Impact of Global Climate Change on Stream Low Flows in a Hydraulic Fracking Affected Watershed

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Abstract*- The impact of fresh water withdrawals for hydraulic fracturing has concerned water resource scientists and communities interested in sustainable water resource management. Specifically, low flow conditions in watersheds may be further reduced due to global climate change, as it has the potential to decrease streamflow. Since an earlier study found that the current rate of fracking had some impact on water availability, this study was conducted in order to ascertain whether or not the current fracking trend will have an impact in stream low flow in the future. This study was conducted on the Muskingum watershed in Eastern Ohio, which has been subjected to the rapid expansion of hydraulic fracking. The watershed model, Soil and Water Assessment Tool (SWAT), was used for watershed simulation using the climate output of Coupled Model Intercomparison Project Phase 5 (CMIP5). Precipitation and temperatures outputs from Max Planck Institute Earth System Model (MPI-ESM) were used to evaluate the variation in streamflow during the 21st century using three Representative Concentration Pathways (RCP) scenarios: RCP 2.6; RCP 4.5; and RCP 8.5. Three future periods, namely, 2035s (2021-2050), 2055s (2051-2070) and 2085s (2070-2099) were set against the baseline condition (1995-2009). Lowest flow was projected to increase across the watershed during 2035s period compared to the remaining 50 years period, under the highest forced climate scenario (RCP8.5). Similarly, mean flow also could be expected to decrease during 2035s in the eastern, north-western and south western portion of the watershed. Additionally, the streamflow was simulated using current fracking scenarios and 2035s climate output in order to assess the impact of water withdrawal for a continuous trend of current fracking rates. A modest effect on stream low flow was detected, when extreme scenario (RCP 8.5) was considered, especially in the headwater streams. While results indicate that 14 of 32 subbasins were affected, with maximum difference up to 55% in lowest 7 days minimum low flow (considered lowest value from each year), negligible impact was detected on mean monthly and annual streamflow. Analysis with RCP 2.6 and RCP 4.5 indicated that stream low flow would not be affected especially in higher order streams. Even though a localized effect of hydraulic fracking to reduce the environmental flow was detected; this research indicated that future climate change may not have additional adverse impacts if hydraulic fracking trends are stable.

Keywords: CMIP5; Climate Model; Hydrologic Analysis; MPI-ESM, SWAT; Low Flow; Drought

I. INTRODUCTION

Water resources managers have a particular concern about the water resources management during low flow in order to optimally utilize the freshwater resources for various purposes including water supply, recreation, wildlife conservation and reservoir flow regulation. Hydrological, droughts are the most crucial and categorized as the most stressful events in the hydrological cycles. Therefore, stream low flow due to hydrologic drought has become a particular interest of research topics among scientists due to its characteristics of reducing the groundwater, lowering of the reservoir or lake level and decreasing streamflow discharge for consecutive years [1].

Various natural factors contribute to low flow variability leading to the social and economic impacts [2]. Additionally, fluctuation of low flow is affected by anthropogenic impacts, which may cause supplementary severe conditions in the dry period [1]. For example, a large amount of water abstraction for industrial uses, irrigation, power generation and domestic water use reduces the downstream water volume [3]. Similarly, agricultural practices may also cause significant increase in the frequency of low flow discharge [4-6], leading to the frequent low flow and complications in optimal allocation of water resources.

In addition to conventional anthropogenic influences, water withdrawals for hydraulic fracking have been an emerging critical issue, especially for low flow periods when severe drought occurs [7]. A significant amount of water has been used from the streams and reservoirs for hydraulic fracking without consideration for ecological and environmental impacts. While the fracking water volume is small in comparison with the total water availability in any area, the water withdrawal for drilling and fracturing operations over a small tributary might be ecologically stressful and may threaten the sustainable water resource management. For example, it may create additional deficits to municipal water supplies and adversely impact aquatic life in the stream during low flow period. Spatially, this imbalance can be further worsened for specific small tributaries, and the streamflow variation may be more prominent at the sub basin scale [8]. There are also various impacts from fracking operations such as groundwater contamination, drying out the groundwater wells and streams, however these studies were outside the scope of this paper.

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Declining flow rates may be further stressed due to increasing rise in global temperature [9, 10] and future precipitation trend associated with global climate change leading to the alteration in the hydrological cycle and threatening the sustainable water resources management. Therefore, there is a pressing need to explore the impact of global climate change on stream low flows, especially for a watershed which is subjected to the long term water demands for hydraulic fracking. Therefore, this study was conducted in order to determine the impact of projected global climate change during stream low flow conditions in the watershed under continued hydraulic fracking in the future.

II. MATERIALS AND METHODOLOGY

A. Climate Model

World Climate Research Program (WCRP) has developed the multi-model climate dataset through Coupled Model Intercomparison Project (CMIP) and made freely available through the Program for Climate Model Diagnosis and Intercomparison (PCMDI) [11, 12]. Various phases of CMIP have increased slowly over the years. The third phase of CMIP; Coupled Model Intercomparison Project Phase 3 (CMIP3) [13, 14] has provided important information to the Intergovernmental Panel on Climate Change (IPCC) fourth assessment repot [15]. Similarly, IPCC's fifth assessment report relies heavily in Coupled Model Intercomparison Project Phase 5 (CMIP5). CMIP5 dataset incorporates four newly developed sets of climate forcing scenarios called representative concentration pathways (RCPs). RCP 8.5, RCP 6.0, RCP 4.5 and RCP 2.6 [16, 17] are scenarios with concentration, emission and land-use trajectories [18]. Among these scenarios, RCP 8.5 is the highest emission scenario, including greater greenhouse gas concentrations and warming effects than other three scenarios. Similarly, RCP 6.0 is considered as a midrange emission scenario and RCP 4.5 as a low range emission scenario. RCP 2.6 is considered as a strong mitigations scenario, which includes the increase of greenhouse gases and temperature changes to the first part of the 21st century and decreasing trends for both features on the second half of century [12, 19]. CMIP5 incorporates Earth System Models (ESMs), Atmosphere-Ocean General Circulation Models (AOGCMs) and Earth System Models of Intermediate Complexity (EMICs), which helps to study the impact of carbon responses on climate change [12].

Since CMIP5 has incorporated new General Circulation Model (GCM) projections with relatively more physical process than previously published dataset CMIP3 [20], the recently available CMIP5 data has been utilized for this study. A widely used, Soil and Water Assessment Tool (SWAT) [21] was developed in order to simulate the coupled impact of hydraulic fracking and future climate change on stream low flow. While there are several publications regarding the application of CMIP3 dataset to assess the variability on hydrological regimes [22, 23], relatively limited articles have been published [24] using CMIP5 data. To the authors' knowledge, no studies have been conducted yet, for the evaluation of stream low flow due to the integrated effect of climate change and fracking, particularly in a watershed, which has a tremendous potential for hydraulic fracking.

The Max Planck Institute Earth System Model (MPI-ESM) is a newly revised model in the CMIP5 with the essential addition of carbon cycle, radiative transfer scheme, aerosol forcing and integration of dynamic vegetation at the land surface [25, 26]. The model has three configurations: MPI-ESM low resolution (MPI-ESM-LR), mixed resolution (MPI-ESM-MR) and paleo resolution (MPI-ESM-P). Among these configurations, MPI-ESM-LR has been widely used for the experimentations and simulations of CMIP5 [25].

B. Study Area

The study was conducted in the Muskingum watershed, which is located in the eastern part of the Ohio, USA (Figure 1). The Muskingum watershed is one of the major watersheds of Ohio, which covers almost 20% (8000 square mile) area of entire Ohio. This is a Hydrologic Unit Code (HUC)-4 watershed characterized with several wetlands, lakes and reservoirs. The average flow at the outlet of the watershed is 78 cubic meters per second (cms) and average annual precipitation over the entire watershed is almost 990 mm. The development of oil and natural gas is evolving substantially in this region. Currently, 90% of the total numbers of wells located in Ohio are concentrated in this watershed as several drilling companies are exploring in this region for oil and gas development. The water consumption for hydraulic fracking was noteworthy than the agricultural water consumption during 2012. The surface water consumption for the studied area, Muskingum watershed is depicted in Table 1 during 2012. Even though the fracking water withdrawal was far less than other primary use such as public, power, mineral extraction, industry and other uses, this might be very useful to study the fracking impact during low flow period in extreme drought conditions. In comparison to ground water withdrawal for hydraulic fracking, it was merely 1% as compared to surface water withdrawal during year 2012. In order to evaluate the impact of climate change and water withdrawal for fracking in stream low flow, SWAT model was developed. The impact of fracking without considering climate change was also conducted in this watershed in a previous study [27]. The input data needed for SWAT model development are briefly described in the following section.

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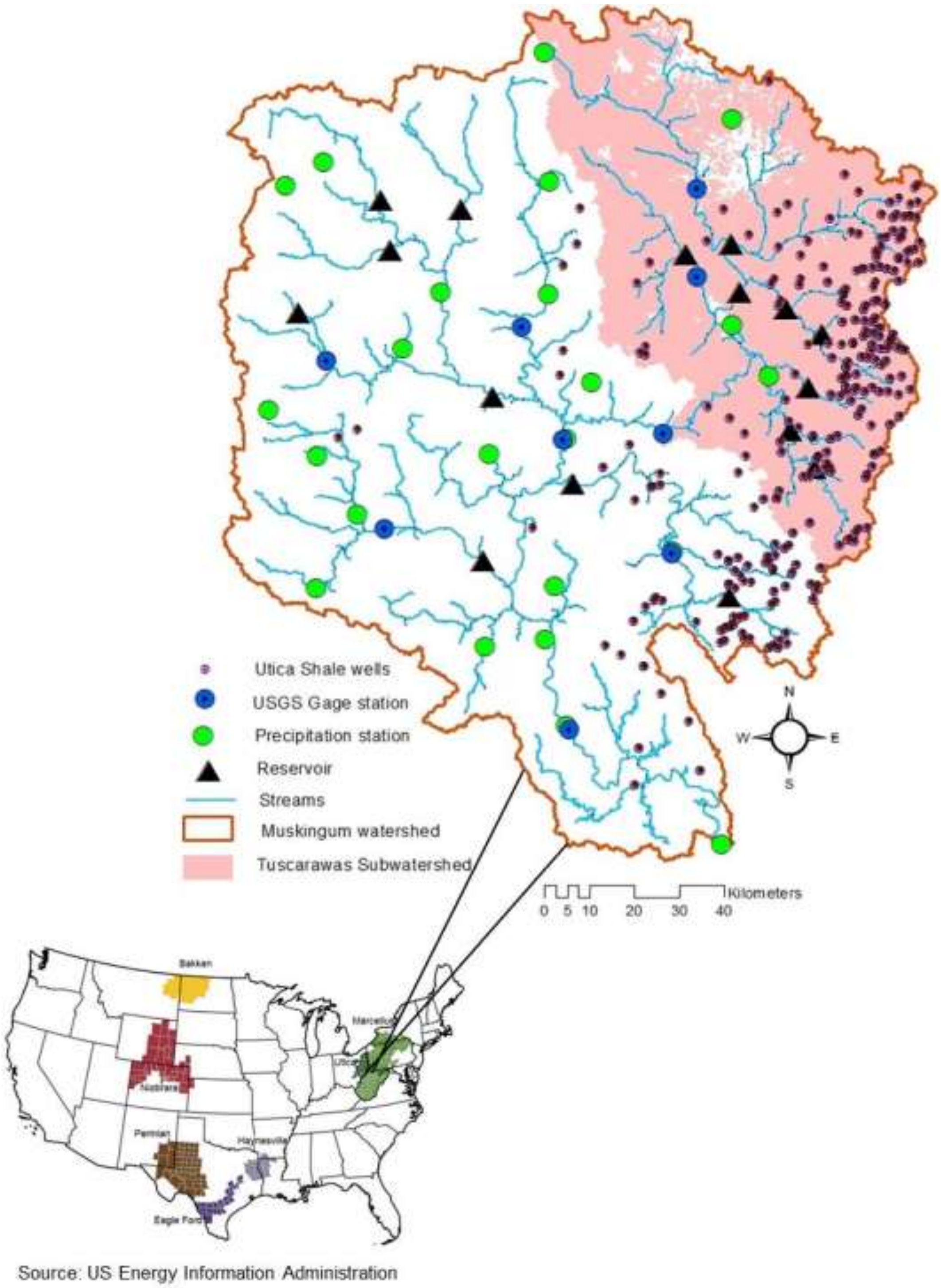

Figure 1 Muskingum watershed with location information of shale wells, USGS flow gage, precipitation, reservoir, streams and Tuscarawas subwatershed

TABLE 1 SURFACE WATER WITHDRAWAL FOR VARIOUS PRIMARY USES BASED ON FACILITIES IN THE MUSKINGUM WATERSHED DURING YEAR 2012 (SOURCE: OHIO DEPARTMENT OF NATURAL RESOURCES (ODNR))

Primary Use	Surface Water (cubic meters/day)	Number of Facilities
Agriculture	220	13
Golf Course	308	38
Hydraulic fracking	334	36
Miscellaneous	677	7
Industry	716	6

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Mineral Extraction	2448	16
Public	10516	23
Power	196225	6
Total	211444	145

C. SWAT Model Input

The digital elevation model (DEM) needed for watershed delineation and soil data (STATSGO) for watershed modeling were utilized from the United States Geological Survey (USGS) and United States Department of Agriculture (USDA), respectively. Land use data were downloaded from the National Land Cover Database 2006 (NLCD 2006). The complexity of landscape was obtained by the division of land use and subdivision of sub-watersheds into total 6176 HRUs. Similarly, precipitation and temperature datasets were utilized from 23 precipitation and 19 temperature gage stations in order to adequately address the spatial variability of the rainfall and temperature. The daily streamflow data needed for the multi-site model calibration and validation were obtained from nine USGS locations within the watershed from period 1993 to 2009. Since the watershed was characterized with several reservoirs and point sources, daily mean reservoir outflow were obtained from the United States Army Corps of Engineers (USACE) and major point sources with greater than 0.026 cms were used from the Ohio Environmental Protection Agency (OEPA). The water use data from the watershed for various purposes such as ground water, irrigation, water supply, power plant, industry and hydraulic fracking were obtained from the Ohio Department of Natural Resources (ODNR). All types of information related with oil and natural gas were utilized from the ODNR. However, the information related with the water use and water recycling associated with fracking well was utilized from the fracfocus. The spatial location of climate stations including USGS gauging stations, reservoirs and fracking wells are presented in Figure 1. Readers can refer our earlier publication [27] for additional input information for the SWAT model development and modelling issues of hydraulic fracking in SWAT.

D. Model Calibration and Validation

The multi-site SWAT model calibration and validation were performed using automated calibration, validation and uncertainty analysis, developed in Swat Calibration and Uncertainty Program (SWAT-CUP) [28]. Sequential Uncertainty Fitting version 2 (SUFI-2) algorithm was selected in SWAT-CUP that finds out the most favorable model parameters within the uncertainty ranges of 95% after incorporating the possible parameters ranges [27, 28]. Twenty-one model parameters (not shown) were initially selected and optimal set of model parameters were chosen based on the model performance. The SWAT model was calibrated at nine USGS stations using streamflow data from 1993 to 2009. Two years of streamflow data were used for model spin up period in order to stabilize the initial hydrological conditions. The model was calibrated at nine various locations of the watershed both in daily and monthly scale using USGS streamflow data from 2002 to 2009. The model was also validated using the independent datasets from 1995 to 2001 at nine subsequent USGS locations. The goodness of fit was evaluated with a popularly used objective functions including Nash-Sutcliffe efficiency (NSE), R-square (R^2), root mean square error (RMSE), percentage bias (Pbias) etc. Readers can refer [27] for the detail description of these statistical criteria.

E. Climate Change Analysis

In order to evaluate future impacts on freshwater resources under climate change scenario, the latest daily time scale of climate data (precipitation, minimum and maximum temperature) were downloaded from publicly available archives for CMIP5 climate data, using bias corrected-constructed analogs (BCCA) [19] downscaling technique. The spatial resolution was selected at 1/8 degree across the watershed. For this study, two CMIP5 simulations were analyzed: one for the evaluation of various climate model performances, and the second for future projected climate change. Since several climate models exist with different climate forcing functions, it was essential to evaluate the performance of each climate model and find an appropriate model in a given watershed. For this, historical climate data was downloaded from 1961 to 1990 at two climate stations (0335747 and 0014891) for two forced scenarios (RCP 4.5 and 8.5). The study indicated that the Max Planck Institute earth system model (MPI-ESM) was superior in its performance, based on the correlation coefficient.

In order to best conduct a future climate change study, RCP 2.6, RCP 4.5 and RCP 8.5 forced scenarios were selected from 2020 to 2099 for 23 climate stations, and downscaled to the same climate stations which were used for SWAT model calibration and validation for the hydrological simulations.

III. RESULT AND DISCUSSION

A. SWAT Model Calibration and Validation

The model performance is satisfactory both for daily and monthly simulation. The statistical criteria measuring the performance of the model including *NSE*, R^2, and *Pbias* are listed in Table 2. The time series of the observed flow vs. simulated flow using the calibrated and validated SWAT model are reported in Figure 2 and Figure 3, respectively. The calibrated model was utilized for the prediction of future streamflow using bias corrected downscaled climate data at various stations.

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TABLE 2 THE STATISTICAL CRITERIA MEASURING THE PERFORMANCE OF THE MODEL

USGS Gage Station	**Scale**	**Calibration**				**Validation**			
		R^2	NSE	RSR	PBIAS	R^2	NSE	RSR	PBIAS
3117000	Monthly	0.89	0.89	0.34	-0.4	0.9	0.86	0.37	6.76
	Daily	0.42	0.42	0.76	-0.03	0.45	0.45	0.74	-1.6
3124500	Monthly	0.59	0.53	0.68	-15.6	0.63	0.61	0.62	-9.45
	Daily	0.43	0.4	0.85	-15.88	0.53	0.47	0.73	-9.93
3139000	Monthly	0.64	0.64	0.6	-4.15	0.72	0.71	0.54	-2.65
	Daily	0.51	0.49	0.71	-4.09	0.63	0.6	0.63	-2.7
3036500	Monthly	0.5	0.49	0.72	9.25	0.63	0.56	0.66	17.72
	Daily	0.47	0.46	0.73	9.09	0.41	0.4	0.78	17.75
3129000	Monthly	0.68	0.66	0.59	2.87	0.67	0.55	0.67	20.93
	Daily	0.57	0.56	0.66	2.87	0.54	0.47	0.73	20.82
3140500	Monthly	0.68	0.67	0.58	1.48	0.76	0.69	0.55	12.61
	Daily	0.63	0.63	0.61	1.52	0.69	0.65	0.59	12.53
3146500	Monthly	0.79	0.72	0.53	11.15	0.76	0.71	0.54	12.27
	Daily	0.42	0.4	0.77	11.26	0.43	0.42	0.76	12.24
3142000	Monthly	0.71	0.69	0.56	12.85	0.77	0.68	0.56	-1.16
	Daily	0.55	0.47	0.73	12.91	0.51	0.49	0.71	-2.39
3150000	Monthly	0.73	0.72	0.53	0.31	No Data			
	Daily	0.65	0.65	0.59	0.36				

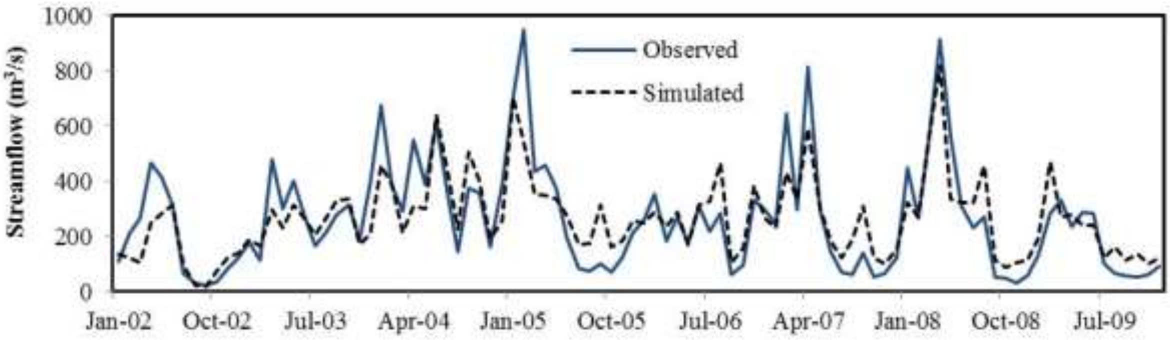

Figure 2 Streamflow calibrations at watershed outlet (USGS gage 03150000) from January 2002 to December 2009

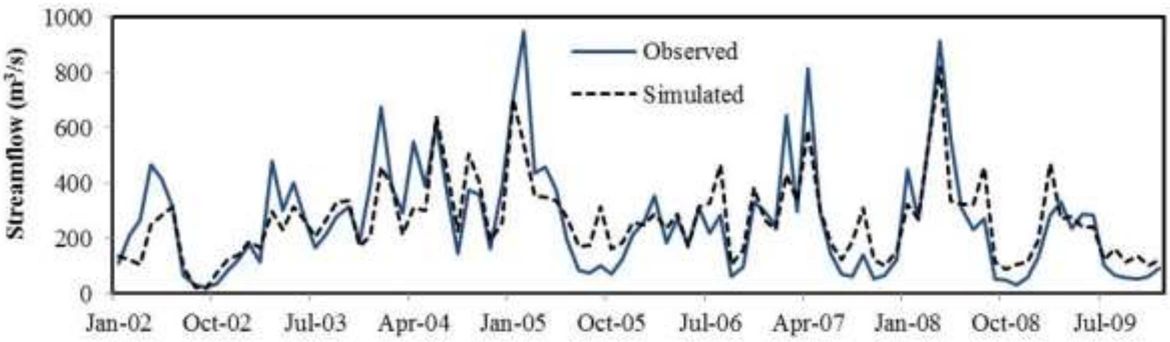

Figure 3 Streamflow validation at USGS gage 03142000 from January 1998 to March 2001 (long term data were not available in USGS gage 03150000.)

B. Selection of a Climate Model

The performance of 19 climate models were examined by comparing model projected data for a historical period with observed data using squared correlation coefficient. For this, CMIP5 datasets using BCCA downscaling methods were downloaded for RCP scenarios 4.5 at precipitation stations 00335747 and 00014891 and RCP scenarios 8.5 at station

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00014891. The performance of the model varied significantly, and the model performances in terms of squared correlation coefficients for monthly mean precipitations are presented in the Figure 4. Out of the 19 models, the performance of MPI-ESM-LR was superior, which was determined based on the squared correlation coefficient (Figure 4). Both the configurations: MPI-ESM-LR and MPI-ESM-MR performed well for RCP 8.5 and RCP 4.5 at station 0014891 (not shown). However, the performance of MPI-ESM-LR model with RCP 4.5 was relatively better at station 00335747 (Figure 4). As the MPI-ESM-LR configuration fitted well with the observed output in all the correlation tests and used with wide range for the CMIP5 simulations, MPI-ESM-LR was selected for this specific study.

Subsequently, MPI-ESM-LR dataset for RCP 8.5 was selected for the assessment of climate change on the hydrological cycle at three time periods: 2035s, 2055s and 2085s.

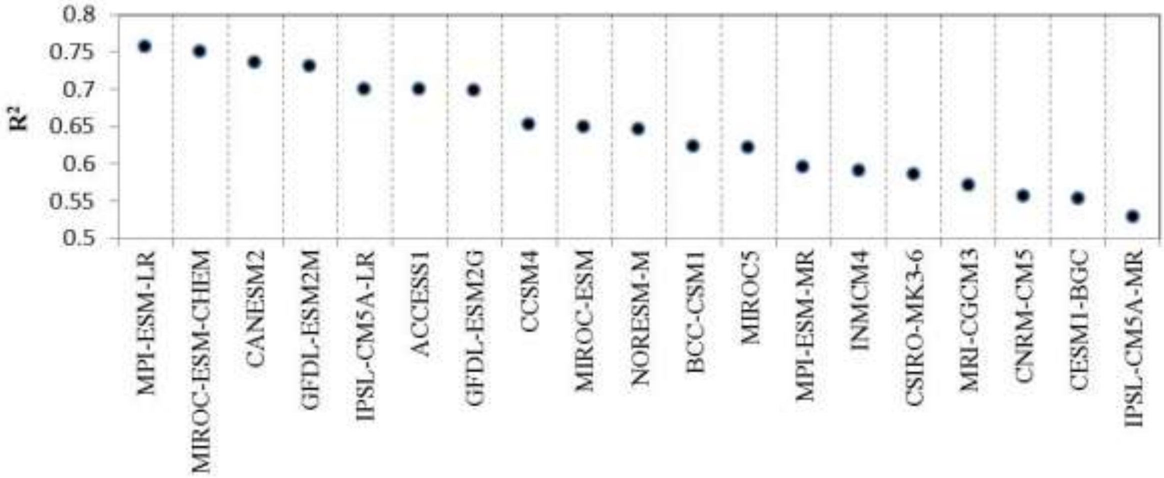

Figure 4 Squared correlation coefficient for 19 BCCA models under RCP 4.5 scenario of CMIP5 at precipitation station 00335747

C. Reference Periods and Scenarios

Future Climate change was studied for future periods from 2021 to 2099. It is categorized as: 2035s, 2055s and 2085s which are basically 2021-2050, 2051-2070 and 2070-2099 respectively. These time periods were also adopted by the climate assessment report from NOAA [29]. Past fourteen years from 1995 to 2009 were regarded as baseline period in order to compare with above mentioned three future periods. In the next step, climate dataset for three periods were incorporated in a SWAT model to simulate the streamflow for future climate change.

In order to analyze the fracking impact on stream, the current fracking operation of 2012 was applied in the calibrated and validated SWAT model for the evaluation of climate change effect over a period of 2035s. An analysis was limited for fracking and climate change with 2035s assuming that the current trend of hydraulic fracking would remain intact. Typically, baseline and current scenarios were developed to assess the impact on water resources under current level of fracking. The baseline scenario referred to the watershed conditions of 2012 for period 2035s without incorporating water use for hydraulic fracturing. The current scenario utilized watershed and current fracking conditions of 2012 for future period (2035s). Fracking in the other two periods were not evaluated in this study due to tremendous uncertainties of unconventional drilling trends in the future as the continuous operation of hydraulic fracking depends upon the several political and socio-economic factors. Monthly fracking water use was provided in the model from the water use input file. The simulated flow for current fracking trends during this period was compared with the flow without fracking conditions.

D. Climate Change in the Basin

The bias corrected downscaled precipitation and temperature were utilized for all stations (23 for precipitation and 19 temperatures) to best represent the spatial variability of precipitation and temperature and create better predictions of streamflow for future. The motive behind this study was to evaluate extreme scenarios first, to determine if climate change could have adverse impacts in the future if the current trend of hydraulic fracking continues. This is essential because various GCMs and scenarios may or may not be required if the impact is not significant, even for the maximum scenarios. Therefore, the results were presented under the highest emission scenarios (RCP 8.5).

The hydrologic cycle is mainly influenced by patterns of temperature and rainfall; therefore, the simulated flow pattern over the 21st century was consistent with the variability of rainfall and temperature patterns that could be expected in this century (not shown). This assessment was performed for three future periods against the baseline periods. The percentage exceedance flow taken at the outlet of the watershed indicated that the chances of the occurrence of low flow would be higher in 2055s than 2035s and 2085s for RCP 8.5; however, high flow could be expected in 2055 while using RCP 4.5 (Figure 5) and lowest flow could be realized in 2035 while using RCP 2.6. The percentage change in the annual mean, seasonal mean and

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monthly mean flow at the outlet of the watershed is presented for RCP 8.5 in Figure 6. The monthly mean percentage change showed that September might be a stressful month in all three periods as the study showed 12.2%, 12.8% and 21.6% reduction in the streamflow, respectively indicating that water withdrawal in the September month needed to be considered seriously for the water resources management (Figure 6a). Results from the early period of 21st century (2035s) shows that the reduction of flow by -5.4% in January, -14.2% in June, -1% in July and -12% in September could be expected. On seasonal scale, mean seasonal flow showed an increase for all periods except summer in the 2035s period (Figure 6b) for RCP 8.5, which was consistent with the precipitations trend of the period. An increasing trend was also revealed in the annual mean streamflow of three consecutive future periods (Figure 6c), which was consistent with the increasing trend of mean annual precipitations (not shown). The increment was found out to be approximately 38 cms in the 2035s, 46 cms in the 2055s, and 49 cms in the 2085s compared to the baseline annual mean flow. The increase in average annual streamflow, were approximately 15%, 18.2% and 19.3% in the 2035s, 2055s and 2085s, respectively.

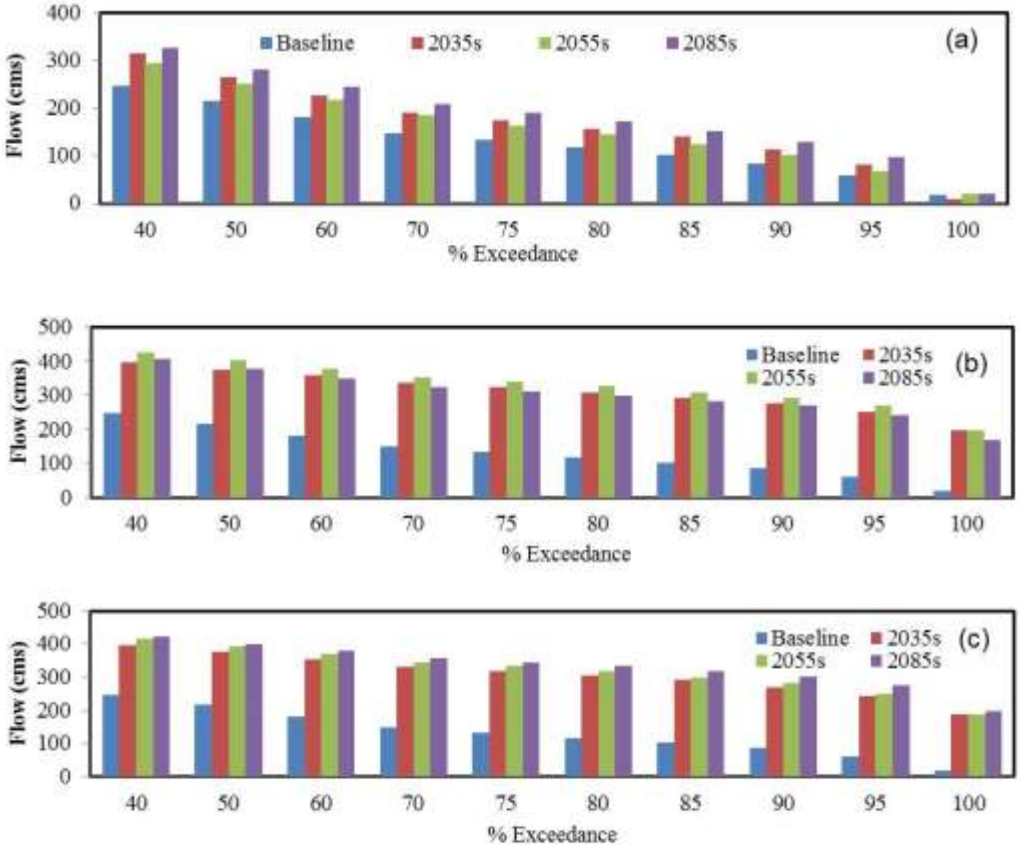

Figure 5 Percentage exceedance for mean flow volume for three future periods (2021-2050, 2051-2070 and 2070-2099) as compared to baseline period (1995-2009) at the outlet of the watershed using RCP 8.5 (a), RCP 4.5 (b), RCP 2.6 (c)

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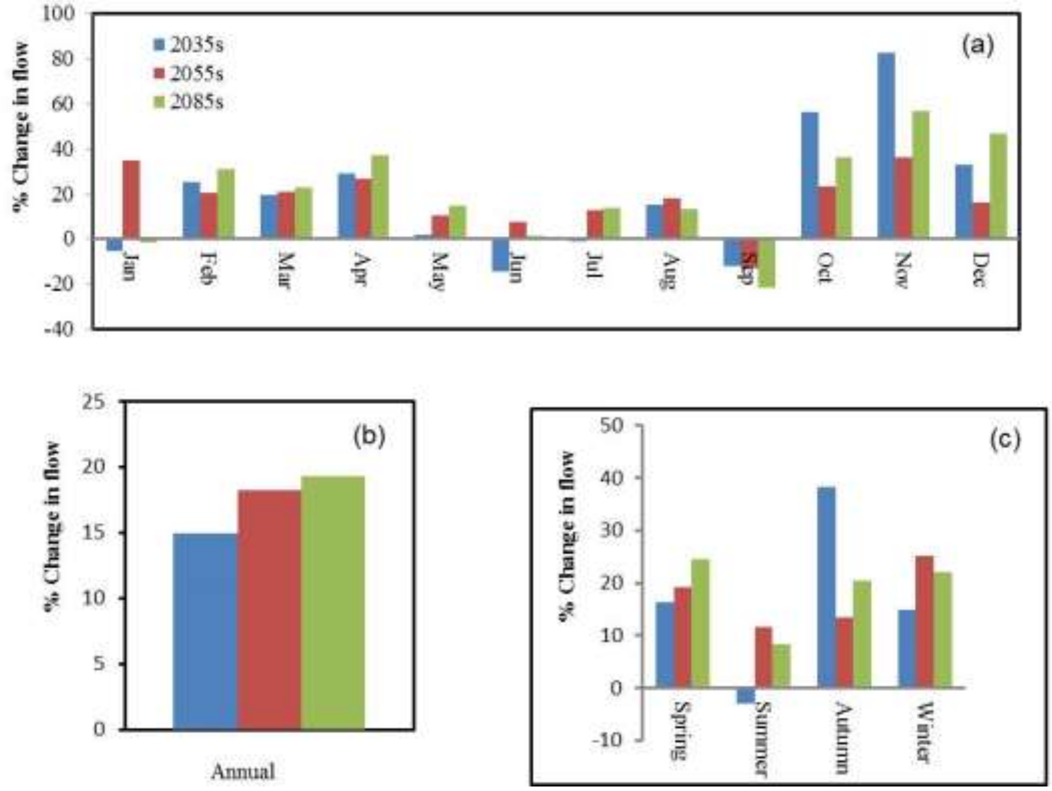

Figure 6 a) Percentage change in monthly mean flow volume for three future periods (2021-2050, 2051-2070 and 2070-2099) as compared to baseline period (1995-2009) at the outlet of the watershed, b) average seasonal flow, and c) average annual flow for similar three periods using RCP 8.5

The increasing pattern was detected for RCP 4.5 up to 2055s, and the percentage increase in 2085s was slightly less than 2055s (Figure 7a). This trend was also observed for seasonal (Figure 7b) and annual (Figure 7c) flow. A consistently increasing flow pattern was found from 2035 to 2085s for RCP 2.6 (Figure 8). The lowest flow was detected in 2035s compared to the remaining other two periods in all the monthly, seasonal and annual scale.

The increment of flow for low flow periods, especially during the latter part of the century, showed a positive signal for water resources management. The percentage increase in seasonal and annual scale flow for RCP 4.5 (Figure 7) and RCP 2.6 (Figure 8) was consistent with the monthly precipitation pattern (not shown).

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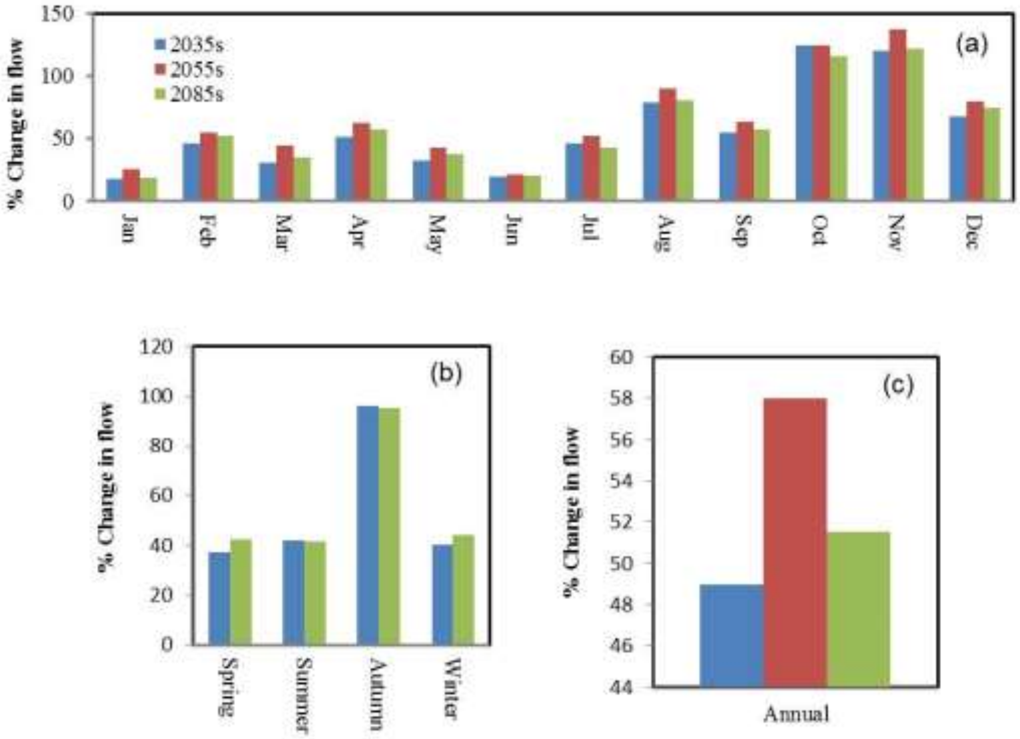

Figure 7 a) Percentage change in monthly mean flow volume for three future periods (2035s, 2055s and 2085s) as compared to baseline period (1995-2009) by MPI-ESM-LR-4.5 at the outlet of the watershed, b) average seasonal flow, and c) average annual flow for similar three periods

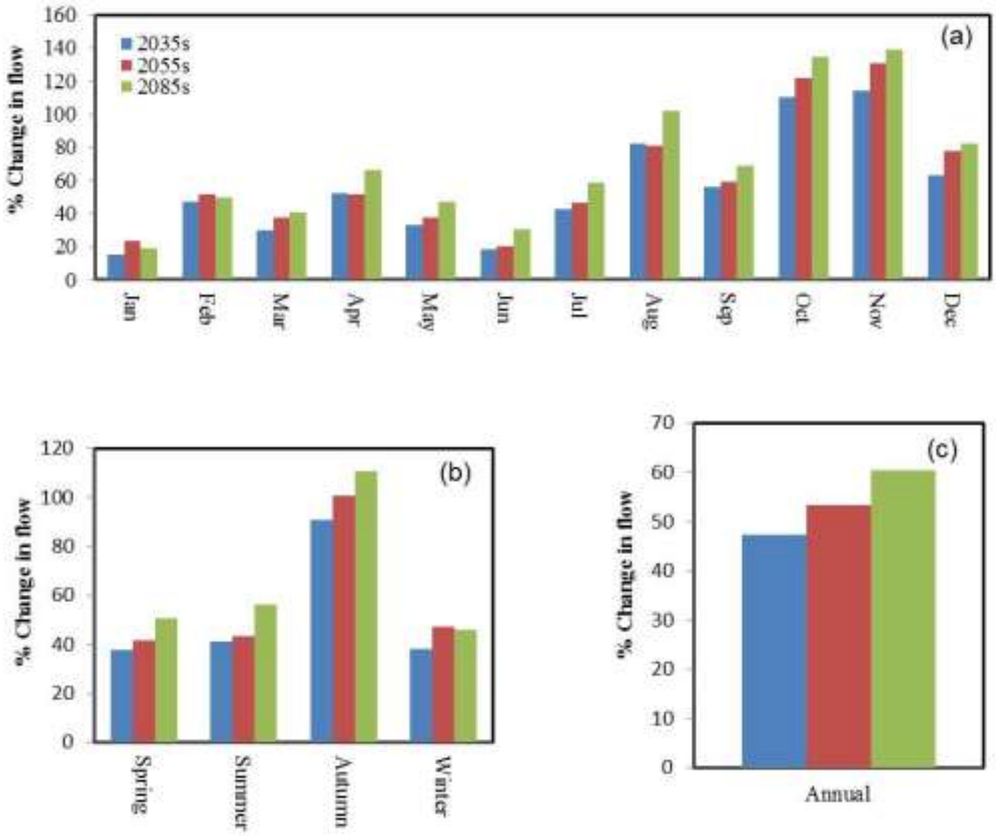

Figure 8 a) Percentage change in monthly mean flow volume for three future periods (2035s, 2055s and 2085s) as compared to baseline period (1995-2009) by MPI-ESM-LR-2.6 at the outlet of the watershed, b) average seasonal flow, and c) average annual flow for similar three periods using RCP 2.6

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Low flow conditions (for few months) are possible only under the RCP 8.5 scenario as indicated in the earlier analysis. So, this highest emission scenario was used to evaluate the impact of fracking conditions on stream low flow. Then, in order to evaluate the impact of climate change on the hydrological cycle for the entire watershed, streamflow outlets from all subbasins were systematically compared with baseline period and presented in Figure 9. The monthly flow could be expected to increase in all three periods for all scenarios (Figure 9) except the possible decrease in low flow for RCP 8.5 (Figure 9).

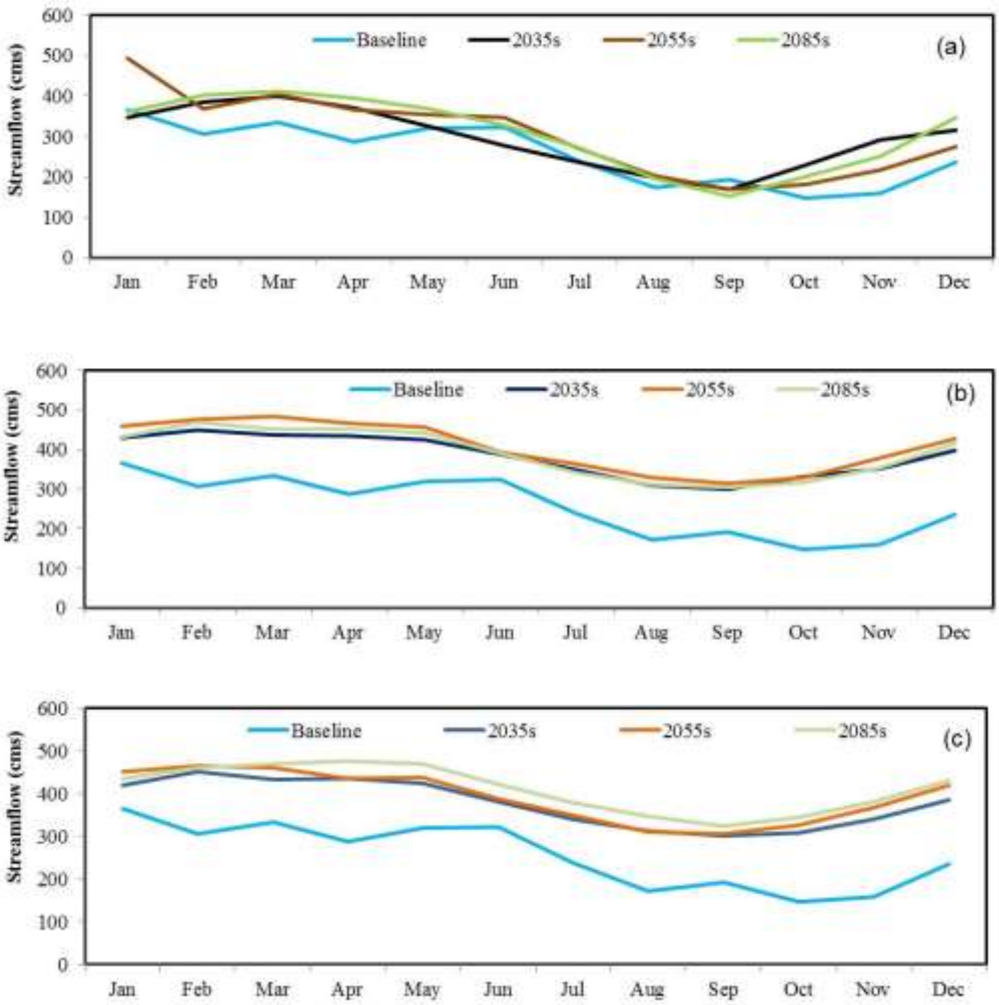

Figure 9 Monthly mean flow volume for three future periods (2035s, 2055s and 2085s) and baseline period (1995-2009) at the outlet of the watershed for RCP 8.5 (a), RCP 4.5 (b), RCP 2.6 (c)

Similarly, thematic maps were created to explain the variation of streamflow in the future compared to baseline (in terms of the percentage change in flow). However, these maps were based on the annual mean and minimum streamflow to spatially represent the percentage change in annual flow volumes across the watershed using the maximum emission scenario (RCP 8.5). While the watershed may experience low flow in the early 21st century (2035s) for specific months, the annual percentage mean change in streamflow showed that the watershed would experience wet conditions in the 2021 to 2050 period (Figure 10). Yet, projections for the eastern portion of the Tuscarawas subwatershed, encompassing eastern and western portion of Muskingum watershed, remained drier than other watershed portions in this period (Figure 10). During 2055s period, drier portions would be expected on the eastern portion of the Tuscarawas subwatershed region in the same pattern of period 2035s, but the percentage of the wet zone would increase compared to the first 30 years (Figure 11).

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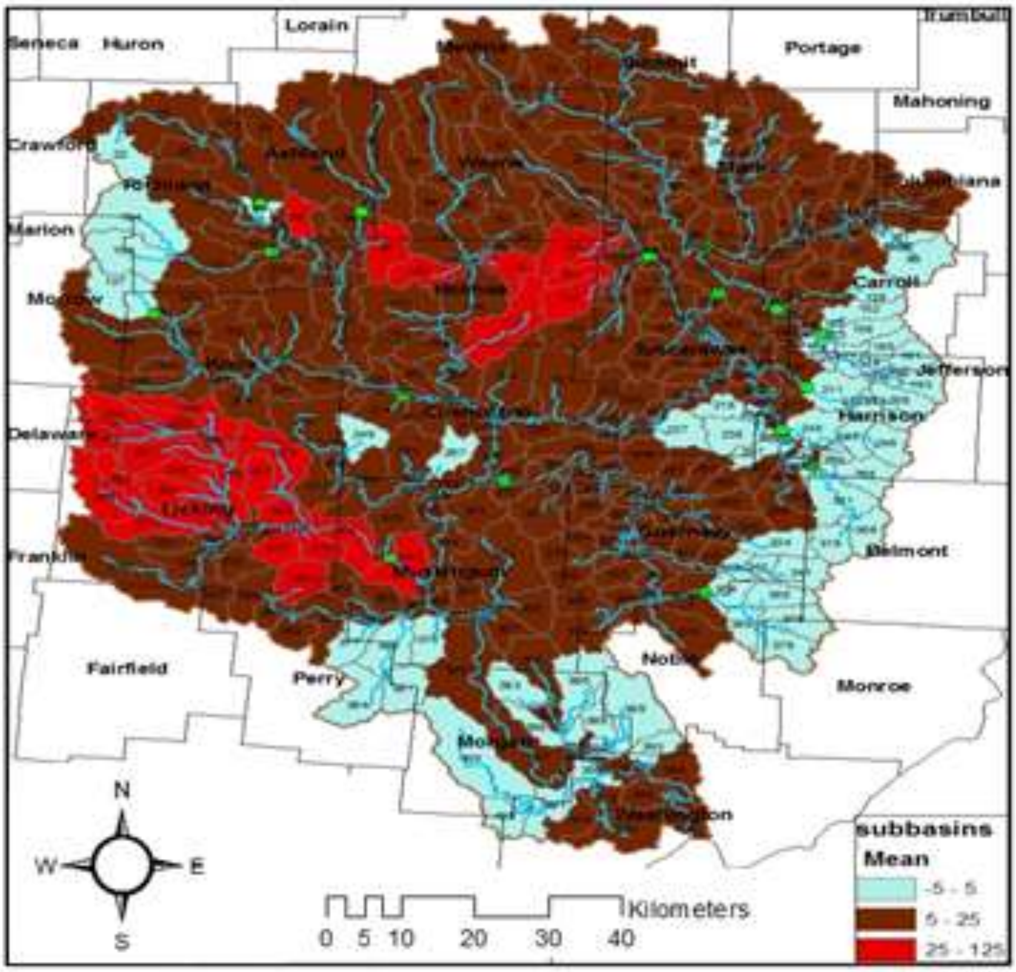

Figure 10 Percentage change in annual mean streamflow for 2035s period against baseline period (1995-2009)

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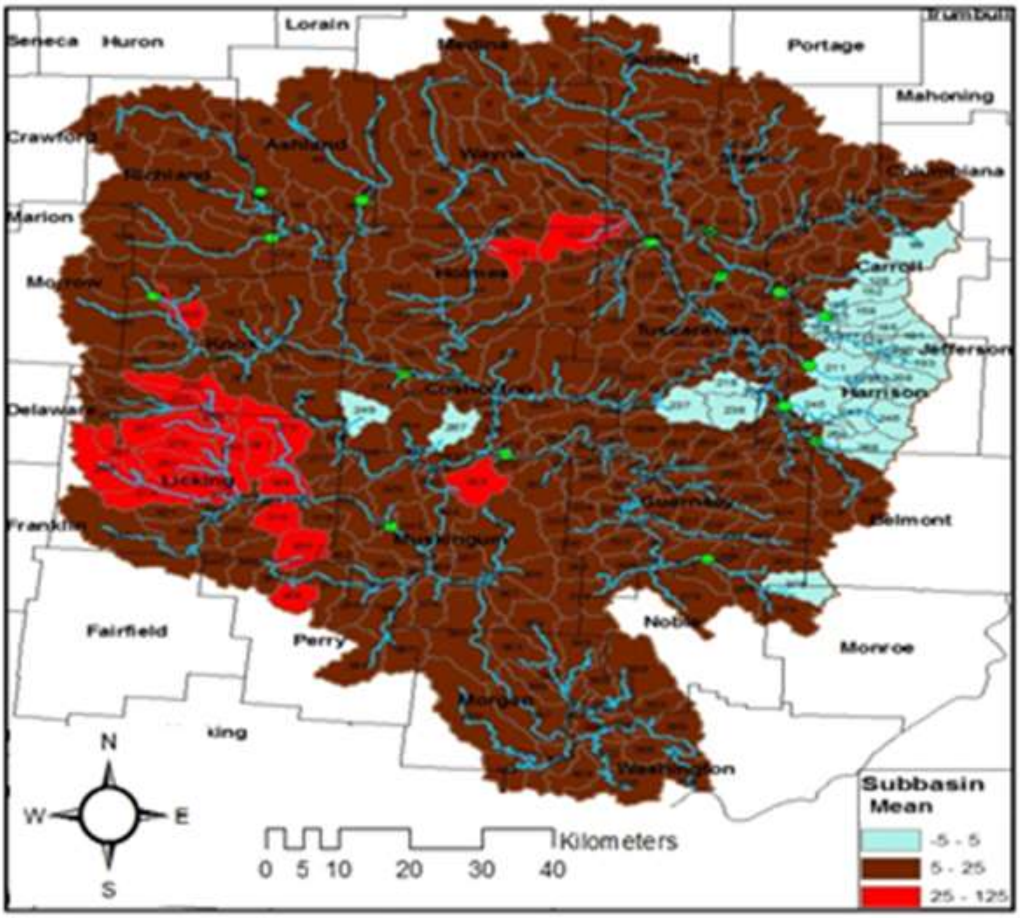

Figure 11 Percentage change in annual mean streamflow for 2055s against baseline period (1995-2009)

During 2085s, the wet zone would be expected to increase through a larger extent of the watershed (Figure 12), whereas, the drier region would be expected only in the eastern portion of the Tuscarawas subbasins. This analysis concluded that the drier regions could remain more prevalent in the first 30 years than other 50 year periods, and the watershed would get progressively wetter in future time periods.

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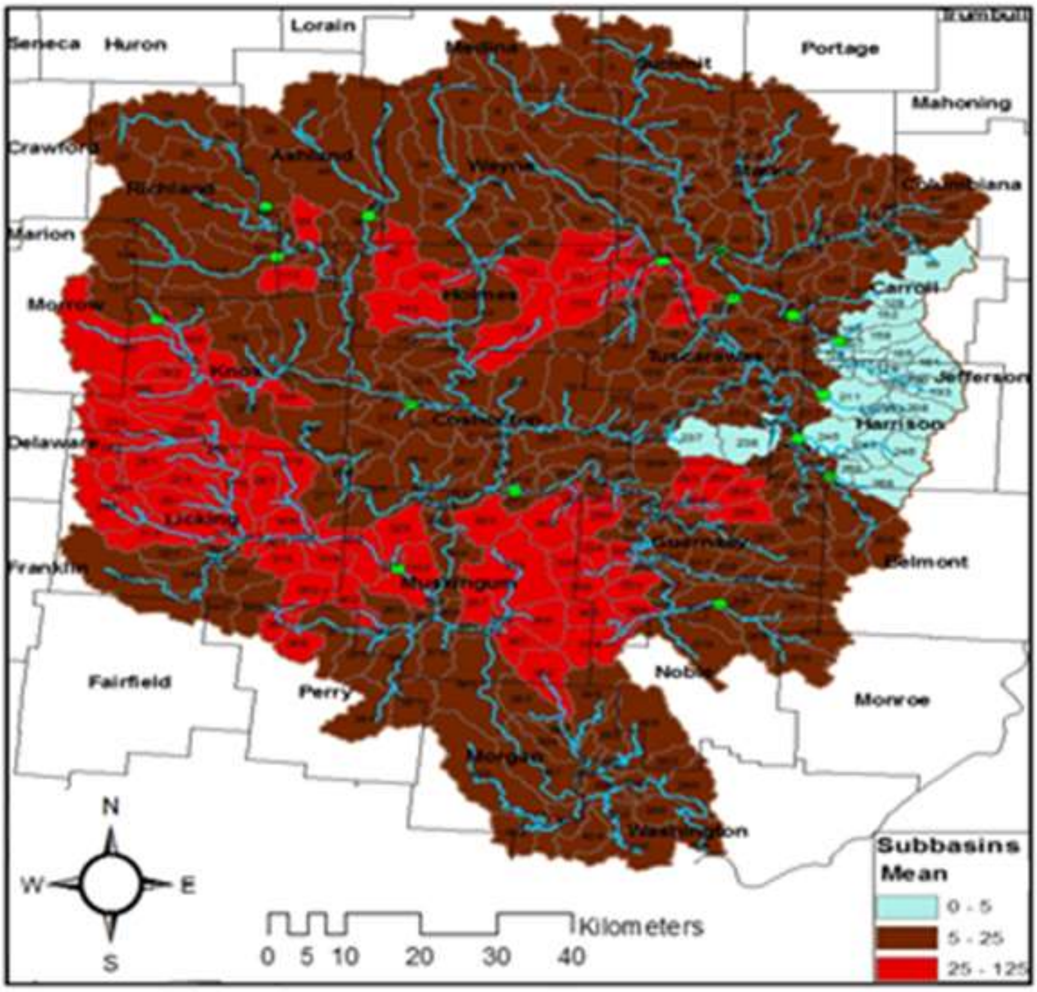

Figure 12 Percentage change in annual mean streamflow for 2085s against baseline period (1995-2009)

The annual minimum flow percentages across the watershed are fairly dry in the first 30 years compared to remaining 50 years (Figure 13) as some portion of the watershed experienced high flow in this period. Importantly, Figure 13 was based on the annual minimum flow, which decreased even though the increasing pattern of annual streamflow was detected. Conversely, the larger wetter regions were experienced for the second 20 year period (2055s) (Figure 14). Similarly, progressively larger portion of wetter area with increased percentage difference in minimum flow was detected in the last 30 years period (Figure 14). It is interesting to note that 2055s showed the major dry portion in the 1st and 2nd order streams (Figure 14), whereas 2085s showed the dry portion in the major stream regimes (Figure 15).

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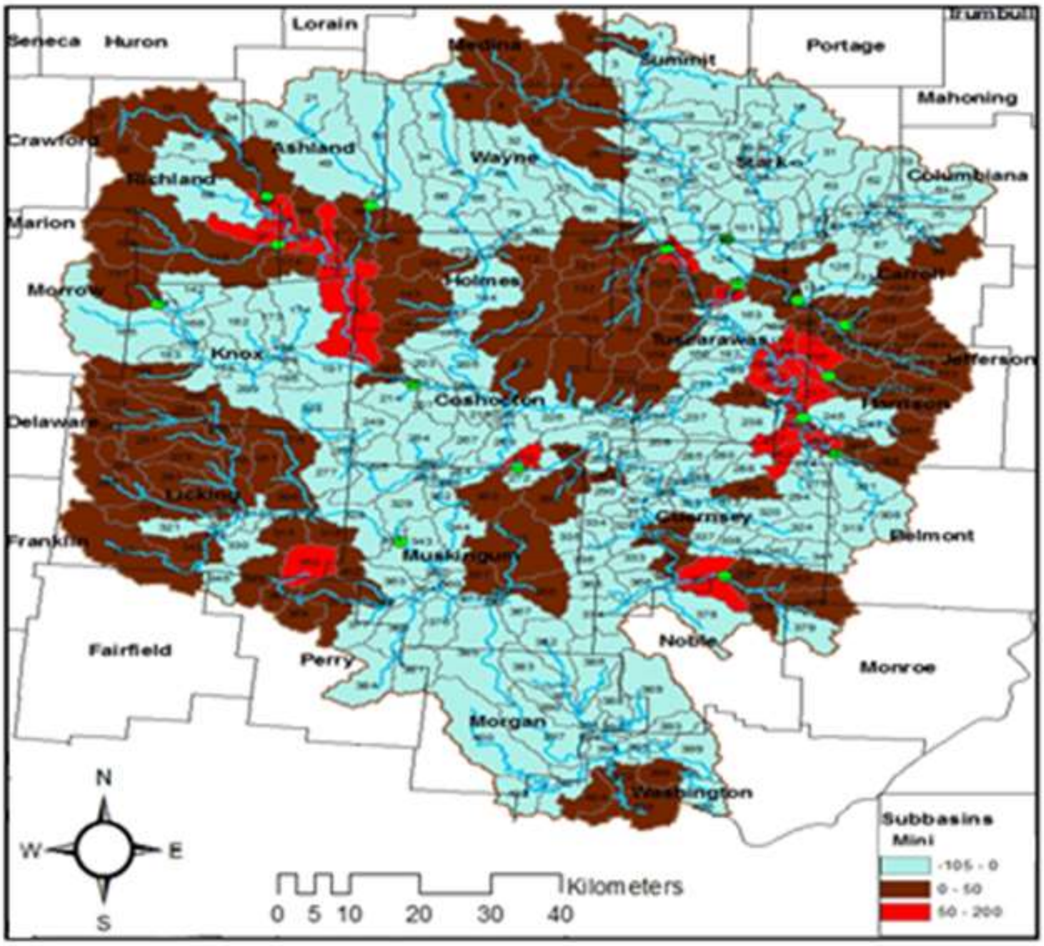

Figure 13 Percentage change in annual minimum streamflow for 2035s against baseline period (1995-2009)

DOI: 10.5963/JWRHE0501001

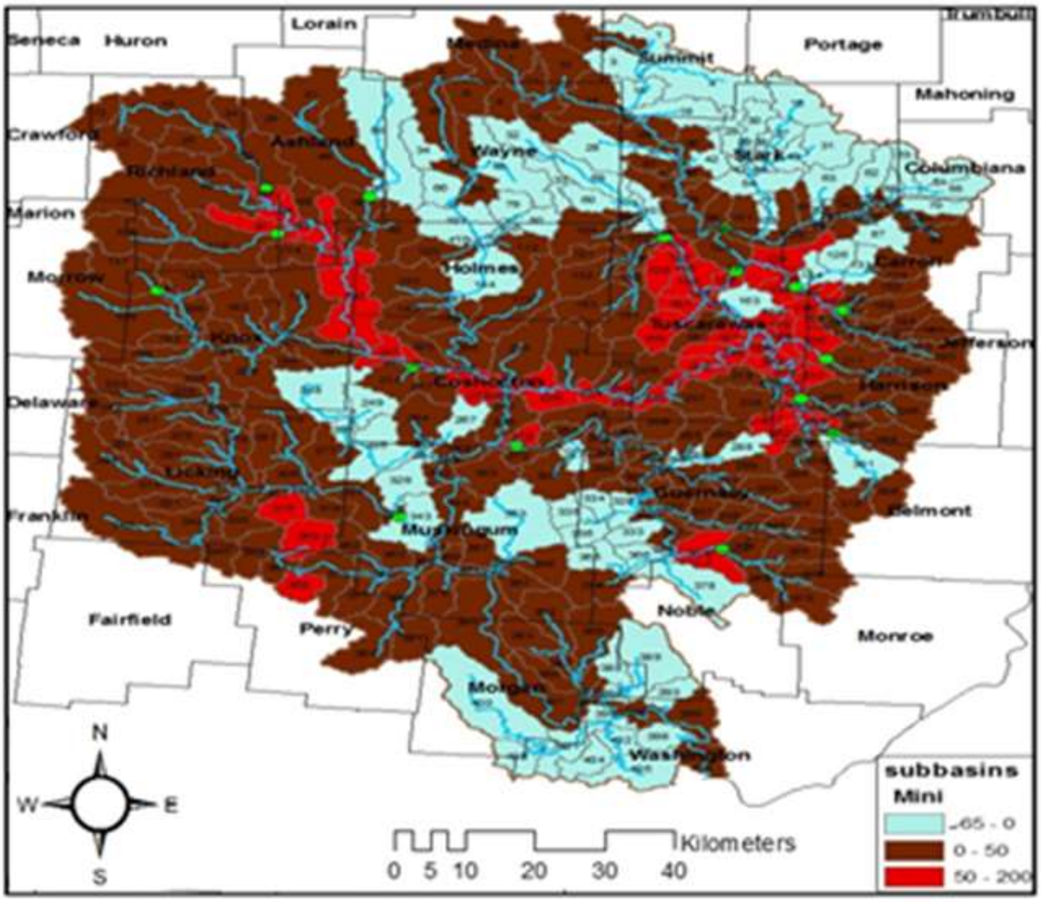

Figure 14 Percentage change in annual minimum streamflow for 2055s against baseline period (1995-2009)

DOI: 10.5963/JWRHE0501001

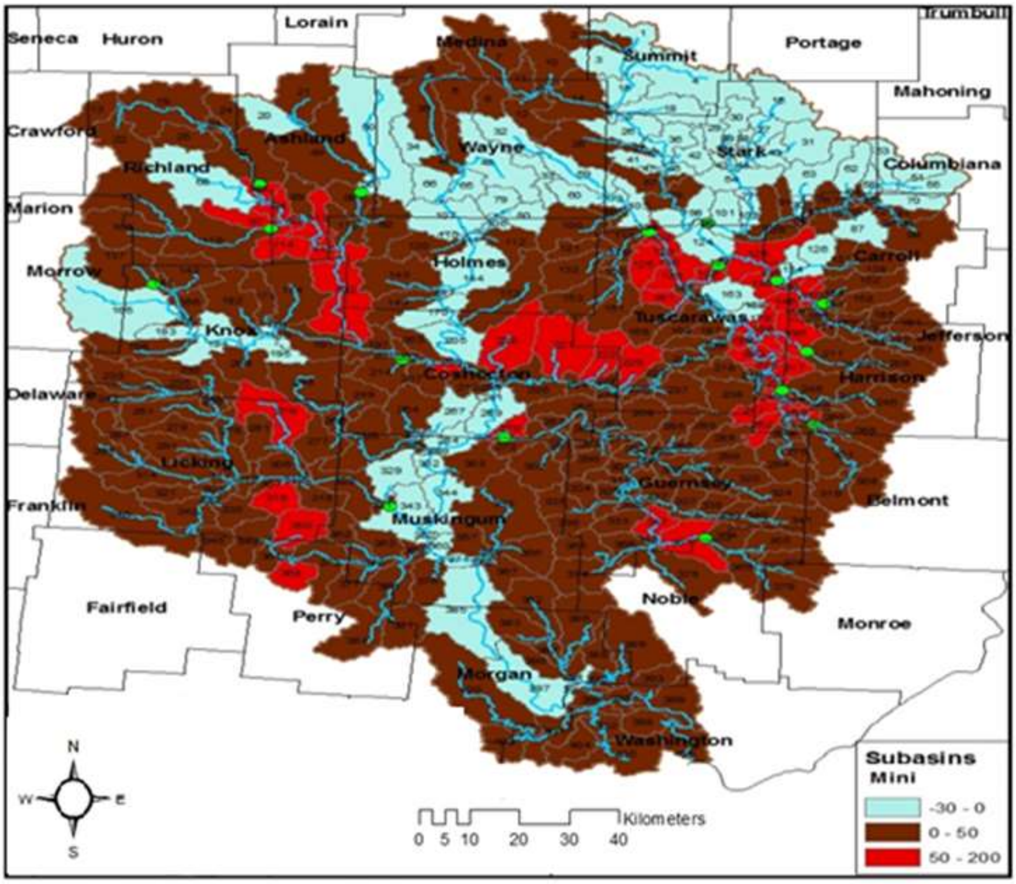

Figure 15 Percentage change in annual minimum streamflow for 2085s against baseline period (1995-2009)

E. Hydraulic Fracking with Climate Change

Similarly, the impact of water withdrawals for hydraulic fracking with the future climate change (2035s) was evaluated over 32 subbasins. The subbasins where current water withdrawals for fracking exist were analyzed, assuming that the fracking trend would likely remain fairly similar in the future. Here, the impact of fracking was not analyzed during the rest of the two periods for two primary reasons: i) it was not sure how the fracking rate would continue in future as this might be governed by socio-economic and political conditions in future; ii) increased streamflow was realized in other periods.

Results revealed no impact on yearly mean flow as compared to the current and baseline scenarios (Figure 16). Some impacts were detected on seven days monthly minimum flow (Figure 17) in 14 out of 32 subbasins; however, the difference was just greater than 2%. In fact, this study included all the upstream subbasins as further progressively analyzing the downstream node of the streams. Hence, the area of consideration increased in the downstream node but the percentage change in streamflow showed a decreasing trend in those respective nodes. Percentage changes in seven days monthly minimum flow for baseline and current scenario with the increase in drainage area are displayed in Figure 18. Maximum changes up to 55% in 7 days low flow (minimum annual) were observed in the watershed if fracking withdrawals are continued on first order streams. The result varied from 3% to 55% on all affected subbasins, indicating the minimum change in a large drainage area. In general, current fracking conditions showed a change of 34% of the total sources with more than 5% change in seven days minimum low flow. Interestingly, all these changes were limited to the first order streams with no impact for higher order streams at all. The same analysis was repeated for RCP 4.5 and RCP 2.6 (not shown). Analysis indicated that the negligible decrease in flow (2% to 3%) was encountered in three out of 32 subbasins while considering RCP 4.5. Also, results concluded a negligible decrease (3% to 4%) in only two subbasins while considering RCP 2.6. No impact was detected in the rest of the subbasins while using RCP 4.5 and RCP 2.6.

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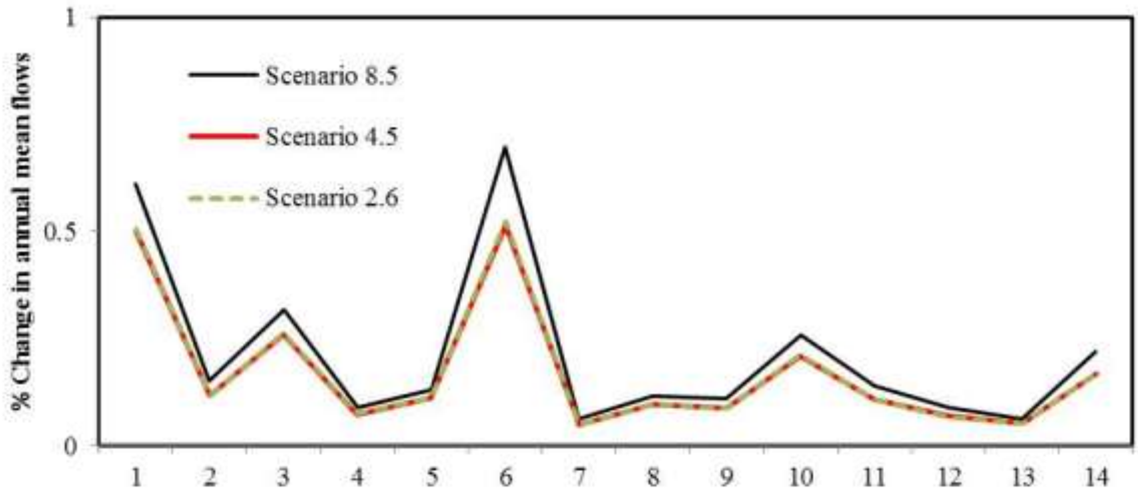

Figure 16 Percentage change in annual mean flow for current and baseline scenario during 2035s periods

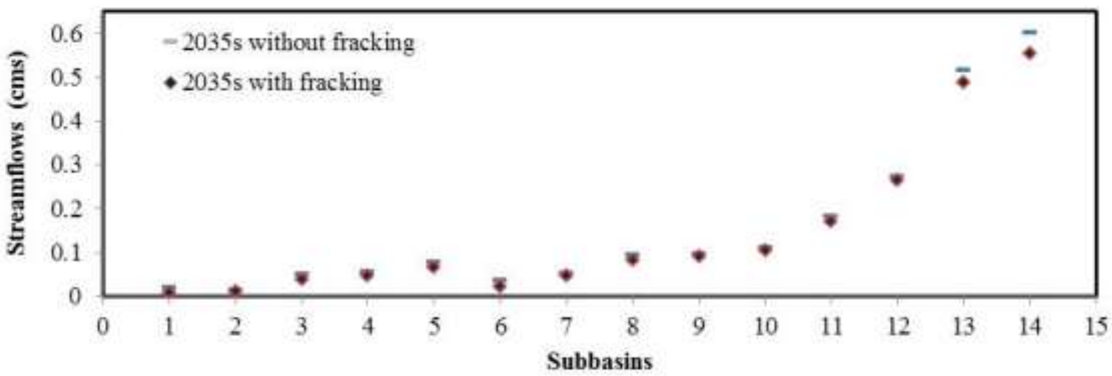

Figure 17 Seven days monthly minimum flow (considered the minimum value from each year) for current and baseline scenario during 2035s period using RCP 8.5

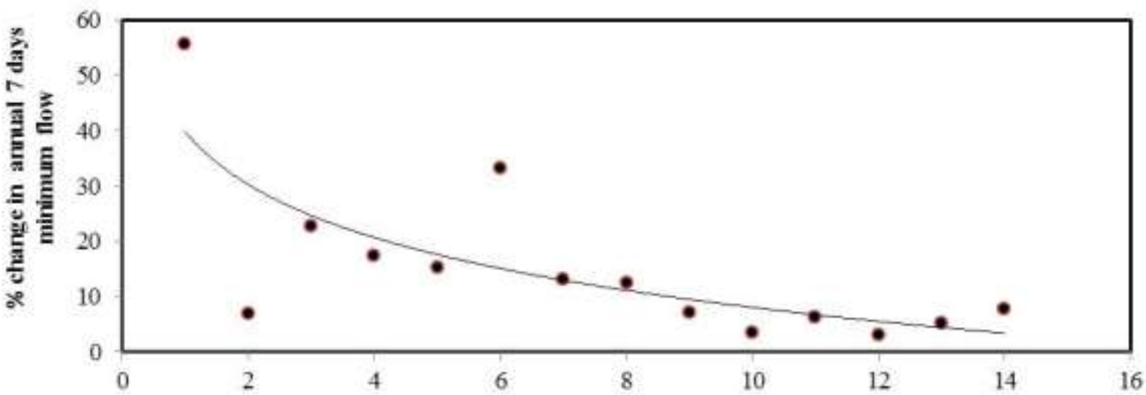

Figure 18 Percentage change in 7 days minimum flow for current and baseline scenario (considered one minimum value from each year) during 2021-2050 periods using RCP 8.5 over the 14 subbasins in downstream where the 14^{th} subbasin was largest in area (1589 km^2) and first subbasin was the smallest in area (42.88 km^2)

Although this analysis suggests possible variability in the hydrological cycle due to future projections of global climate change, impacts from hydraulic fracking and other water resource limitations may be buffered for the later part of the century except for certain months (e.g. September of 2035s). Period 2035s could be critical for sustainable water resource management in some months, especially for the first order streams compared to the other two periods. However, increase in flow could be

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expected even in 2035s compared to the baseline period. Regardless, it is recommended that planners devise a policy framework that incorporates the appropriate adaptations and mitigation measures to preserve water resources in light of future climate change scenarios, especially during summer seasons of the early 21st century. While climate change studies, including this research, have inherent uncertainty related to future emission scenarios of the greenhouse gasses, land cover changes and energy fluxes, this research constitutes a comprehensive framework for the systematic variation of streamflow in response to future climatic conditions, particularly in a watershed affected by hydraulic fracking.

IV. CONCLUSION

The potential impact of climate change on streamflow in the Muskingum watershed was evaluated using the MPI-ESM-LR model with RCP 8.5, RCP 4.5 and RCP 2.6 scenario for the 21st century. The research objective was to determine whether the projected global climate change would enhance low flow conditions in the watershed under continued hydraulic fracking in the future. For this, the SWAT model was used to simulate future streamflow using bias corrected downscaled data. The correlation coefficient used to evaluate the performance of various climate models suggested that the performance of MPI-ESM-LR model was one of the best models. This study found a consistent increase in temperature and precipitation for all three time periods as compared to the baseline period, especially for RCP 8.5.

The variation in the streamflow was consistent with the precipitation and temperature patterns of the region. Results concluded that flow would increase in the coming decade as indicated by mean annual percentage increase with 38.3% in 2035s, 46.9% in 2055s and 49.6% in 2085s. However, the analysis on a monthly scale depicted that the coming decade would have a critical reduction of flow during September (low flow period). Similarly, the assessment on a regional scale across the watershed suggested that 2035s would be a relatively dry period among the three modeled periods, characterized by a reduction in streamflow in some months.

Similarly, the assessment of the streamflow using current rate of fracking revealed that the low flow period would be the crucial period over the year as 7 days minimum monthly flow indicated some variation when compared with the lowest flow, either with or without fracking; this effect was negligible in larger order streams but clearly visible in smaller order streams.

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