameters of aquifer properties not mentioned here are considered either do not affect the groundwater flow or their values were calculated that cannot change.

Table 3: Parameters of groundwater aquifer used for sensitivity analysis and their effects on groundwater inflow and peak flow

Parameters	Effect of increase on groundwater inflow	Effect of increase on peak flow
Upper evaporation fraction	Decrease	Decrease
Lower groundwater loss rate	Decrease	Minimal change
Upper zone moisture	Increase	Increase
Water table elevation	Increase	Increase
Tension slope	Minimal change	Increase
Conductivity	Minimal change	Decrease
Conductivity slope	Decrease	Decrease

The observed and simulated flow series are visually compared at the outfall of the Lucas Creek Catchment in Figure 4. In the figure, the observed flow is shown as outfall (obs) and simulated flow as outfall. It can be seen from the figure that there is a good agreement between the simulated flow and the observed flow. This indicates that the model has performed quite well during calibration (Figure 4a) and validation (Figure 4b) periods. Table 4 presents the other criteria of NS, R^2 and RMSE for daily flow and PBIAS for Q_{10} and Q_{90}.

High values of NS and R^2; 0.76 and 0.80, respectively during calibration (2007-2013) and 0.72 and 0.79 during validation (2014-2016) shows that the model has performed quite well. Likewise, low values of RMSE (3.11 during calibration and 1.74 during validation) indicate the satisfactory calibration of the model. For Q_{10} and Q_{90}, PBIAS values are also found to be low indicating that the trends in discharge series for high and low flows are well captured.

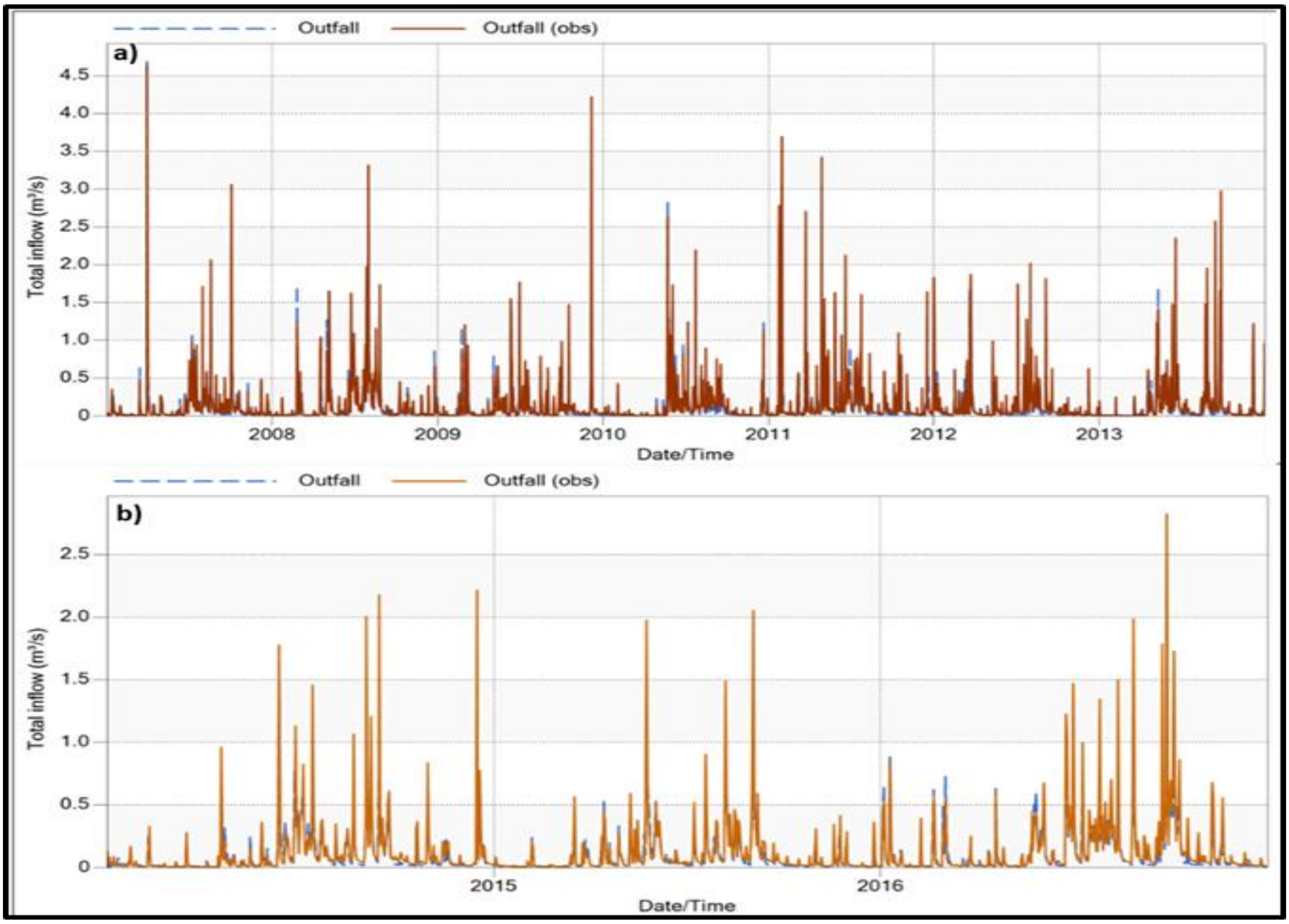

Figure 4: Model performance during: a) calibration (2007-2013) and b) validation (2014-2016)

Table 4: Statistical criteria for model assessment during calibration and validation

Period	Daily flow			Q_{10}	Q_{90}
	NS	R^2	RMSE	PBIAS (%)	PBIAS (%)
Calibration (2007-2013)	0.76	0.80	3.11	5.26	5.79
Validation (2014-2016)	0.72	0.79	1.74	8.82	6.86

3.2 CLIMATE CHANGE IMPACTS BASED ON FDC

Variations in the flow regime under climate change are assessed using FDCs. FDCs compare the magnitude of a specific event against its probability of exceedance. The effects of climate change on the flow regime for all the GCMs are shown in Figure 5 under RCP 2.6, RCP 4.5 and RCP 8.5. Under RCP 2.6, most of the GCMs have predicted a rise in the high flow at 0.001% exceedance probability ($Q_{.001}$) except GCM5 and GCM7 (Figure 5a). The maximum increase in $Q_{.001}$ is forecasted by GCM1 which is almost double that of the baseline. On the other, GCM7 projects the maximum increase in the low flow at 90% exceedance probability (Q_{90}) while all other GCMs have shown a decreasing trend. All the GCMs have predicted an increment in the $Q_{.001}$ under RCP 4.5 with GCM5 showing the highest increase of 18.5 m^3/s that is almost three times more than that of the baseline (Figure 5b). Similarly, GCM3 shows that $Q_{.001}$ would be increased to 12 m^3/s in the 2090s. However, both GCM3 and GCM5 also forecasts a reduction in Q_{90} that is almost double than that of the baseline. Similar to RCP 4.5, all the GCMs have shown an increase in the $Q_{.001}$ under RCP 8.5. GCM5 has shown the highest increment that is twofold from the baseline and the minimum increment is projected by GCM3 (Figure 5c). However, most of the GCMs have shown a decline in Q_{90} except GCM7 that does not show any change in Q_{90}. Overall, most of the GCMs have forecasted an increase in the peak flow in the 2090s. Nevertheless, mixed behavior is observed for the low flows.

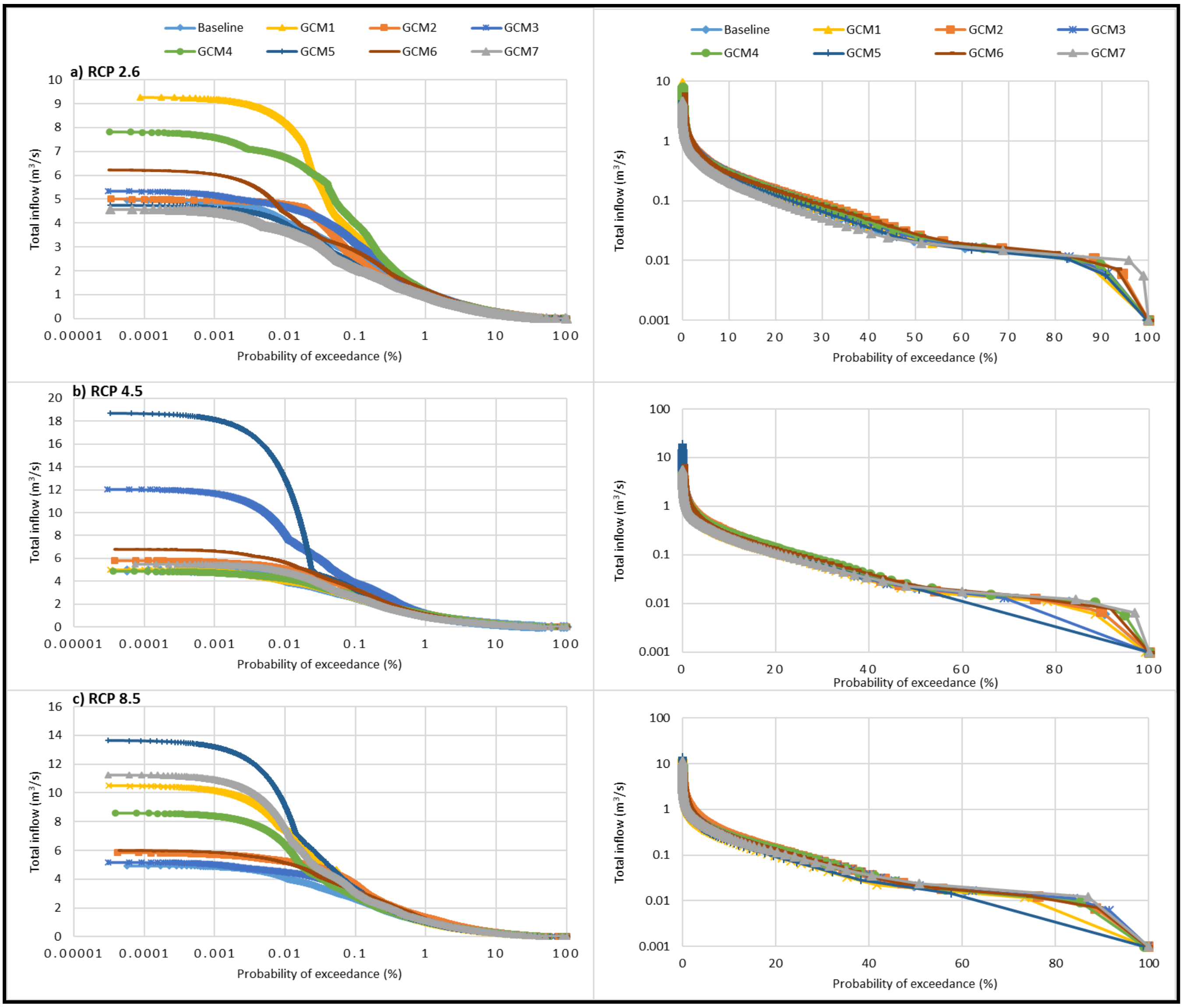

Figure 5: Comparison of flow duration curves in the 2090s (2081-2100) under a) RCP 2.6, b) RCP 4.5 and c) RCP 8.5

3.3 CLIMATE CHANGE IMPACTS BASED ON THE IHA METHOD

3.3.1 ALTERATIONS IN MONTHLY STREAMFLOW MAGNITUDES

Figure 6 shows the alterations in the magnitudes of monthly median streamflow under all the scenarios in the 2090s. Under RCP 2.6, April, May, August and September would observe the maximum increment and the highest decrease is projected in October for all the GCMs (Figure 6a). GCM7 has followed a pattern indicating a rise in the first half of the year while a decrease in the second half of the year. The utmost rise is forecasted by GCM7 (250%) in April which is followed by GCM3 in August (245%). Similarly, GCM7 estimates the highest increment in September (260%) and shows the least changes in October (-58%) under RCP 4.5 (Figure 6b). Under RCP 8.5, all the changes are varying from -50% to 300% over the annual cycle of the year (Figure 6c). Climate change scenarios of all the GCMs show that the streamflow of the Lucas Creek catchment would observe minimal changes in January, March and November. On the other hand, the highest changes would be observed in August and September as six of the GCMs predict an increase in the streamflow.

It is clear that substantial variations in the monthly streamflow would be observed in the 2090s under climate change. The increased air temperature would further exaggerate the urban heat island in the urban catchments. This expansion of urban heat island would result in more warm environments and increased rainfall intensity and frequency (Wilby, 2007). Various studies have warned of significant variations in the flow of rivers and streams in New Zealand. An example of this significant variation is the Waikato basin. The Waikato basin and its tributaries would experience a decrease in the daily streamflow under climate change as a result of reduced rainfall and elevated evapotranspiration (Pham et al., 2015). Substantial changes in the rainfall would result in increased mean flow however, a decline would be observed in summer (ME, 2016, ME, 2018, Lorrey et al., 2017).

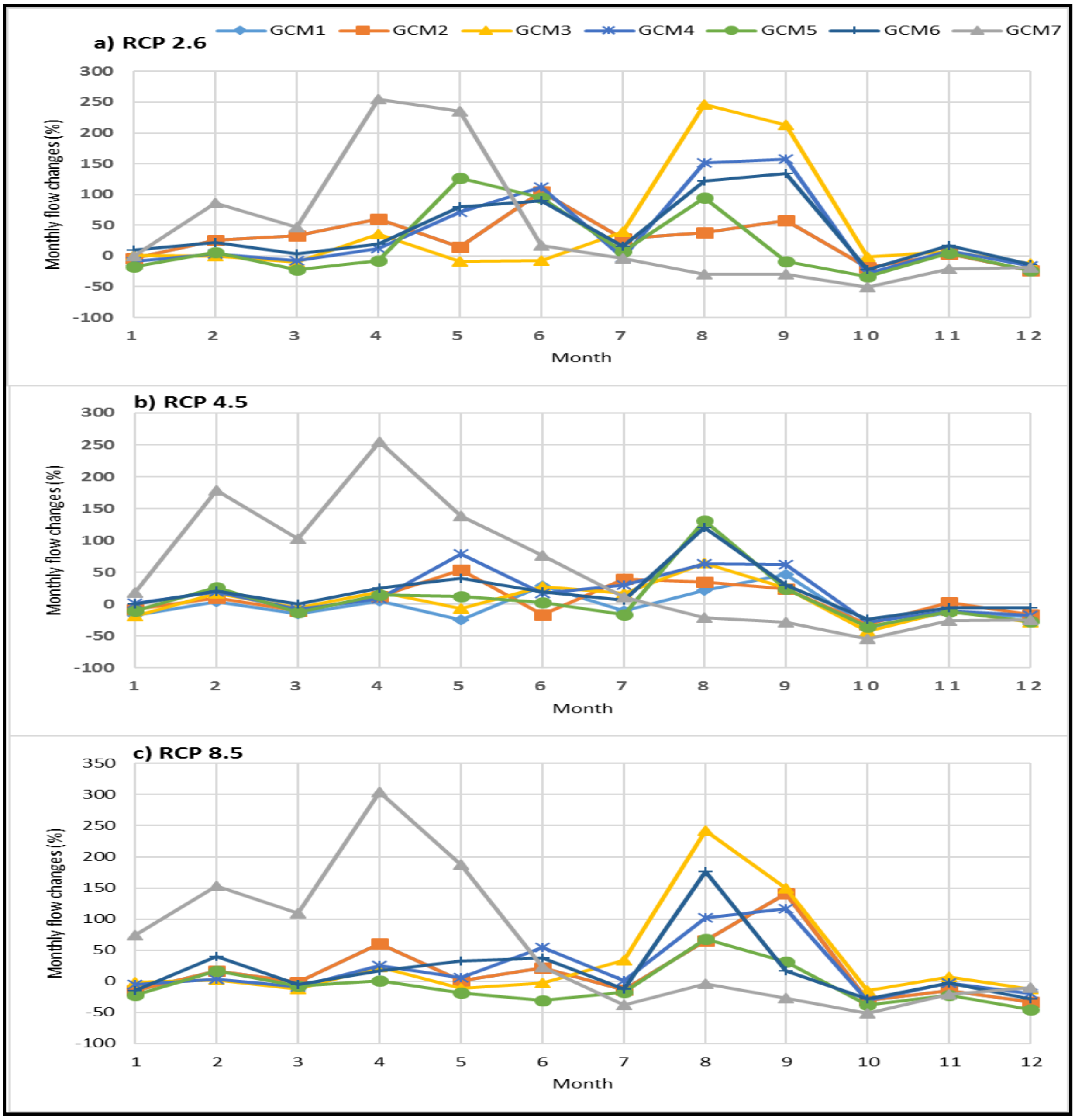

Figure 6: Changes in the monthly magnitudes of flow in the 2090s (2081-2100) under a) RCP 2.6, b) RCP 4.5 and c) RCP 8.5

3.3.2 CHANGES IN MAGNITUDE OF ANNUAL EXTREME CONDITIONS OVER DIFFERENT DURATIONS

Alterations in the magnitudes of annual extreme conditions over various durations are presented in Figure 7 under RCP 2.6, RCP 4.5 and RCP 8.5. Under the three scenarios, 1-day, 3-day, and 7-day annual minimum conditions have minimal negative trends less than 14% projected by all the GCMs. GCM7 has the maximum positive change in the 7-day minimum parameter (75%) under RCP 8.5 while for the 30-day minimum condition is changed to the maximum value (70%) under RCP 2.6 by GCM1. The 90-day minimum parameter has more than 40% decrease under all the three scenarios predicted by GCM7. The results show that extreme minimum conditions would yield higher positive changes under RCP 2.6 and RCP 4.5 compared to RCP 8.5.

In the same way, the magnitudes of maximum flow conditions have observed a diverse pattern. The figure shows that all the GCMs show a mixed behavior for 1-day, 3-day, 7-day and 90-day annual maximum flow conditions under RCP 2.6 and RCP 4.5. However, 1-day, 3-day, 7-day and 90-day annual maximum flow conditions would mainly increase under RCP 8.5. The maximum reduction in 3-day annual maximum flow is shown by GCM5 up to -22% under RCP 2.6. For the 30-day annual maximum parameter, all the GCMs are following the same pattern indicating a decrease in the 2090s under all the three climate scenarios. The maximum decrease is predicted by GCM1 (-24%) under RCP 4.5. It is evident that the percentage in the maximum flow conditions is decreasing with the increase in their durations. Additionally, the maximum flow conditions are showing less variation under climate change compared to the minimum flow conditions. The base flow index has shown variations ranging from -18% to 18% for all the GCMs except GCM7. GCM7 has forecasted a significant increase in the base flow index showing the highest values (73%) under RCP 8.5. Similarly, most of the GCMs have shown an increase in base flow index under RCP 4.5 however, a decrease is predicted under RCP 2.6 and RCP 8.5. It is clear that magnitudes of all the annual extreme parameters over different durations would be altered under the influence of climate change in the future.

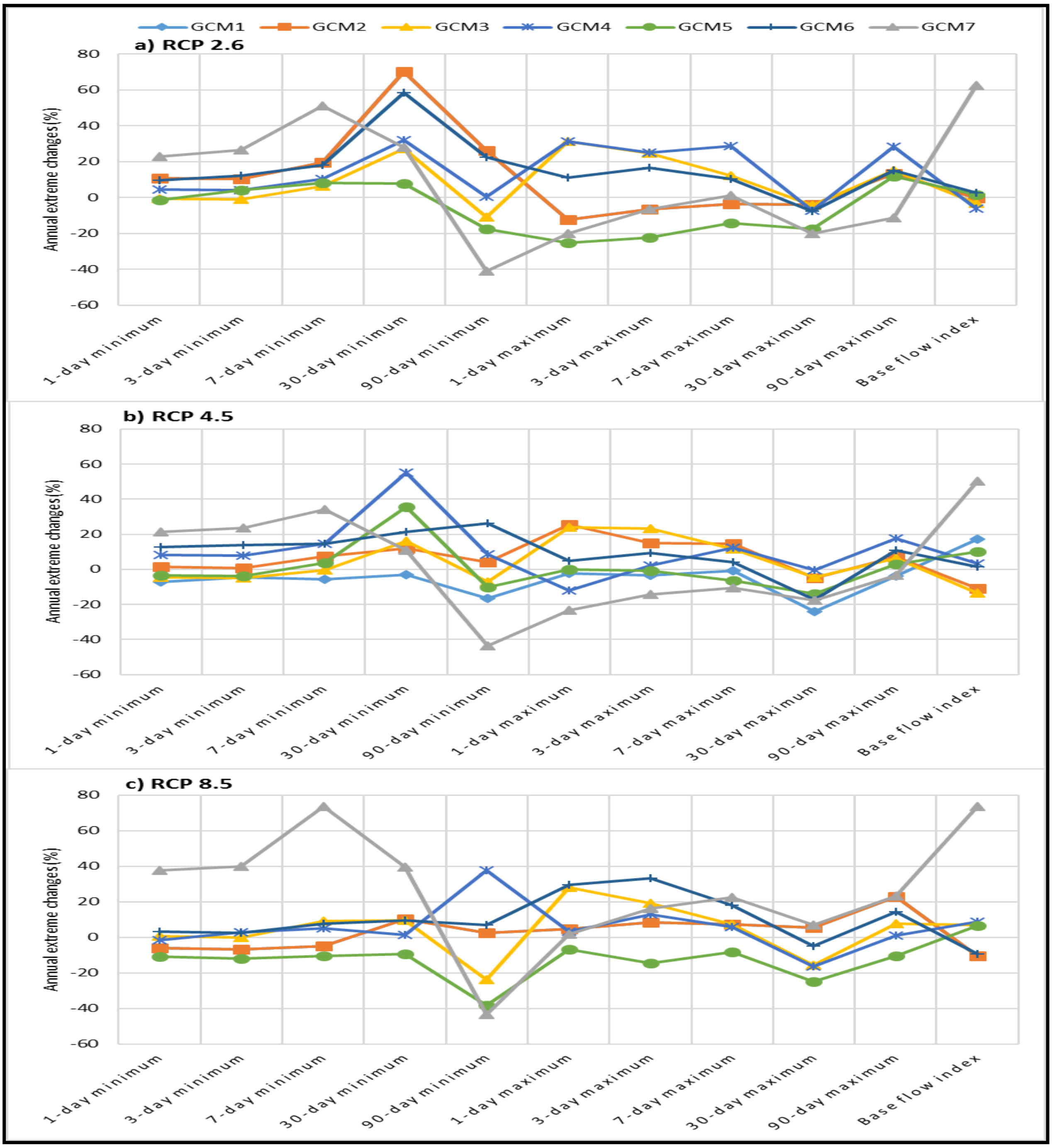

Figure 7: Changes in the annual extreme flow in the 2090s (2081-2100) under a) RCP 2.6, b) RCP 4.5 and c) RCP 8.5

3.3.3 CHANGES IN TIMING, RATE AND FREQUENCY OF ANNUAL EXTREMES

Figure 8 shows the variations in the changes in timing, duration of pulses and rate change of annual extremes in the 2090s. The timings of 1-day minimum streamflow are forecasted by GCM7 to be shifted upward by more than 200 days under all the three emission scenarios (Figure 8a). However, most of the GCMs have predicted a backward shift under the three scenarios with GCM5 showing the maximum backward shift of 85 days under RCP 8.5. Similarly, a backward shift is forecasted by most of the GCMs for the timings of maximum flow; nevertheless, the variations are less compared to the timings of minimum flows. The highest positive shift of the maximum flow is shown by GCM6 for 52 days. For low pulses, the duration is forecasted to increase in the 2090s under all the three scenarios (Figure 8b). A maximum positive or upward change of 78 days is shown by GCM5 under RCP 2.6 while some of the GCMs have also shown nil change in the low pulses such as GCM4 and GCM6 under RCP 2.6 and GCM1 under RCP 8.5. On the other hand, all the GCMs have projected a decrease in the duration of high pulses except GCM7. GCM7 has forecasted an increase under RCP 4.5 and RCP 8.5. Some GCMs have also predicted that high pulse duration would not be changed in future such as GCM5 under RCP 2.6, GCM2 under RCP 4.5 and GCM4 under RCP 8.5. The alterations in rising rate and fall are illustrated in Figure 8c. All the GCMs show a wide range of changes however, it is apparent that the rise rate would be decreased and the fall rate would be increased in the 2090s under all the three scenarios.

Figure 8: Changes in a) timing, b) duration of pulses and c) rate change of annual extremes in the 2090s (2081-2100) under RCP 2.6, RCP 4.5 and RCP 8.5

Climate change effects on high pulse count, low pulse count and number of reversals are presented in Table 5. It can be seen from the table that high pulse count and number of reversals would observe an increasing trend while low pulse count would observe a decreasing trend in the 2090s. High pulse is projected to rise by all the GCMs except GCM7 which shows a decrease under all the three scenarios. Low pulse count is estimated to decrease to a maximum level of 40% as shown by GCM7 under RCP 4.5 and RCP 8.5. Similarly, an increase in the number of reversals is forecasted by all the GCMs indicating that the changes in the flow from one form to another would become more frequent in the future. The maximum change in the number of reversals is forecasted by GCM1 up to 18% in the 2090s.

Table 5: Changes in high and low pulses count and number of reversals in the 2090s

Indicators	*GCMs*	*2090s (2081-2100)*		
		RCP 2.6 (%)	RCP 4.5 (%)	RCP 8.5 (%)
High pulse count	GCM1	9.7	9.7	9.7
	GCM2	-3.2	6.5	3.2
	GCM3	8.1	3.2	0.0
	GCM4	6.5	8.1	1.6
	GCM5	6.5	6.5	12.9
	GCM6	6.5	6.5	-3.2
	GCM7	-27.4	-32.3	-24.2
Low pulse count	GCM1	-16.6	-13.3	-13.3
	GCM2	-16.6	-20	-13.3
	GCM3	-36.6	-40	-40
	GCM4	-13.3	-16.6	-20
	GCM5	-23.3	3.3	-23.3
	GCM6	-20	-23.3	-16.6
	GCM7	-6.6	0	-26.6
Number of reversals	GCM1	18.0	10.1	4.4
	GCM2	6.1	4.4	6.1
	GCM3	14.0	13.6	14.0
	GCM4	6.1	7.0	13.6
	GCM5	12.3	9.6	12.7
	GCM6	8.8	17.1	15.4
	GCM7	10.5	11.4	8.8

3.4 FLOW REGIME ALTERATIONS AND STREAM ECOLOGY

Variations in the flow regime have direct effects on the aquatic ecosystem and stream ecology. The magnitude and duration of flow directly affect plant colonization, stream morphology and level of pollutants in the waterways. The structure of the aquatic ecosystem is disturbed with the increment of the stressful situations of high flows and low flows in the waterways (Richter et al., 1996). Similarly, the timing and rate of annual extreme conditions effect on reproduction and survival behaviors of the invertebrates in the waterways. The changes in the frequency of annual extreme conditions affect drought and flooding situations in the waterways that are linked to the availability of soil moisture for riparian vegetation and plants.

Increased monthly flow magnitude and duration of streamflow would have both constructive and damaging effects based upon the level of increment and many other parameters related to the hydro-morphology. The increased quantity of streamflow would generate reliable water supplies for aquatic organisms and plants (Cui et al., 2018). The deteriorated water quality and increased erosion have already affected the availability of native fish and aquatic ecosystem in the Lucas Creek (NSC, 2010). The sustainable and healthy aquatic ecosystem would be beneficial to the macroinvertebrate and waterway vegetation as they play a significant role in the alterations in stream flow. Clausen and Biggs (1997) found that smaller streams in New Zealand have a large concentration and variety of invertebrates and frequent floods have a positive relationship with them. Moreover, a prolonged and stable low flow is quite acceptable for the biological habitats in the waterways (Clausen and Biggs, 2000).

Conversely, the alterations in the flow regime have more detrimental effects on the stream ecology compared to the beneficial ones. The increased frequency and magnitude of high flow events would change the behavior of aquatic ecosystem and risks of flooding would be multiplied. Additionally, alterations in the low flows would create survival problems for the riparian vegetation and fish in the urban waterways (Roesner and Bledsoe, 2003). The elevated risks of frequent floods could enhance water quality problems and erosion in the waterways (Moores et al., 2016). Clausen and Biggs (1997) highlighted that higher flood frequencies impact negatively on the periphyton biomass in the small streams of New Zealand. Therefore, it is proposed that increased streamflow due to climate change, would further alter the shape of the stream cross section and wash away the vital vegetation and small organisms.

3.5 UNCERTAINTIES AND LIMITATIONS OF FUTURE PROJECTIONS

There are several uncertainties associated with the climate change scenarios coming from the GCMs. Firstly, each of the GCMs has a specific structure, resolution, parameters and boundary conditions that result in a primary source of error. Secondly, embedded uncertainties of GCMs are transferred to the grid or station level data during the dynamical or statistical downscaling process. Bias corrections are performed to remove the errors however, it is not possible to overcome all the errors. Therefore, multiple ensembles are used to see broader interpretations.

On the other hand, there are certain limitations of the study associated with the application of PCSWMM. These are related to; (1) assumption of model parameters to remain stationary under the changing climate, (2) insufficient observed data for model calibration and validation, (3) assumption of groundwater aquifer parameters, (4) calculation of parameters related to land-use and soil, and (5) other small ponds and reservoirs in the catchment.

4 CONCLUSIONS AND RECOMMENDATIONS

This work is focused on the assessment of variations in flow regime of an urban catchment using multiple ensembles of CMIP5. The projections of seven GCMs are used under three RCP scenarios. Calibrated and validated model (PCSWMM) was applied to simulate the flow time series at daily time step. The analysis is performed using the FDC and the IHA method. The following conclusions can be made from the present study:

1. High values of NS and R^2; 0.76 and 0.80, respectively during calibration (2007-2013) and 0.72 and 0.79 during validation (2014-2016) showed that PCSWMM had performed quite well. Likewise, low values of RMSE (3.11 during calibration and 1.74 during validation) and PBIAS for Q_{10} and Q_{90} advocate the satisfactory calibration of the model. Following this, the model was run for the baseline period (1985-2005) and the future period (2081-2100) for further scenario analysis.

2. Variations in the flow regime based on FDC indicate that under RCP 2.6, most of the GCMs have predicted a rise in the high flow $Q_{.001}$ except GCM5 and GCM7. The maximum increase in $Q_{.001}$ is forecasted by GCM1 which is almost double to the baseline. On the other, GCM7 projects the maximum increase in the low flow Q_{90} while all other GCMs have shown a decreasing trend. Under RCP 4.5, GCM5 shows the highest increase of 18.5 m^3/s that is almost three times more than the baseline. However, GCM3 and GCM5 forecast a reduction in Q_{90} that is almost twice to the baseline. Like RCP 4.5, all the GCMs have shown an increase in the $Q_{.001}$ under RCP 8.5. GCM5 has shown the highest increment that is twice to the baseline and the minimum increment is projected by GCM3. However, most of the GCMs have shown a decline in Q_{90} except GCM7 that does not show any change in Q_{90}.

3. Climate change scenarios from all the GCMs show that the streamflow would observe minimal changes in January, March and November and the highest changes would be observed in August and September based on the IHA method. The extreme minimum conditions would observe higher positive changes under RCP 2.6 and RCP 4.5 compared to RCP 8.5. Similarly, the magnitudes of maximum flow conditions have observed a distinct pattern. All the GCMs show a mixed behavior for 1-day, 3-day, 7-day and 90-day annual maximum flow conditions under RCP 2.6 and RCP 4.5. However, 1-day, 3-day, 7-day and 90-day annual maximum flow conditions would mainly increase under RCP 8.5. The base flow index has shown variations ranging from -18% to 18% for all the GCMs except GCM7 that shows the highest increase under all the three scenarios. Annual extremes' timings, duration of high pulses, rise rate and low pulse count have observed a declining pattern. However, duration of low pulses, fall rate, number of high pulse count and number of reversals have followed an inclining trend.

4. Variations in the flow regime of the Lucas Creek catchment are predicted by both FDC and the IHA method. Nevertheless, the extent of variations is different for every GCMs in the 2090s. Such as GCM7 has predicted fewer variations in the flow regime under FDC compared to the IHA. However, the variations in the flow regime are apparent in the future.

5. Transformed flow regime of the urban waterways as a result of climate change would have positive and negative influences on the aquatic ecosystem. Elevated magnitudes and duration of streamflow would be useful for the macroinvertebrates and plants. On the other hand, continuous variations and enhanced risks of severe and frequent floods would push more adverse effects in comparison to benefits. For example, vital vegetation and small organisms could be washed away because of frequent floods and more erosion could occur.

This paper presents the preliminary results of climate change effects on the flow regime of the urban waterways. Nevertheless, climate change data available at a finer spatial and temporal scale would be good to assess the variations in the flow regime. Climatic data at higher temporal resolution is considered to be more realistic to capture all the storm events at small urban catchments. Additionally, a better understanding of the relationship among climate change, hydrological flow regime and aquatic ecosystem would lead towards a proper investigation in the future studies.

ACKNOWLEDGEMENTS

We are thankful to the Auckland Council (AC) and the National Institute of Water and Atmospheric Research (NIWA), New Zealand for providing observed data, geographical maps and RCM rainfall projections. We are also grateful to Computational Hydraulics International (CHI), Canada for granting PCSWMM license.

REFERENCES

AC (2017) The Unitary Auckland Plan. Auckland, New Zealand.

Akhter, M. S. & Hewa, G. A. (2016) 'The use of PCSWMM for assessing the impacts of land use changes on hydrological responses and performance of WSUD in managing the impacts at myponga catchment, South Australia' Water, 8(11).

Akhter, M. S., Shamseldin, A. Y. & Melville, B. W. (2017) Statistical rainfall downscaling of a CMIP5 ensemble in urban catchments: An Auckland area case study In Proceedings of 1st International Conference on Water and Environmental Engineering.

Alamdari, N., Sample, D., Steinberg, P., Ross, A. & Easton, Z. (2017) 'Assessing the Effects of Climate Change on Water Quantity and Quality in an Urban Watershed Using a Calibrated Stormwater Model' Water, 9(7):464.

Butchart-Kuhlmann, D., Kralisch, S., Fleischer, M., Meinhardt, M. & Brenning, A. (2018) 'Multicriteria decision analysis framework for hydrological decision support using environmental flow components' Ecological Indicators, 93:470-480.

CHI (2018) Calibrating a SWMM5 model using the SRTC tool. Computational Hydraulics International (CHI), see https://support.chiwater.com/78011/calibrating-a-swmm5-model-using-the-srtc-tool (accessed 15/07 2018).

Clausen, B. & Biggs, B. (1997) 'Relationships between benthic biota and hydrological indices in New Zealand streams' Freshwater Biology, 38(2):327-342.

Clausen, B. & Biggs, B. J. F. (2000) 'Flow variables for ecological studies in temperate streams: groupings based on covariance' Journal of Hydrology, 237(3):184-197.

Cui, T., Yang, T., Xu, C.-Y., Shao, Q., Wang, X. & Li, Z. (2018) 'Assessment of the impact of climate change on flow regime at multiple temporal scales and potential ecological implications in an alpine river' Stochastic Environmental Research and Risk Assessment, 32(6):1849-1866.

Da silva, C., Schardong, A., Garcia, J. & Oliveira, C. (2018) 'Climate Change Impacts and Flood Control Measures for Highly Developed Urban Watersheds' Water, 10(7):829.

Finney, K. & Gharabaghi, B. (2011) Using the PCSWMM 2010 SRTC Tool to Design a Compost Biofilter for Highway Stormwater Runoff Treatment.

Franczyk, J. & Chang, H. (2008) 'The effects of climate change and urbanization on the runoff of the Rock Creek basin in the Portland metropolitan area, Oregon, USA' Hydrological Processes, 23(6):805-815.

Hamel, P. & Fletcher, T. D. (2014) 'The impact of stormwater source-control strategies on the (low) flow regime of urban catchments' Water Science and Technology, 69(4):739-745.

Hashmi, M., Shamseldin, A. Y. & Melville, B. W. (2011) 'Comparison of SDSM and LARS-WG for simulation and downscaling of extreme precipitation events in a watershed' Stochastic Environmental Research & Risk Assessment, 25(4):475-484.

IPCC (2013) The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Press, C. U., Cambridge, United Kingdom and New York, NY, USA.

James, W. (2005) Rules for Responsible Modeling. 4th edn. Guelph, Ontario, Canada, Computational Hydraulics International (CHI).

James, W., Rossman, L. A. & James, W. R. C. (2010) User's guide to SWMM 5:[based on original USEPA SWMM documentation].) CHI.

Lee, A., Hewa, G., Pezzaniti, D. & Argue, J. R. (2008) 'Improving stream low flow regimes in urbanised catchments using water sensitive urban design techniques' Australian Journal of Water Resources, 12(2):121-132.

Lorrey, A. M., Pearce, P. R., Barkus, C., Anderson, S. J. & Clement-Jones, A. (2017) Auckland Region climate change projections and impacts: summary report. Council, A., Auckland, New Zealand.

ME (2016) Climate Change Projections for New Zealand: Atmosphere Projections Based on Simulations from the IPCC Fifth Assessment. Wellington, New Zealand.

ME (2018) Climate Change Projections for New Zealand: Atmosphere Projections Based on Simulations from the IPCC Fifth Assessment. Wellington, New Zealand.

Metcalf, Eddy, I., Hassan, W. H., Nile, B. K. & Al-Masody, B. A. (2017) 'Climate change effect on storm drainage networks by storm water management model' Environmental Engineering Research, 22(4):393-400.

Moores, J., Gadd, J., Yalden, S. & Batstone, S. (2016) Urban Development and the NPS-FM: Lucas Creek Catchment Case Study. Industries, M. F. P., Auckland, New Zealand.

NSC (2010) Lucas Creek stormwater management plan. Auckland.

Pham, H. X., Shamseldin, A. Y. & Melville, B. W. (2015) 'Assessment of Climate Change Impact on Water Balance of Forested and Farmed Catchments' Journal of Hydrologic Engineering, 20(10).

Richter, B. D., Baumgartner, J. V., Powell, J. & Braun, D. P. (1996) 'A Method for Assessing Hydrologic Alteration within Ecosystems' Conservation Biology, 10(4):1163-1174.

Roesner, L. A. & Bledsoe, B. P. (2003) 'Physical effects of wet weather flows on aquatic habitats: present knowledge and research needs' Water Environment Research Foundation Fort Collins, CO.

Rummukainen, M. (2010) 'State-of-the-art with Regional Climate Models' Wiley Interdisciplinary Reviews: Climate Change, 1(1):82-96.

Wilby, R., Charles, S., Zorita, E., Timbal, B., Whetton, P. & Mearns, L. (2004) Guidelines for use of climate scenarios developed from statistical downscaling methods. Supporting material of the Intergovernmental Panel on Climate Change, available from the DDC of IPCC TGCIA 27.

Wilby, R. L. (2007) 'A review of climate change impacts on the built environment' Built Environment, 33(1):31-45.

Zahmatkesh, Z., Karamouz, M., Goharian, E. & Burian, S. J. (2014) 'Analysis of the effects of climate change on urban storm water runoff using statistically downscaled precipitation data and a change factor approach' Journal of Hydrologic Engineering, 20(7):05014022.