Scenario Analysis for the Impact of Hydraulic Fracturing on Stream Low Flows: A Case Study of Muskingum Watershed in Eastern Ohio

Final Progress Completion Report

Submitted By

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Abstract

Oil and natural gas production in the United Sates has increased tremendously for the last few years. Significant amount of water is needed for the production of oil and natural gas through the application of advanced technique called Hydraulic fracturing (fracking). This has raised a serious concern about the potential impact on hydrological cycle, due to water withdrawal for fracking, especially for low flow period. Therefore, a comprehensive analysis is essential for the evaluation of stream low flow conditions due to unanticipated water withdrawal. In addition, the atmospheric greenhouse gases are believed to be increasing, leading to future climate change, which may alter the hydrologic flow regime in the future and threaten the hydrological and environmental sustainability. Therefore, this study was initiated to investigate the potential impact of fracking and climate change on stream low flows. Since limited modeling studies have been conducted to investigate the impact of hydraulic fracking for watershed scale studies, a systematic review and documentation of existing watershed models was conducted; this was important because an appropriate selection of watershed model for these studies is still a matter of investigation. A widely used watershed model, Soil and Water Assessment Tool (SWAT), was found to be appropriate for the representation of fracking process in term of spatial and temporal scale. Various future scenarios were developed based on the possible future climatic conditions, which was conducted in two steps: i) first, analysis was conducted for immediate future by generating probable set of climate data (precipitation, temperature) based on the historical records of the climate data; ii) second, climate change data from Coupled Model Intercomparision Project (CMIP5) using Max Planck Institute earth system model (MPI-ESM) were analyzed for

21st century to see the effect of climate change on stream low flows. Analysis showed that water withdrawal due to hydraulic fracking had localized impact on the water resources, especially during low flow period. 30% of the withdrawal locations showed more than 5% changes in 7 days minimum monthly flow. The flow alteration due to hydraulic fracking decreased with increase in the drainage area. Environmental low flows such as 7Q10, 4B3 and 1B3 also varied in a decreasing pattern with increased drainage area.

Similarly, the highest forced scenario, Representative Concentration Pathways (RCP) 8.5 under MPI-ESM climate model of CMIP5 was selected for the evaluation of the future climate change in the watershed. Three future periods 2035s (2021-2050), 2055s (2051-2070) and 2085s (2070-2099) was assessed against the baseline period (1995-2009). Lowest flow is projected to increase across the watershed during 2035s compared to remaining 50 years. Additionally, the 2035s climate outputs were integrated with current fracking trend to analyze the combined effect of fracking and climate change. This particular analysis was limited for first 30 years of 21st century (2035s), and analysis was conducted assuming current rate of fracking remains intact. The result was in consistent with the conclusion from the step one (mentioned above).While there was negligible impact on mean streamflows, some impact on 11 locations (out of 32) in 7 days minimum low flow, was detected. The variation was revealed only during low flow period indicating low flow period was the most critical period, especially for small order streams. This analysis under various fracking and climate change scenarios can be useful information for policy makers and planners for appropriate water resources management in future.

List of Abbreviations

AGNPS	Agricultural Non-Point Source
AnnAGNPS	Annualized Agricultural Non-Point Source
APEX	Agricultural Policy/Environmental Extender
BASINS	Better Assessment Science Integrating Point and Nonpoint Sources
BCCA	Bias Corrected Constructed Analogs
CMIP	Coupled Model Intercomparison Project
DEM	Digital Elevation Model
DWSM	Decision Support System for Agro Technology Transfer
ECHAM6	European Center-Hamburg
EMIC	Earth System Models of Intermediate Complexity
ESM	Earth System Models
GCM	Global Climate Model
GIS	Geographic Information System
GWPC	Groundwater Protection Council
HAMOCC5	Hamburg Ocean Carbon Cycle Model
HEC-HMS	Hydrologic Modeling System
HRU	Hydrologic Response Units
HSPF	Hydrologic Simulation Program-Fortran
HUC	Hydrologic Unit Codes
IPCC	Intergovernmental panel on climate change
JSBACH	Jena Scheme for Biosphere Atmosphere Coupling in Hamburg
MDG	Millennium Development Goals

MPI-ESM	Max Planck Institute earth system model
MPIOM	Max Planck Institute Ocean Model
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEP	National Center for Environmental Prediction
NIWR	National Institutes for Water Resources
NLCD	National Land Cover Dataset
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollution Discharge Elimination System
NSE	Nash-Sutcliffe's Efficiency
N-SPECT	Nonpoint Source Pollution and Erosion Comparison Tool
ODNR	Ohio Department of Natural Resources
OEPA	Ohio Environmental Protection Agency
PBIAS	Percentage Bias
PCMDI	Program for Climate Model Diagnosis and Intercomparison
RCP	Representative Concentration Pathways
RMSE	Root mean square error
RSR	RMSE- Standard Deviation Ratio
SDSM	Statistical Downscaling Model
STATSGO	State Soil Geographic
SWAT	Soil and Water Assessment Tool
UCRB	Upper Colorado River Watershed
USACE	United States Army Corps of Engineers

USDA	United States Department of Agriculture
USEIA	United States Energy Information Administration
USGS	United States Geological Survey
WARMF	Watershed Risk Analysis Management Framework
WCRP	World Climate Research Program

Chapter 1. Introduction

Water resources sustainability is a research topic of particular interest due to its impact in every aspect including economy, energy, ecology and welfare of living beings. Water should be properly used in order to continue human world in the indefinite future without affecting the hydrological cycle and the ecological factors (Gleick et al. 1998). Factors such as urbanization, drought, uncertain climate, flooding and many other anthropogenic activities affect the water resources sustainability. One of them is abstraction of water from different branches of water such as streams and reservoirs for different water use including irrigation, power plant, water supply, recreational purpose, and at present, the most controversial one, natural gas and oil. Likewise, there have been issues regarding the connection of energy source for the impact on regional water availability, quality and its dynamics.

Scope and Objectives

Recently, several drilling companies are advancing to Ohio for oil and gas development; therefore, drilling has been increasing tremendously on the Muskingum watershed. Significant amount of water is withdrawn from the streams and reservoirs without considering its imminent impact to water environment, ecology and human. The impact of water withdrawal may or may not be significant at the watershed or regional scale but certainly, it may have localized effect with alteration of hydrological regime in specific tributaries. In addition, global climate changes have a potential to change the stream low flows significantly. In this context, there is an urgent need to evaluate the impact of hydraulic fracking and global climate change on water resources of Muskingum watershed.

The specific research objectives of this study are:

1. To review existing watershed models, and based on review, select and develop the appropriate model, and apply for Muskingum watershed after model calibration and validation;
2. To develop and apply the model to assess the potential impact of water withdrawals under various water acquisition scenarios associated with hydraulic fracking, especially during low flow or drought period, at various spatial and temporal scales;
3. To assess the potential impact due to future climate changes of the 21st century and also evaluate the combined impact of hydraulic fracking and climate change on hydrological cycle during the first 30 years (2021-2050) of climate change period.

This report is divided into four chapters. Chapter 1 covers the background, scope, objectives, and remaining three chapters are organized in a journal paper format. Since each chapter is separate journal articles, readers may find some redundancy in content.

Chapter 2 describes the review of some watershed models with their potential capability to incorporate hydraulic fracking for watershed scale studies. Also, it describes the process involved during watershed model development in the Muskingum watershed which includes delineation, preparation of input data, model calibration and validation for flow parameter. Current fracking conditions are set up in this developed model to assess the impact in the watershed. This chapter is published in *American Journal of Environmental Sciences* as a peer review journal article.

In chapter 3, the possible impact of fracking in various climatic conditions generated based on historical climate of the region is discussed. The future climate change impact generated based on greenhouse gas emission scenarios is not the scope of this chapter and discussed in chapter 4. This article is currently review on *hydrological sciences journal*.

In chapter 4, CMIP 5 climate projection is used in order to assess the impact of future climate change on hydrology in the Muskingum Watershed during three future periods (2021-2050, 2051-2070, and 2070-2099). Additionally, first 30 years of climate change data is integrated with current rate of fracking in order to analyze how climate change would affect the future low flows from 2021-2050 assuming current rate of fracking is intact. This chapter is published in *Journal of Water Resources and Hydraulic Engineering* as a peer reviewed article.

Reference

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Chapter 2. Hydrologic Modeling to Evaluate the Impact of Hydraulic Fracturing on Stream Low Flows: Challenges and Opportunities

Abstract

Hydraulic fracturing (fracking) has been increasing in the eastern part of Ohio for the last few years leading to the increased stress on water resources, particularly on the hydrological low flows. Yet, evaluation of the various impacts of fracking on stream low flows using appropriate tools is still a challenging issue, even though significant progress has been achieved in recent decades to advance the scientific tools and techniques for watershed modeling. While various existing watershed models are capable of addressing water resource issues, each model is unique and the appropriate selection of model depends upon several factors. Therefore, the objective of this study are: i) to review the current state of art for various available watershed models, including their potential capability, in order to conduct a study related to hydraulic fracking, and ii) to present a case study using best selected model application. Our review indicated that the Soil and Water Assessment Tool (SWAT) is one of the most competent models to assess water issues related to the fracking process at various spatial and temporal scales. The SWAT model incorporating hydraulic fracking is presented in a series of steps: i) in the first step, the preparation of input data for water use and hydraulic fracking is discussed, including detail calibration and validation of the SWAT model for this study; ii) in the second step, a case study is presented to evaluate the impact of hydraulic fracking with stream low flows by analyzing the current fracking trend in watershed; iii) finally, issues and challenges related to data availability and sources of water withdrawal is presented. The SWAT model was calibrated and validated both for daily and monthly scales for 9 various locations of the watershed, with a monthly Nash-Sutcliffe efficiency varying from 0.49 to 0.88 for calibration and from 0.55 to 0.86 for validation. Analysis indicates that fracking practices have negligible impact on annual and monthly flows,

with modest impact on seven days lows flows, especially at the localized scale, varying in the range of 5.2% to 10.6%.

Key Words: Hydraulic Fracturing, Models, SWAT, Low Flow

Introduction

Recently, there has been increasing availability and use of natural gas for the transportation sector and electrical production due to technological developments with hydraulic fracturing (fracking). Production of unconventional shale gas has increased significantly to meet the growing demand for energy and support economic development (USEIA, 2011). One of the most key aspects for the substantial growth of natural gas is the massive use of hydraulic fracturing. Annually, about 35,000 wells undergo some sorts of hydraulic fracturing in U.S (IOGCC, 2010). For State of Ohio, the Ohio Department of Natural Resources (ODNR) has projected that approximately 122 billion gallons of water will be needed if the State of Ohio drills all possible Utica wells (20,000). While the fracking technology has been considered useful in term of gas production and economic development, concern are raised about the large quantity of water needed for fracturing, and possible water resources management issues. Four to six million gallons of water are commonly needed in order to conduct fracking for one Marcellus or Utica shale well (OEPA, 2012). The water withdrawal at such a massive scale can reduce the water level in the streams, which may further reduce the surface water flows or deplete water storage in aquifers. Similarly, surface water withdrawal may also directly reduce the level in reservoirs, lakes and streams.

Regulatory and public agencies are also concerned about water withdrawals for hydraulic fracking. The impact of water withdrawal for fracking may result severe consequences; therefore, the timing, location and volume of water withdrawal for fracking are important particularly during low flow periods. Since hydraulic fracking came in practice recently, the unanticipated water withdrawal for hydraulic fracking can raise several questions about its potential impact on water resources and environment. For example, what are the possible implications on local water quality as the pollutant concentration increases due to decreased stream flows? More importantly, what are the consequences of withdrawing large amount of water from surface and groundwater resources on short and long term water availability?

In fact, there could be alterations in the flow system during various seasons as daily or monthly flows might be reduced far below from the environmental flow limits. This may cause crisis in water supply, aquatic life and water quality, leading to the complete threat in water resources sustainability. Since oil and gas industry is one of the booming sectors over the United States, and also more than 25 States of US have potential for oil and gas production, there could be a significant impact on hydrological cycle in future due to large scale oil and gas production. Therefore, there is a pressing need of a study in order to fully understand the hydrologic process at the watershed scale under the influence of fracking. For this, physically based watershed models might be appropriate tools as these models can represent the physical process within watershed and capable to make an analytical study. There are various watershed models which are capable to simulate the physical and dynamic activities within watershed in order to evaluate the effect of many watershed processes, management practices and anthropogenic influence on hydrologic process (Moriasi *et al.*, 2007). For the last few decades, water resources scientists are successful to develop and advance the existing watershed models, which are operational at various temporal and spatial scales, in order to represent the various anthropogenic influence and watershed intervention in models. Watershed models, which are fully capable to represent the watershed complexity in terms of land use, soil and digital elevation model (DEM) have been extensively explored to deal with water resources issues over the last few decades. However, there are limited reports or published articles which describe possible set of appropriate watershed models in order to simulate the watershed response under active hydraulic fracking conditions. Therefore, existing watershed models have to be carefully reviewed, and their potential capabilities/limitations to conduct study related with hydraulic fracking needs to be explored. In this context, this study is unique in two ways; i) first, it thoroughly reviews the existing watershed models with their potential capabilities and limitations, including issues and challenges in order to conduct simulation study under hydraulic fracking conditions; and ii) second, a brief case study will be presented to explain the various processes involved for hydraulic fracking study using the selected model based on the review. While there are several opportunities of utilizing various watershed models to deal with water resources issues, we will discuss several challenges for watershed modeling and future policies issues in active hydraulic fracking watershed in later part of this manuscript.

Watershed Models for Hydraulic Fracking

Since hydraulic fracking involves the water withdrawal from any location of the stream, reservoir and ground water, one of the approaches to consider this system in the model is to incorporate as negative point sources. In fact, water withdrawal for hydraulic fracking is somehow the opposite process of point source discharge. Alternatively, positive water use input can represent the water withdrawal as some models have these features. Therefore, watershed models which can incorporate the spatially located point sources in the system besides its advanced hydrologic features could be potentially considered for this type of study. The lists of widely used watershed models that can be potentially applied for the evaluation of the impact of hydraulic fracking on water resources, but not limited to followings, are:

- Hydrologic Simulation Program-Fortran (HSPF) or Loading Simulation Program C++ (LSPC);
- Soil and Watershed Assessment Tool (SWAT);
- European Hydrological System Model (MIKE SHE);
- Agricultural Policy/Environmental Extender (APEX);
- Watershed Risk Analysis Management Framework (WARMF);
- Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS);
- Watershed Assessment Model (WAM)

The details of these model components and their potential capabilities to incorporate hydraulic fracking have been summarized in Table 1-1. These models work mostly in continuous scale with daily and sub-daily output for streamflow. In addition, these models can incorporate the addition and diversion (withdrawal) of the water for fracking from the various points of the watersheds (Table 2-1). Although all above-mentioned models are potentially capable to simulate watershed response and have their unique features, selection of appropriate model is a crucial step in order to represent hydraulic fracking for hydrologic analysis. For example, a model which is very proficient for urban area study may not be appropriate for agricultural watershed and vice versa. More importantly, model selection depends upon several factors including modeler's knowledge, understandings and technical capabilities, availability of data and several other factors. While the description of all the model processes and the model structure is beyond the scope of this article, the following section briefly presents the major features of the existing watershed models to represent fracking for hydrologic assessment. The readers can refer various journal articles for details of the model description (Borah and Bera, 2003).

Hydrologic Simulation Program-Fortran (HSPF) (Bicknell *et al.*, 1996) is a watershed model for continuous simulation, which simulates hydrology and water quality including non-point sources and point sources. It considers simulation on pervious, impervious surface, stream channels and reservoirs, respectively for the simulation of stream flow and water quality. It is also called as parameterized intensive model as some of the component are lumped into parameters. HSPF and SWAT both can be potentially used for hydraulic fracking studies as both models have been used and compared in various watershed conditions.

Recently, several literatures were published based on the comparison between SWAT and HSPF (Singh *et al.*, 2005; Van Liew *et al.*, 2003; Im *et al.*, 2003). For example, Xie *et al.* (2013) compared the performance of HSPF and SWAT for hydrologic analysis in Illinois River. The authors showed that HSPF depends on the calibration method to achieve better result, and SWAT can achieve better result despite of the limited data for calibration. Although, HSPF can simulate better sub-daily streamflow simulation, it requires numerous parameters to characterize hydrological cycle with intensive calibration process (Im *et al.*, 2003; Saleh *et al.*, 2004). Borah and Bera (2003) reviewed both SWAT and HSPF and concluded that SWAT is a very promising model in order to conduct study on agricultural watersheds, and HSPF is capable for simulation in mixed agriculture and urban watersheds. Since this study is primarily focused for stream low flow conditions due to water withdrawal for fracking, SWAT could be a better choice as SWAT is considered as a better simulator on low flow (Singh *et al.*, 2005).

Borah and Bera (2003) reviewed eleven watersheds models and found that HSPF, MIKE SHE, and SWAT have strong hydrologic component applicable to watershed-scale catchments. SWAT model was also compared with fully distributed MIKE SHE and authors concluded that both models are equally competent during calibration (El-Nasr *et al.*, 2005) while performance of MIKE SHE model was marginally better for overall stream flows prediction.

Golmohammadi *et al.* (2014) evaluated three widely used hydrological distributed watershed models: MIKE SHE, APEX and SWAT for flow simulation of small size watershed in, Canada. MIKE SHE was concluded as more accurate for simulating streamflow at watershed outlet and SWAT was regarded as another potential model as there was no significant difference in model performance.

A Report on Model selection (USACE and DES, 2008), for a study in Central Oahu Watershed, sorted out few highly used watershed models including SWAT, WARMF, and HSPF based on various specific model skills. Authors reported that WARMF model was less recognized than SWAT and HSPF. Similarly, the successful applications of HEC-HMS (Verma *et al.,* 2010) and WAM model for watershed scale studies (Bottcher *et al.,* 2012) have been described in several studies.

Even though we found models performance rating different for different application studies for various models, we selected SWAT model due to numerous reasons: i) SWAT models has advanced in comparison to other models and can disintegrate watershed into multiple subbasins and hydrologic response units (HRUs) for continuous simulation of flow at various scales (Jha, 2011); ii) model is widely accepted worldwide by scientific community and well supported by USDA; iii) model is also considered suitable for the ungagged watershed (USEPA, 2012) and watershed characterized with limited data. SWAT has been widely used for the assessment of the impact of intensive water use on the water balance and its components. In addition, SWAT is user friendly and new users can successfully apply it for the analysis of various water resource problems. It has been extensively supported through various international conferences, training workshops, online swat user group forum, broad online documentation, supporting software and open source code. While Mike SHE and HSPF are equally competent, SWAT model is chosen for this study based on its historical credentials, diverse application and open source code so that it can be modified for the intended purpose.

The successful model application for SWAT varies from drainage areas of 7.2 km^2 to 444,185 km^2 (Douglas-Mankin *et al.*, 2010). Several journal articles have been published on the application of this model to assess low flow conditions (Rahman *et al.*, 2010; Steher *et al.*, 2008) and the likely impact of many management practices on runoff (Arabi *et al.*, 2008). Since various publication records reveals enough evidences that SWAT can be potentially applied for wide and diverse watershed conditions (Gassman *et al.*, 2007; Gassman *et al.*, 2010), this is a unique opportunity to apply this model for the assessment of impact sustained due to hydraulic fracking. A systematic approach has been presented in the following section to explore the potential of SWAT model to incorporate hydraulic fracking in the watershed for the hydrologic assessment.

Overview of SWAT

SWAT is a physically-based watershed model, which is developed to predict the long term impact of watershed management in terms of hydrologic and surface water quality response of large watershed (Arnold *et al.*, 2007). SWAT simulates different physical and hydrological process across river watersheds. The model is popularly used across the various regions of the world and has many peer review publications (Gassman *et al.*, 2007; Gassman *et al.*, 2010).

Initial input to SWAT model is geographical information such as digital elevation model to spatially delineate watershed in terms of different sub-watersheds. Further, land use, soil and slope information are utilized to subdivide the sub-watersheds into smaller hydrologic response units (HRU's), which are composed of similar land use, soil and management characteristics.

The loss in flow is due to evapotranspiration and the transmission of flow through the bed. Potential evapotranspiration is determined by various methods such as Hargreaves method (Hargreaves and Samani, 1985), Penman-Monteith (Allen, 1986; Monteith, 1965), and Preistly-Taylor (Priestley and Taylor, 1972). SWAT consists of two components: i) runoff generation through the land; ii) and movement of water using appropriate routing scheme. The readers are suggested to refer SWAT user's manual for water balance equation adopted in SWAT model.

The model estimates the surface runoff from each HRU using two infiltration methods; Soil Conservation Service's curve number (CN) method (USDA, 1972) or the Green and Ampt infiltration method.

Since fracking has potential to threaten the management practices in critical conditions due to the alteration of the volume and the intensity of water withdrawal both at spatial and temporal scales, SWAT model can be utilized to incorporate water withdrawal for fracking in a similar way that it has been used for other water use and withdrawal. For example, simulation of irrigation on agricultural land is performed under five sources: reservoir, stream reach, shallow aquifer, deep aquifer and a water body out of watershed. That is, users can utilize any of these sources for providing additional water input and water withdrawal through positive and negative value, respectively. Few options for incorporating water withdrawal for hydraulic fracking are: i) to use point sources option in SWAT model with negative value, ii) imitate water withdrawal and irrigation scenario in the agricultural practices for fracking assessment. Alternatively, water use input as positive and negative value can be used as an option to represent water withdrawal and water discharge as sink and source in SWAT model to represent hydraulic fracking. In addition, the incorporation of GIS technology in SWAT provides ample potential for inputs and response through spatial locations of fracking operations. The simulation in SWAT can be executed for any particular desired dates and period.

While SWAT model was used within the Fayetteville Shale in Arkansas for analyzing the potential impacts of water extraction for hydraulic fracturing (Jackson *et al.*, 2013), we are not aware of published research paper using any hydrologic models to assess the impact of hydraulic fracturing on stream low flows. Even though EPA has initiated to conduct a study to evaluate the impacts of fracturing on water resources using SWAT model in upper Colorado River watershed, the result has not been published yet in peer review journals.

The detailed process for development of the model, which includes watershed delineation, preparation of input files, model calibration, parameterization and validation, is described in the following section.

Study Area

The simulation study was focused in the Muskingum watershed (Figure 2-1) of eastern Ohio, which is one of the most affected regions due to hydraulic fracking. Watershed covers a significant portion of Ohio State (20%) with an approximately 8,000 square miles in area. The watershed covers some or entire portion of the 26 counties in Ohio.

Originating at the union of Tuscarawas and Walhonding River near Coshocton, Muskingum River, the largest river in the watershed, eventually drains into the Ohio River at Marietta after flowing 109 miles to the South. Some of the major sub streams of the river are Tuscarawas, Walhonding, Licking River and Wills Creek. The Watershed is a HUC-4 watershed (0504), which is subdivided into number of HUC-8 level watersheds. The maximum, minimum and average flows at the outlet of the watershed are 23,900 cfs, 477 cfs, and 2,760 cfs, respectively. The average annual precipitation over the entire watershed is approximately 39 inches. The minimum elevation range in watershed from sea level is 177 and maximum up to

459 m. Watershed is characterized with several lakes and reservoirs for water supply, recreation and flood reduction purposes. Interestingly, more than 90% (approximation) of natural gas wells in Ohio lie in this watershed (Figure 2-2); most of them are concentrated in the eastern portion of the watershed.

Methodology

Model Input

The current version of the SWAT model (SWAT, 2012) was utilized for this study. The model requires the inputs including digital elevation model (DEM), land use, soil, reservoir, weather, water use, point source, for successful simulation of the stream flows. The data needed for model development has been presented in Table 2-2 with necessary source and format.

30 m resolution DEM from USGS National Elevation dataset and ARCGIS were utilized in order to delineate stream networks. The watershed was delineated with a number of subbasins (406). Since the National Land Cover Dataset (NLCD) is compatible with the SWAT model, datasets of 30 m resolution (NLCD, 2006) was utilized from NLCD database. The reason for selecting NLCD data for year 2006 is to adequately represent the land use pattern during model calibration period (2002-209). The watershed land use was mainly dominated with forest (47%) comprising both deciduous and evergreen. Other major land use categories of the watershed include agricultural land with row crops (23%) followed by hay (19%), and urban areas (10%). Nearly 1% of the watershed includes industrial area, water, range grass, southwestern arid range etc. In order to adequately represent the storage effect in hydrologic analysis, the spatial location of existing major reservoirs (Table 2-3) were identified in the watershed and manually added at a suitable location (Figure 2-1). Since the watershed is relatively larger in size, we utilized the State Soil Geographic dataset (STATSGO) (USDA, 1991), which is in-built in SWAT model. In the next step, we selected the threshold in each subbasin for landuse (5%), soils (15%) and slopes

(15%) in order to eliminate minor land uses and assign multiple HRU's for each sub basin resulting 6176 HRUs in the watershed. Since hydrological modeling requires spatially distributed long term climate data, data including precipitation, maximum temperature and minimum temperature, located at various spatial locations within the watershed, were utilized from National Climatic Data Center (NCDC) in order to capture the spatial variability of precipitation and temperature. Only 23 precipitation stations and 19 temperature gauge stations, with continuous data record for a longer period, were available within the watershed (Figure 2-1). Rest of the meteorological data including solar radiation, wind speed, and relative humidity were utilized through weather generator option available in SWAT model. Daily streamflow data available from period 1993 to 2009 were downloaded at 9 USGS locations (Figure 2-1) within the watershed in order to conduct multi-site model calibration and validation. Since watershed comprises number of multi-purpose reservoirs, storage effect and flood reduction due to these reservoirs should be incorporated in a model. For this, daily mean outflows from reservoir were obtained from US Army Corps of Engineers (USACE) through the personal communication.

Major point sources data (>0.5MGD) were downloaded from Ohio Environmental Protection Agency (OEPA) and included in SWAT model calibration. Similarly, water use data for various purposes including surface and ground water, irrigation, power plant, industry, mineral extraction, water supply and hydraulic fracturings were downloaded from Ohio Department of Natural Resources (ODNR). However, ODNR does not provide any withdrawal information for less than 100,000 gal/day; therefore, information was additionally confirmed for smaller withdrawal from OEPA in order to include all facilities especially for water supply data. The spatial locations of oil and natural gas wells and sources for freshwater, which was needed as model input were utilized from ODNR. Since, a part of water withdrawal for hydraulic fracking is recycled, we utilized the information related with recycled water, fracture data and fresh water required per well from fracfocus, the National hydraulic fracturing chemical registry. Figure 2-3 shows the fresh water withdrawal, part of the water recycled and the vertical depth of wells in various years in Muskingum watershed.

Calibration and Validation

A hydrologic model needs to be appropriately calibrated and validated before conducting any scenario analysis related with watershed management. Since model calibration is a process of determining the suitable model parameters with successive iteration, SWAT-CUP (Abbaspour, 2007) was selected to calibrate the suitable model parameters using continuous flow data from 2001 to 2009. The optimizing algorithm, SUFI-2 was utilized, which takes into account the possible parameters ranges and determine the optimum model parameters within the uncertainty range of 95% (Abbaspour *et al.,* 2007). Twenty one model parameters (not shown) were selected in order to conduct multi-site model calibration and validation within the watershed. The selected model parameters were based on the similar past studies (Abbaspour *et al.,* 1999; Abbaspour *et al.,* 2007; Faramarzi *et al.,* 2009; Schuol *et al.,* 2008; Yang *et al.,* 2008).

Since the USGS observed flow data were available since 1993, the model was simulated for 15 years from 1995 to 2009. The model was allowed three years (1993- 1995) of spin up time period before the simulation period in order to stabilize the hydrological conditions such as antecedent moisture content and base flow. The model was calibrated at 9 various locations of the watershed in a daily as well as monthly time scale using the continuous stream flow data available from 2002 to 2009. The SWAT model simulation was validated with independent datasets from period 1995 to 2001 and the performance of the model was evaluated using various statistical measures including, Percent of bias (PBAIS), coefficient of determination (R^2) (White *et al.*, 2005), and Nash-Sutcliffe coefficient of Efficiency (NSE) (Nash and Sutcliffe, 1970) .

Model Evaluation Criteria

Performance evaluation of the model is always a key issue for any hydrological modeling as there is not a single best statistical measure to check the performance of a model's outputs with observed data. There are three non-dimensional and one dimensional measure which are widely used to assess the goodness of fit. These model performance measures are coefficient of determination (R^2), Nash-Sutcliffe coefficient of Efficiency (NSE) (Nash and Sutcliffe, 1970), Root Mean Square Error (RMSE), and percent of bias (PBAIS), which are mathematically represented as follows.

$$R^2 = \frac{\left[\sum_{i=0}^{n}\left(O_{obs,i} - \bar{O}_{obs}\right)\left(O_{sim,i} - \bar{O}_{sim}\right)\right]^2}{\left[\sum_{i=0}^{n}\left(O_{obs,i} - \bar{O}_{obs}\right)^2\right]\left[\sum_{i=0}^{n}\left(O_{sim,i} - \bar{O}_{sim}\right)^2\right]}$$

R^2 varies from 0 to 1 which indicates the proportion of the total variances in the observed data.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_{sim,i} - O_{obs,i})^2}{\sum_{i=1}^{n}(O_{obs,i} - \bar{O}_{obs,})^2}$$

NSE is a measure of how well the actual and simulated data fits and its coefficient varies from -∞ to 1. The perfect model shows the value very close to 1.

$$PBIAS = \frac{\sum_{i=1}^{n} O_{sim,i} - \sum_{i=1}^{n} O_{obs,i}}{\sum_{i=1}^{n} O_{obs,i}} = \frac{\bar{O}_{sim,i} - \bar{O}_{obs}}{\bar{O}_{obs}}$$

Here, $O_{obs,i}$ and $O_{sim,\,i}$ are observed and simulated streamflow for each i^{th} observation and n is the number of observations. Similarly, $\bar{O}_{obs}$ and $\overline{ON}_{sim}$ are the mean observed and simulated streamflow. PBIAS is simply an indication of the deviation of the simulated result with the observed data.

Similarly RMSE-observations standard deviation ratio (RSR) is also another model statistics, which standardizes RMSE with standard deviation of observed data.

$$RSR = \frac{RMSE}{STDEV_{obs}}$$

The Ideal value of RSR is zero indicating the perfect match of the observed data and simulated result.

Result and Discussion

Fracking and Analysis

The calibrated and validated SWAT model was integrated with water use, point sources data and fracking condition of year 2012 in order to analyze the streamflow with given rate of fracking condition. Monthly consumptive water use was provided in model from the water use input file based on the removal of water from reach, shallow aquifer, and reservoirs within subbasin. Since the continuous lake outflow data were not available, 50 percentile of the available data from USACE was applied for a period of 1995 to 2009 in order to best represent the lake outflow. When this study was conducted, only the fracking data up to year 2012 were available; therefore, current period in this manuscript actually represent the conditions of year 2012.

Model Simulation

The performance of the model was evaluated through various criteria including visual inspection and goodness of fit. The performance of the model was satisfactory both in daily and monthly scale during model calibration and validation period. Figure 2-4 and Figure 2-5 provide the box plot of daily and monthly statistical parameters including *NSE*, R^2, *RSR* and *PBIAS* to measure the performance of the model. In majority of watershed locations, *NSE, RSR* and *PBIAS* were well above the minimum suggested ranges of Moriasi *et al.* (2007) (*NSE* > 0.5, *RSR* ≤ 0.7 and *PBIAS* ±25%). *NSE* values varied from 0.40 to 0.65 for daily streamflow calibration, and it varied from 0.4 to 0.65 for streamflow validation (Figure 2-4). Similarly, the NSE was obtained in the range of 0.49 to 0.89 for monthly streamflow calibration, and 0.55 to 0.86 for monthly streamflow validation (Figure 2-5). However, the validation of the model was limited to 8 USGS stations as the long term data were not available at the outlet. The nearest stations (USGS 3142000) near to the outlet also did not have a continuous record beyond 1998; therefore, validation at this station was accomplished using three years of data (Figure 2-5).

Since SWAT model can relatively better simulate the monthly streamflow compared to daily streamflows, the performance of the model was relatively promising in monthly scale compared to daily scale. Performance of the model was satisfactory for all stations except at one station (USGS 03136500). The model performance at this station was affected due to lack of reservoir outflow data as this station was immediately below the reservoir. As expected in any watershed modeling, the performance of the model was relatively better in the downstream portion of the watershed as these stations covers large portion of watershed. Furthermore, the performance of the model was also assessed through the visual inspection of observed and simulated streamflow time series over a long period. The performance was found to be satisfactory during calibration (Figure 2-6) and validation period (Figure 2-7). Despite of the slight underestimation in daily and monthly simulated peak, the model captured the overall spatial and temporal pattern of stream flow satisfactorily.

Impact due to Fracking

Our analysis depicted the consistent increasing drilling trend in Muskingum watershed. Model was used to quantify the effect of these withdrawals over this period. 32 subbasins were affected by fracking, which had drainage area less than 140 km^2. Analysis was categorized in yearly and monthly periods; mean for current year, dry and high flow season were calculated, separately. Results revealed that the greater alterations were found in seasonal mean (high flow) than the yearly mean flow. However, these changes were only detected in 5 subbasins out of 32 subbasins, with less than 1.5 percentage difference, indicating that impact is not significant in yearly and seasonal mean flow (high flow season) in the streams. Also, dry flow seasonal mean showed significant variances only in two subbasins (5.9% and 20.16%) with no significant changes on the remaining subbasins. However, the difference was noticed when the monthly analysis was performed. Minimum 6 percentage difference was observed while comparing current and baseline scenario.

Since it is essential to maintain environmental low flows for sustainable water availability including downstream right, aquatic habitat and others, low flows for current fracking period was evaluated considering water withdrawal over the watershed. The result showed that the water withdrawal during low flow period (August through November) was about 43% of the total water withdrawal (Figure 2-8). However, this difference was relatively more when hydraulic fracking effect is analyzed over the 7 days minimum monthly low flows. Out of 32 subbasins, 8 subbasins with less than 118 km^2 drainage area revealed more than 5% difference in 7 days minimum monthly flow while comparing baseline (without hydraulic fracking) and current scenarios (Figure 2-9). Figure 2-9 also presented both the monthly mean and seven days monthly minimum flows only in 8 subbasins; the impact in other subbasins was not significant. Interestingly, major impacts were observed in first order streams. The subbasins which showed the differences in 7 days low flows and monthly minimum flows are displayed in Figure 2-9. The spatial location of the affected subbasins is shown in Figure 2-10. In general, our analysis shows lesser impact on the annual and seasonal water balance; however, the effect might be critical over low flow such as 7 day minimum flow, especially on lower order of streams.

The case study revealed that the impact of water withdrawal is revealed during low flow period, and this effect is particularly true in small order streams. Our analysis does not show any significant impact in monthly and annual scale. Nevertheless, some localized impact in the first order stream for few days can be encountered. Similarly, baseflow variation during low flow period suggests that ground water is dominant component for the discharge into most of the rivers during this period. However, the result might be different in various subbasins in accordance with the existing water use and point source discharge of that particular subbasin.

Modeling Challenges for Hydraulic Fracking Study

While we selected SWAT models for this study, the issues and challenges associated with SWAT model application will be similar to the issues associated with abovementioned models discussed in this article if the users select other models. Therefore, we will present the challenges and difficulties in model application in a generic term, irrespective of the types of the model chosen.

Model Calibration, Validation and Uncertainties

The lacks of water withdrawal data for various purposes such as irrigation, water supply and for various other purposes are neither well recorded nor easily available. On the other hand, lack of required datasets for long term calibration and validation is another issue to evaluate the appropriate selection of watershed models in order to quantify the effect of hydraulic fracking on water resources management. The quantity of water needed for hydraulic fracking also varies from case to case basis, and there is no specific record of the water withdrawal information for hydraulic fracking as it relies in the geological condition, depth, lateral length, type of rock and other physical conditions of the sites. The water used for fracking eventually ends up in underground disposal wells and hence removed from the hydrologic cycle. The water used for fracking also primarily used from various sources including municipal water systems, streams, reservoirs, private ponds etc. The exact water withdrawal location is always uncertain and raises several questions for the reliability of the modeling results. In addition, certain amount of water will be disposed to the streams/rivers after treatment of drilled wastewater. The amount of water disposed also varies from location to location; exact data are needed to make a reliable prediction using models. Therefore, modeler needs to make an assumption due to lack of exact disposed water from each site. Also, the water disposed could be surface water or in some case ground water. More importantly, the representation of exact timing of water withdrawal and disposal within a year in a simulation model is another challenging issue because company can withdraw water any time after receiving the license from concerned federal agencies (in this case, ODNR). Similarly, modeler's also needs to rely on the assumption of exact location of well sites because companies may drill at any convenient location of the watersheds. Another limitation is that modeler is always uncertain about the possible changes in population and land use change practice in near future while developing future scenarios of water acquisition due to hydraulic fracking.

Flowback and Produced Water Effect

The disposed flow may have pronounced effect on water quality at certain sections of the stream but not for the entire streams. In future, detail database should be prepared and existing models should be modified to incorporate the possible consequences of accidental discharge, leak and spills of flowback and produced water.

Scaling Issues

The impact of fracking may vary both at temporal and spatial scales, and intensive study is needed for any generalization of the study. For instance, the impact of withdrawal may have different range of impact on daily water availability and monthly water availability. Furthermore, the spatial distribution of the fracking locations within the watershed also affects the net amount of water within the tributaries. That is, if the frakings wells are concentrated near to the particular tributaries, it may have significant impact for those particular tributaries; however, it may not have substantial effect far downstream of the stream or at the watershed outlet. Therefore, modeler's need to acquire appropriate information of fracking wells and their spatial locations. The scale of fracking that affect water resources sustainability is still a matter of further investigation and could be an interesting topics for future research.

Consequences and Future Outlook

The oil and gas production may result impact on water resources and environmental sustainability leading to the demand on policy changes in future. For example, the hydrological and biological conditions of the watershed will be affected due to fracking; therefore, water withdrawal for fracking should be incorporated in NPDES permitting and TMDL development of the affected watershed in future. The hydraulic fracking may also change the current land use practices; therefore, the locations of best management practices to be adopted within the watershed might be shifted in future.

Proper development of complete database of hydraulic fracking information is needed for the use of current watershed models to deal with the complex intervention in watershed due to hydraulic fracking. For this, stakeholder participation should be encouraged and information should be shared through the active stakeholders' consultation. More specifically, the complete database of hydraulic fracking is needed in future before analyzing impact of hydraulic fracking on water resources.

US government should devise future policies for the environmental safeguard and water resources sustainability against fracking. Decision-support systems will be useful to provide policy level solutions to the active stakeholders related with hydraulic fracking and its impact on water resources. Therefore, hydrologic models should be advanced to incorporate hydraulic fracking in future. While the site specific conditions may be different from location to location, generic effect of fracking on water resources can be extrapolated using such simulation study.

Conclusion

In this paper, the state of art of existing watershed models has been presented to conduct simulation study due to water withdrawal associated with hydraulic fracking. The capabilities of widely adopted 7 watershed models (HSPF, MIKESHE, SWAT, WARMF, APEX, WAM and HEC-HMS) to incorporate fracking was systematically reviewed and documented with proper citation. Our study does not warrant only the above-mentioned models to incorporate fracking for simulation study as there are numerous watershed models available. While most of the watershed models have an option of incorporating hydraulic fracking process, the SWAT model was selected among the various candidate watershed models. A separate case study was presented to demonstrate the potential application of SWAT model for the assessment of hydraulic fracking and its impact on the water resources, especially for low flow period.

Simulated flows in ungauged locations under the current fracking situation were used to assess the potential impact of water withdrawal for hydraulic fracking on water resources both at spatial and temporal scales. The study suggested that the impact was more significant during low flow than average flow or peak flow period. 7 days minimum flows showed some variation when compared with the 7 days minimum flow without fracking indicating that proper regulations of drilling activities are needed during the low flow period. Such flow alteration may bring the daily flow below the environmental flow limits, which may eventually threaten the water resources sustainability.

Even though simulation studies are always associated with a certain degree of uncertainty, this study concludes that SWAT could be a potential tool for the hydrologic assessment and water quality evaluations in the future under different scenarios of hydraulic fracking. This study also concludes that fracking has a modest effect on seven day low flows; therefore, this study addressed water quantity impacts due to hydraulic fracking, which continues to be an interesting research topic for the future.

Overall, this research summarizes following issues which might be helpful to improving hydrologic assessments and management strategies in the future.

- Watershed models can be utilized to evaluate several water acquisition scenarios associated with hydraulic fracking both at spatial and temporal scales with some modification, if any.
- Lack of sufficient data and information for hydraulic fracking study at various spatial locations is one of the major limitations.
- Complete database regarding the information of exact withdrawal and water disposal location is needed in future.
- Coupling of groundwater and surface water modeling process is needed in future for thorough investigation.

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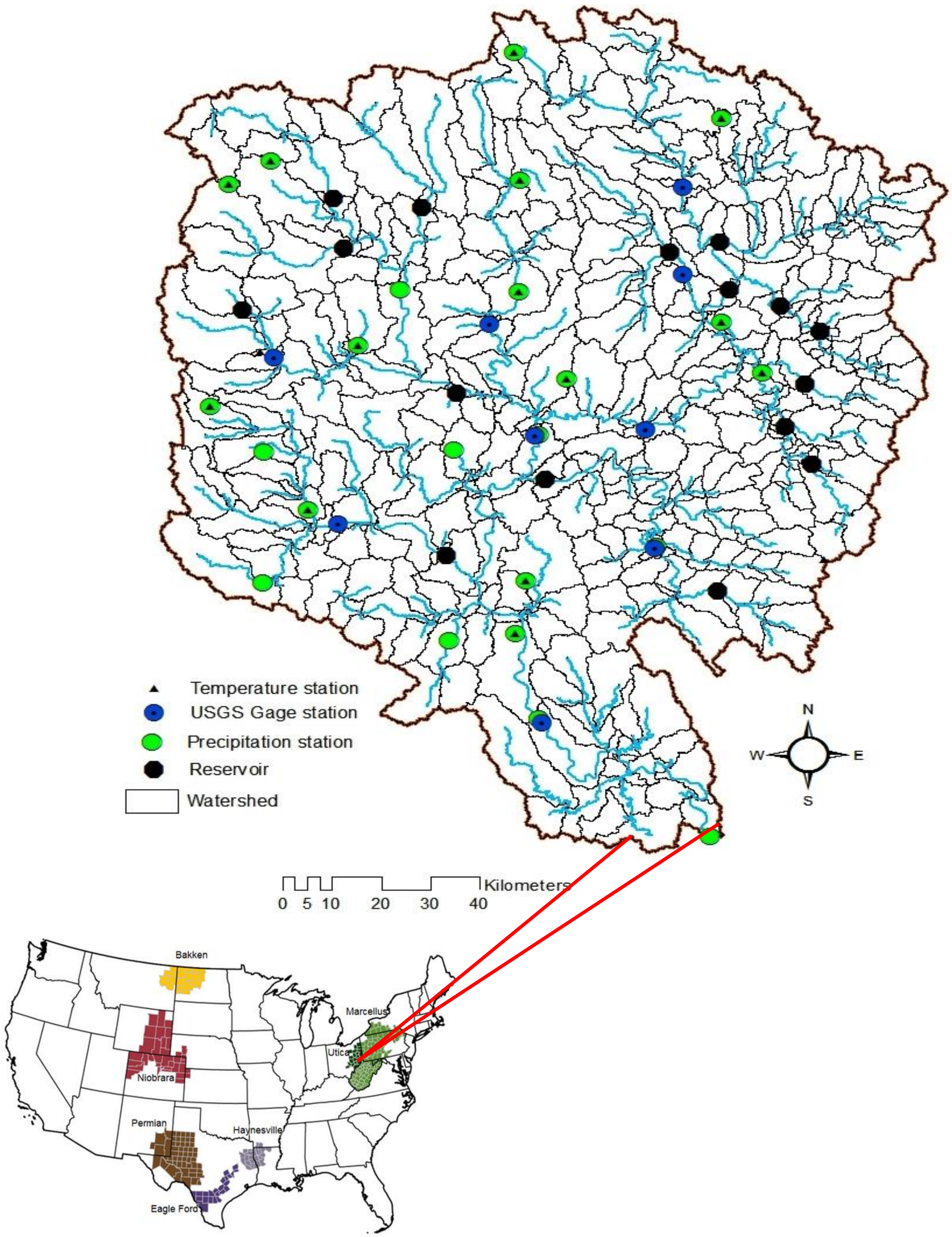


Figure 2-1: Location of climate stations including reservoir and USGS gage stations in the Muskingum watershed.

Source: US Energy Information Administration

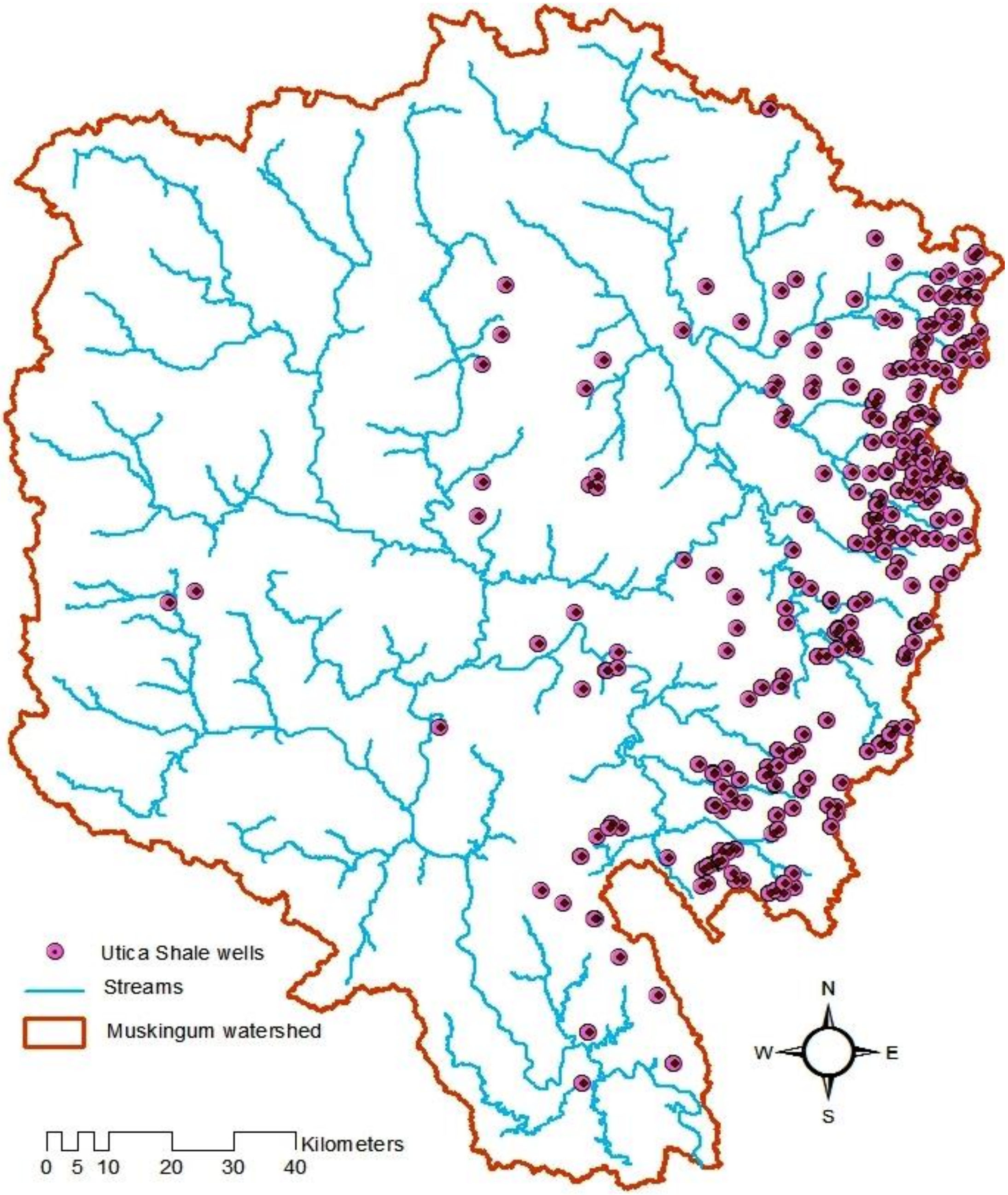


Figure 2-2: Utica shale wells in Ohio.

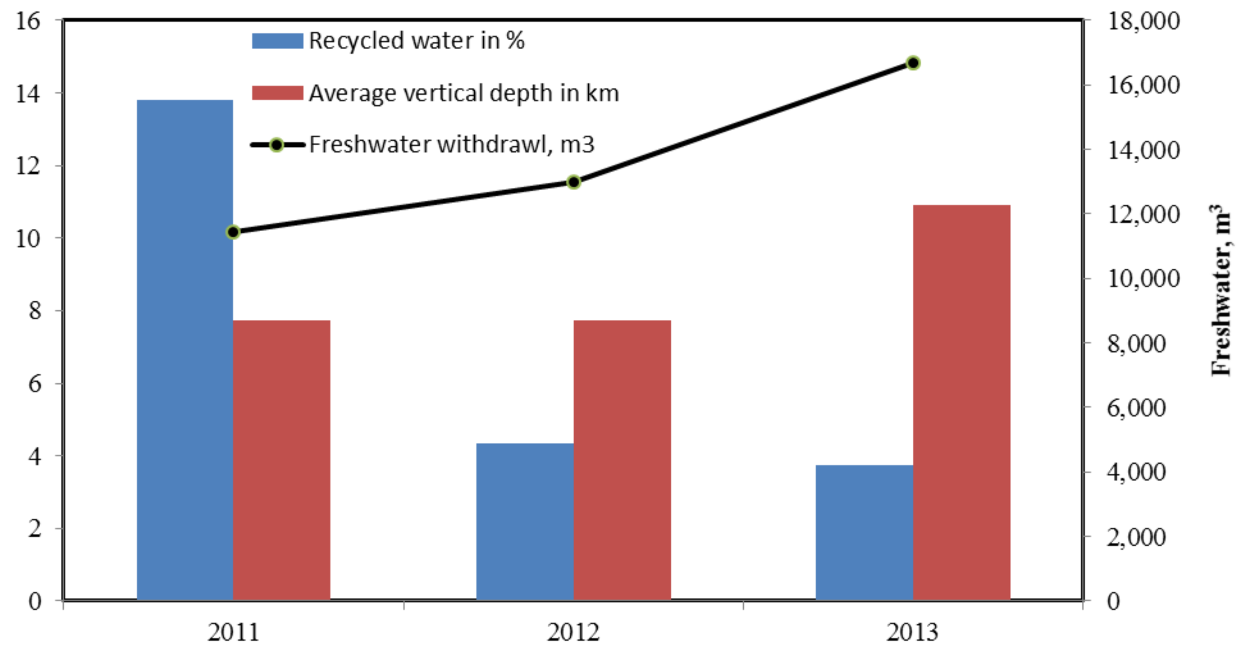
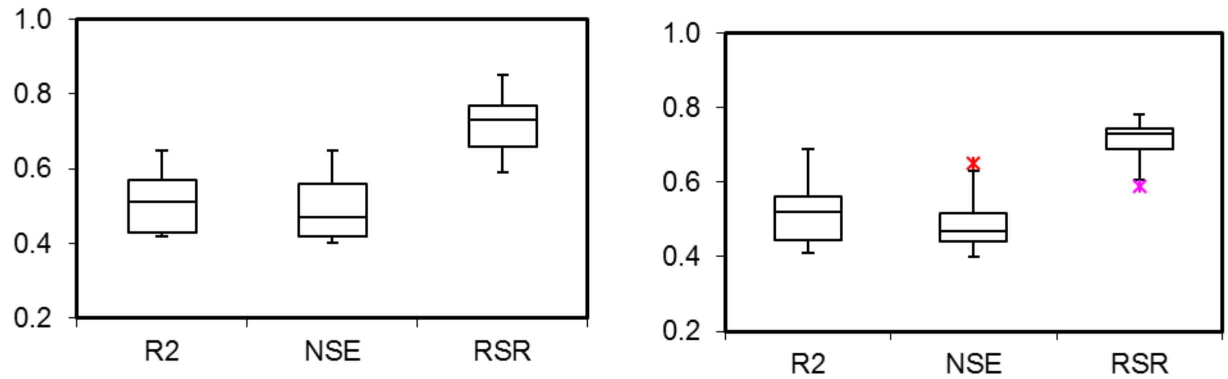
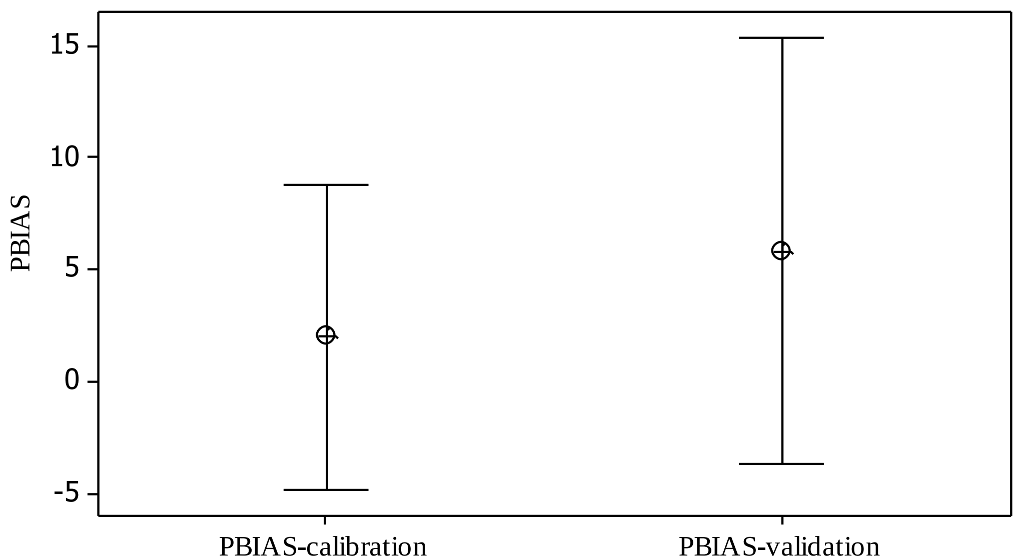


Figure 2-3: Fresh water withdrawal, average vertical depth and recycled water for hydraulic fracking in Muskingum watershed in various years



(a) Calibration (b) Validation



Interval Plot of PBIAS (95% CI for the Mean)

Figure 2-4: Daily model statistics at 9 USGS gage stations during model calibration (a) and validation (b) period. The lower panel shows the interval plot of percentage bias (PBIAS) error for calibration and validation

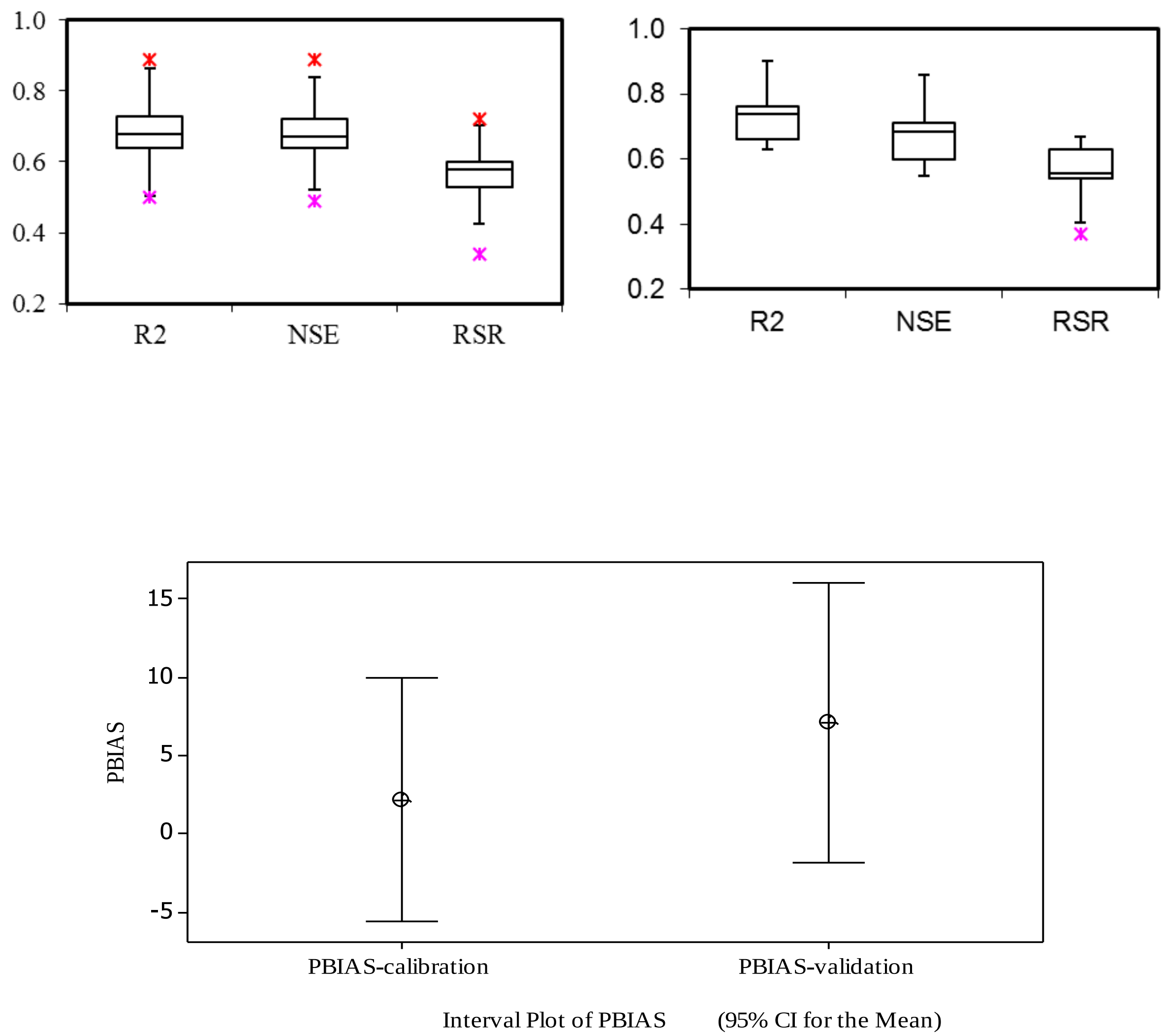


Figure 2-5: Monthly model statistics at 9 USGS gage stations during model calibration (a) and validation (b) period. The lower panel shows the interval plot of percentage bias (PBIAS) error for calibration and validation.

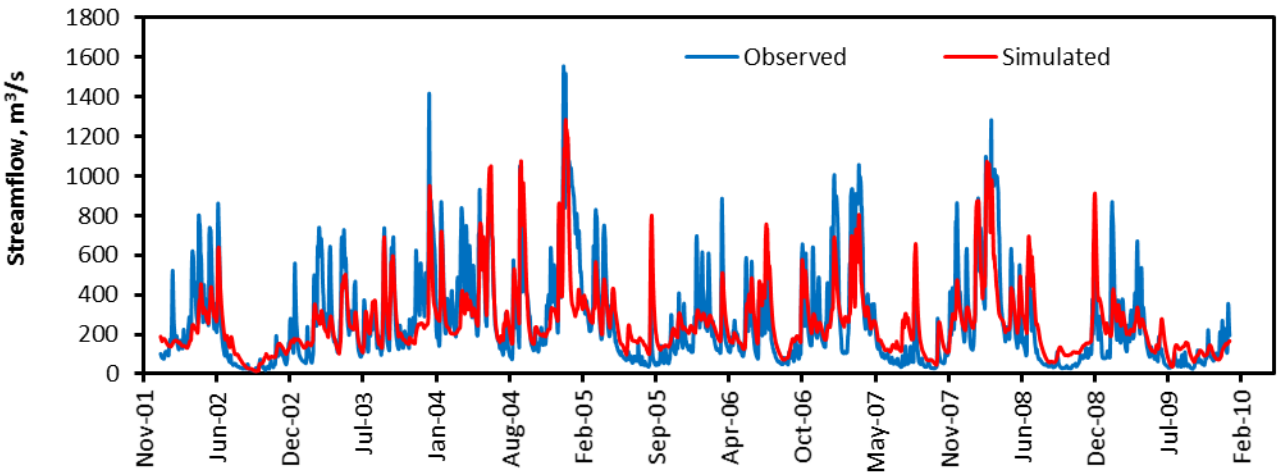


Figure 2-6: Daily streamflow calibration at watershed outlet (USGS gage 03150000).

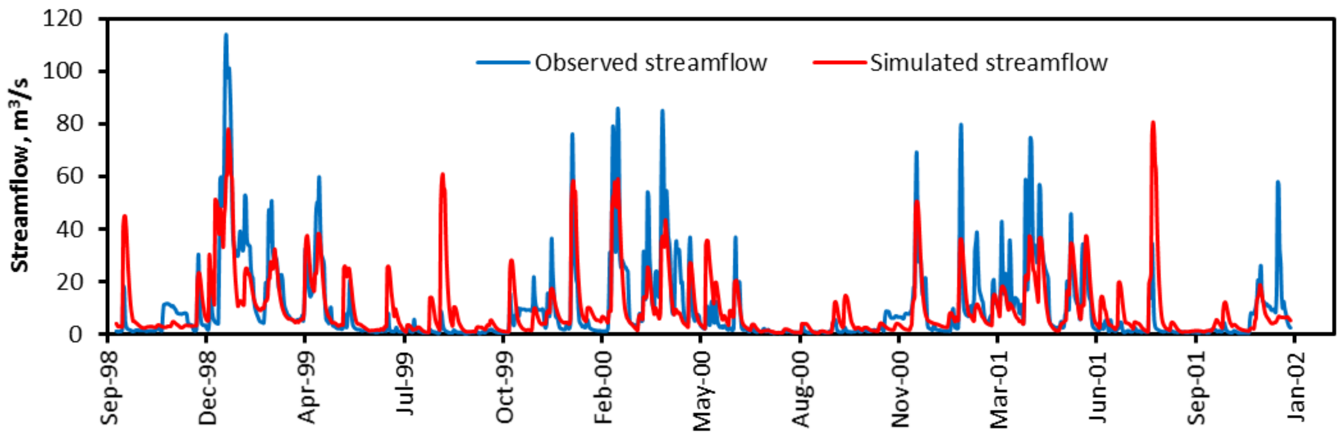


Figure 2-7: Daily streamflow validation at USGS gage 03142000 (the closest station to watershed outlet as outlet did not have long term record beyond year 2000).

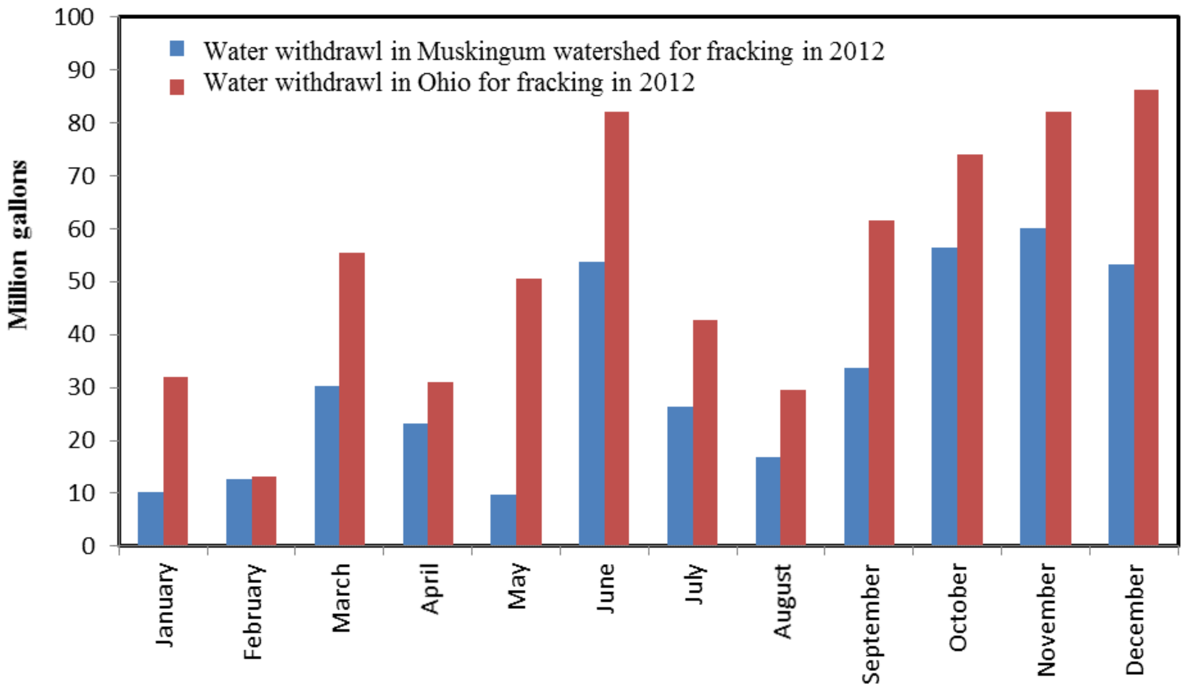


Figure 2-8: Water withdrawals for hydraulic fracturing in 2012 in Muskingum watershed and Ohio, respectively.

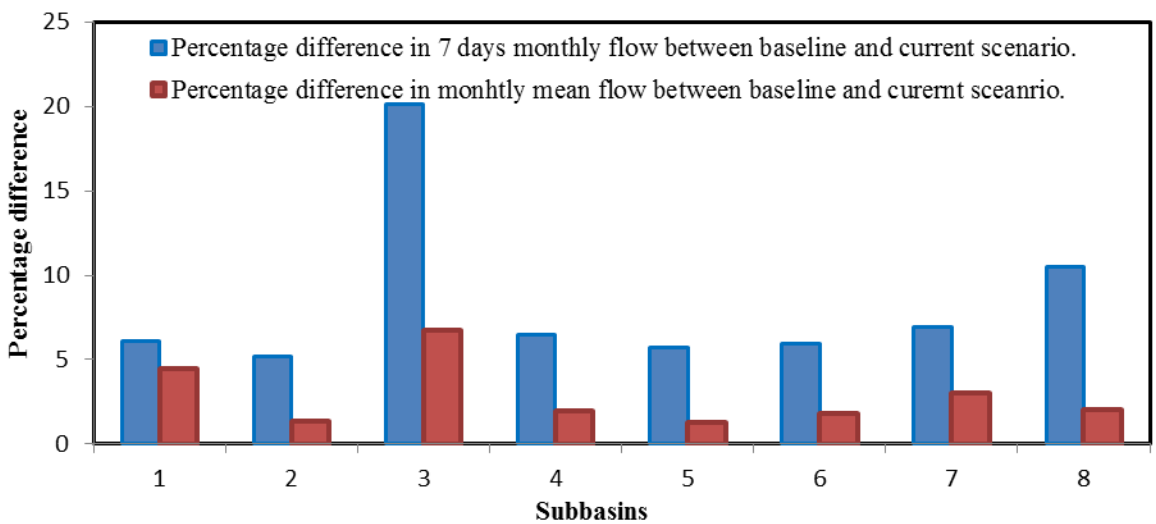


Figure 2-9: Percentage differences of 7 day minimum monthly flow and monthly mean between baseline and current fracking scenario on 8 affected subbasins for current period.

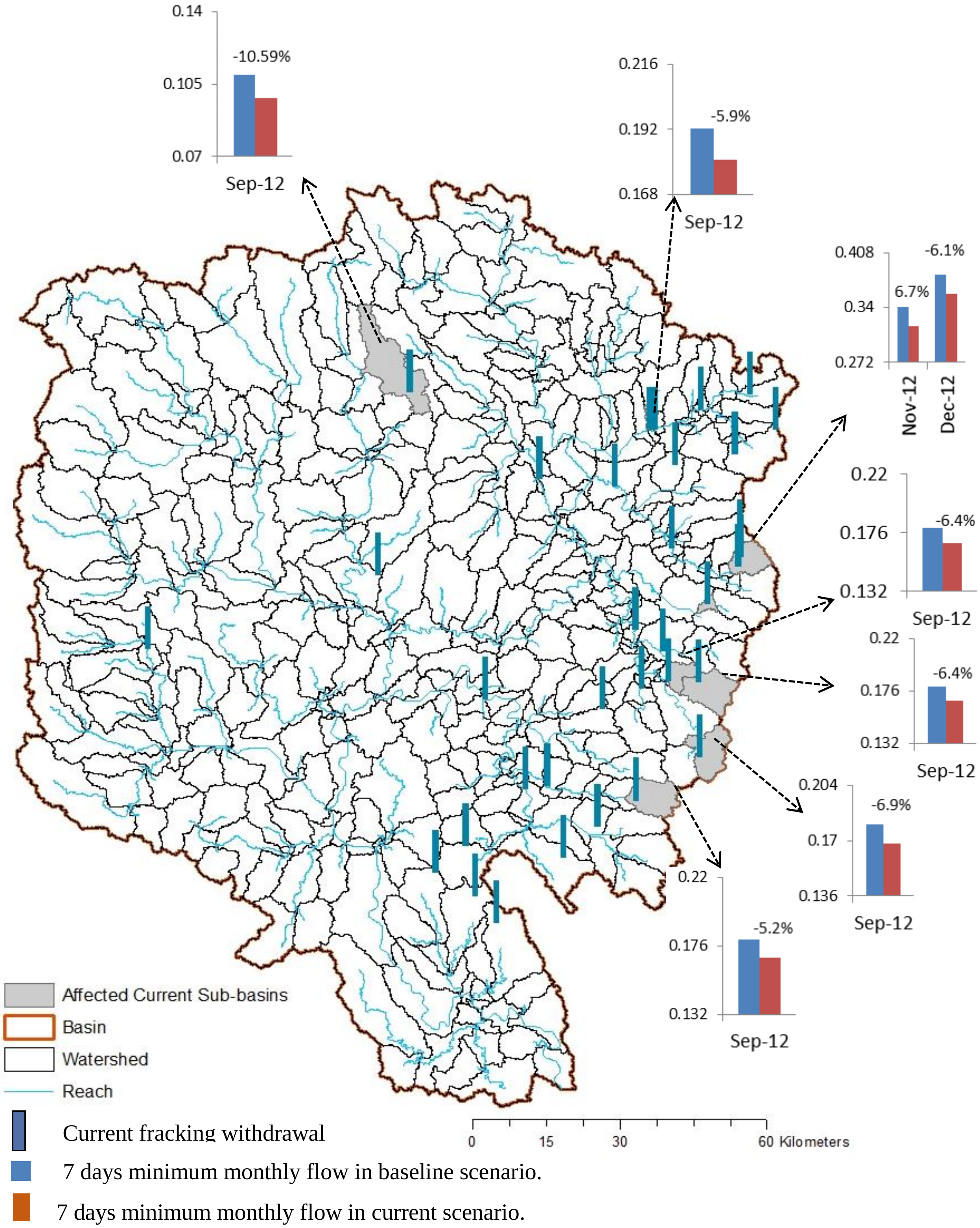


Figure 2-10: Impact of current fracking scenario on 7 day minimum monthly flow in Muskingum watershed.

Table 2-1: List of watershed models possibly used for hydraulic fracking study

Models	**Model inputs for hydrologic analysis**	**Computational time scale**	**Options to incorporate point source/water withdrawal for hydraulic fracking**	**Internet source**	**Time scale**
HSPF/LSPC	DEM/landuse/soil/precipitation/temperature and climate data	Daily/Sub-hourly	Yes	http://www.epa.gov/athens/wwqtsc/html/lspc.html	Continuous
SWAT	DEM/landuse/soil/precipitation/temperature and climate data	Daily/hourly	Yes	http://swat.tamu.edu/	Continuous
MIKE-SHE	DEM/landuse/soil/precipitation/temperature and climate data	Daily/hourly	Yes	http://www.mikepoweredbydhi.com/download/mike-by-dhi-2014	Continuous
APEX*	DEM/landuse/soil/precipitation/temperature and climate data	Daily	Yes	http://epicapex.tamu.edu/apex/	Continuous
WARMF	DEM/landuse/soil/precipitation/temperature and climate data	Daily/hourly	Yes	http://www.epa.gov/athens/wwqtsc/html/warmf.html	Continuous
HEC-HMS	DEM/landuse/soil/precipitation/temperature and climate data	Daily/hourly	Yes	http://www.hec.usace.army.mil/software/hec-hms/downloads.aspx	Continuous/event-based
WAM	DEM/landuse/soil/precipitation/temperature and climate data	Daily/hourly	Yes	http://www.epa.gov/athens/wwqtsc/html/wamview.html	Continuous

**Some components are available in hourly scale as well*

Table 2-2: Data and sources used for the study.

Data Type	Data	Source
GIS	DEM of 30-meter resolution	USGS
	Land cover datasets, 2006	NLCD
	Soil data	USDA, STATSGO
Climate data	Precipitation and temperatures	NCDC
Hydrology	Streamflows	USGS
	Lake and reservoir outflow	USACE
Water Use (Surface and ground water)	Water use for irrigation, public, power, mineral extraction, industries and golf course	ODNR Ohio EPA
Major point sources	Flow discharge	Ohio EPA
Information related with hydraulic fracking	hydraulic fracking information including sources of drilling water	ODNR
	Drilling water estimate per well and future drilling trend	FracFocus

Table 2-3: Major reservoirs in the Muskingum watershed.

Watershed	Reservoirs	Locations	Drainage area (km^2)
Tuscarawas River watershed	Leesville	McGuire Creek	124.32
	Atwood	Indian Fork	181.3
	Tappan	Little Stillwater	183.89
	Clendening	Stillwater Creek	181.3
	Beach City	Sugar Creek	776.97
	Piedmont	Stillwater Creek	217.56
Walhonding River watershed	Charles Mill	Black Fork	559.44
	Pleasant Hill	Clear Fork	515.41
	North Branch of Kokosing	North Branch	116.5
Will Creek watershed	Wills Creek	Mainstem	1872.6
	Senecaville	Seneca Fork	313.39
Licking River watershed	Dillion	Mainstream	1937.24

Chapter 3. Scenario Analysis for Assessing the Impact of Hydraulic Fracturing on Stream Low Flows Using SWAT Model

Abstract

Scientists and water users are concerned about the potential impact on water resources, particularly during low-flow periods, due to fresh water withdrawals for unconventional oil and gas development (hydraulic fracturing, or "fracking"). Most water management decisions are based on the hydrologic or biologic conditions, which are estimated using long term historical records of low-flow periods without accounting for water withdrawals for hydraulic fracking. This raises a question as to whether current policies of point source permitting, which rely on low-flow conditions, are appropriate given the current trends of water demand for hydraulic fracking. Moreover, additional water withdrawals from surface water during low-flow periods may pose a threat to the sustainability of water supplies and aquatic ecosystems, particularly during drought years. The objective of this paper is to assess the potential impact of hydraulic fracturing on water resources in the Muskingum watershed of Eastern Ohio, USA, especially due to the trend of increased withdrawals for hydraulic fracking during drought years. The Statistical Downscaling Model (SDSM) was used to generate thirty years of plausible future daily weather series in order to capture the possible dry periods. The generated data were incorporated in the Soil and Water Assessment Tool (SWAT) to examine the level of impact due to fracking at various scales. Analyses showed that water withdrawal due to hydraulic fracking had noticeable impact, especially during low-flow periods. Clear change in the seven day minimum flows was detected among baseline, current and future scenarios when the worst case scenario was implemented. The flow alteration in hydrologically-based (*7Q10*, i.e. 7-day 10-year low flow) or biologically-based (*4B3* and *1B3*) design flows due to hydraulic fracking increased with decrease

in the drainage area, indicating that the relative impact may not be as great for higher order streams. Nevertheless, change in the annual mean flow was limited to 10%.

Keywords: Hydraulic fracturing (fracking), SWAT, SDSM, Low-flow, drought

Introduction

Shale gas production in the United States is projected to increase by threefold, covering a significant portion of all natural gas produced by 2035 (USEIA 2011). Development of unconventional shale gas is technologically enabled by a key technique called hydraulic fracturing (fracking) (Hubbert and Willis 1972, Yew and Weng 2014). However, a large amount of water (26,500 m^3) is required for fracking, which has attracted the attention of public and regulatory agencies (Craig 2012, Nicot et al. 2012, Rahm and Riha 2012). Scientists and water users are concerned about the extent of potential impacts of this water consumption, especially from surface water (Entrekin et al. 2011), at different spatial and temporal scales. The impact could be significant if further consideration is not given to the timing, location and volume of water withdrawal for fracking, especially during low-flow periods (USEPA 2011c, Cothren et al. 2013).

The water quality standards issued by the Federal and State agencies are developed based on low-flow conditions (Sharma et al. 2012, Saunders et al. 2004). For example, the Environmental Protection Agency (EPA) and State agencies issue National Pollution Discharge Elimination System (NPDES) permit limits based on hydrologically-based design flows (e.g. *7Q10*, the 7-day 10-year low flow) and biologically-based design flows (*4B3, 1B3*). The hydrologically-based design flow is the extreme low-flow calculated exclusively based on the hydrologic records considering the lowest flow from each year, whereas the biologically-based design flow is computed considering all the low-flow events over the period of record (Eslamian 2014). These regulatory low-flow criteria are developed based on statistical analysis of long term historical stream flows records without anticipating water withdrawal for fracking. This raises a question as to whether the permit conditions developed for low-flow periods are adequate to protect water quality in the current and future conditions of fracking. Overestimation of low flows may lead to underestimation of pollutant levels below wastewater discharges; therefore, proper consideration of potential water withdrawals for fracking is essential in the permitting process. In addition, reservoirs and streams used for water supply purposes will be at critical stages during low-flow (drought) periods, which will be further reduced due to the sudden withdrawal for fracking. Therefore, water use for fracking not only reduces water quality, by reducing the assimilating capacities of the stream for pollutants, but also affects water availability for various water supply purposes.

These issues are very common in the Muskingum watershed of the Eastern Ohio, leading to the critical challenges for water resources sustainability. Several lakes (e.g. Seneca) and ground water resources are extensively used for water supply in this region. Almost one million residents of the watershed rely on private wells (Angle et al. 2001). However, groundwater use for fracking is very nominal (1%), since stream water is more convenient for use in fracking industries. Also, a significant amount of water is used for fracking and only a limited amount of water is returned to streams as flow back. In this context, detailed analysis is needed to evaluate the impact of hydraulic fracking on assimilating capacities of streams for NPDES permitting and water resources availability during low-flow periods.

Few studies have been conducted related with the impact of fracking on stream low-flows. The United States Environmental Protection Agency (USEPA) has conducted a study to evaluate the potential impact of hydraulic fracturing on drinking water resources in the Upper Colorado River Basin (USEPA 2012). Similarly, research was conducted in the Fayetteville Shale play to assess the impact on flow regime and on the environmental flow criteria of the stream (Cothren et al. 2013). This study demonstrated the impact of hydraulic fracking on environmental flow components, especially on small scales. While these studies addressed the impact of hydraulic fracking on stream flows in general, extensive analysis of stream low flows due to water withdrawal for hydraulic fracking has not been conducted yet.

In our earlier study (Sharma et al. 2015), we explored various potential watershed models to conduct a simulation study under fracking conditions and reported that the Soil and Water Assessment Tool (SWAT) could be an appropriate tool for this purpose. We conducted a multi-site model calibration and validation using SWAT in the study watersheds with satisfactory model performance, and reported several modeling challenges, opportunities and issues in a simulation study. Our previous study indicated a modest effect on watershed hydrology due to the current rate of water withdrawal for fracking. The purpose of the present study was to evaluate the potential impact on water resources of extreme conditions (climate, rainfall, and fracking withdrawals) in the future by developing various scenarios. In order to develop various water acquisition scenarios, weather and scenario generator tools of the Statistical Downscaling Model (SDSM) (Wilby et al. 2013) were adopted to generate possible climate and precipitation data and then integrated with the SWAT model to develop future scenarios. In the next step, all the scenarios were analyzed at different spatial and temporal scales to investigate the potential impact of water withdrawals on water budgets during low-flow periods.

Theoretical Background

Hydrologically-Based Design Flow

This design flow was orginally introduced by the United States Geological Survey (USGS) and has been popularly used by various States in the US for National Pollutant Discharge Elimination System permitting (NPDES) (Wiley 2006). The xQy hydrologically-based design flow is computed as the x-day consecutive average low flow with a return period of y-year. The lowest x-day flow from each year of the record period is determined. The distribution of these values is plotted and the y-year value is determined either empirically if the record is long enough or using a statistical law (Pyrce 2004). Hence xQy intends to characterize the lowest flows of each year. For example, *7Q10* refers to the minimum consecutive average 7-day low flow of each year with an expected return period of 10 years.

Biologically-Based Design Flow

This design flow was orginally introduced by the United States Environmental Protection Agency (USEPA) (Rossman and EPA 1990). This method is different from the hydrologically-based design flow as it uses the *n* lowest flow events within a given period of record of *n* years, irrespective of the individual years. It means that several lowest flow events from a given year may be incorporated for statistical analysis in biologically-based design flow computation, whereas there may be no event from other years. While the hydrologically-based design flows evaluate the risk of being below a threshold one year out of y, the biologically-based design flow intends to quantify the cumulative effects of consecutive low-flow events on aquatic life. *4B3* and *1B3* are the 4-day and 1-day average biologically-based flows, respectively, which can be expected once in three years.

Hydraulic Fracking

Hydraulic fracturing, introduced in the 1940s (Montgomery and Smith 2010), is the technique of injecting large amount of water mixed with sand and chemicals at high pressure, which fractures rock underground at great depth and releases the gas (Beaver 2014). Drilling requires approximately 2 to 4 weeks duration and the expected life of a well is typically 20 to 50 years. The water is typically needed for a few days to a week during the drilling process, depending upon the site conditions. Water is withdrawn from surface and groundwater sources, treated water from a treatment plant, and recycled water from the flow back and produced water (Gregory et al. 2011). Water usage per well varies depending upon the type of shale and its thickness, configuration and dimension of the well (e.g., length, depth, horizontal or vertical orientation, multiple leg or single leg) and fracturing operation. Water use per well is estimated to range from 25 m^3 for coalbed methane production to 49,200 m^3 for shale gas production (GWPC and ALL Consultant 2009, Nicot et al. 2012). Similarly, the fracturing process for a shale gas well requires 8,700 m^3 to 94,600 m^3 of water per well (USEPA 2011a) and an additional 151–3,790 m^3 of water is required for drilling vertically per well (GWPC and ALL Consultant 2009). The Marcellus shale data in Pennsylvania shows the water required is from 7,570 to 15,100 m^3 per well (Gregory et al. 2011, Satterfield et al. 2008). In general, 15,100 to 22,700 m^3 of water is commonly needed to frack a single Marcellus or Utica shale well (OEPA 2012).

Soil and Water Assessment Tool (SWAT)

The SWAT is a physically-based watershed model, which is developed to predict the long term impact of watershed management in terms of hydrologic and water quality response of large watersheds (Arnold et al. 1998). The SWAT simulates different physical and hydrological processes across river watersheds. The model is widely used in different regions of the world for surface water and ground water modeling, as described in many peer reviewed publications (Gassman et al. 2010). SWAT simulates ground water by partitioning soil profiles into three layers: soil layers; shallow aquifer; and deep aquifer. The shallow aquifer, which lies between the soil layers and deep aquifer, closely resembles a reservoir. Surface water and ground water modeling procedures in SWAT are described in articles by Vazquez-Amábile and Engel (2005) and Arnold et al. (1996). Similarly, SWAT can simulate reservoirs by calculating the water balance, incorporating inflow, outflow, rainfall, evaporation, any seepage and diversions. There are three options available to compute the outflow from the reservoir (Neitsch et al. 2005): i) input the observed outflow; ii) specify the outflow release rate; or iii) specify the monthly fixed volume of the reservoir.

Initial inputs to SWAT include geographical information such as digital elevation model (DEM) to spatially delineate the watershed in terms of different sub-watersheds. Further, land use, soil and slope information are utilized to subdivide the sub-watersheds into smaller hydrologic response units (HRU's), which are composed of similar land use, soil and management characteristics.

Statistical Downscaling Model (SDSM)

The SDSM is a climate change scenario generator used for risk assessment and climate studies (Wilby et al. 2002). The SDSM uses tools such as the stochastic weather generator and regression based downscaling technique as a means for weather generation (Wilby et al. 2002). The weather generator is used to generate synthetic data of weather such as precipitation, and maximum and minimum temperatures. Precipitation is simulated based on the occurrence of wet or dry periods, and on the amount of precipitation and temperature. The occurrence is modeled by a Markov chain method and the amount is sampled randomly from a suitable distribution such as a Gamma distribution. The weather generator has been used in many studies for infilling missing data and matching local climate information based on predictor variables. Five main steps were followed to generate plausible dry period precipitation through the SDSM: 1) identification of predictors and predictands; 2) SDSM model calibration; 3) parameter file generation; 4) incorporating missing data using the weather generator; and 5) generating future dry period precipitation using the scenario generator tool.

Materials and Methodology

Study Area

This research was conducted on the Muskingum watershed (Figure 3-1), which is located in the eastern part of the Ohio. It covers an area of more than 20,720 km^2, which is nearly 20% of the State. Muskingum is the largest river in the watershed, which originates at the union of the Tuscarawas and Walhonding Rivers near Coshocton, and eventually drains into the Ohio River at Marietta. The main tributaries of this river are the Tuscarawas, Walhonding, Licking Rivers and Wills Creek. The Muskingum watershed is a HUC-4 watershed (0504), which is subdivided into six HUC-8 watersheds: Licking (05040006), Walhonding (05040003), Mohican (05040002), Tuscarawas (05040001), Wills (05040005) and Muskingum (05040004). The Muskingum watershed contains nearly 19% of Ohio's wetlands and 28% of the state's lakes and reservoirs (Auch 2013).

Utica Shale in eastern Ohio has great potential for the production of natural gas and oil. Currently, most of the unconventional natural gas wells in Ohio lie in the Muskingum watershed (Figure 3-2). Recently, several drilling companies are advancing to Ohio for oil and gas development and drilling has increased tremendously on this watershed. Most of the wells are concentrated on the eastern portion of watershed, the Tuscarawas sub-watershed, which covers the area of 6,327 km^2 within the Muskingum watershed (Figure 3-3). This sub-watershed covers all or partial areas of the thirteen counties of Ohio. The northern portion of this sub-watershed is significantly covered by industrial and urban land uses whereas the southern portion is dominated by forest cover. Additionally, there are a number of reservoirs in the eastern part of the watershed that are used for municipal water supplies.

SWAT Model Input

The DEM of 30 m resolution was downloaded from USGS National Elevation Dataset in order to delineate stream networks using ArcGIS, resulting in 406 sub-basins. Similarly, land use data of 30 m resolution were downloaded from the National Land Cover Database 2006 (NLCD 2006) to best represent the land use pattern within the calibration period (from 2002 to 2009) of this model. The watershed was comprised of forest (47%), agriculture land with row crops (23%), hay (19%), and urban areas (10%). The remaining 1% of land use includes industrial area, water, range grass and forested wetlands. The existing 12 reservoirs were spatially located manually at proper locations of the watershed with reference to the stream outlet. The soil data taken from the State Soil Geographic dataset (STATSGO) (USDA 1991) were included as a default in the SWAT with a map at 1:250,000 scale. The appropriate numbers of HRUs (6,176) were obtained by assigning multiple HRUs for each subbasin in order to account in detail for the complexity of the landscape. These large numbers of HRUs were achieved despite eliminating minor land uses, soils and slopes by selecting thresholds of 5%, 15% and 15%, respectively. The large numbers of HRUs were highly beneficial for accurate prediction of streamflows (Arnold et al. 1996).

Seventeen years of climate data, including precipitation and the maximum and minimum temperature were downloaded from the National Climatic Data Center (NCDC) website. Altogether, 23 precipitation stations and 19 temperature gauge stations were located within the watershed (Figure 3-1). The remaining meteorological time series inputs such as solar radiation, wind speed, and relative humidity were available from the SWAT's built-in weather generator. The daily streamflow data needed for model calibration and validation were available from the USGS website for 9 USGS gauging stations from 1993 to 2009 (Figure 3-1). The reservoir daily mean outflows data were available from the US Army Corps of Engineers (USACE) for the same duration.

Data on point source discharges greater than 1,890 m^3/d were collected from the OEPA and used as model inputs before calibrating the model. Similarly, other water use information was obtained from the ODNR in order to adequately represent the watershed conditions before model calibration and validation. The consumption of water for hydraulic fracking was more significant than the consumption of water for agriculture during 2012. The surface water withdrawal in Muskingum watershed in 2012 was 334 m^3/d for hydraulic fracking, 308 m^3/d for golf course irrigation, 220 m^3/d for agriculture and 716 m^3/d for industry. Ground water withdrawal for hydraulic fracking in the same year was small (1%) compared to surface water withdrawal.

Water withdrawal information was verified from ODNR and OEPA. Similarly, the locations of oil and natural gas wells and sources for freshwater withdrawals greater than 378 m^3/d, were collected from ODNR. The completed well data, freshwater required per well, and recycled water quantities were obtained from FracFocus, which is the national hydraulic fracturing chemical registry. A summary of input data required, sources and format is presented in Table 1.

Model Calibration and Validation

In order to reduce the uncertainty in model prediction, a hydrologic model needs to be properly calibrated and validated (Engel et al. 2007). For this, SWAT-CUP (Abbaspour et al. 2007) was selected to calibrate the model parameters using streamflow time series at various locations using SUFI-2 algorithm. The efficiency of SUFI-2 for large-scale modeling studies is suggested by Yang et al. (2008). Since model calibration is an iterative process of establishing the best agreement between simulated and observed data, 21 model parameters (not shown), as discussed in several earlier studies (Abbaspour et al. 1999, Abbaspour et al. 2007, Faramarzi et al. 2009, Schuol et al. 2008a, Yang et al. 2008), were selected for model calibration and validation at various locations of the watershed. Since sufficient model parameters were chosen for model calibration, the model predictions were assumed to be reliable.

The model simulations were run for 15 years using observed data at 9 USGS stream gauge stations (Figure 3-1) from 1995 to 2009 including the calibration and validation period. A warm up period of two years was used in order to minimize the effect of initial unknown parameters and stabilize the hydrologic component of the model. The model was then calibrated in a daily time scale on 9 different USGS stream gauges from 2002 to 2009. In the next step, validation of the model was performed from 1995 to 2001 using statistical criteria measuring the goodness of fit such as the coefficient of determination (R^2) (Krause et al. 2005), Nash-Sutcliffe coefficient of Efficiency (*NSE*) (Nash and Sutcliffe 1970), Percent Bias (*PBIAS*). Also, we compared the simulated and observed flows for less than 75 percentile low flows. For better assessment of the model, users can perform the full split sample test, inverting the roles of the calibration and validation periods. A detailed description of the model evaluation criteria is not included in this paper. Readers can refer to Sharma et al. (2015) for additional information on model evaluation procedures.

Scenario Analysis

The calibrated and validated SWAT model was integrated with water use and point sources data in order to develop theoretically realistic scenarios with different rates of fracking development. The baseline, current and future scenarios were developed to assess the impact on water resources under various levels of fracking. The baseline scenario referred to the watershed conditions for 2012, with water consumption including public water supply, domestic, industrial and other water uses for irrigation, livestock, mining, power plants and point sources, but no hydraulic fracturing water use. The current scenario utilized watershed conditions in the year 2012, including the fracking withdrawal rate of 2012 in addition to other consumptive uses. As the fracking boom was just beginning in 2012, we only had three years of drilling data available for this study. The future scenario projected the current rate of development of natural gas in the Muskingum watershed up to year 2030, based on the recent drilling trends. However, drilling water demands were the only parameters changed and other consumptive use was considered constant in all the scenarios. The future scenario was developed into two separate scenarios with respect to temporal scale. The "future scenario on current climate period" was developed by simulating streamflows using the projected hydraulic fracking conditions of year 2030 but using current climate conditions (2012). Similarly, the "future scenario on future climate period" referred to the projected hydraulic fracking condition of the year 2030 simulated over a climate period of 30 years, which was generated based on historical climate records. Monthly consumptive water use was provided from the water use input file based on the removal of water from stream reaches, shallow aquifers, and reservoirs within the subbasin.

Since hydraulic fracking in Ohio is predominantly occurring in the eastern part of the state, detailed analysis for the future scenario was conducted for the Tuscarawas sub-watershed, as it covers the major eastern portion of the Muskingum watershed. Future fracking wells in the watershed (Figure 3-4) were estimated based on the past three years of drilling trends in Ohio. Even though ODNR data reports 865 wells were drilled in Ohio, drilling information on only 517 wells were available from FracFocus. Therefore, projections up to 2030 were based on actual wells drilled from FracFocus. The future scenario was adopted with fracking wells increasing by

224 wells per month in Ohio by 2030. Even though the future trend of hydraulic fracking is uncertain and depends on many political and socio-economic constraints, we assumed that the extreme increase in fracking assumed in the future scenario would provide an idea of the maximum environmental impact on stream low-flows for policy makers. This study was motivated by the growing concern of communities and scientists about water resources availability in this region. The extreme worst case scenario analyzed for the future period was particularly important as an indicator of potential conflicts among water uses.

A similar trend of hydraulic fracking that was experienced in Ohio was assumed in the Tuscarawas subwatershed. Subbasins with a minimum net area of 2 km^2, after eliminating residential and water bodies, were used for analysis. This resulted in 149 out of 168 potential subbasins to study in this subwatershed. The water withdrawal for each well was estimated based on water use trends in the Muskingum watershed for 2012 and 2013, available from FracFocus. The water use for each well in the Muskingum watershed was approximately 12,870 m^3 in 2012 and 16,656 m^3 in 2013 (Table 2). Based on this increasing trend, the freshwater withdrawal for each well was assumed to be 17,034 m^3 in 2030. The existing trends indicate a decreasing use of recycled water from 2012 (4.3%) to 2013 (3.7%); hence, recycled water for 2030 was considered simply as 4% of initial withdrawals. Water was assumed to be taken from multiple nearby sources such as the nearest streams and reservoir in the watershed, as suggested by Arthur et al. (2010). For the temporal distribution of the water use for fracking, especially 5 to 7 days are allowed for fracturing the well or using the freshwater (Sullivan et al. 2013). Generally, density of 4,047 m^2 are considered for the development of shale wells (Myers 2009, Robbins 2013), and this information was used to determine the maximum possible limit of the wells in the watershed. Therefore according to the distribution of projected numbers of 2030 wells on 149 subbasins with consideration of 17,034 m^3 of freshwater and 4% recycled water for each well for consecutive 7 days which was equally distributed for 149 subbasins of Tuscarawas watershed. Later, this projected trend was integrated with 30 years of plausible climate data in the SWAT model to simulate future scenarios. The future possible climate data was generated using a statistical downscaling model (SDSM) based on historical climate records of the region.

Developing Future Climate

In this research, the SDSM tool was utilized to generate the future climate data by establishing the quantitative relationship between local surface variables (predictands) and large scale variables (predictors). The National Center for Atmospheric Research (NCAR) and the National Centers for Environmental Prediction (NCEP) have developed more than 50 years of global analysis of atmospheric components (Kalnay et al. 1996). Therefore, this reanalysis data was selected to recover the missing measured data in the data assimilation system and make consistent climate variables throughout the reanalysis period. Large scale predictors including mean temperatures, vorticity at surface and 850 hPa, zonal velocity and many more were selected from predictors obtained from NCEP/NCAR reanalysis data for the period of 1961-1990, based on regression techniques (Table 3). The observed data were used from 1961 to 1975 to develop the regression model (calibration) and then regression weights produced a parameter file to validate for the period from 1976 to 1990. This process was repeated for all the precipitation stations. Once the missing data (1961-1990) were infilled using a weather generator tool, the scenario generator from the SDSM was applied to generate precipitation. In order to generate a possible set of dry period precipitations, we used the historical set of observed precipitation and temperature data in the respective stations (23 precipitation and 11 temperature stations). The SDSM model was used to generate a possible set of future precipitation for a 30 year period. Since our intention was to run the model for a worst case, low flow scenario, we generated the 25th percentile precipitation datasets within the watershed at all stations.

Results

Model Simulation

The model calibration and validation were performed on a daily and monthly time scale. The model performance was satisfactory during calibration and validation period with reasonable accuracy, which was assessed through a visual inspection and statistical criteria. The daily and monthly statistical criteria measuring the performance of the model, such as *NSE*, R^2 and *PBIAS* are listed in Table 4 and Table 5, respectively. Analysis showed that *NSE* and *PBIAS* were satisfactory and mostly above the recommended ranges (Moriasi et al. 2007) (*NSE* > 0.5 and *PBIAS* ±25%) except at a few stations, especially for monthly simulation. The *NSE* values varied from 0.40 to 0.65, and 0.4 to 0.65 for daily streamflow calibration and validation, respectively (Table 4). Similarly, the *NSE* varied from 0.49 to 0.89 for monthly streamflow calibration, and 0.55 to 0.86 for monthly streamflow validation (Table 5). The simulated streamflows slightly underestimated the daily and monthly peaks, which is consistent with previous findings (Bieger et al. 2014, Santhi et al. 2014). The mean observed and simulated low flows lower than the 75th percentile were compared with *PBIAS* (17%) and R^2 (0.78) (not shown). Overall, the model captured the temporal pattern of streamflow with reasonable accuracy.

Scenario Evaluation

Our earlier study (Sharma et al., 2015) analyzed the impact of water withdrawal for the current conditions of hydraulic fracking, and found modest impact on seven-day low flows. The present study analyzed the increasing drilling trend in the Muskingum watershed in order to determine the potential impact on environmental low flows and sustainable water availability for multiple uses. Low flows were evaluated for various fracking scenarios (Table 6); results are described in the subsequent section.

Future and Baseline Scenario for Current Climate Period

Sixteen subbasins with increasing drainage areas in the Tuscarawas watershed were selected to assess the impact of fracking on low flows at various locations. The analysis was accomplished by comparing the baseline scenario against the “future scenario on current climate period”, i.e. only changing the withdrawals due to fracking activities. Figure 3-5 shows the relative change in the 7-day minimum flows between the baseline and future scenarios. The average flow measured during the seven consecutive days was computed, and minimum value from such record was compared for baseline and future scenario corresponding to various drainage areas. The link between the degree of impact of fracking and subbasin size is presented in Figure 3-6. This shows that the effect of withdrawal decreases with an increase in the drainage area, but remains above about 20%, which still represents a significant impact. Some outliers observed in the graph are mainly due to the interactions of other water use components and point sources on the same subbasins. A difference of approximately 9% in annual average flow was predicted between the two scenarios (Figure 3-7).

Future, Baseline and Current Scenarios for Future Climate Period

Environmental flow criteria were analyzed, using a plausible set of generated climate data for sixteen similar subbasins of the Tuscarawas watershed. These flow criteria were evaluated by using DFLOW 3.1 (EPA 2006) as a Windows-based tool, which was developed by the EPA. Figure 3-8 presents the comparison in *7Q10* between the baseline (without fracking) and future scenarios for the 30 year simulation period. Significant differences were detected under the future scenario compared with the baseline. The excess withdrawal due to future fracking reduced *7Q10* to zero for drainage areas less than 800 km^2.

Figure 3-9 shows the decreasing trend in the percentage difference in *7Q10* with the increase in drainage area when the baseline scenario was compared with the future scenario. A relatively smaller difference was detected when analysis was conducted in a large drainage area. However, the percentage difference in 7Q10 remains significant (about 15%) even for the largest drainage areas considered. Additionally, comparisons between the baseline and future scenario for 1B3 and 4B3 were performed on six different sub basins, and also showed a similar decreasing trend. The difference in the *4B3* and *1B3* between the two scenarios is shown in Figure 3-10. Figure 3-11 shows the decreasing trend in percentage differences in both criteria with an increase in drainage area.

Analysis was also conducted to see the effect of the future scenario on the flow duration curve, as it is one of the important statistical tools used to quantify hydrologic regimes (Kim et al. 2009). The ninety-five percentile flow exceedance was considered as the threshold for the extreme low flows, which indicates a stressful drought period as streams drop to the lowest level. Similarly, the seventy-five percentile flow exceedance was considered as low flow, which is the dominant low-flow condition sustained by the ground discharge into the streams. A subbasin with a drainage area of 920 km^2 was selected to analyze the flow duration curve between the current and future scenarios for a period of 30 years (Figure 3-12). The results showed that the high flow was not affected in this drainage area. However, the low flows were slightly affected as the alteration was noticed below 85% flow exceedance. The time series of the baseline, current and future scenario depicts the visible change in the base flow (not shown) indicating the impact of fracking withdrawals on flows in low-flow periods.

Conclusion

In this paper, the impacts of hydraulic fracking on water resources, especially during low-flow periods, was explored in the Muskingum watershed of Eastern Ohio, USA considering the worst case scenario. The watershed model, SWAT, was selected for the simulation of stream flows. The simulated flows at various locations were used to generate three scenarios that represent the range of potential impacts of water withdrawals for hydraulic fracking. The baseline scenario was based on realistic conditions of all water use data, but excluded withdrawals for fracking. The current scenario also used actual data for all water uses, including the present rate of water withdrawal for hydraulic fracking. The future scenario was modeled using 30 years of generated climate data based on the historical temperature and precipitation to the SWAT model. The SDSM was used to generate future temperature and precipitation based on the occurrence of the 25th percentile dryer period precipitation in a 30 year period (1961-1990). Since we were not sure whether or not the highest temperature and precipitation would occur simultaneously, we simply used the generated temperature. The condition might be more critical if the lowest precipitation and highest temperature occurred simultaneously.

Seven-day low flows showed some variability when compared baseline scenario with future projected scenario, indicating that flow alteration during low-flow periods might be an important consideration for regulation of water supply and quality. Simulations showed that *7Q10* could be reduced to zero for drainage areas less than 800 km^2 due to projected future fracking activity. The percentage decrease in *7Q10* for larger drainage areas (>6000 km^2) could be 15% or more. The difference due to fracking withdrawals was also noticeable on flow duration curves and base flow time series, further reinforcing the potential impact of fracking during low-flow periods. Even mean annual flows were forecast to decrease by 9% or more under the future scenario.

It is important to note that the analysis was conducted using a worst case scenario, assuming that fracking would continue to increase at the current trend. Based on the results of this study, we can conclude that the impact of hydraulic fracking may be very serious for the headwater streams. Impacts on higher order streams will be less severe, but potentially significant enough to affect aquatic life, water quality, and regulatory decisions..

The hydrologic (*7Q10*) and biological (*4B3* and *1B3*) design streamflows in subbasins of the Muskingum watershed were altered substantially, and in some cases (i.e., for headwater streams) dramatically, due to water withdrawal for hydraulic fracking in extreme scenarios. Therefore, it is essential that planners and decision makers account for water withdrawal for fracking while setting environmental flow criteria in NPDES permitting, particularly for headwater streams. This may prove challenging in a state like Ohio, where different agencies issue permits for oil and gas drilling activities (ODNR) and wastewater discharges (OEPA).

Uncertainties exist in the complex watershed model associated with the input data, model development, future projected well drilling and water use, future advancement in drilling technology, climate, etc. However, this study has shown that modeling tools are available to estimate the impact of fracking withdrawals on streamflows and provide regulators with a better understanding of potential management options

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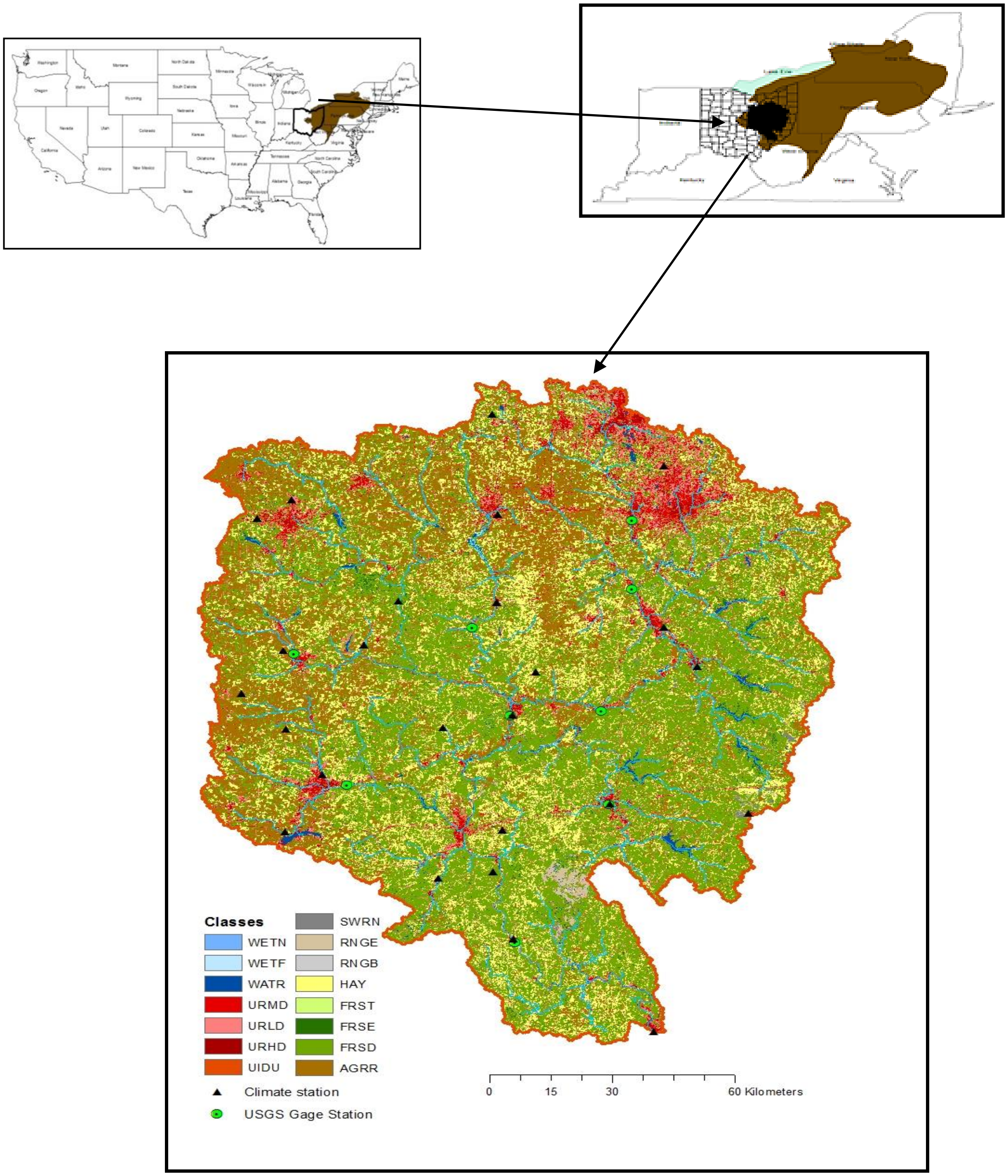

Figure 3-1: Location map with climate and USGS stations in the Muskingum watershed. Legend represents the herbaceous wetland (WETN), wetland forest (WETF), open water (WATR), urban medium density (URMD), urban low density (URLD), urban high density (URHD).

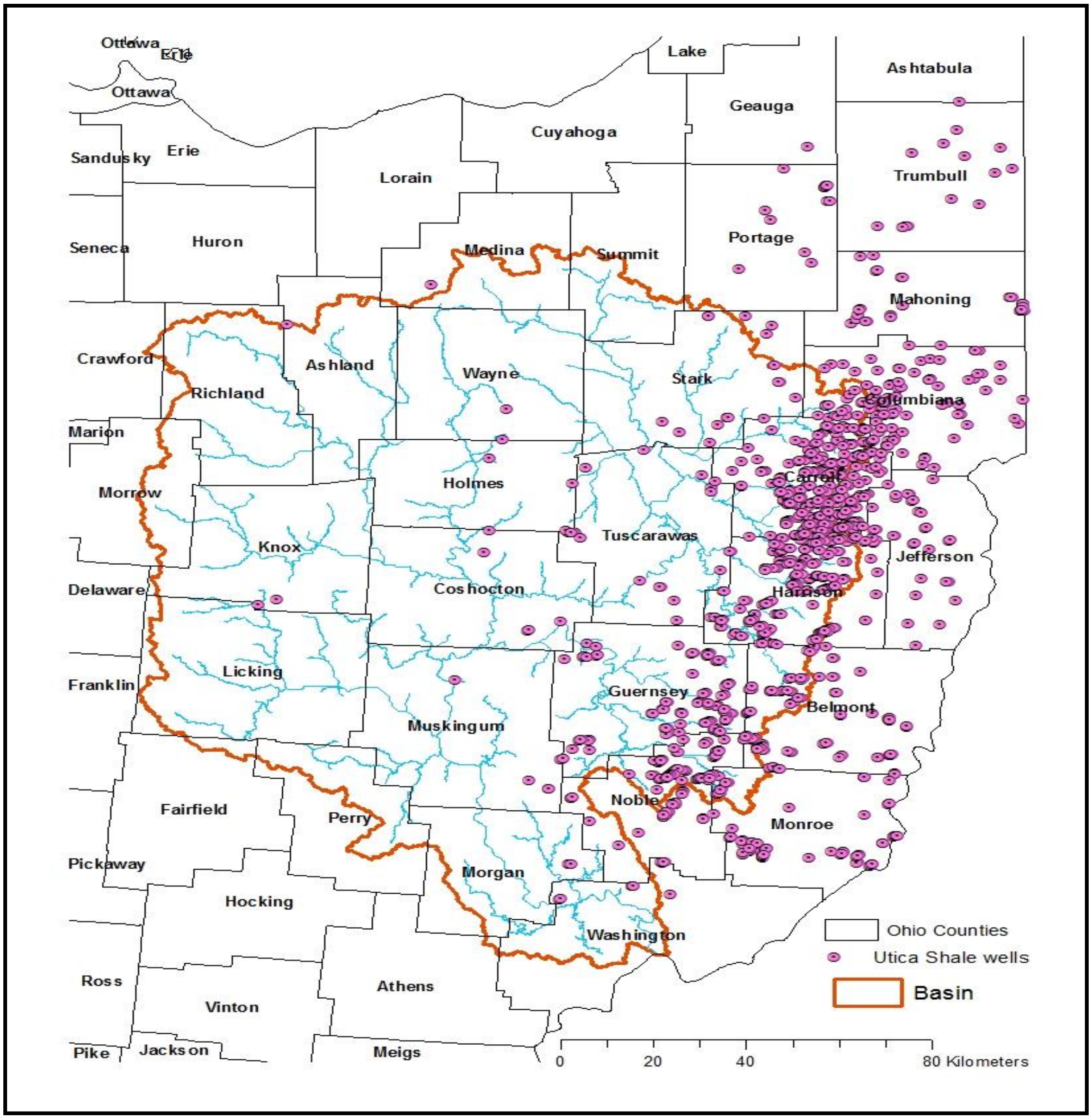

Figure 3-2: Utica shale wells in the State of Ohio from January 2011 to September 2013, indicating more wells in the Eastern Ohio.

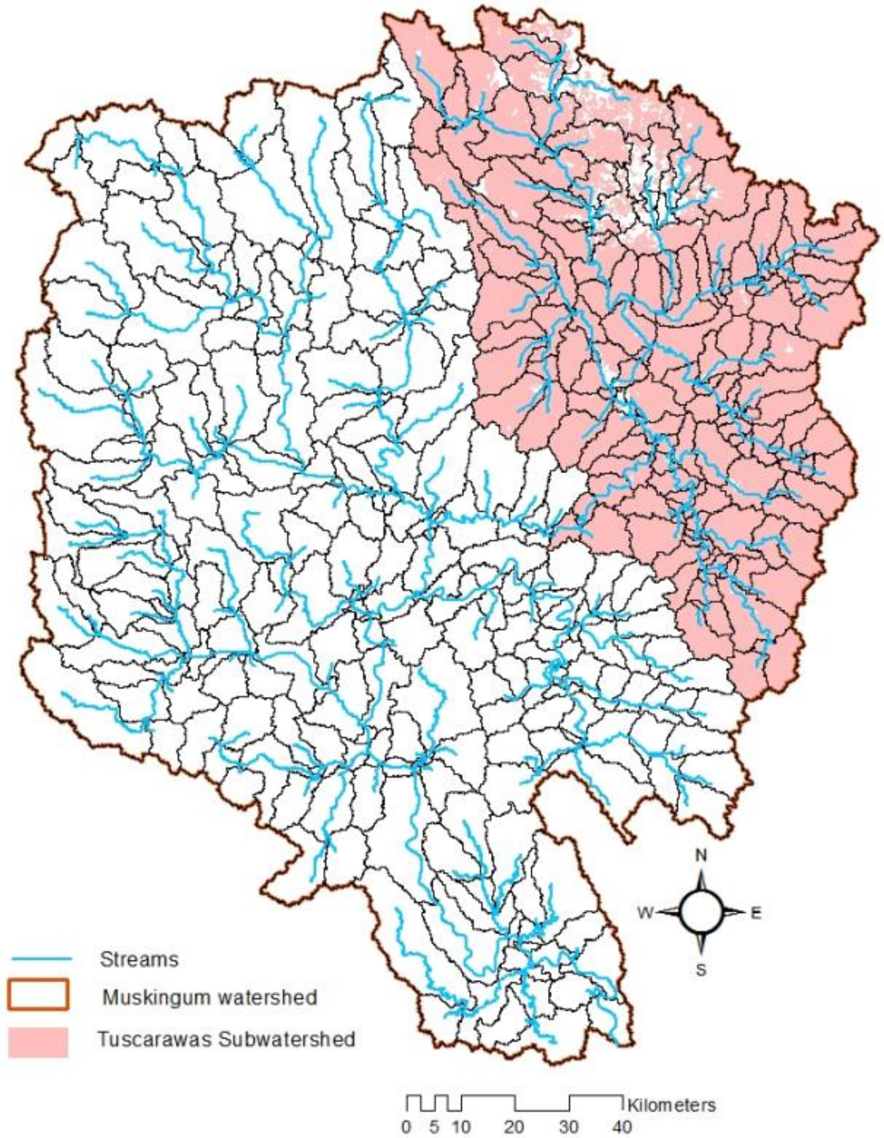

Figure 3-3: Tuscarawas sub watershed (red color) in upper part of the Muskingum watershed, where the drilling for hydraulic fracking has been increasing significantly.

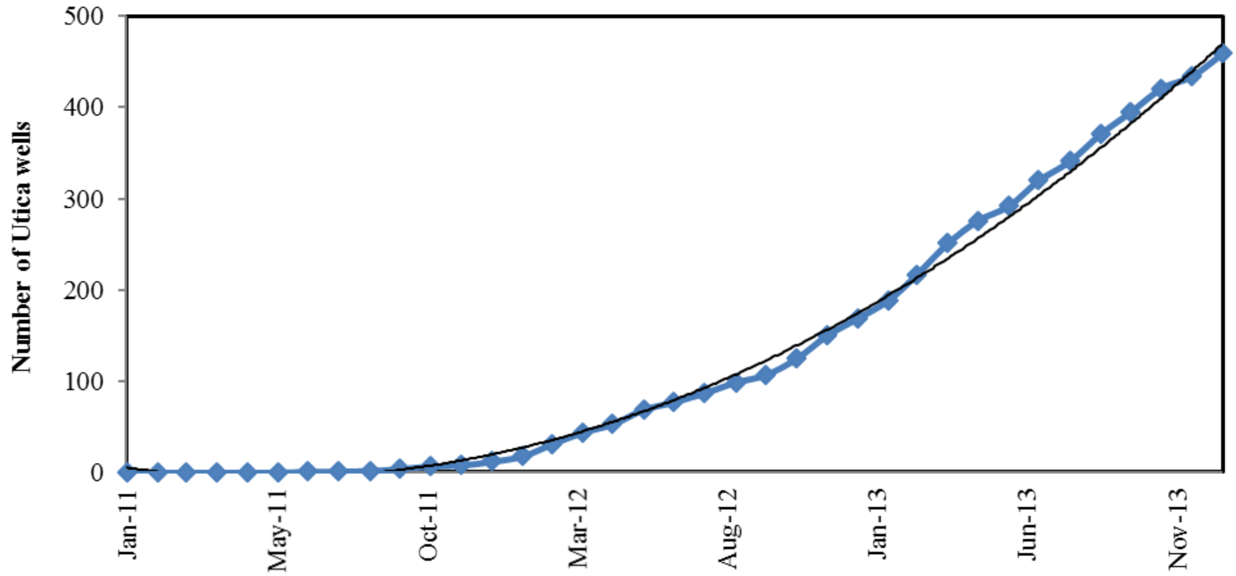

Figure 3-4: The trend of Utica wells in Ohio from January 2011 – May 2014.

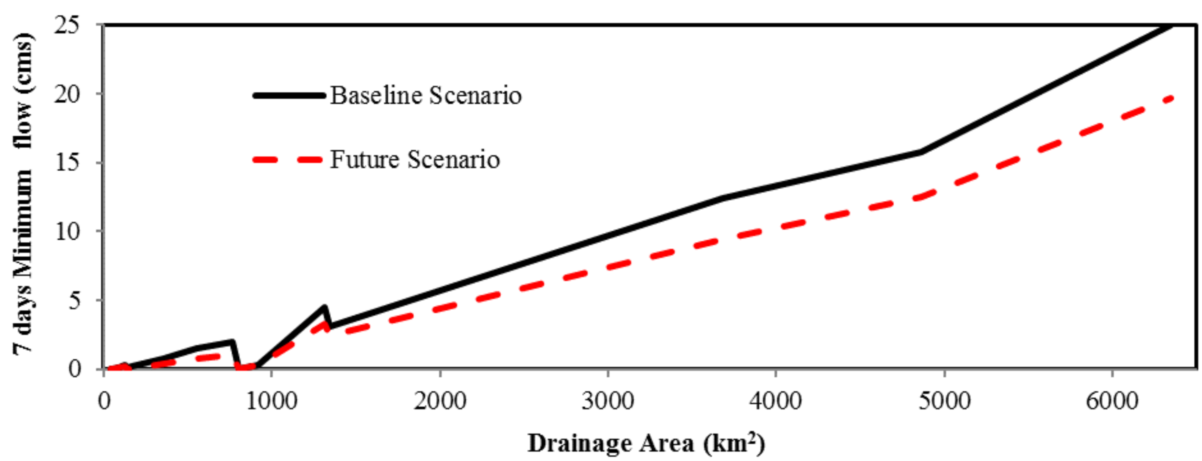

Figure 3-5: The seven-day monthly minimum flow during low-flow period for baseline and future scenario analyzed for current climate period in Muskingum Watershed.

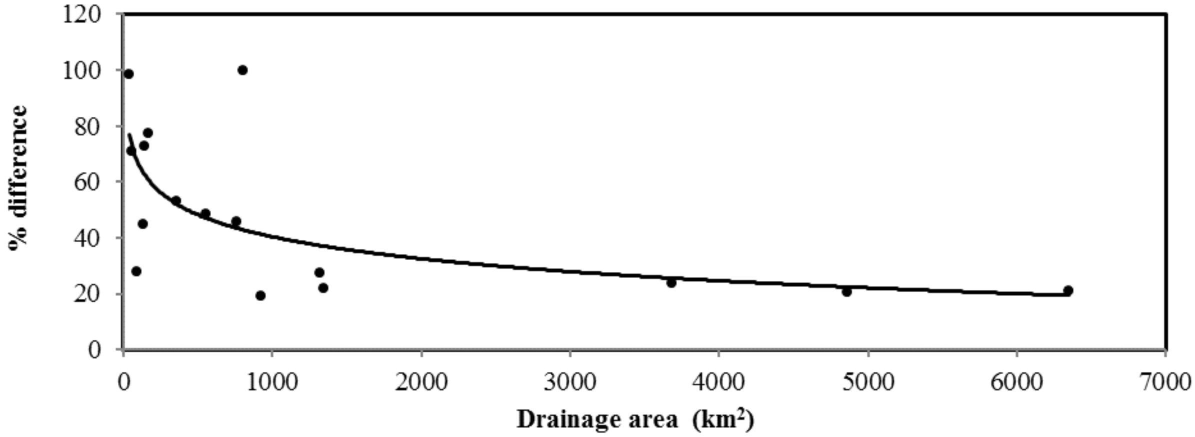

Figure 3-6: The percentage difference in the 7 day minimum flows between the baseline and future hydraulic fracking scenarios simulated using current climate data in Muskingum watershed.

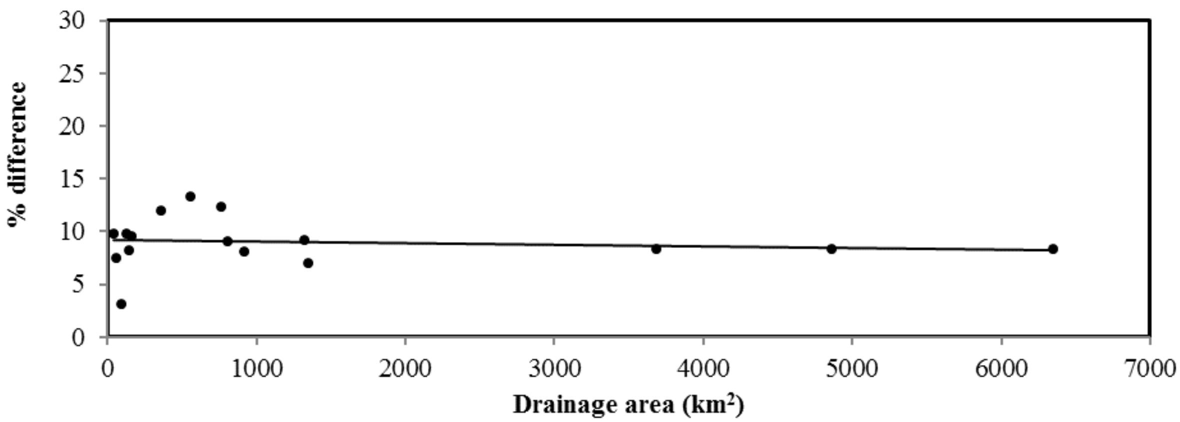

Figure 3-7: The percentage difference in annual average flows between the baseline and future hydraulic fracking scenarios simulated using current climate data in Muskingum watershed.

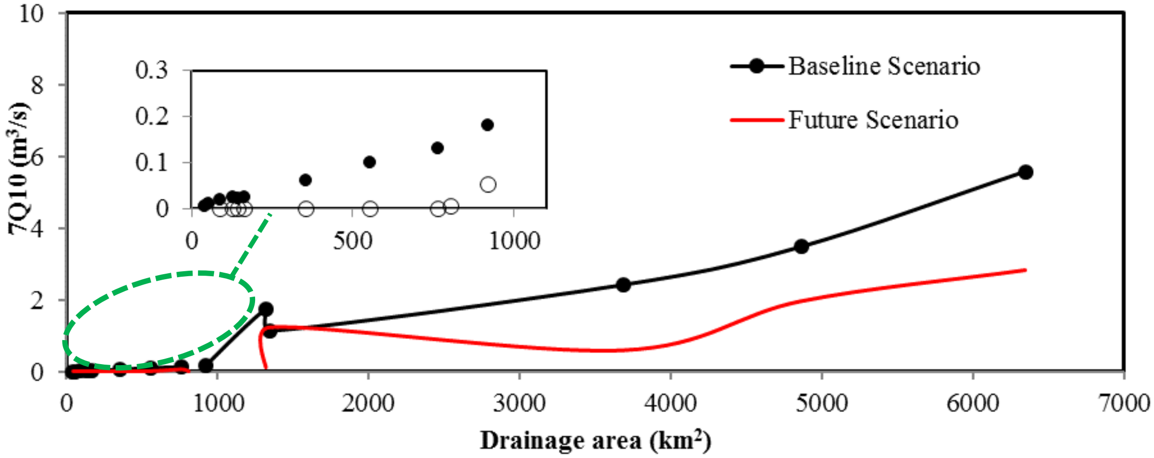

Figure 3-8: The 7Q10 flows for the baseline and future projected hydraulic fracking scenarios using the climate data of future period for 30 years generated by SDSM.

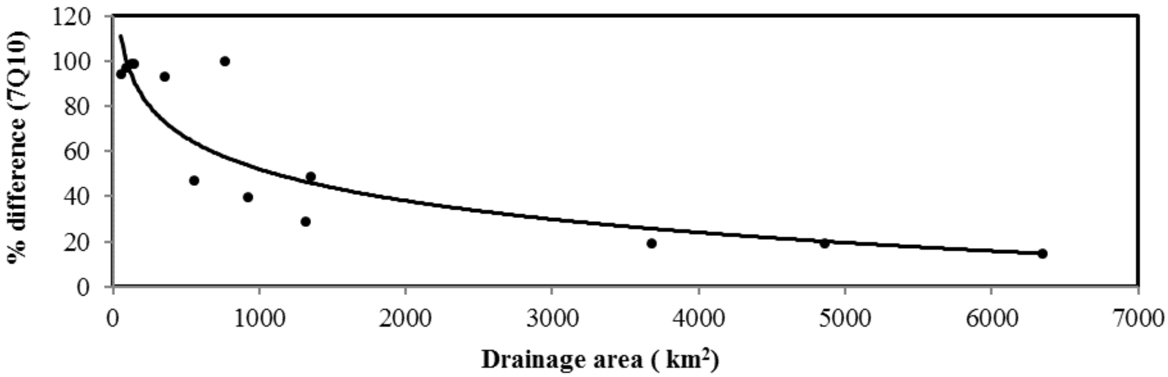

Figure 3-9: The percentage difference in 7Q10 between the baseline vs. projected future hydraulic fracking scenario using 30 years of projected climate data from SDSM.

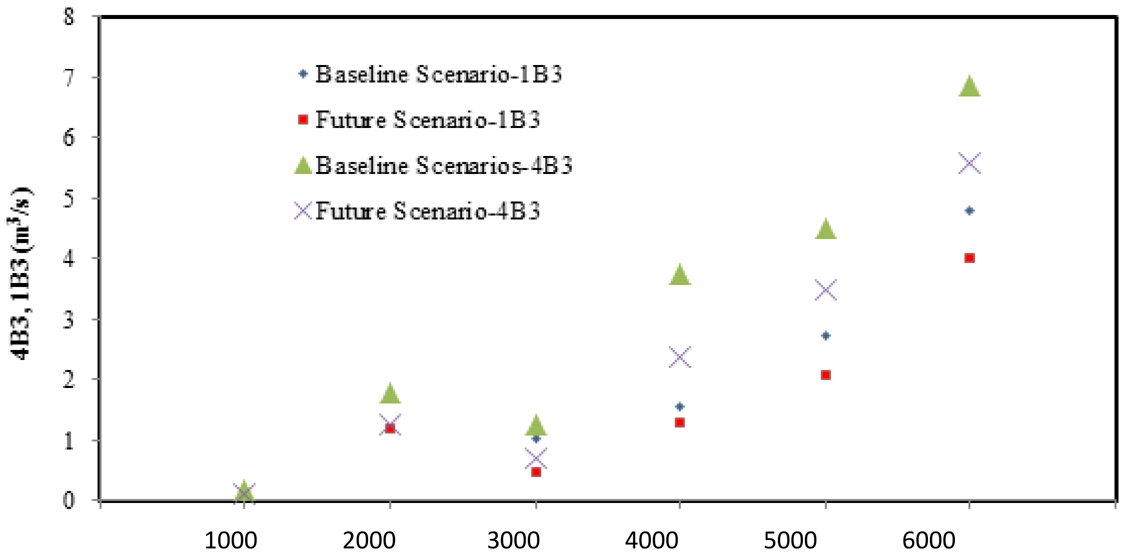

Figure 3-10: The 4B3 flows for the baseline vs. future fracking scenario using the climate data generated by SDSM for 30 years.

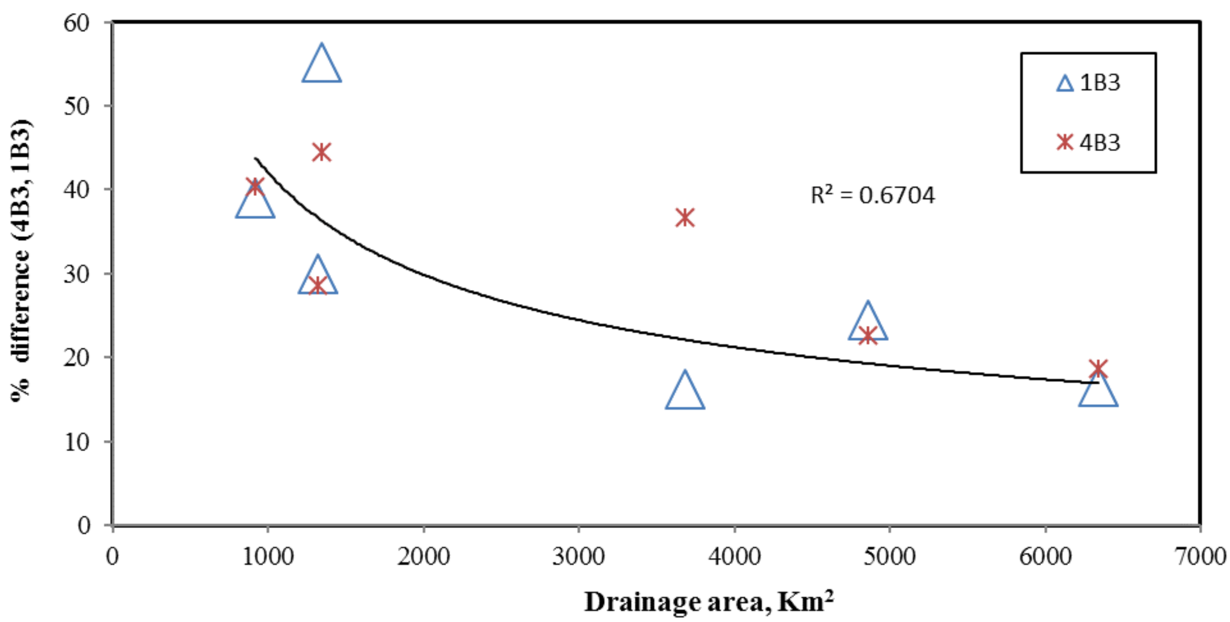

Figure 3-11: The percentage difference in 4B3 and 1B3 between the baseline and future hydraulic fracking scenarios using climate data generated by SDSM for 30 years.

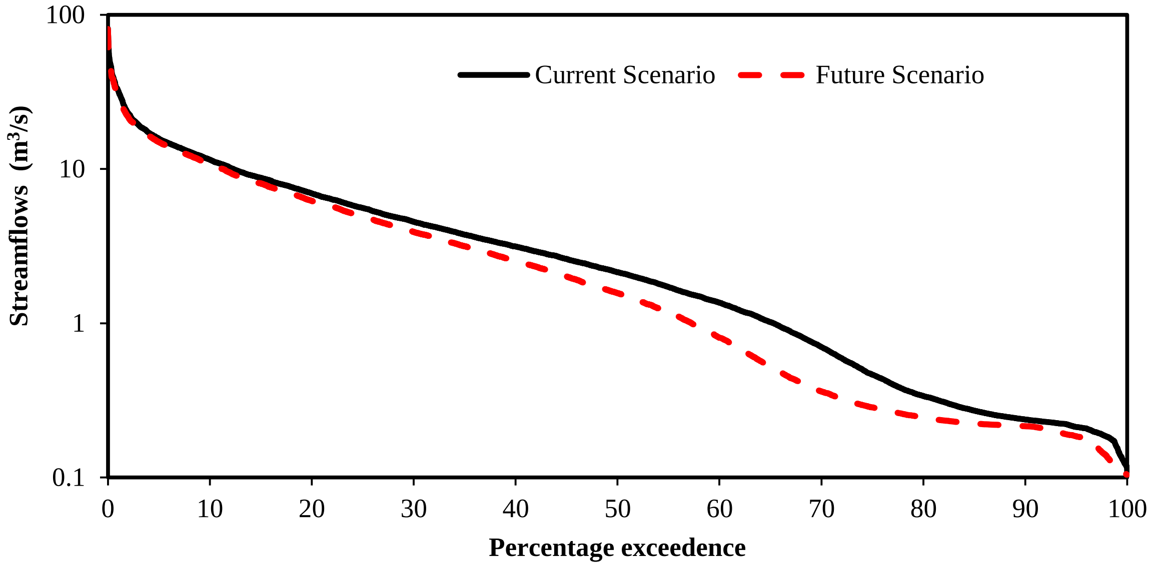

Figure 3-12: The flow duration curve for the current and future hydraulic fracking scenarios using the climate data generated by SDSM for 30 years in Muskingum watershed.

Table 3-1: The data used for SWAT model development in the Muskingum watershed

Data Type	Data	Source
GIS	30-meter DEM	USGS National Geospatial Program (NGP) http://viewer.nationalmap.gov/viewer/
	Land use and Land cover 2006	USGS National Geospatial Program (NGP), National Land Cover Dataset (NLCD), http://viewer.nationalmap.gov/viewer/
	Soil Data	Geographic STATSGO soil map (scale of 1:250,000)
Climate	Rainfall and Temperatures	NOAA's National Climatic Data Center (NCDC) http://www.ncdc.noaa.gov/cdo-web/
Hydrology	Streamflows	USGS http://waterdata.usgs.gov/usa/nwis/sw
	Reservoir outflow	U.S. Army Corps of Engineers (USACE)
Stream Networks/Water Bodies	Streams and flow direction, reservoirs	USGS National Geospatial Program (NGP) National hydrograph dataset (NHD)
Water Use (Surface and Ground Water)	Irrigation, Public, Power, Mineral Extraction, Industries and Golf Course	Ohio Department of Natural Resource (ODNR) Ohio Environmental Protection Agency (OEPA)
Point Sources	Flow discharge	OEPA
Oil and Natural Gas	Wells for Hydraulic Fracking	ODNR
	Sources of Drilling Water	ODNR
	Drilling Water Estimate per well and Future Drilling Trend	FracFocus (http://fracfocus.org) (National hydraulic fracturing chemical registry)

Table 3-2: Water withdrawal for hydraulic fracking in the Muskingum watershed, 2011-2013.

Year	Average Vertical Depth (m)	Freshwater (m^3)	Recycled Water (%)
2011	7,717	11,449	13.79
2012	7,734	13,011	4.35
2013	10,897	16,680	3.74

Table 3-3: List of predictors used in the SDSM model to downscale the NCEP reanalysis data

Station Parameters	Predictor Variable
Precipitation	Zonal velocity component at surface level
	Zonal velocity component at 850 hpa
	Geostrophic airflow velocity at 850 hpa
	Vorticity at surface level
	Vorticity at 850 hpa
	Sea level pressure
	Specific humidity at 500 hpa
	Specific humidity at 850 hpa
Temperature	Mean Temperature
	Near surface specific humidity

Table 3-4: The statistical criteria measuring the daily performance of the SWAT model during the calibration (2002-2009) and validation (1995-2001) period

USGS Gage Station	Calibration			Validation		
	R^2	*NSE*	*PBIAS*	R^2	*NSE*	*PBIAS*
3117000	0.42	0.42	0%	0.45	0.45	-2%
3124500	0.43	0.40	-16%	0.53	0.47	-10%
3139000	0.51	0.49	-4%	0.63	0.60	-3%
3136500	0.47	0.46	9%	0.41	0.40	18%
3129000	0.57	0.56	3%	0.54	0.47	21%

3140500	0.63	0.63	2%	0.69	0.65	12%
3146500	0.42	0.40	11%	0.43	0.42	12%
3142000	0.55	0.47	13%	0.51	0.49	-2%
3150000	0.65	0.65	0%	No Data		

Table 3-5: The statistical criteria measuring the monthly performance of the watershed model during the calibration (2002-2009) and validation (1995-2001) period.

USGS Gage Station	Calibration			Validation		
	R^2	*NSE*	*PBIAS*	*R^2*	*NSE*	*PBIAS*
3117000	0.89	0.89	0%	0.9	0.86	7%
3124500	0.59	0.53	-16%	0.63	0.61	-9%
3139000	0.64	0.64	-4%	0.72	0.71	-3%
3136500	0.50	0.49	9%	0.63	0.56	18%
3129000	0.68	0.66	3%	0.67	0.55	21%
3140500	0.68	0.67	1%	0.76	0.69	13%
3146500	0.79	0.72	11%	0.76	0.71	12%
3142000	0.71	0.69	13%	0.77	0.68	-1%
3150000	0.73	0.72	0%	No Data		

Table 3-6: Characteristics of the various scenarios that were used for analysis.

Scenarios	**Climate conditions**	**Hydraulic Fracking**
Baseline (without fracking) scenario	Current	No
Current (with fracking) scenario	Current	Yes
Future scenario on current climate period	Current	Projected fracking
Future scenario on future climate period	Future	Projected fracking

Chapter 4. Impact of Global Climate Change on Stream Lowflows in a Hydraulic Fracking Affected Watershed

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, and Drought.

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 (Smakhtin, 2000).

Various natural factors contribute to low flow variability leading to the social and economic impacts (Burn et al. 2008). Additionally, fluctuation of low flow is affected by anthropogenic impacts, which may cause supplementary severe conditions in the dry period (Smakhtin, 2000). For example, a large amount of water abstraction for industrial uses, irrigation, power generation and domestic water use reduces the downstream water volume

(Benejam et al. 2010). Similarly, agricultural practices may also cause significant increase in the frequency of low flow discharge (Wilber et al. 1996; Kottegoda and Natale 1994; Eheart and Tornil 1999), 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 (Burton et al. 2014). 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 (Cothren et al. 2013). There are also various impact from fracking operations such as groundwater contamination, drying out the groundwater wells and streams, however these studies were outside the scope of this paper.

Declining flow rates may be further stressed due to increasing rise in global temperature (Vorosmarty et al. 2000; Alcamo et al., 2003) 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.

Materials and Methodology

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) (Brekke et al. 2013, Taylor et al. 2011). Various phases of CMIP have increased slowly over the years. The third phase of CMIP; Coupled Model Intercomparison Project Phase 3 (CMIP3) (Meehl et al. 2005; 2007a) has provided important information to the Intergovernmental Panel on Climate Change (IPCC) fourth assessment repot (IPCC, 2007). 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 (Moss et al. 2010, Vuuren et al. 2011) are scenarios with concentration, emission and land-use trajectories (Janssen 2013). 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 (Maurer et al. 2014; Taylor et al. 2012). 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 (Taylor et al. 2012).

Since CMIP5 has incorporated new General Circulation Model (GCM) projections with relatively more physical process than previously published dataset CMIP3 (Knutti and Sedlacek 2013), the recently available CMIP5 data has been utilized for this study. A widely used, Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998) 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 (Arnell et al. 2013, Vliet et al. 2013), relatively limited articles have been published (Ficklin et al., 2013) 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 (Giorgetta et al. 2013, Hagemann et al. 2013). 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 (Giorgetta et al. 2013).

Study Area

The study was conducted in the Muskingum watershed, which is located in the eastern part of the Ohio, USA (Figure 4-1). 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 m^3/s 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 4-1 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 (Sharma et al., 2015). The input data needed for SWAT model development are briefly described in the following section.

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 4-1. Readers can refer our earlier publication (Sharma et al. 2015) for additional input information for the SWAT model development and modelling issues of hydraulic fracking in SWAT.

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) (Abbaspour et al., 2007). 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 (Abbaspour et al., 2007, Sharma et al. 2015). 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 Sharma et al. (2015) for the detail description of these statistical criteria.

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) (Maurer et al. 2010) 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.

Result and Discussion

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 4- 2. The time series of the observed flow vs. simulated flow using the calibrated and validated SWAT model is reported in Figure 4-2 and Figure 4-3, respectively. The calibrated model was utilized for the prediction of future streamflow using bias corrected downscaled climate data at various stations.

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 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 4-4. Out of the 19 models, the performance of MPI-ESM-LR was superior, which was determined based on the squared correlation coefficient (Figure 4-4). 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 4-4). 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.

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 (Kunkel et al. 2013). 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.

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 4-5) and lowest flow could be realized in 2035 while using RCP 2.6. The percentage change in the annual mean, seasonal mean and monthly mean flow at the outlet of the watershed is presented for RCP 8.5 in Figure 4-6. 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 4-6a). 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 4-6b) 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 4-6c), 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.

The increasing pattern was detected for RCP 4.5 up to 2055s, and the percentage increase in 2085s was slightly less than 2055s (Figure 4-7a). This trend was also observed for seasonal (Figure 4-7b) and annual (Figure 4-7c) flow. A consistently increasing flow pattern was found from 2035 to 2085s for RCP 2.6 (Figure 4-8). 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 later 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 4-7) and RCP 2.6 (Figure 4-8) was consistent with the monthly precipitation pattern (not shown).

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 4-9. The monthly flow could be expected to increase in all three periods for all scenarios (Figure 4-9) except the possible decrease in low flow for RCP 8.5 (Figure 4-9).

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 4-10). 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 4-10). 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 4-11).

During 2085s, the wet zone would be expected to increase through a larger extent of the watershed (Figure 4-12), 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.

The annual minimum flow percentages across the watershed are fairly dry in the first 30 years compared to remaining 50 years (Figure 4-13) as some portion of the watershed experienced high flow in this period. Importantly, Figure 4-13 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 4-14). Similarly, progressively larger portion of wetter area with increased percentage difference in minimum flow was detected in the last 30 years period (Figure 4-14). It is interesting to note that 2055s showed the major dry portion in the 1st and 2nd order streams (Figure 4-14), whereas 2085s showed the dry portion in the major stream regimes (Figure 4-15).

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 4-16). Some impacts were detected on seven days monthly minimum flow (Figure 4-17) 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 4-18. 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.

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 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.

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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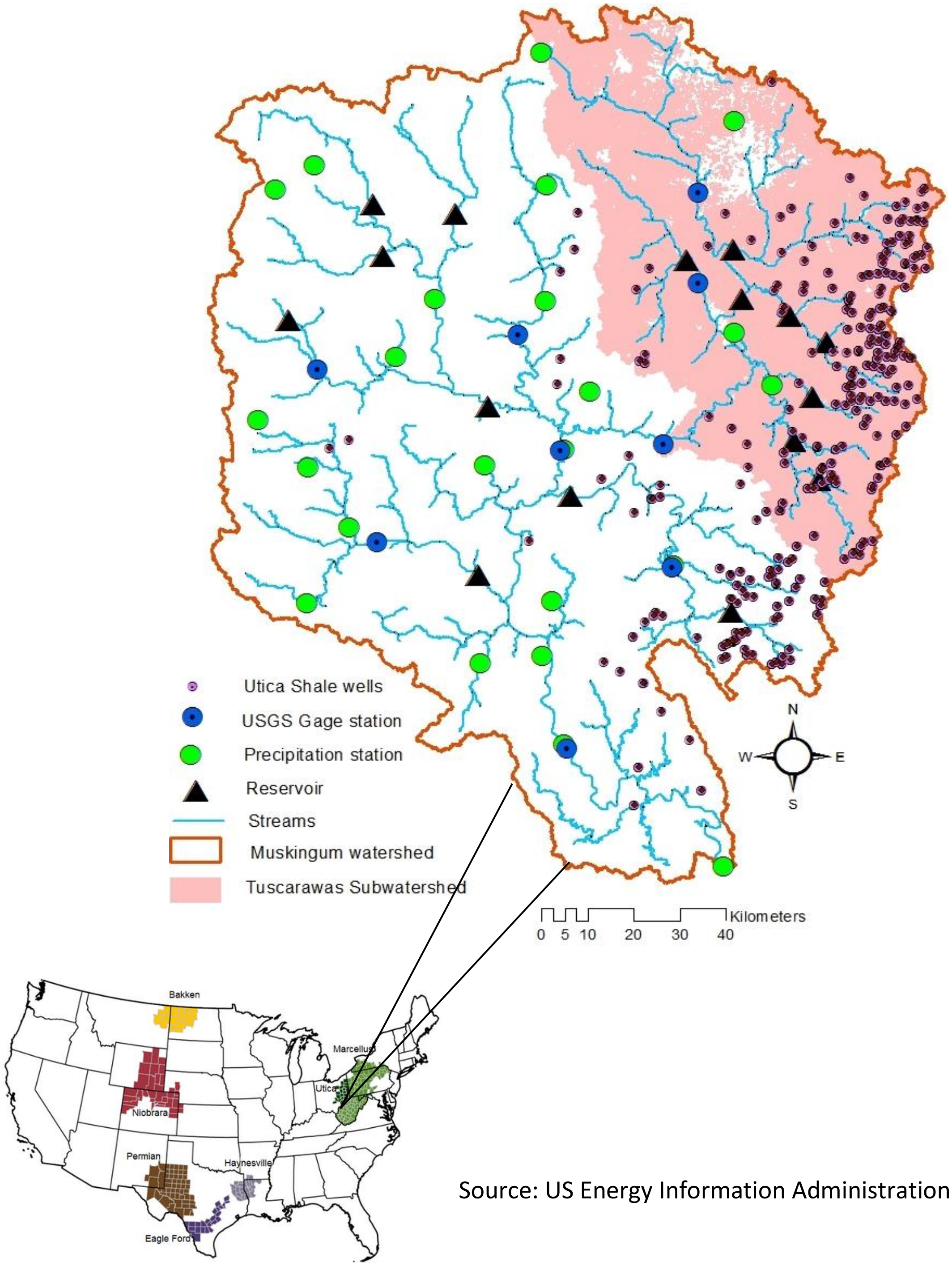
Table 4-1: Surface Water withdrawal for various primary uses based on facilities in the Muskingum Watershed during year 2012 (Source: Ohio Department of Natural Resources (ODNR)).

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

Table 4-2: 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				



Source: US Energy Information Administration

Figure 4-1: Muskingum watershed with location information of shale wells, USGS flow gage, precipitation, reservoir, streams and Tuscarawas subwatershed.

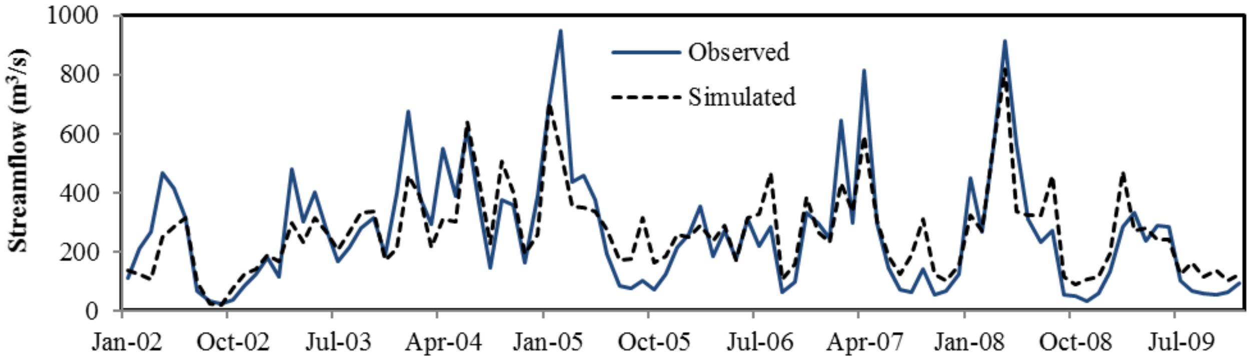


Figure 4-2: Streamflow calibrations at watershed outlet (USGS gage 03150000) from January 2002 to December 2009.

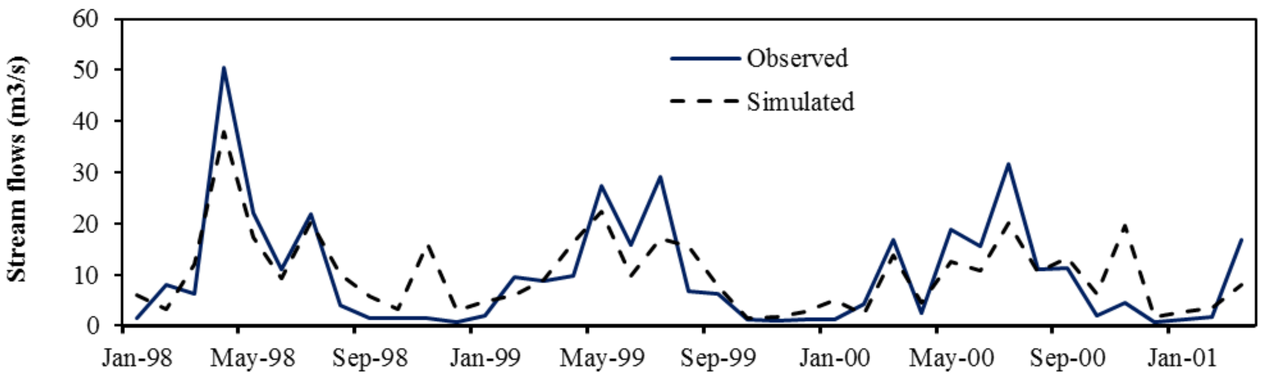


Figure 4-3: Streamflow validation at USGS gage 03142000 from January 1998 to March 2001 (long term data were not available in USGS gage 03150000).

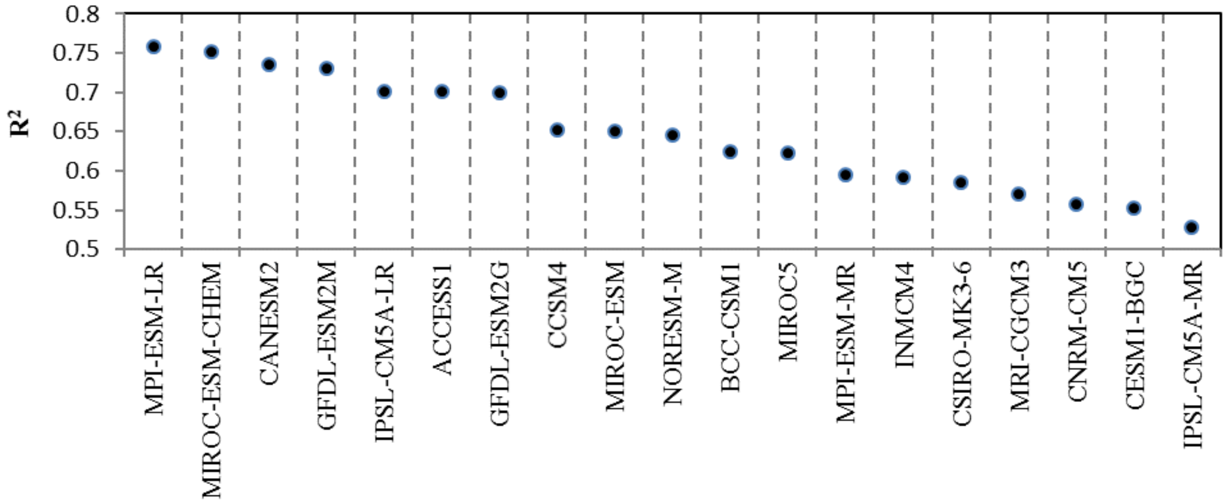
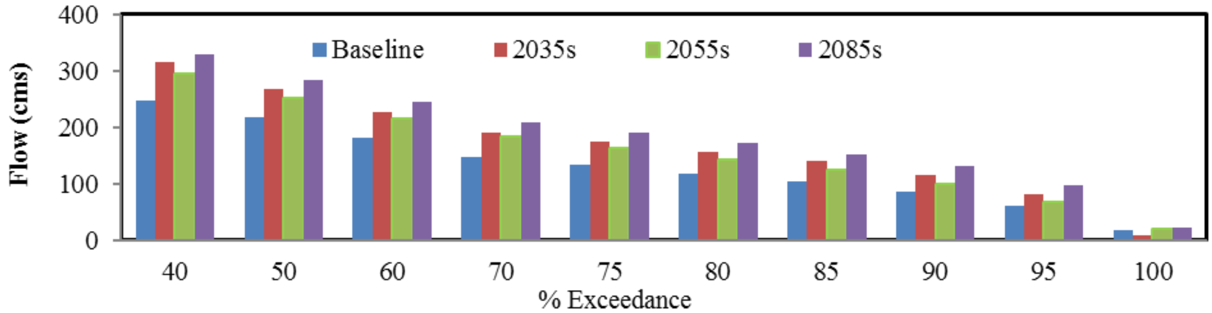
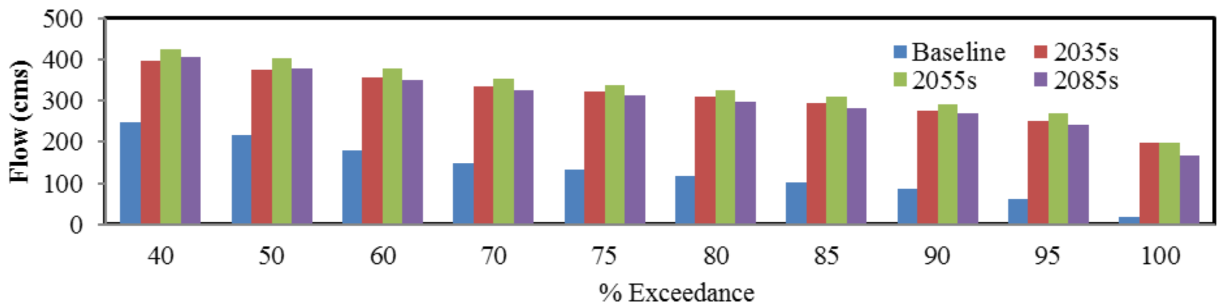


Figure 4-4: Squared correlation coefficient for 19 BCCA models under RCP 4.5 scenario of CMIP5 at precipitation station 00335747.

(a)



(b)



(c)

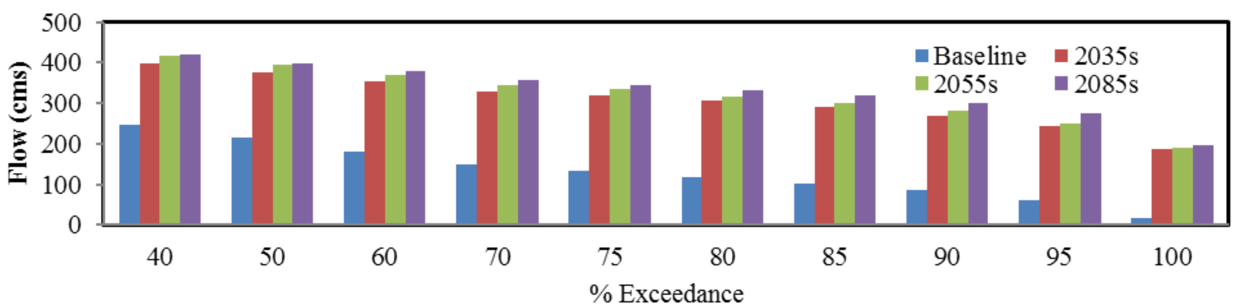
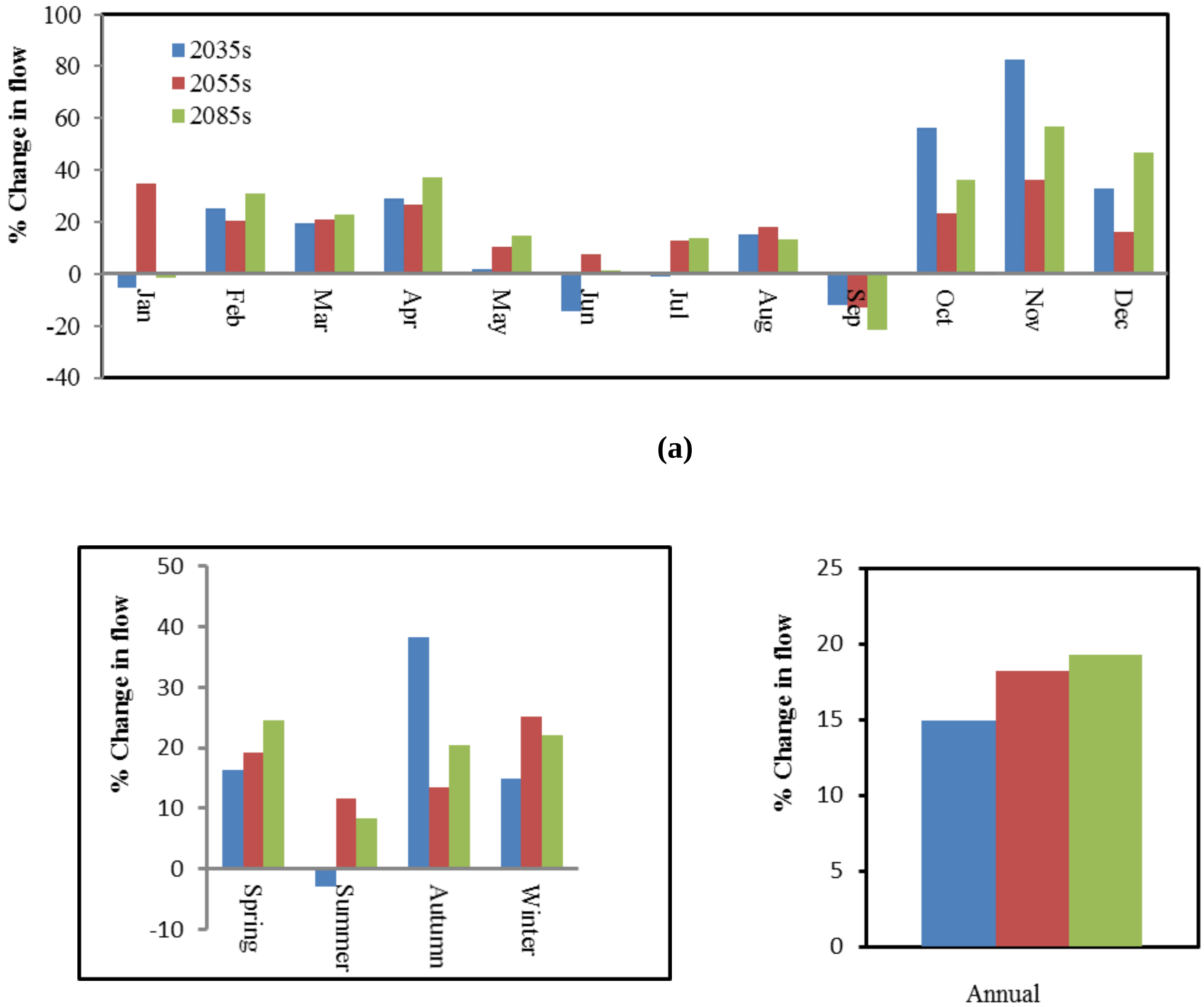


Figure 4-5: Percentage exceedance for mean flow volume for three future periods (2021-2050, 2051 to 2070 and 2070 to 2099) as compared to baseline period (1995-2009) at the outlet of the watershed using RCP 8.5 (a), RCP 4.5(b), RCP 2.6 (c).



(a)

(b) **(c)**

Figure 4-6: Percentage change in monthly mean flow volume for three future periods (2021 to 2050, 2051 to 2070 and 2070 to 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.

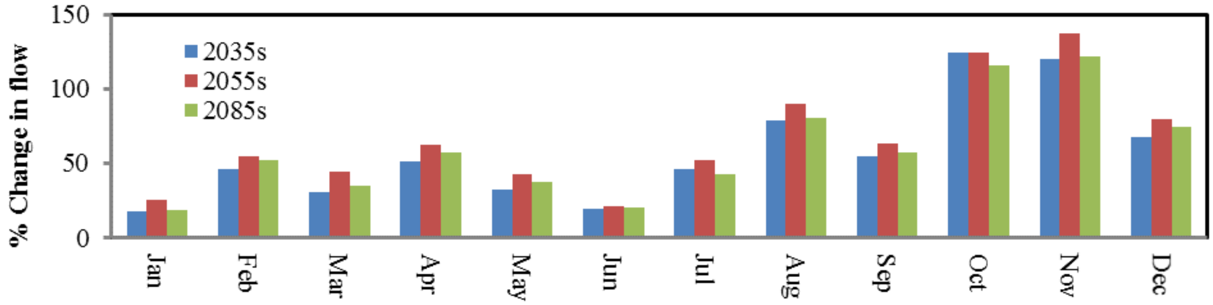
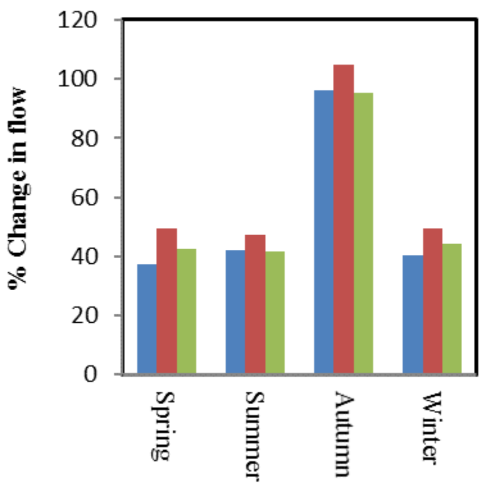


Figure - (a)



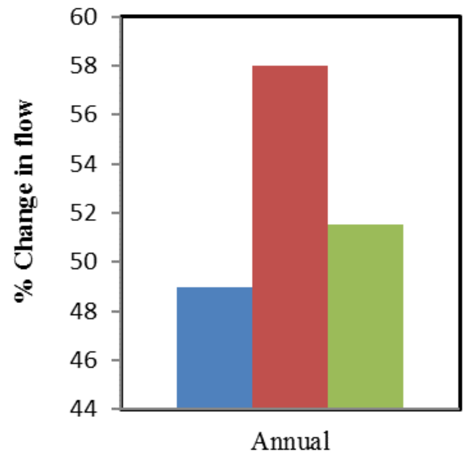


Figure - (b) **Figure - (c)**

Figure 4-7: 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 using RCP 8.5.

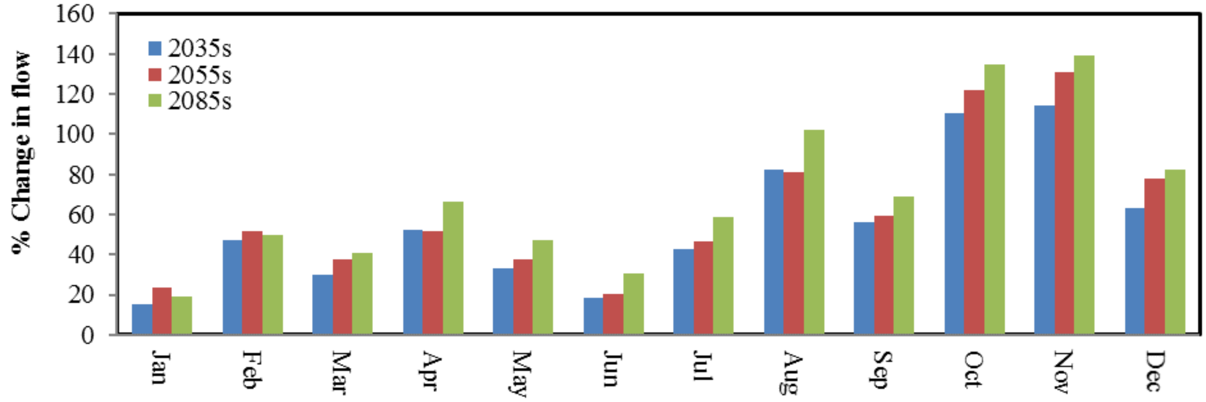


Figure - (a)

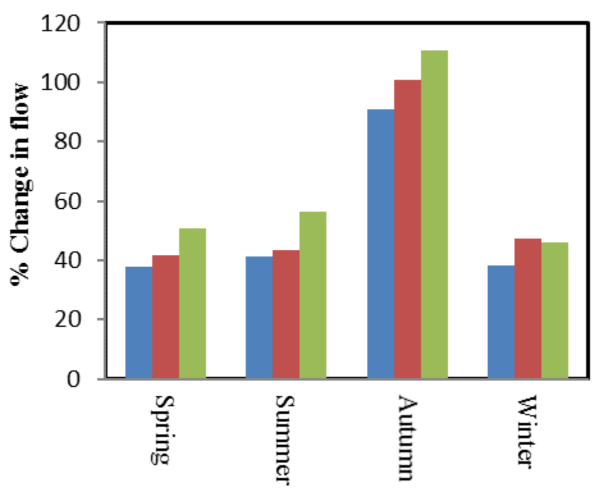


Figure - (b)

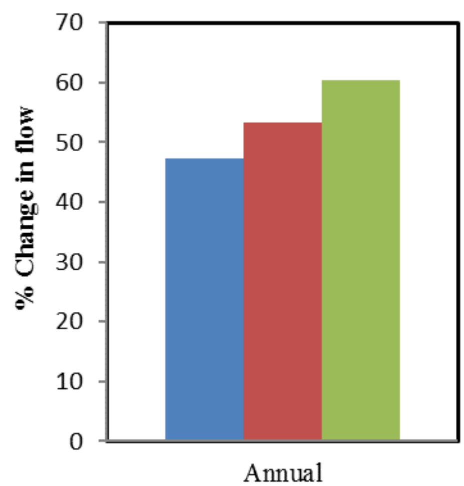


Figure - (c)

Figure 4-8: 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 8.5.

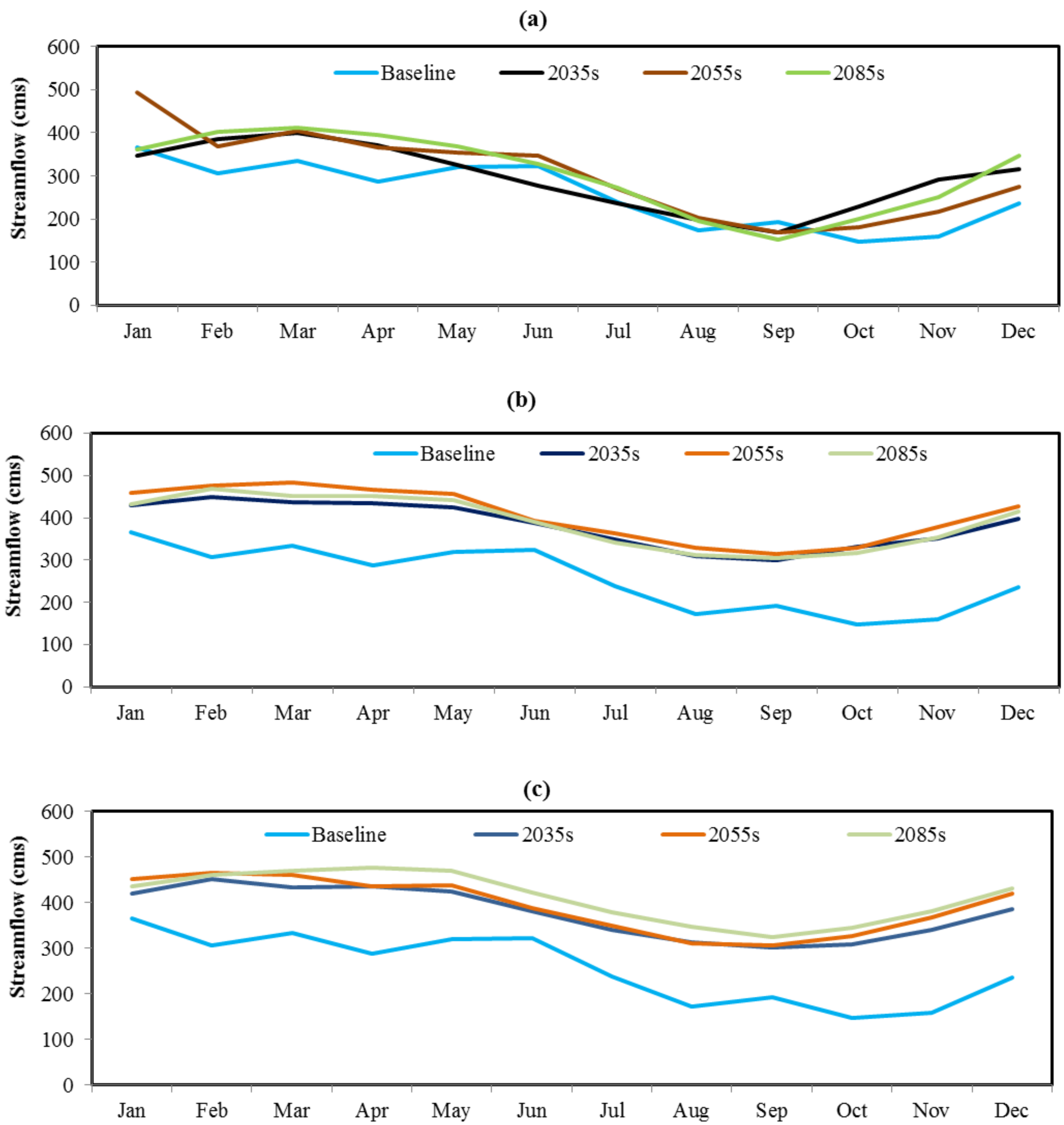


Figure 4-9: Monthly mean flow volume for three future periods (2035s, 2055s and 2085s) and baseline period (1995-2009) at the outlet of the watershed for RCP 8.5 (a), RCP 4.5 (b), RCP 2.6 (c).

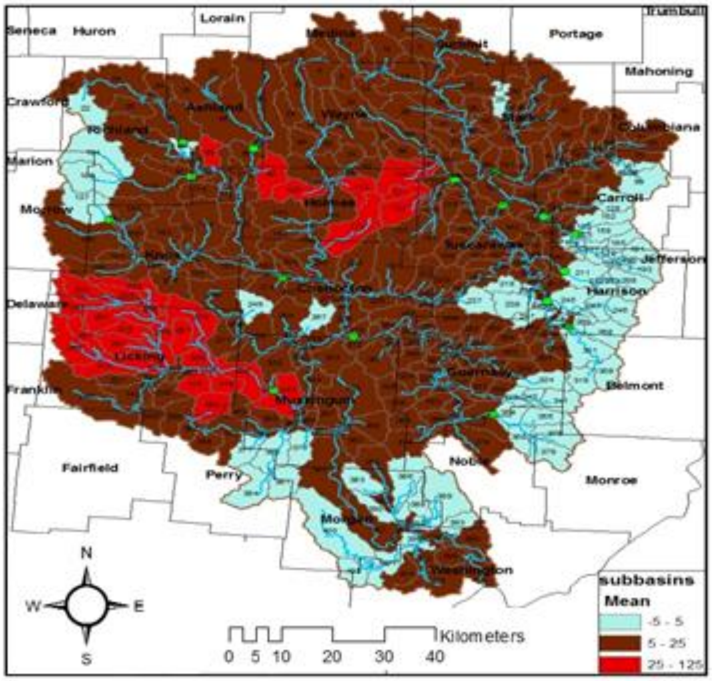


Figure 4-10: Percentage change in annual mean streamflow for 2035s period against baseline period (1995-2009).

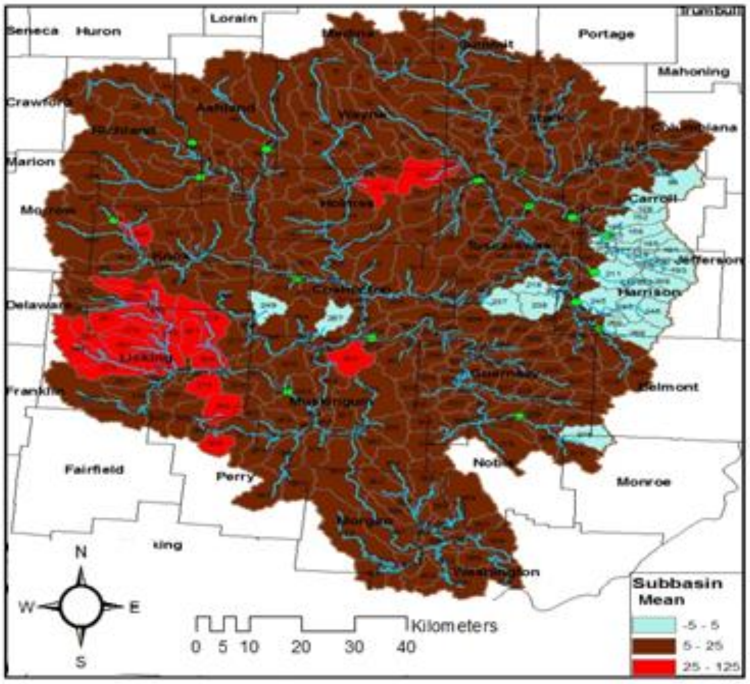


Figure 4-11: Percentage change in annual mean streamflow for 2055s against baseline period (1995-2009).

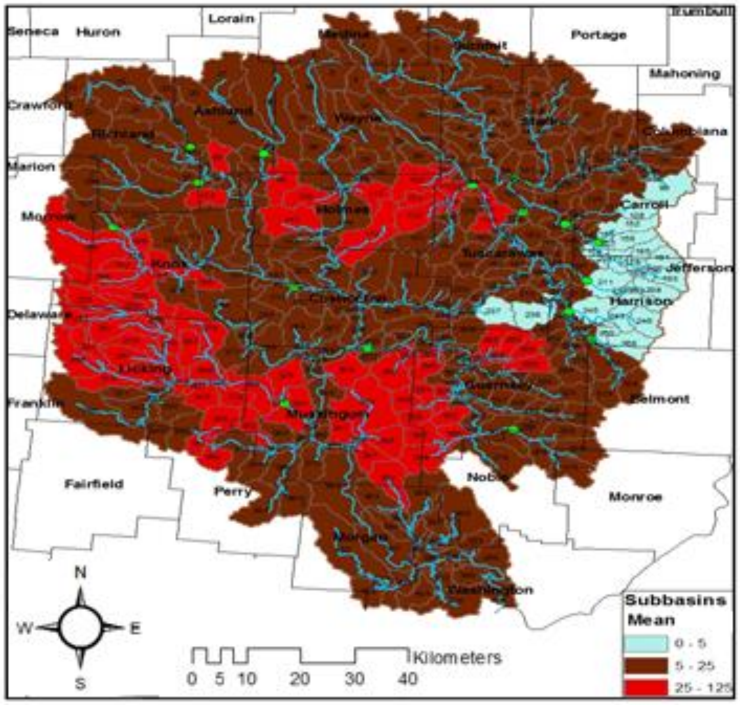


Figure 4-12: Percentage change in annual mean streamflow for 2085s against baseline period (1995-2009).

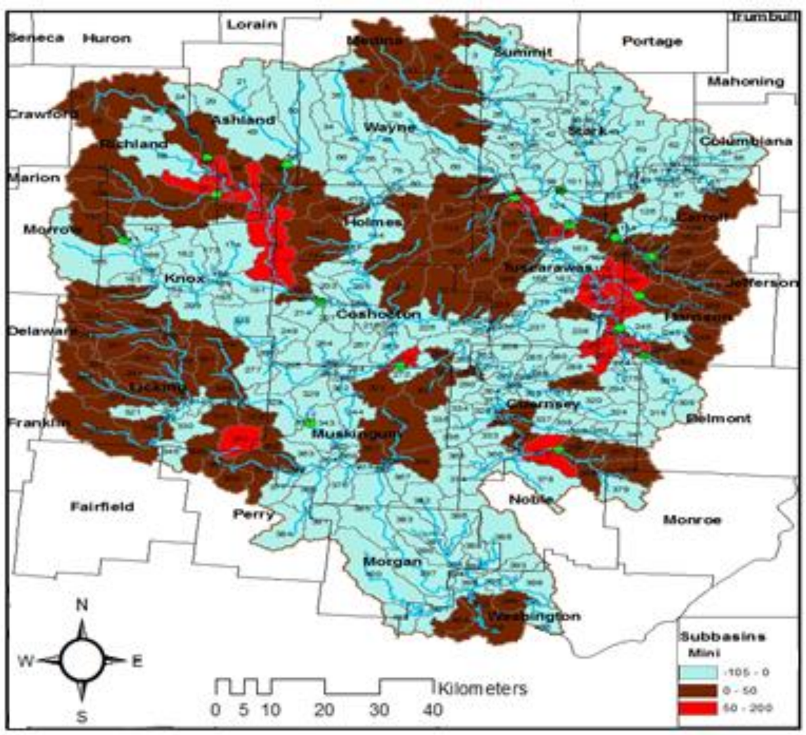


Figure 4-13: .Percentage change in annual minimum streamflow for 2035s against baseline period (1995- 2009).

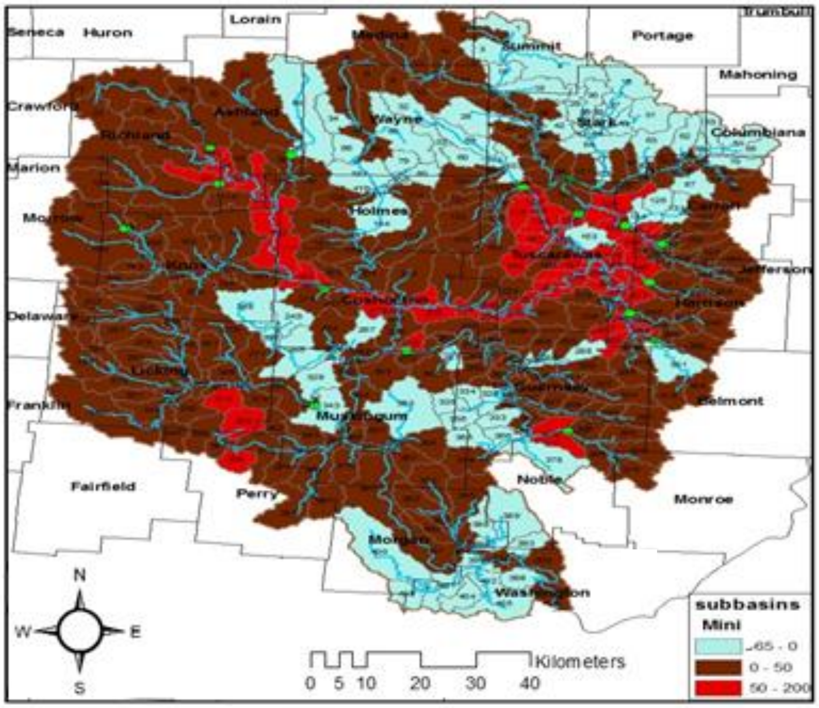


Figure 4-14: Percentage change in annual minimum streamflow for 2055s against baseline period (1995 - 2009).

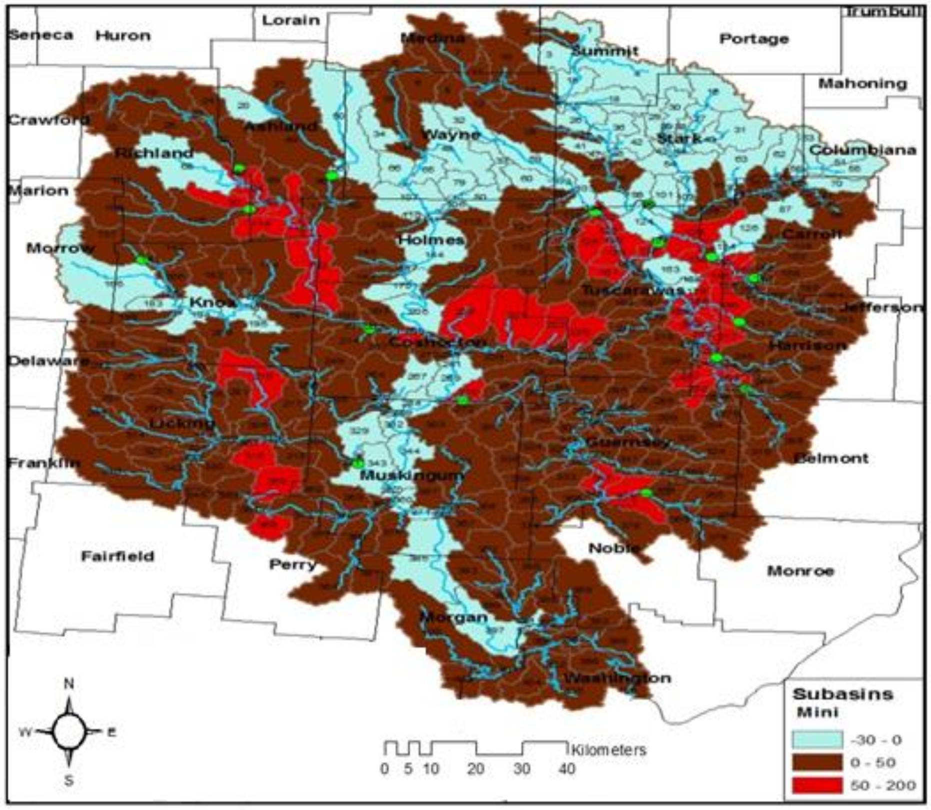


Figure 4-15: Percentage change in annual minimum streamflow for 2085s against baseline period (1995- 2009).

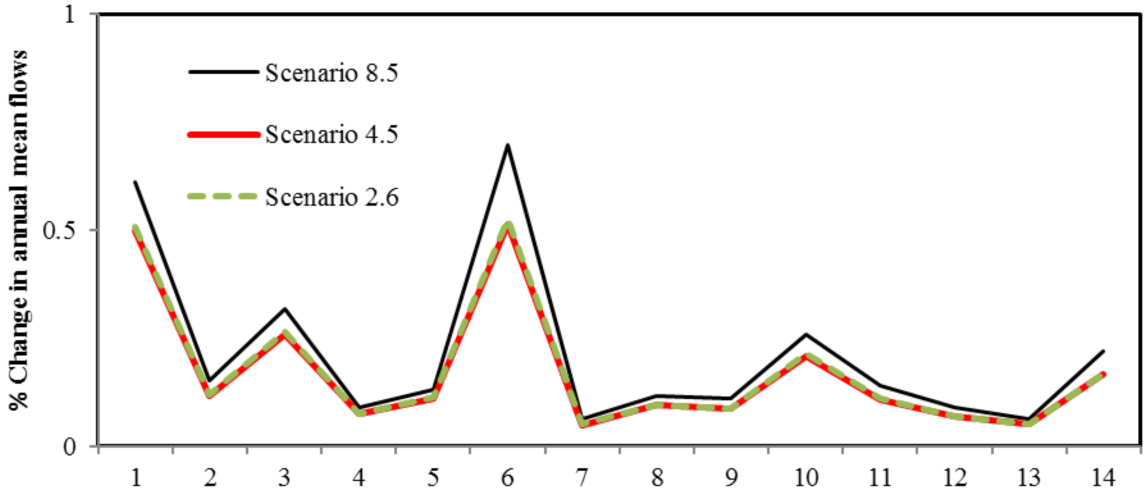


Figure 4-16: Percentage change in annual mean flow for current and baseline scenario during 2035s periods.

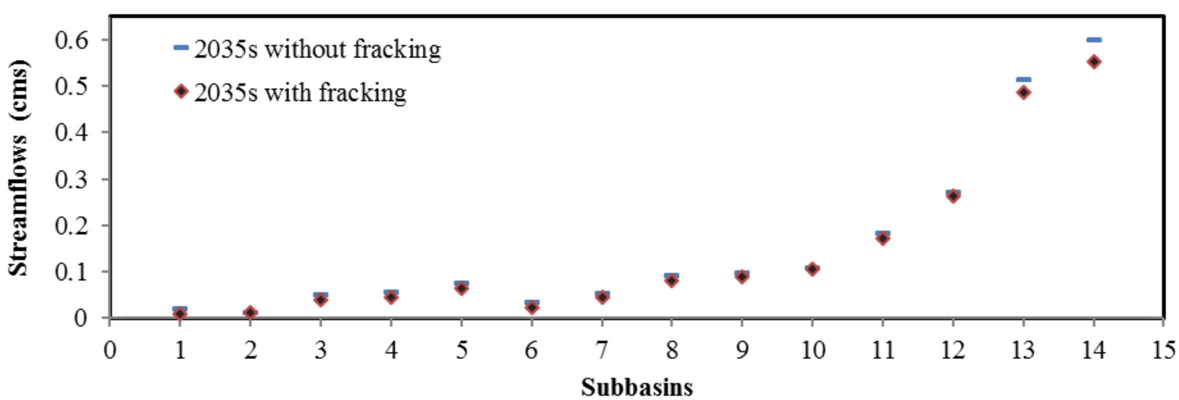


Figure 4-17: Seven days monthly minimum flow (considered the minimum value from each year) for current and baseline scenario during 2035s period using RCP 8.5.

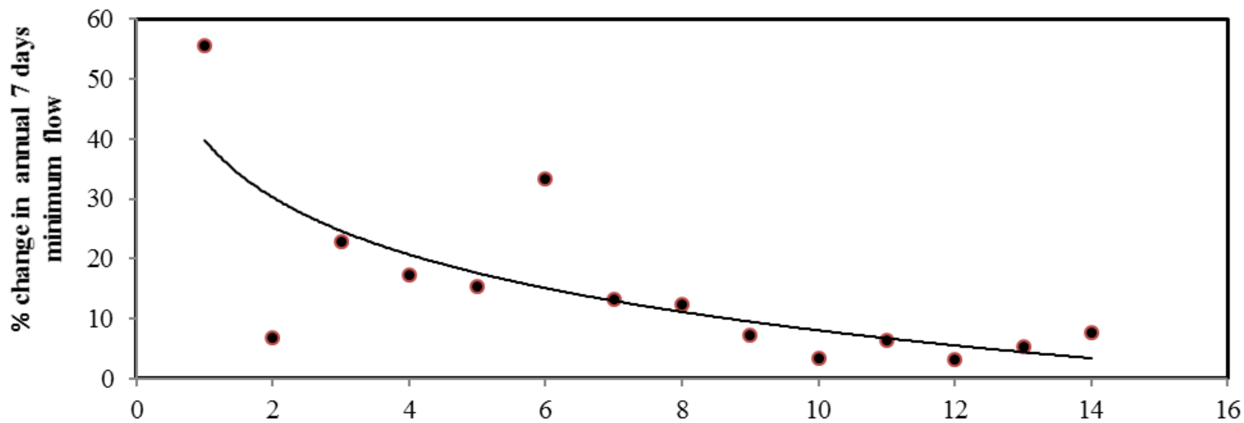


Figure 4-18: Percentage change in 7 days minimum flow for current and baseline scenario (considered one minimum value from each year) during 2021-2050 periods using RCP 8.5 over the 14 subbasins in downstream where the 14th subbasin was largest in area (1589 km2) and first subbasin was the smallest in area (42.88 km^2).