Modeling Impact of Hydraulic Fracturing and Climate Change on Stream Low Flows: A Case Study of Muskingum Watershed in Eastern Ohio

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ABSTRACT

Oil and natural gas production in the United Sates has increased tremendously for the last few years. A 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 periods. 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 the fracking process in terms 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 the immediate future by generating a probable set of climate data (precipitation, temperature) based on historical records of the climate data; ii) second, climate change data from Coupled Model Intercomparision Project (CMIP5) using the Max Planck Institute earth system model (MPI-ESM) were analyzed for the 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, Representative Concentration Pathways (RCP) with the highest forced scenario (8.5) under MPI-ESM climate model of CMIP5 was selected for the evaluation of future climate change in the Muskingum watershed. Three future periods 2035s (2021-2050), 2055s (2051-2070) and 2085s (2070-2099) were assessed against the baseline period (1995-2009). A large change in hydrological behavior was experienced in significant portions of the watershed. Lowest flow was projected to increase across the watershed during 2035s than the periods 2055s and 2085s. 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 to first 30 years of 21st century (2035s), and analysis was conducted assuming the current rate of fracking remains intact. The result was consistent with the conclusion from step one (mentioned above).While there was negligible impact on mean streamflows, significant impact on 11 locations (out of 32), with maximum difference up to 55%, in 7 days minimum low flow, was detected. The variation was significant during low flow period, indicating that low flow period was the most critical period, especially for small order streams. This analysis under various fracking and climate change scenarios can provide useful information for policy makers and planners for appropriate water resources management in the future.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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 Engineering Center - 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 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 withdrawal of water from different sources 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 drilling. Likewise, there have been issues regarding the connection of energy source for the impact on regional water availability, quality and its dynamics.

Significant amount of energy has been produced in the United States for the residential and industrial use from oil and natural gas, such as by 37% and 25% in 2010 respectively (USEIA 2011a). Natural gas production is expected to increase by nearly 30%, rising from 22 trillion cubic feet in 2010 to 28 trillion cubic feet in 2035 (Cooley and Donnelly 2012), in response to the growing demand for energy to meet domestic needs, and ultimately exporting to support economic development. This is changing the United State towards more energy independence. However, this positive side of energy is suppressed by the controversy over environmental and water resource impact due to the strong relation between natural gas production and water use. The requirement of large amount of water for unconventional shale gas development is supported by the advancement of a technique, hydraulic fracking. While hydraulic fracking is significantly increasing in various parts of the United States and beneficial for energy production, the degree of impact, especially in terms of water quantity, caused by the fracking has yet to be analyzed in order to protect water resources.

Similarly, future climate change is expected due to the various reasons including anthropogenic influence, land use change, growth of population and industries leading to the increased greenhouse gases and aerosols. The climate change will vary the trend of precipitation pattern, temperatures, evaporation and evapotranspiration leading to the alteration of the hydrologic behavior of watershed at spatial and temporal scale (Hailemariam 1999).

In order to study the response of watersheds due to water withdrawal for fracking and future climate change, a suitable type of watershed model is needed. Since hydraulic fracking is a relatively new topic and very few studies have been conducted to develop various water acquisition scenarios, selection of an appropriate watershed model and its potential application for such study is still a matter of investigation. For this, a systematic review of existing literature and currently available watershed models was conducted. A physically-based watershed model, Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998), was found to be most suitable, and therefore applied to the Muskingum watershed in the eastern part of Ohio. Finally, the SWAT model was utilized to simulate streamflows for various scenarios such as baseline, current, future fracking and future climate change. All these scenarios are described briefly in Chapters 3 and 4, respectively.

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 on the water environment, ecology and humans. 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; and
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.

Methodology for Objective I

a. Review and select the most suitable model in order to best incorporate the hydraulic fracking;
b. Delineate all the land area, stream or reaches and reservoirs of the Muskingum watershed;
c. Prepare input data, such as climate, soil, land features, etc. for model simulation;
d. Calibrating and validating the model using United States Geological Survey (USGS) streamflows records;
e. Run the model simulations using current hydraulic conditions as model inputs; and
f. Analyze the changes and degree of impact in the stream low flow.

Methodology for Objective II

a. Prepare the baseline, current and future fracking scenarios
b. Prepare thirty years of synthetically generated precipitation data using statistical downscaling model (SDSM)
c. Run the SWAT simulations for scenario analysis for baseline, current and future fracking scenario with current and future climate data
d. Compare and analyze among these scenarios and evaluate the impact at spatial and temporal scale

Methodology for Objective III

a. Download the bias corrected and fine downscaled CMIP5 climate model, MPI-ESM-LR, developed using the downscaling technique called daily Bias Corrected Constructed Analogs (BCCA)

b. Run the SWAT simulations for three future time periods of 2035s (2021-2050), 2055s (2051-2070), and 2085s (2070-2099) to simulate the streamflow
c. Analyze these future flows scenarios to baseline scenario (1995-2009)
d. Integrate the current fracking trend with 2035s future climate output from the CMIP5 model in order to develop the current fracking scenario
e. Evaluate the impact of current fracking trend in 2035s climate period by comparing scenarios with and without incorporating fracking

Thesis Structure

This thesis is divided into four chapters. Chapter 1 covers the background, scope, objectives and thesis structure, and the remaining three chapters are organized in a journal paper format. Since each chapter is a separate journal article, 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.

In Chapter 3, the SWAT model developed in Chapter 2 is used to assess the potential impact using various fracking scenarios. In addition, generation of plausible set of climate data to analyze the impact of fracking in immediate future using statistical downscaling technique is discussed. This chapter simply discusses the possible impact of fracking in various climatic conditions, which is generated based on historical climate of the region. The future climate change impact generated based on greenhouse gas emission scenarios is not the scope of this chapter and discussed in Chapter 4.

In Chapter 4, the calibrated and validated SWAT model developed in chapter 2 is used to simulate future streamflow based on climate model. In this chapter, several climate models are evaluated to find the suitable climate model for this region. Future bias corrected and finely downscaled 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, the 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 the current rate of fracking remains intact. This analysis is limited to 2021-2050; and the analysis for other periods (2051-2070, and 2070-2099) only includes climate change impact in low flows as we are not sure how the fracking will continue in late 21st century in the watershed.

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Chapter 2. Modeling Impact of Hydraulic Fracturing on Stream Low Flows: A Case Study of Muskingum Watershed

Abstract

Hydraulic fracking has been tremendously increasing in eastern part of Ohio for the last few years leading to the increased stress on the hydrological and environmental low flows. Yet complexity exits on assessing the various impacts of hydraulic fracturing on hydrology even though tremendous attempts have been made, and significant progress has been achieved to advance the scientific tools and techniques to deal with the watershed issues for the last few decades. Currently, there is no defined watershed model which can better incorporate the hydraulic fracking information in its input structure. While various existing watershed models are capable to address the water resources and environmental problems, each model is unique and the appropriate selection of models depends upon several watershed characteristics including available data, resources, accuracy desired and several other factors. This suggests a pressing need for researchers and water resources scientists to select an appropriate model based on their scope of research and study. In this study, the current state of art for various available watershed models will be discussed and thoroughly reviewed including their potential capability and limitations in order to conduct a study related with hydraulic fracking. Based on review, the Soil and Water Assessment Tool (SWAT) model was found to be appropriate for the representation of fracking process in various spatial and temporal scales. Therefore, SWAT model was utilized as a tool to analyze the impact of rapidly growing hydraulic fracking on stream low flows in Muskingum watershed of eastern Ohio. The study was conducted in series of steps. In the first part, issues related to data availability of water withdrawal, the sources and temporal withdrawal was presented in order to illustrate the

need for accurately calculating the effect of withdrawal for fracking in streams. In the second step, the preparation of input data for water use and hydraulic fracking was discussed, which includes detail calibration and validation process of SWAT model for this study. In the third step, the impact of hydraulic fracking in low flows was explored by analyzing the current fracking trend in watershed.

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

Introduction

Recently, significant production of the shale gas has influenced the growth of domestic natural gas supplies and their price reduction. The reason behind this inclination is due to the growing demand for energy and ultimately exporting to support economic development (USEIA 2011a). This has caused the increasing interest in the use of natural gas for transportation sector and electricity production. One of the important aspects for the substantial growth of natural gas is the increased use of hydraulic fracturing. Annually, about 35,000 wells undergo some sorts of hydraulic fracturing in U.S (IOGCC 2009). However, as the fracking technology has been a huge positive aspect in term of increasing the production of gas, the concern regarding the large amount of water needed for fracturing has been taken as negative from an environmental aspect. Four to six million gallons of water are commonly needed to frack a single Marcellus or Utica shale well (OEPA 2012). The result of water withdrawal can reduce the water level in aquifer that may reduce the surface water flows, or reduce other sources in order to recharge the depleted water storage in aquifers. Similarly, surface water withdrawal can also directly reduce the level in reservoirs or lakes and the streams flows.

Regulatory agencies and the public are also making intense pressure regarding the water withdrawal necessary for hydraulic fracking. The impact of water withdrawal for fracking may result in severe consequences if no consideration is taken care on the timing, location and volume of water withdrawal for hydraulic fracking, especially during low flow period. The possibility of unanticipated water withdrawal for hydraulic fracking has raised 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 ground water resources on short and long term water availability?

There might be dramatic alterations in the flow system during various seasons as daily or monthly might drops down below the environmental flow limits. This may cause crisis in water supply, aquatic life, water quality leading to the complete jeopardy in water resources sustainability. Therefore, there is a pressing need of a study for better understanding of the hydrologic process of the watershed under the influence of fracking. For this, physically based, watershed models can be considered as best tools which can represent the physical conditions of the watershed and make an analytic study. There are various watershed models which can successfully simulate the physical and dynamic activities of watershed in order to evaluate the effect of many watershed processes and management activities on soil, water quantity and quality (Moriasi et al. 2007). Over 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 conduct studies related with various anthropogenic influence and watershed intervention. 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. However, there are no existing reports or published articles which describe the appropriate selection of 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 capability 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 models with their potential capabilities and limitations, including issues and challenges in order to conduct simulation study for the development of various scenarios due to water withdrawal in hydraulic fracking; and ii) second, a brief case study will be presented to explain the various processes involved for hydraulic fracking study with the selected model based on the review.

Overview of Hydrologic Models

Various watershed models, which might be potentially used to evaluate the impact of hydraulic fracking on water availability are: Agricultural Non-Point Source (AGNPS), Annualized Agricultural Non-Point Source (AnnAGNPS), Decision Support System for Agro Technology Transfer (DWSM), Hydrologic Simulation Program-Fortran (HSPF), Hydrologic Modeling System (HEC-HMS), European Hydrological System Model (MIKE SHE), Soil and Watershed Assessment Tool (SWAT), Watershed Risk Analysis Management Framework (WARMF), Variable infiltration capacity (VIC), Agricultural Policy/Environmental Extender (APEX), Nonpoint Source Pollution and Erosion Comparison Tool (N-SPECT) and Better Assessment Science Integrating Point and Nonpoint Sources (BASINS). Although all models are potentially capable to simulate watershed response and have their unique features, selection of appropriate model is a crucial step for water resources study. For example, a model which is very proficient for urban area study may not be appropriate for agricultural land and vice versa. More importantly, model selection depends upon several factors including modeler's knowledge, understandings and technical capabilities, availability of data, time, resources, accuracy desired and purpose of the study. The following section briefly describes and presents the major features of the existing watershed models, which can be possibly used for the hydrologic assessment of fracking process.

Hydrologic Simulation Program-Fortran (HSPF) (Bicknell et al. 1996) is a continuous simulation, dynamic model, 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. HSPF simulates stream flow and water quality using three main modules: PERLND, IMPLND, and RCHRES. It is also called as parameterized intensive model as the plant growth component and tile flow component are lumped into parameters.

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 effectiveness of the calibration procedure to achieve better result, and SWAT can achieve better result provided that calibration data are less. Although, HSPF is preferred for better simulating stream flows than SWAT, it requires numerous parameters to characterize hydrological cycle. Similarly, calibration process is very long and laborious (Im et al. 2003 and A.

Saleh et al 2004). SWAT is considered as a better simulator on low flow (Singh et al. 2005).

Borah and Bera (2003) reviewed eleven hydrologic and non-point source pollution models and found that AGNPS, AnnAGNPS, DWSM, HSPF, MIKE SHE, and SWAT have all three major components (hydrology, sediment and chemical) applicable to watershed-scale catchments. They concluded that SWAT is a very promising model in case of studying predominantly agricultural model, and HSPF is capable for simulation in mixed agriculture and urban watersheds. SWAT model was also compared with fully distributed MIKE SHE and authors concluded that both models are equally competent during calibration (Abu et al. 2005), while MIKE SHE was slightly better for overall prediction of stream flows.

Golmohammadi et al. (2014) evaluated three widely used hydrological distributed watershed models: MIKE SHE, APEX and SWAT for flow simulation of 52.6 km^2 Canagagigue Watershed in Southern Ontario, Canada. MIKE SHE was concluded as more accurate for simulating mean daily/monthly flow at the outlet of watershed than that of SWAT and APEX model. SWAT was regarded as another potential model as the only difference with MIKE SHE was in the validation period.

A Report on Model selection for Central Oahu Watershed study sorted out four top rated watershed models, which were N-SPECT, SWAT, WARMF, and HSPF based on thirteen specific model capabilities. Authors reported that WARMF model was considered less established than SWAT and HSPF.

Variable Infiltration Capacity 4.1.1 model (VIC) (Liang et al. 1996; Nijssen et al. 1997) is traditional large-scale cell based hydrologic model with hourly to daily time scale. VIC can be a suitable (Kari et al. 2011) if researches have to perform only water yield on a large watershed.

SWAT model has stepped forward in comparison to other models as it can disintegrate watershed into multiple subbasins and hydrologic response units (HRUs) for continuous simulation of streamflow and water quality at various temporal and spatial scales (Jha 2011). Therefore, SWAT has been extensively used for the assessment of the impact of intensive water use on the water balance and its components. Model is also considered suitable for the watershed which is characterized with limited data and ungagged watershed (USEPA 2012). In addition, SWAT is very user friendly and any new user can successfully apply it for the analysis of various water resource problems. It has been extensively used and widely supported through various international conferences, training workshops, online SWAT user group forum, broad online documentation and supporting software, open source code (Gasman et al. 2014). While Mike SHE and HSPF are equally competent, SWAT model is chosen for this study based on its historical credentials and diverse application, and also its source code is open and can be easily 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 et al. 2010). Several journal articles have been published on the application of this model to assess low flow conditions (Cibin et al. 2010; Rahman et al. 2010; Steher et al. 2008) and the potential impact of many management practices on surface water (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. 2010; Gassman et al. 2007), this is a unique opportunity to apply this model for the hydraulic fracking assessment. In fact, this study presents a systematic approach 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 water quality response of large watershed (Arnold et al. 2007). SWAT simulates different physical and hydrological process across river watersheds. The model is widely used in different regions of the world and has many peer review publications (Gassman et al. 2010; Gassman et al. 2007).

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 a land phase (Controls the amount of water) and water routing phase (represents the movement of water etc.). The land phase is represented by water balance equation

$$SW_t = SW_0 + W + \sum_{i=1}^{t} (R_{day,i} - Q_{surf,i} - E_{a,i} - w_{seep,i} - Q_{gw,i})$$

Where SW_t is final soil water content (mm); SW_0 is initial soil water content (mm); $R_{day,i}$ is amount of precipitation on day i (mm); $Q_{surf,i}$ is the amount of surface runoff on day i (mm); $w_{seep,i}$ is amount of percolation and bypass flow exiting the soil profile bottom on day i (mm) and $Q_{gw,i}$ is the amount of return flow on day i (mm), t is time (days). Surface runoff is estimated for each HRU and then routed to final streams, ponds or reservoirs. 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.

Fracking has threatened the management practices in critical conditions due to the alteration of the volume and the intensity of water withdrawal at both 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 water on cropland 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 is: i) to use point sources option in SWAT model with negative value, ii) imitate watershed management scenario related to the agricultural practices for fracking assessment. In addition, the incorporation of GIS technology in SWAT provides ample potential for inputs and response through spatial and temporal scales related to 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 withdrawal for hydraulic fracturing (Jackson et al. 2013), no research paper has been published yet 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 potential impacts of hydraulic fracturing on drinking water resources using SWAT model in upper Colorado River watershed, the result has not been published yet.

Based on the intensive review of existing models and their capabilities, SWAT model has been considered as one of the most suitable models in order to assess the potential impact of fresh water withdrawal for hydraulic fracking on water resources, especially during low flow periods. 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.

Case Study

The case study presented here includes the Muskingum watershed (Figure 2.1), which is located in eastern part of the Ohio. It covers more than 8,000 square miles area, which is nearly 20% of the Ohio state. Muskingum River is the largest stream in the watershed, which originates at the union of the Tuscarawas and Walhonding River near Coshocton, and eventually drains into the Ohio River at Marietta. The main sub streams of this river are Tuscarawas, Walhonding, Licking River and Wills Creek. The 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). The maximum, minimum and average flows at the outlet of the watershed are 23,900 cfs, 477 cfs, and 2,760 cfs, respectively. The mean daily precipitation over the entire watershed is slightly greater than 39 inches. The elevation range in watershed varies from 177 m to 459 m from sea level. 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.

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, groundwater and management for successful simulation of the stream flows.

Digital elevation model (DEM) of 30 meters resolution was downloaded from USGS National Elevation dataset in order to delineate stream networks using ArcGIS resulting into 406 subbasins after the watershed delineation. Similarly, land use data of 30 meters resolution was downloaded from National Land Cover Database 2006 (NLCD 2006) in order to best represent the land use pattern within the calibration period (2002-209) of this model. Watershed was comprised of deciduous, evergreen forest (46.62%), agriculture land with row crops (23.15%), hay (18.83%), and urban areas (10.42 %) (Table 2.1). Remaining 0.98% of land use includes industrial area, water, range grass, southwestern arid range; wetlands-forest and. Existing 12 reservoirs were spatially located manually at a proper location of watershed with reference to the stream outlet (Table 2.2). The Soil data was taken from the State Soil Geographic dataset (STATSGO)

(USDA 1991) included as a default in SWAT with a map at 1:250,000 scale. The appropriate numbers of HRUs (6176) were obtained by assigning multiple HRUs for each subbasin and by eliminating minor land uses, soils and slopes. This was accomplished by selecting the threshold in each subbasin of 5%, 15% and 15%, respectively. Seventeen years of climate data including precipitation, maximum and minimum temperature were downloaded from National Climatic Data Center (NCDC) website. Altogether 23 precipitation stations and 19 temperature gauge stations were located within the watershed (Figure 2.1). Figure 2.3 and Figure 2.4 show the general trend of average monthly precipitation and seasonal monthly precipitation in fall and winter season. Remaining meteorological time series inputs such as solar radiation, wind speed, and relative humidity were available by SWAT built-in weather generator. Daily streamflow data needed for model calibration and validation were available from USGS website for 9 spatial locations from 1993 to 2009.

Figure 2.5 represents the general trend of the monthly average flow in downstream gage (USGS03150000) of Muskingum watershed. Reservoir daily mean outflows data were available from US Army Corps of Engineers (USACE) for same duration.

Point sources greater than 0.5 MGD were collected from Ohio Environmental Protection Agency (OEPA). Similarly, surface and ground water use for irrigation, power plant, industry, mineral extraction, water supply and hydraulic fracturing were obtained from Ohio Department of Natural Resources (ODNR). Since, ODNR does not include any withdrawal less than 100,000 gal/day, additional verification from OEPA was sought in order to include missing facilities; however, this was true only for water supply data.

Similarly, the locations of oil and natural gas wells and sources for freshwater were collected from ODNR. The fracture data and fresh water required per well and recycled water were obtained from fracfocus, which is the national hydraulic fracturing chemical registry. The input data including their sources and format are presented in Table 2.3.

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). Since SWAT model comprises numerous parameters, SWAT-CUP (Abbaspour et al. 2007) was selected to calibrate the model parameters using time series from 2001 to 2009. For this, SUFI-2 algorithm was utilized, which includes all the possible uncertainties on the parameters ranges and tries to optimize the model parameters by capturing most of the measured data in the 95% prediction uncertainty (95PPU) (Abbaspour et al. 2007). Since model calibration is an iterative process, to produce the best agreement between simulated and observed data, several model parameters were selected for model calibration and validation at various locations of the watershed.

The model simulations were run for 15 years using USGS–gage observed data from 1995 to 2009. Simulations were started from 1/1/1993 excluding 2 years of warm-up period in order to minimize the effect of initial unknown parameters and stabilize the hydrologic component of the model. 21 parameters were selected (Table 2.5) based on previous studies (Abbaspour et al. 1999; Abbaspour et al. 2007; Faramarzi et al. 2009; Schuol et al. 2008a; Yang et al. 2008). The model was calibrated in a daily time scale on 9 different stream gauges from 2002 to 2009. In the next step, validation of the model was performed from 1995 to 2001 using statistical parameters measuring the goodness of fit such as coefficient of determination (R^2) (White et al. 2005), Nash-Sutcliffe coefficient of Efficiency (NSE) (Nash and Sutcliffe 1970) and Percent of bias (PBAIS).

Model evaluation criteria

Multi objective functions are always essential for calibration and validation of model because there is not a single statistical measure of model performance (Moriasi et al., 2007). There are four widely used non-dimensional measures to assess model performance, which are mathematically represented as follows.

$$R^2 = \left(\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_{obs}^{mean}\right)\left(Y_i^{sim} - Y_{sim}^{mean}\right)}{\left[\sum_{i=1}^{n} \left(Y_i^{obs} - Y_{obs}^{mean}\right)^2 \sum_{i=1}^{n} \left(Y_i^{sim} - Y_{sim}^{mean}\right)^2\right]^{0.5}} \right)^2$$

Where $Y_i^{obs}$the i^{th} value of observed data, Y_i^{sim} is the i^{th} value of simulated data, Y_{obs}^{mean} is the mean of observed data, Y_{sim}^{mean} is the mean of the predicted outputs and n is the total number of observations. R^2 varies from 0 to 1 indicating the proportion of the total variances in the observed data.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n} \left(Y_i^{obs} - Y^{mean}\right)^2} \right]$$

NSE indicates how well the observed and simulated data fits the 1:1 line. It ranges from ∞ to 1. The performance of the model is generally acceptable if the value ranges between 0 and 1. NSE with value 1 is considered as the perfect model.

$$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right) X\ 100}{\sum_{i=1}^{n}\left(Y_i^{obs}\right)}\right]$$

Where PBIAS is the deviation of simulated data in percentage. It indicates whether the simulated data is larger or smaller than observed data. PBIAS with 0 value is considered as perfect harmonizing with observed data.

$$\mathrm{RSR} = \frac{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}}{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_{obs}^{mean}\right)^2}}$$

RSR is the ratio of the root mean square error (RMSE) and standard deviation of measured data. The performance of model depends on lower RSR with zero being the perfect simulated model.

Current 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 develop realistic current fracking analysis. 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 was not available, 50 percentile of the available data from USACE was applied for a period 1995 to 2009 in order to best represent lake outflow for current period.

Model Simulation

The model performance was satisfactory in calibration and validation period with reasonable accuracy, which was assessed through visual inspection and statistical criteria. The model parameters representing the best simulation are reported in Table 2.5. Similarly, the daily and monthly statistical parameters measuring the performance of the model such as NSE, R2, RSR and PBIAS are listed in Table 2.6 & Table 2.7, respectively. Analysis showed that NSE, RSR and PBIAS were well above the recommended ranges in the literature (NSE > 0.5, RSR ≤ 0.7 and PBIAS ±25%) (Moriasi et al. 2007). The NSE values varied from 0.40 to 0.648, and 0.395 to 0.647 for daily streamflow calibration and validation, respectively (Table 2.6). The NSE varied from 0.488 to 0.886 for monthly streamflow calibration, and 0.547 to 0.863 for monthly streamflow validation (Table 2.7). The statistical parameters for monthly calibration were better than daily flow calibration, which is not surprising, since watershed models such as SWAT were originally intended for monthly simulation. Performance of the model was satisfactory for all stations except one (USGS 03136500) for monthly calibration. There could be many reasons for this; but one likely reason could be the lack of outflow data from the reservoir, as this station was immediately below the reservoir. The performance of the model was comparatively better in the downstream USGS gage of the watershed compared to upstream gage. This is consistent with the previous findings which suggest that the hydrologic model calibration is relatively easy for bigger watersheds due to the lumping of watershed characteristics. The performance of the model was also evaluated through the graphical comparison of observed and simulated streamflow time series, and found to be satisfactory during calibration (Figure 2.6) and validation period (Figure 2.7).

The simulated streamflow were slightly underestimating than observed daily and monthly peak, which is consistent with the previous findings (Bieger et al. 2014; Santhi et al. 2014). Overall, the model captured the spatial and temporal pattern of stream flow satisfactorily with reasonable accuracy.

Impact due to Fracking

Our analysis depicted the consistent increasing drilling trend in Muskingum watershed. 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 in the current period (Figure 2.8). Model was used to quantify the effect of these withdrawals over the current year as 2012 because recent fracking record was available only up to this period. 32 subbasins were involved for fracking in current period, 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. 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 and current scenarios (Figure 2.9). Figure 2.10 presented both the monthly mean and seven days monthly minimum flows in 8 subbasins. Interestingly, all the significant impacts were observed in first order streams. The subbasins which show the differences in 7 days monthly minimum flows are displayed in Figure 2.11. In general, current scenario shows less impact on the annual and seasonal water balance but signifies that 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 significant during low flow period, and this effect is significant particularly in small order streams. Similarly, baseflow variation during low flow period suggests that ground water is dominant component for the discharge into most of 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.

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 various 12 watershed models (AGNPS, AnnAGNPS, DWSM, HSPF, HEC-HMS, MIKE SHE, SWAT, WARMF, VIC, APEX, N-SPECT and BASINS) and their limitations was systematically reviewed and documented with proper citation. The SWAT model was found to be appropriate among the various candidate watershed models for hydraulic fracking. 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 on low flow period.

The study was conducted for various spatial drainage area of the watershed and analyzed the degree of impact on various temporal scales. 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. The study suggested the critical issue of flow alteration during low flow periods. The impact was more significant during low flow than average flow or peak flow period as 7 days minimum monthly flows showed large variation when compared with the 7 days minimum flow without fracking.

The study suggests that, for the proper regulation of drilling activities, serious consideration must be given to the low flow period. The dramatic alteration in the flow system during daily or monthly low flow, as daily or monthly, which might drop below the environmental flow limits, may cause crisis in water supply, aquatic life, and water quality. This eventually may threaten the water resources, and ecosystem sustainability will be in complete jeopardy. In addition, this paper facilitates future applications of SWAT model for hydrologic assessment and exploring water quality problems due to hydraulic fracking. While uncertainties exist on the complex watershed model associated with the input data, model development and various hypothetical scenarios, this research concludes that SWAT can be an appropriate model for the study related with hydraulic fracking and its impact on water balance.

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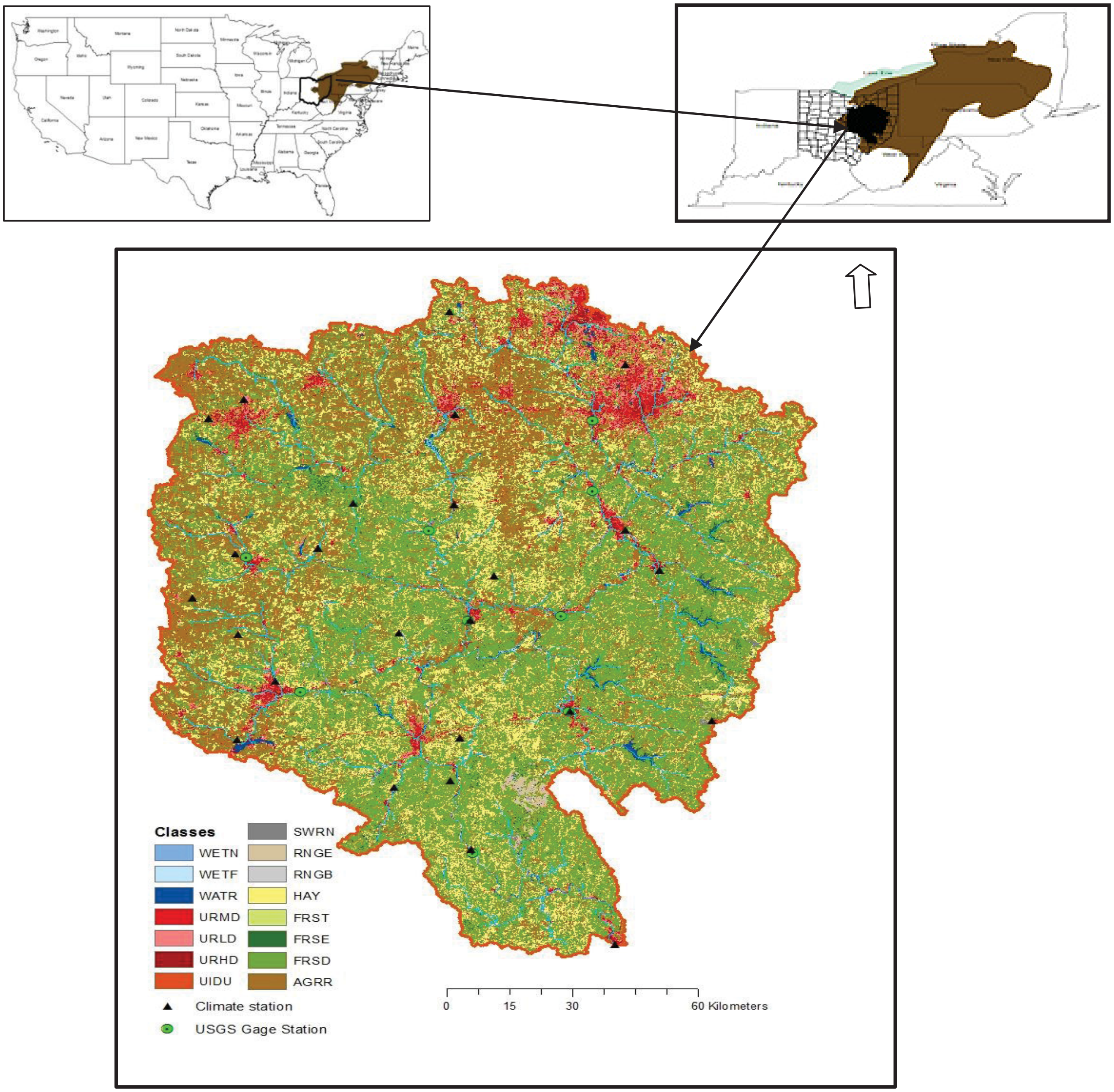

Figure 2.1 Location and NLCD map with climate and USGS stations in the Muskingum watershed.

Legend represents the herbaceous wetland (WETN), wetland forest (WETF), open water (WATR), urban medium density (URMD), urban low density (URLD), urban high density (URHD), industrial (UIDU), bare rock or sandy or clays (SWRN), grass land (RNGE), shrub land (RNGB), hay (HAY), mixed forecast (FRST), evergreen forest (FRSE), deciduous forest (FRSD) and agriculture (AGRR).

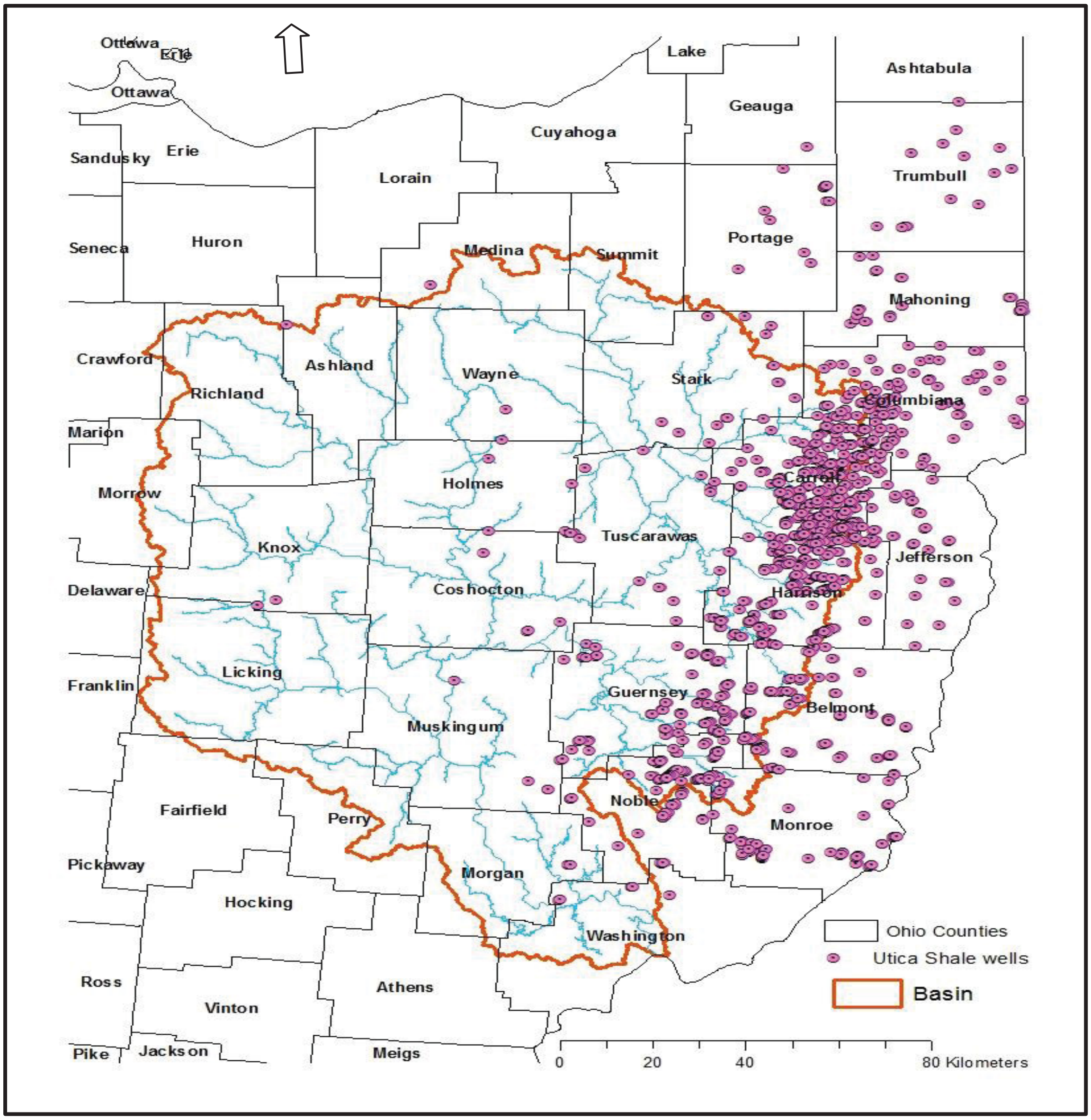

Figure 2.2 Utica shale wells in Ohio from January 2011 to September 2013.

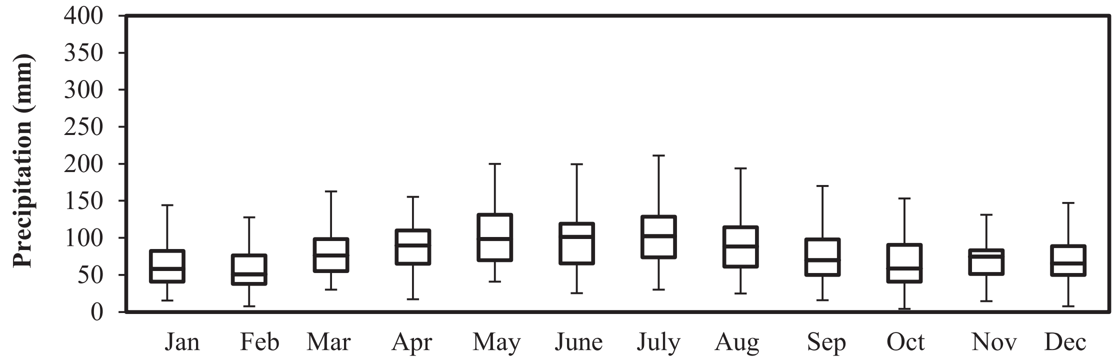

Figure 2.3 Total monthly precipitation in Muskingum watershed, average over the period from 1954 to 2008.

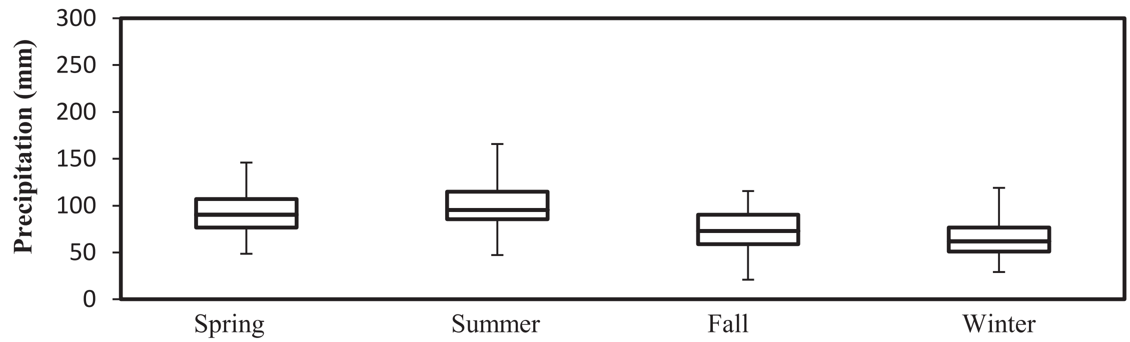

Figure 2.4 Average seasonal precipitation in Muskingum watershed (1954 – 2008).

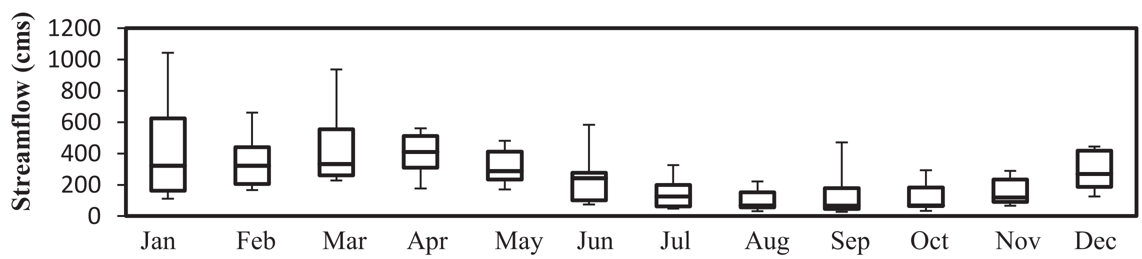

Figure 2.5 Observed monthly streamflow, averaged from October 2001 to January 2009 at USGS 03150000 in the Muskingum River at McConnelsville, Ohio.

*Interquartile range box: a) Top line - Q3 (75 percentile)
b) Middle line - Q2 (Median)
c) Bottom line - Q1 (25 percentile)

*Upper whisker = minimum data point between maximum data value or within 1.5 box height from the top the box

* Lower whisker = maximum data point between minimum data value or within 1.5 box height from the bottom of the box

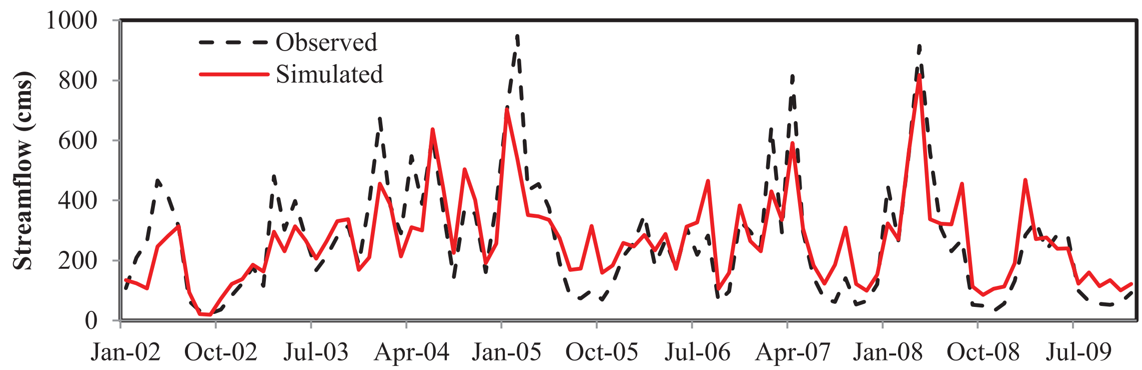

Figure 2.6 Streamflow calibration at watershed outlet (USGS gage 03150000).

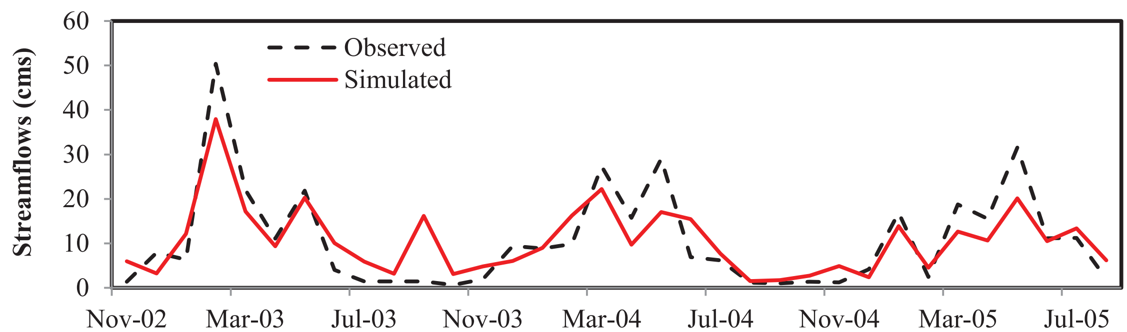

Figure 2.7 Streamflow validation at watershed outlet (USGS gage 03142000).

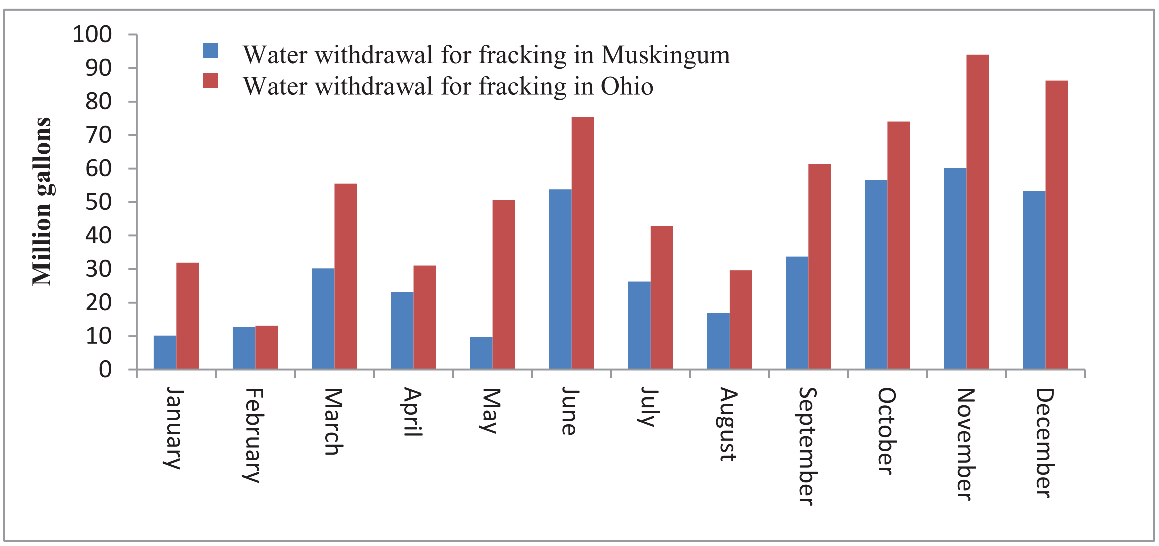

Figure 2.8 Water withdrawals for hydraulic fracturing in 2012 in Muskingum watershed and Ohio, respectively.

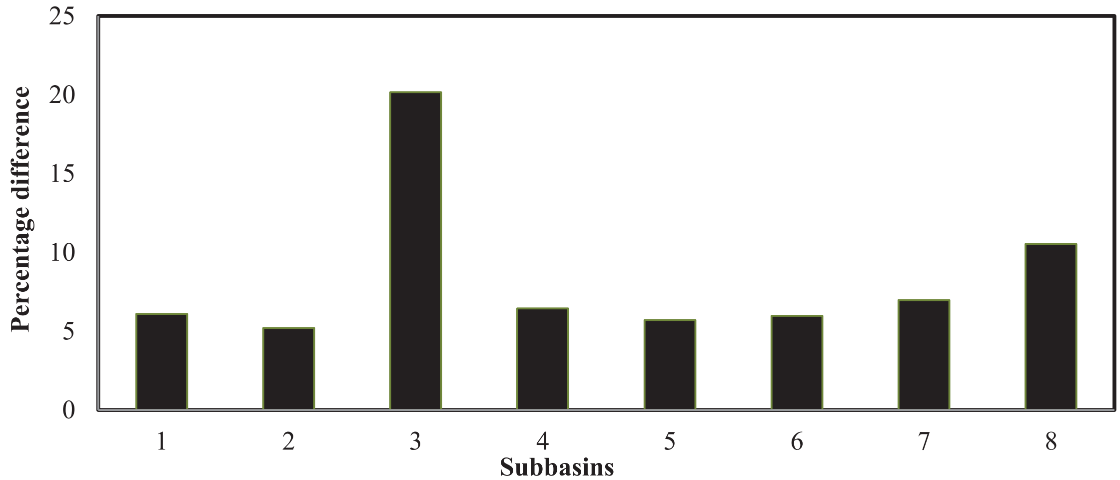

Figure 2.9 Percentage difference in 7 day minimum monthly flow between baseline and current fracking scenario on 8 affected subbasins during current period.

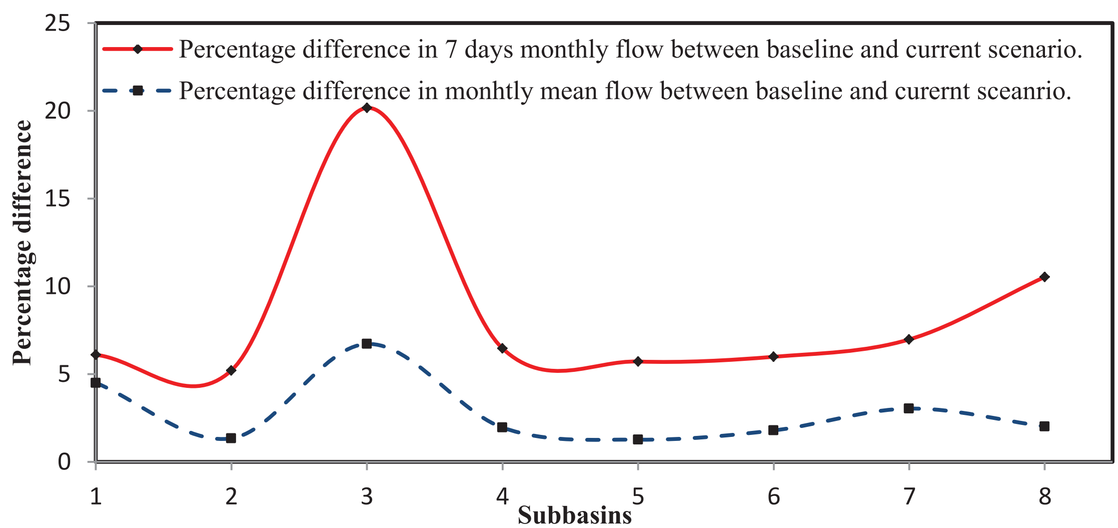

Figure 2.10 Percentage differences of 7 day minimum monthly flow and monthly mean between baseline and current fracking scenario on 8 affected for current period subbasins.

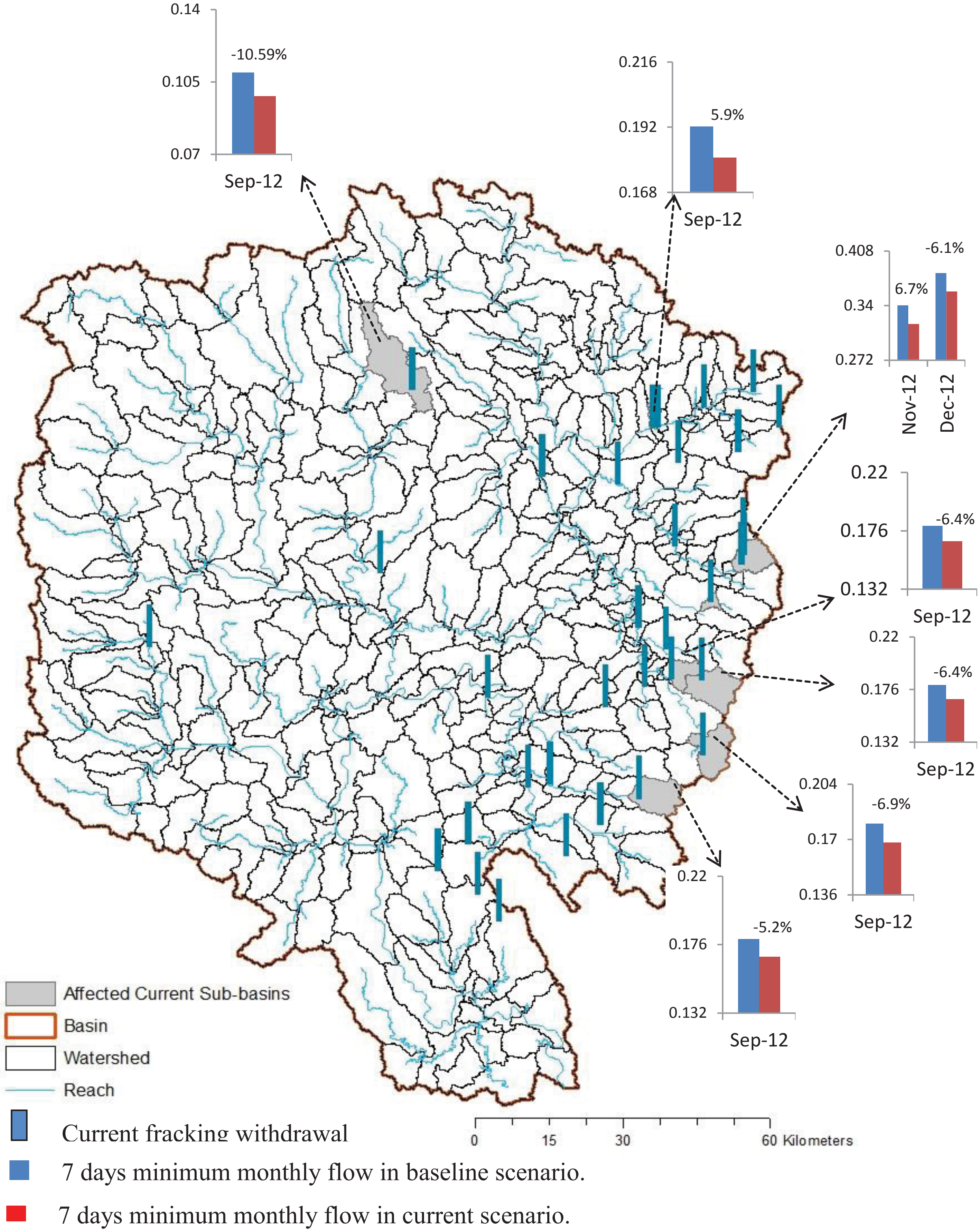

Figure 2.11 Impact of current fracking scenario on 7 day minimum monthly flow in Muskingum watershed.

Table 2.1 Landuse percentage distribution for Muskingum watershed.

Land Use Categories	% Watershed Area
Forest-Deciduous	46.46
Agricultural - row crops	23.15
Hay	18.83
Residential-Low	7.87
Residential-Medium	2.1
Residential-High	0.45
Water	0.4
Range-Grasses	0.4
Forest-Evergreen	0.16
Industrial	0.12
Southwestern US (Arid) Range	0.03
Wetlands-Forested	0.03

Table 2.2 Twelve Muskingum reservoirs input in the model.

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

Table 2.3. Data and sources used for the study.

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)
StreamNetworks Water Bodies	Streams and flow direction, reservoirs	USGS National Geospatial Program (NGP) National hydrograph dataset (NHD), http://viewer.nationalmap.gov/viewer/nhd.html?p=nhd
Water Use (Surface and Ground Water)	Irrigation, Public, Power, Mineral extraction, Industries and Golf Cource	Ohio Department of Natural Resource (ODNR) Ohio Environmental Protection Agency (OEPA)
Point Sources	Flow discharge	OEPA
Oil and Natural Gas	Wells - Current Hydraulic fracture	ODNR
	Sources of drilling water - Current Hydraulic fracture	ODNR
	Drilling water estimate per well and future Drilling trend	FracFocus (National hydraulic fracturing chemical registry)

Table 2.4 Hydraulic fracking water withdrawal in Muskingum watershed.

Year	Average Vertical Depth (m)	Freshwater (Gal)	Recycled water (%)
2011	7717	3,024,416.87	13.793
2012	7,734.00	3,437,175.44	4.347
2013	10,897.22	4,406,259.95	3.742

Table 2.5 Model parameters used in the hydrologic calibration.

Notations	Parameters	Range	Final value
v _Surlag.bsn	Surface runoff lag time	0.5 -10	8.654
v _SMTMP.bsn	Snowmelt base temperature	0 -10	1.283
v _SMFMX.bsn	Maximum melt rate for snow during year (occurs on summer solstice)	0 -10	3.85
v _SMFMN.bsn	Minimum melt rate for snow during the year (occurs on winter solstice)	0 -10	4.383
v _TIMP.bsn	Snow pack temperature lag factor	0 -1	0.705
r _CN2.mgt	SCS runoff curve number for moisture condition II	-0.4	0.9494
v _ALPHA BF.gw	Base flow alpha factor	0 -1	0.719
v _REVAPMN.gw	Threshold depth of water in the shallow aquifer for 'revap' to occur	0-500	119.166
v _GW _DELAY.gw	Groundwater delay time	0-500	254.166
v _GW _REVAP.gw	Groundwater revap. coefficient	0-0.2	0.193
v_ GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur	0-3000	585
v _ESCO.hru	Soil evaporation compensation factor	0-1	0.9333
r _SOL AWC.sol	Soil available water storage capacity	-0.2	-0.0623
r_ SOL K.sol	Soil conductivity	-0.2	-0.065
r _SOL BD.sol	Soil bulk density	-1.1	0.2525
v _EPCO.hru	Plant uptake compensation factor	0.01-1	0.9
r _OV_ N.hru	Manning's n value for overland flow	0.01-10	0.1
v _CH_ N2.rte	Manning's n value for main channel	0-0.15	0.1275
v _CH_ K2.rte	Effective hydraulic conductivity in the main channel	-500.01	156.24
v_Sno50cov.bsn	Snow water equivalent that corresponds to 50% snow cover	0-0.918	0.6165
v_Snocovmx.bsn	Minimum snow water content that corresponds to 100% snow cover	0-500	130.833

Table 2.6 Statistical parameters measuring the daily performance of the watershed model.

	Calibration				Validation			
USGS Gage Station	R^2	NSE	RSR	PBIAS	R^2	NSE	RSR	PBIAS
3117000	0.416	0.415	0.765	-0.026	0.446	0.445	0.744	-1.596
3124500	0.426	0.400	0.846	-15.882	0.526	0.473	0.726	-9.927
3139000	0.510	0.494	0.711	-4.094	0.6315	0.5998	0.6326	-2.702
3136500	0.471	0.464	0.732	9.094	0.406	0.395	0.777	17.753
3129000	0.567	0.564	0.660	2.866	0.536	0.470	0.727	20.819
3140500	0.629	0.627	0.611	1.518	0.686	0.647	0.594	12.534
3146500	0.418	0.403	0.773	11.262	0.425	0.415	0.764	12.241
3142000	0.547	0.469	0.729	12.907	0.505	0.491	0.714	-2.395
3150000	0.650	0.648	0.593	0.359	No data			

Table 2.7 Statistical parameters measuring the monthly performance of the watershed model.

	Calibration				Validation			
USGS Gage Station	R^2	NSE	RSR	PBIAS	R^2	NSE	RSR	PBIAS
3117000	0.886	0.886	0.337	-0.404	0.904	0.863	0.369	6.76
3124500	0.592	0.533	0.683	-15.598	0.6317	0.613	0.6218	-9.452
3139000	0.644	0.640	0.600	-4.150	0.715	0.714	0.535	-2.65
3136500	0.500	0.488	0.716	9.245	0.628	0.5639	0.66	17.724
3129000	0.676	0.657	0.586	2.875	0.667	0.547	0.673	20.929
3140500	0.680	0.669	0.576	1.483	0.760	0.693	0.554	12.609
3146500	0.794	0.717	0.532	11.147	0.758	0.707	0.540	12.270
3142000	0.709	0.689	0.558	12.845	0.773	0.680	0.564	-1.158
3150000	0.728	0.716	0.533	0.311	No data			

Chapter 3. Scenario Analysis for the Impact of Hydraulic Fracturing on Stream Low Flows Using SWAT Model: A Case Study of Muskingum Watershed in Eastern Ohio.

Abstract

Scientists and environmentalists are concerned about the potential impact of fresh water withdrawal on water environment and ecosystem due to hydraulic fracturing, especially during low flow periods. Most of the water management decisions are based on hydrologic or biologic conditions, which are developed using long term historical records of low flow periods without expecting water withdrawal for hydraulic fracking. This raises a serious question whether the criteria based on low flow conditions are appropriate or not given the current trends of hydraulic fracking. In addition, unanticipated water withdrawal during low flow periods may pose a serious threat to the sustainability of water supplies and aquatic habitat. Therefore, the major objective of this paper is to assess the potential impact of hydraulic fracturing on water balance of Muskingum watershed in eastern Ohio using widely accepted watershed model, Soil and Water Assessment Tool (SWAT). SWAT model was calibrated and validated to simulate the streamflows for various scenarios. Baseline scenario corresponds to water availability without hydraulic fracking, whereas the current scenario represents the water availability with current status of hydraulic fracking. Similarly, future scenario represents the water availability in immediate future with increased hydraulic fracking. Statistical downscaling model (SDSM) was used to generate thirty years of plausible future daily weather series based on occurrence of 25 percentile of historical dry period. The generated data was incorporated in SWAT model to simulate flows for future scenario in order to examine the level of impact due to fracking at spatial and temporal scales. 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. A significant change in the seven day minimum flows was detected among baseline, current and future scenarios. The flow alteration due to hydraulic fracking decreased with increase in the drainage area. Similarly, 7Q10, 4B3 and 1B3 flows also varied at different spatial location. These were in a decreasing pattern with increase in drainage area. However, no significant change in the annual mean flow was detected.

Keywords: Hydraulic fracturing, SWAT, SDSM, Low flow

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). Natural shale gas has been taken as a bridge fuel which is reducing the emission of greenhouse gases than other fossil fuel (Howarth 2014). This is changing the United State towards a more self-energy dependent country.

This development of shale gas production is enabled economically by a key technique called hydraulic fracking. However, there are significant negative environmental concerns about the application of hydraulic fracturing, primarily due to the requirement of several million gallons of water in order to fracture the shale rocks at great depth to release natural gas inside. This huge amount of water use for fracking has drawn significant attentions to public and regulatory agencies. Scientists and water users are more concerned about the extent of potential impact of this water withdrawal at different spatial and temporal scales. This impact may be severe if further consideration is not taken on the timing, location and volume of water withdrawal for hydraulic fracking, especially during low flow periods.

All the water quality standards issued by Federal and State agencies are developed based on the low flow. For example, Environmental Protection Agency (EPA) and States agencies issue National Pollution Discharge Elimination System (NPDES) permit limits based on hydrologically-based design flow and the biologically-based design flow such as 7Q10, 1Q10, 4B3, 1B3 etc. These criteria are developed based on the statistical and empirical analysis of long term historical stream flows records without anticipating water withdrawal for hydraulic fracking. This raises serious questions as to whether the permit conditions developed for low flows period are adequate to protect water quality in the current and future conditions of hydraulic fracking. Since the underestimated hydrologic/biologic conditions for permitting threatens the water quality protection and overestimated conditions leads to uneconomical treatment in waste water facilities, proper estimation of these conditions is essential. In addition, reservoirs and streams used for water supply purposes will be at critical stage during low flow (drought) periods, which will be further worsened due to sudden withdrawal for hydraulic fracking. Therefore, water use for hydraulic fracking not only reduces the assimilating capacities of the stream for pollutants, but also affects water availability for water supply purposes.

These issues are very common in eastern Ohio, leading to critical challenges to water resources sustainability. Utica Shale in eastern Ohio has great potential for the production of natural gas and oil. Recently, several drilling companies are advancing to Ohio for oil and gas development and drilling has increased tremendously on the Muskingum watershed. Significant amount of water is withdrawn from the streams and reservoirs during low flow conditions. In this context, detailed analysis is needed to evaluate the impact of hydraulic fracking on assimilating capacities of the stream for NPDES permitting and water resources availability for drinking water purpose.

There are few studies conducted related with the impact of hydraulic fracking on stream low flows. USEPA has conducted a study to evaluate the potential impact of hydraulic fracturing on drinking water resources in Upper Colorado River Basin (UCRB) (USEPA 2012). Similarly, a research has been conducted in the Fayetteville Shale play to assess the impact on flow regime and on the environmental flow criteria of the stream (Cothern et al. 2013). For example, Cothern et al. (2013) demonstrated the impact of hydraulic fracking on environmental flow components, especially on small scales. While those studies addressed impact of hydraulic fracking on stream flows, extensive analysis of stream low flows at various temporal and spatial scales was not addressed in those studies. Therefore, this research is different from previous studies in three different aspects: 1) this study focuses not only on drinking water resources availability but also on downstream water requirements for environmental sustainability; 2) this study is more specifically focused on the low flow availability in immediate future due to combined effect of impending drought and hydraulic fracking; and 3) this study reports how the hydrological low flow and biologically low flow conditions will be affected due to water withdrawal for hydraulic fracking.

To the best of authors' knowledge, this is the first article to show the quantitative evidences of potential impact of water withdrawal for hydraulic fracking on the stream low flow conditions, especially on the Utica shale.

Widely accepted Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998) was used to simulate the flows at various scenarios. The SWAT model was calibrated and validated for the Muskingum watershed for the observed flow. In order to develop various water acquisition scenarios, weather and scenario generator tools of Statistical Downscaling Model (SDSM) (Wilby et al. 2013) was adopted to generate possible future dry precipitation, and the generated climate data was integrated with 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 withdrawal on water balance during low flow period.

Theoretical Background

Hydraulic Fracking

The Hydraulic fracturing, introduced in the 1940s (Montgomery and Smith 2010), is the technique of injecting millions of gallons of water mixed with sand and chemicals at high pressure, which fractures rock in underground at great depth and release the gas (Beaver 2014). Water is withdrawn from the multiple sources such as surface and ground water, treated water from the treatment plant and recycled water from the flow back and produced water (API 2010a). Water usage per well varies depending upon the type of shale and their thickness, formation of well such as its length, depth, horizontal or vertical, and multiple leg or single leg and fracturing operation. Water use per well is estimated to range from 65,000 gallons for methane production to 13 million gallons for shale gas production (GWPC and all consulting 2009; Nicot et al. 2011). Similarly, fracturing process for shale gas well requires 2.3 million to 3.8 million gallons of water per well (U.S. EPA 2011a) and additional 40,000 – 1,000,000 gallons of water is required for drilling vertically per well (GWPC and ALL Consultant 2009). Marcellus shale in Pennsylvania shows water required from two to four million gallons per well (API 2010b; Satterfield et al. 2008). In general, four to six million gallons of water are commonly needed to frack a single Marcellus or Utica shale well (OEPA 2012).

Model

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 watershed (Arnold et al. 2007). SWAT simulates different physical and hydrological process across the river basins. The model is widely used in different regions of the world and has many peer review publications. The detail theoretical description of SWAT model has been already discussed in Chapter 2.

Statistical Downscaling Model (SDSM)

The SDSM is a climate change scenario generator used for risk assessment and climate studies (Wilby et al. 2007). SDSM uses tools such as the stochastic weather generator, and regression based downscaling technique as a means for weather generation (Wilby et al. 2007). Weather generator is used to generate synthetic data of weather such as precipitation, maximum and minimum temperature. Precipitation is simulated based on the occurrence of wet or dry period, and on amount of precipitation and temperature. The occurrence is modeled as a Markov chain method and amount is sampled randomly from a suitable distribution such as Gamma distribution. 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 SDSM: 1) identification of predictors and predictands; 2) SDSM model calibration; 3) parameter file generation 4) incorporating missing data using Weather Generator; and 5) future dry precipitation through Scenario generator tool.

Materials and Methodology

Study Area

This research was conducted on the Muskingum watershed (Figure 2.1) which is located in eastern part of the Ohio. The detail watershed description is given in Chapter 2. At present, approximately more than 90% of natural gas wells in Ohio lie in this watershed (Figure 2.2). Most of them are specially concentrated on eastern portion of watershed, which is called Tuscarawas watershed (Figure 3.1). It covers entire or partial area of the thirteen counties. This subwatershed is one of the largest river systems in the state, which covers the area of 6,327.34 km2 within Muskingum watershed. The northern portion of this subwatershed is significantly covered by industrial and urban land uses. Similarly, the southern portion is dominated by the forest cover. Additionally, there are a numbers of reservoirs in the eastern part of the watershed.

SWAT Model Input

The SWAT model was developed using Digital Elevation Model (DEM) of 30 meters resolution, National Land Cover Database of 2006 (NLCD 2006), precipitation data from National Climatic Data Center (NCDC) and streamflow data from United States Geological Survey (USGS). The detail discussion of SWAT model input is given chapter 2 including the source of data and their format (Table 2.3).

Model Calibration and Validation

The SWAT model calibration and validation procedure using SUFI-2 program has been described in Chapter 2 under heading "Model Calibration and Validation". The calibrated and validated model was used to simulate the streamflows from 1995 to 2009.

Model Evaluation Criteria

Similarly, the performance of the model was assessed using widely used four objective functions such as NSE, RMSE, PBIAS and R^2, which are described in the chapter 2 under heading "Model Evaluation Criteria".

Scenario Analysis

The calibrated and validated SWAT model was integrated with water use and point sources data in order to develop realistic and hypothetical scenarios with different perspectives of hydraulic fracking. Baseline, current and future scenario were developed to assess the impact in water resource under various level of hydraulic fracking.

Baseline model referred to the watershed conditions of the year 2012, which represented the consumptive water including public water supply, domestic, industrial and other water use for irrigation, livestock, mining, power plant and point sources without including the hydraulic fracturing activities. Current scenario referred to the watershed condition of the year 2012 including fracking rate of 2012, whereas baseline scenario referred to the watershed condition for the year 2012 without fracking. Therefore, baseline and current models were developed in calibrated and validated SWAT model using 2012 climate conditions with and without hydraulic fracking, respectively. Future scenario explored the current development of natural gas in Muskingum watershed. Future projection of hydraulic fracturing wells was projected up to year 2030, based on the recent drilling trends; however, all the other water use inputs were similar to the baseline scenario. The future scenarios were developed into two scenarios with respect to temporal scale. "Future scenario on current period" was developed by simulating streamflows using the projected hydraulic fracking condition of year 2030 but using current climate condition (2012). Similarly, "Future scenario on future period" simply referred the projected hydraulic fracking condition of year 2030 simulated over a climate of 30 year period, which was generated based on historical climate. Monthly consumptive water use was provided from the water use input file based on the removal of water from reach, shallow aquifer, and reservoirs within subbasin.

Since, hydraulic fracking is predominantly occurring in eastern part of Ohio, detailed analysis was conducted for a smaller region. Therefore, Tuscarawas watershed was preferred for future scenario as it covers major eastern portion of the watershed. Future fracking wells in watershed (Figure 3.2) was estimated based on past three years of drilling trend in Ohio State. Even though altogether 865 wells were drilled in Ohio, drilling information of only 517 wells were available from "fracfocus". Therefore, future projection up to 2030 was estimated based on actual drilled well. Extreme projection scenario was adopted and this indicated that the fracking wells would increase approximately by 224 wells for each month in Ohio by 2030.

The similar pattern of hydraulic fracking was assumed in Tuscarawas watershed. I considered only those subbasins with minimum net area of 2 km^2 after eliminating residential and water bodies. This resulted into 149 potential subbasins for study out of 168 subbasins in this sub watershed. Water withdrawal for each well was estimated based on water use trend on Muskingum watershed for 2012 and 2013, available from the

Fracfocus. The water withdrawal for each well in Muskingum watershed was approximately 3.4 MG in 2012 and 4.4 MG in 2013 (Table 2.4). Based on this increasing trend, the freshwater water withdrawal for each well was assumed to be 4.5 MG in 2030. Existing trend indicates the decreasing pattern in using recycled water from 2012 (4.3%) to 2013 (3.7 %); hence, recycled water for 2030 was considered simply 4%. Source of water was taken as the nearest stream and reservoirs in the watershed. 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 40 acre units are considered for the development of shale wells (Myers 2009; Duff 2008; Robbins 2013), and this information was used to determine the maximum possible limit of the wells in the watershed. Therefore according to the current trend, 5.766 MG of fresh water was considered to be withdrawn for 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 SWAT model to simulate future scenarios. The future possible climate data was generated using Statistical downscaling model (SDSM) based on historical climate record of the region.

Developing Future Climate

In this research, SDSM technique was utilized to establish the quantitative relationship between local surface variable (predictands) and large scale variables (predictors). 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 data assimilation system and make consistent climate variables throughout the reanalysis period. Large scale predictors including mean temperatures, vorticity at surface and 850 pa height, 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 3.1). The observed data was used from 1961 to 1975 to develop the regression model (calibration) and then regression weights produced 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) was infilled using weather generator tool, scenario generator from SDSM was applied to generate precipitation. A possible stet of projected thirty years of precipitation and temperature data was generated by SDSM using historical records of observed precipitation at various NCDC stations of the watershed in order to find out the 25 percentile precipitation. 25 percentile precipitations specify that the probability of occurring more than that precipitation is 25%, which indicates that even 25 percentile precipitation does not represent the severe drought conditions.

Result and Discussion

Model Simulation

The model performance was satisfactory in calibration and validation period with reasonable accuracy, which was assessed through visual inspection and statistical criteria. The model parameters representing the best simulation are reported in Table 2.5. Similarly, the daily and monthly statistical parameters measuring the performance of the model such as NSE, R2, RSR and PBIAS are listed in Table 2.6 & Table 2.7, respectively. The detail description of the model simulation is discussed in Chapter 2.

Overall, the model captured the spatial and temporal pattern of stream flow satisfactorily with reasonable accuracy.

Scenario Evaluation

Our analysis depicted the consistently increasing drilling trend in Muskingum watershed. Since it was essential to maintain environmental low flows for sustainable water availability including downstream rights, aquatic habitat and others, low flows were evaluated for various fracking scenarios, which are described in subsequent section.

Current Scenario

Since the study was focused on the low flow period, fracking water withdrawal during low flow period was evaluated at the various location of the watershed. The analysis indicated that the water withdrawal during low flow period, primarily from August to November was about 43% of the total water withdrawal in the current period Figure 2.8. The impact of these withdrawals over the current year was quantified in 32 sub watersheds which had a drainage area less than 140 km^2. Analysis was categorized mainly in monthly and annual scale for current scenario. The streamflows was classified into three categories such as mean flow, low flows and high flows for current year (2012). Results revealed that greater alterations can be expected in seasonal 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. The detail discussion about the impact of current trend of fracking on stream low flows is discussed in chapter 2. In general, current scenario had less impact on the water balance but signified that the effect might be critical over low flow such as 7 day minimum flow especially on first order of streams.

Future Scenario

Future and Baseline Scenario for Current Period

Sixteen subbasins in Tuscarawas watershed with increasing drainage areas were selected to assess the impact of fracking on low flows at spatial and temporal scale. The analysis was accomplished comparing baseline scenario against the "Future scenario on current period". As the current scenario analysis indicated the substantial effect on seven days minimum flow, future scenario was also expected to indicate the similar consequences. Figure 3.3 shows the relative change in the 7 days minimum flows during low flow period between baseline and future scenario in current period. Similarly, the degree of impact of fracking in spatial scale is presented in Figure 3.4, which showed that the effect of withdrawal decreases with increase in drainage area. Some outliers in the graph can be observed which are mainly due to the interactions of other water use components and point source on same subbasins. Additionally, 9 percentages difference (approximately) was noticed in annual average flow (Figure 3.5).

Future, Baseline and Current scenario for Future Period

Environmental flow criteria were analyzed, using plausible set of generated climate data over 30 years period based on historical climate, on similar 16 subbasins of Tuscarawas watershed. These limits were evaluated by using DFLOW 3.1 as a window-based tool, which is developed by EPA. Figure 3.6 presents the comparison in 7Q10 between baseline and future scenario for 30 years. Significant differences were detected on future scenario with respect to baseline. The excess withdrawal due to future fracking reduced 7Q10 to zero for drainage area less than 800 km^2.

The percentage difference in 7Q10 between baseline and future scenario was analyzed with increased size of the drainage area. Relatively less difference was detected when analysis was conducted in large drainage area. Figure 3.7 shows the decreasing trend in the percentage difference in 7Q10 with the increase in drainage area when baseline scenario was compared with future scenario. Additionally, the comparison between baseline and future scenario for 1B3 and 4B3 also showed similar trend. The difference in the 4B3 and 1B3 for both scenarios is reported in Figure 3.8 and Figure 3.9, respectively. Similarly, Figure 3.10 and Figure 3.11 show the decreasing trend in percentage difference in both criteria with the increase in drainage area.

The analysis was also conducted to see the effect in flow duration curve as it is one of the important statistics to quantify hydrologic regimes (Kim et al. 2009). 95% flow exceedance was considered as threshold for the extreme low flows, which is very stressful drought period as streams drops to very low level. Similarly, 75% flow exceedance was considered as low flows which is the dominant low flow condition, sustained by the ground discharge into the streams. Subbasin with drainage area 920 km^2 was selected to analyze the flow duration curve between current and future scenario for 30 year period (Figure 3.12). The result showed that the extreme low flow was not affected in this drainage area. However, the low flow was affected as the alteration was noticed below 85 % flow exceedance. The time series of baseline, current and future scenario for baseflow is presented in Figure 3.13 for future period. The changes are visible in the baseflow, which indicates the variation of flows in low flow period.

Conclusion

In this paper, impact of hydraulic fracking on the water resources, especially during low flow period was explored. The study was conducted for various drainage area of the watershed and analyzed the degree of impact in various temporal scales. A widely used watershed model (SWAT) was selected for simulation of stream flows. Simulated flows in ungauged locations were used to generate realistic scenarios to assess the potential impact of water withdrawal for hydraulic fracking on water resources. Baseline scenario was based on the realistic conditions of all water use data excluding fracking water withdrawal. Similarly, current scenario was based on the real data of water management over the river watershed including current water withdrawal for hydraulic fracking. The future scenario was generated by using 30 years of generated climate data based on historical precipitation to SWAT model. SDSM was used to generate future precipitation based on the occurrence of 25 percentile dry precipitation in past 30 years (1961-1990). 7 days minimum monthly flows showed large variation when compared with and without fracking indicating that flow alteration during low flow period will be critical than average flow or peak flow period. The difference was also noticed on flow duration curve and base flow time series implying the clear impact of fracking during low flow period.

The hydrologic (7Q10) and biological (4B3 and 1B3) design streamflows were altered due to water withdrawal for hydraulic fracking, which suggests that planners and decision makers should consider water withdrawal for fracking while setting environmental flow criteria in NPDES permitting for this specific region. The dramatic alteration in the flow system during daily or monthly low flow, which might drop below the environmental flow limits, may cause crisis in water supply, aquatic life, and water quality. This eventually may threaten the water resources and place ecosystem sustainability in complete jeopardy. Therefore, proper regulation of the drilling activities with serious consideration of low flow period is highly essential.

While uncertainties exist in the complex watershed model associated with the input data, model development and various scenarios, the impact studied under different scenarios provides us the better understanding of management conditions. Finally, results might be valuable to planners and decision makers to manage water resources against fracking, especially during low flow period.

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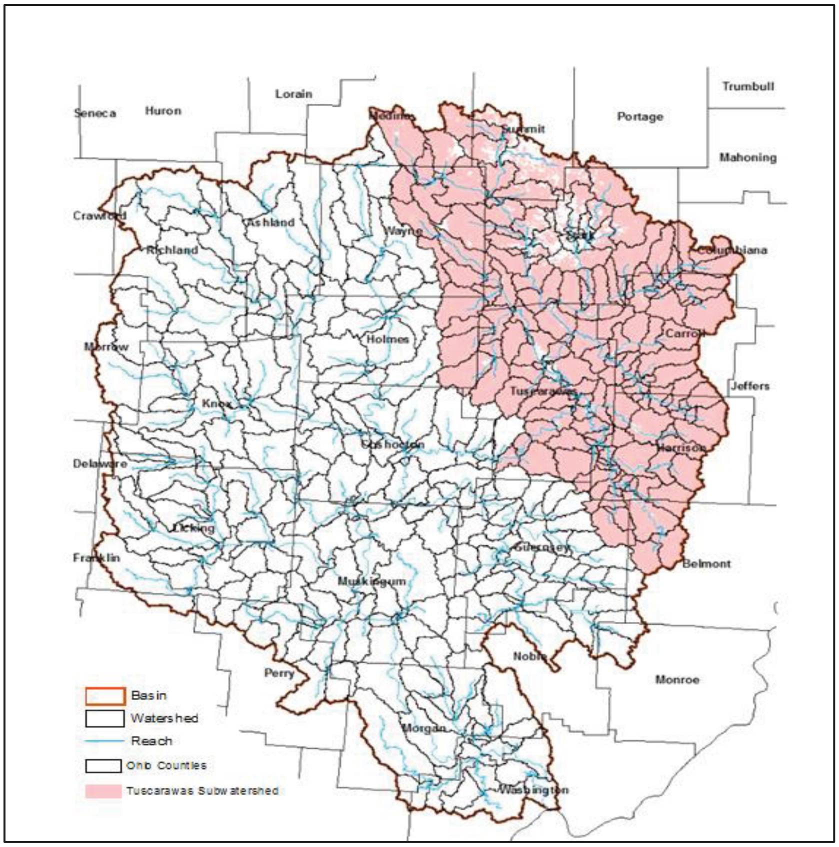

Figure 3.1 Tuscarawas Sub watershed in Muskingum watershed.

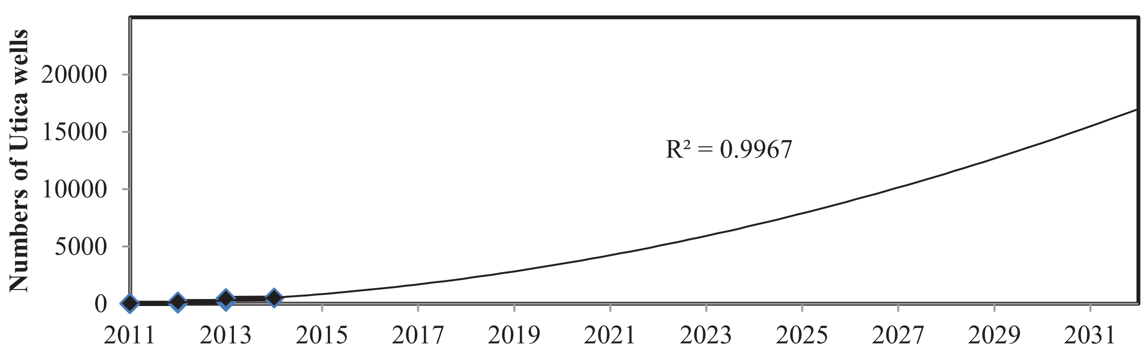

Figure 3.2 Projection of Utica wells in Ohio based on period from January 2011 – May 2014.

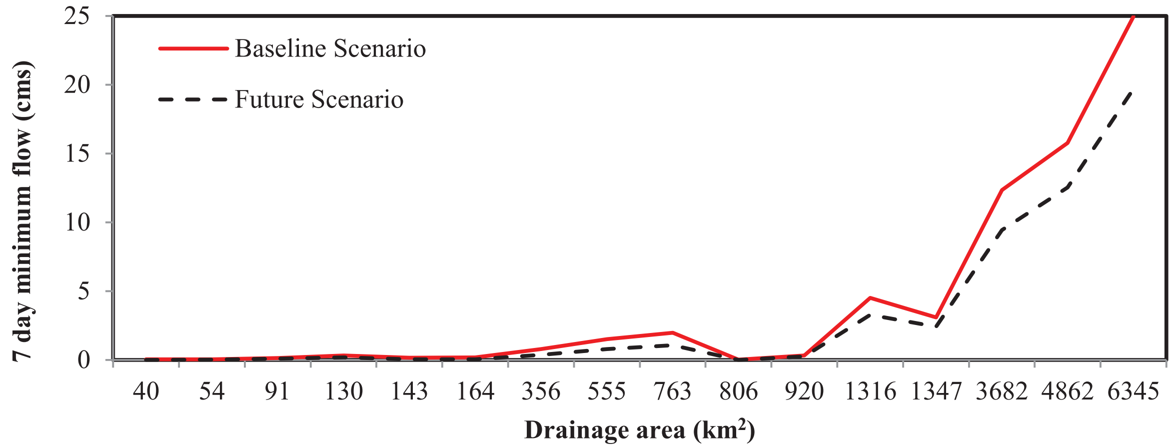

Figure 3.3 Seven day monthly minimum flow during low flow period for baseline and future scenario for current period.

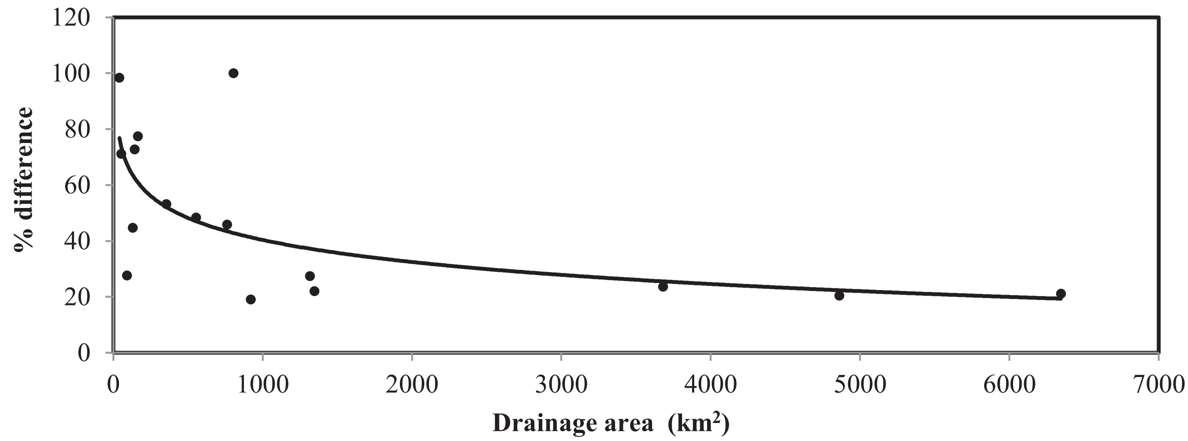

Figure 3.4 Percentage difference in 7 day minimum flows between baseline and future scenario for current period.

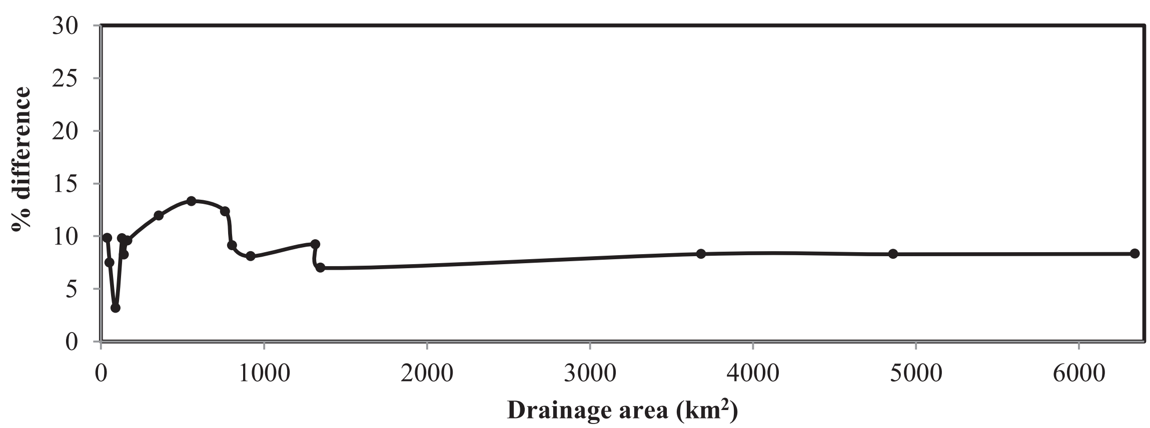

Figure 3.5 Percentage difference on annual average flows between baseline and future scenario for current period.

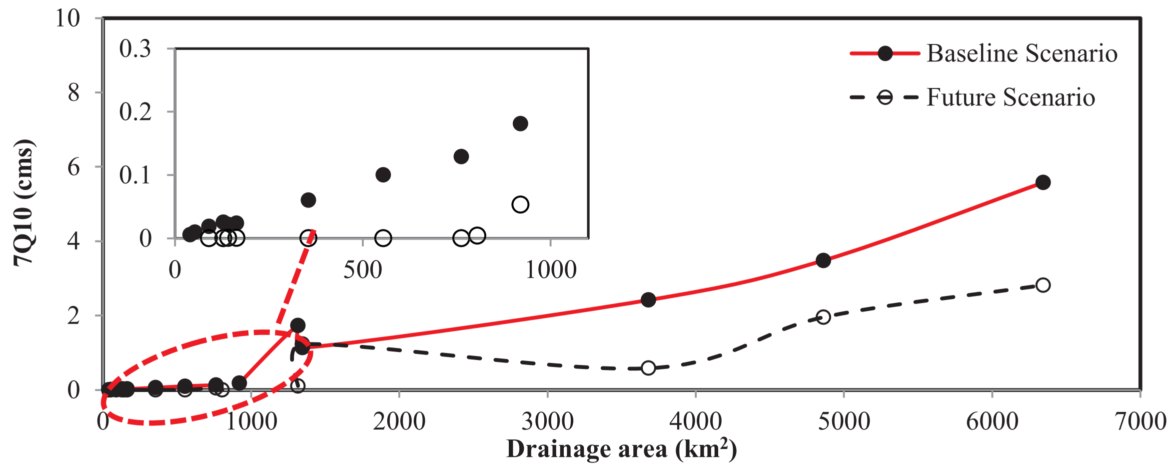

Figure 3.6 7Q10 flows for baseline and future scenario for future period (30 years).

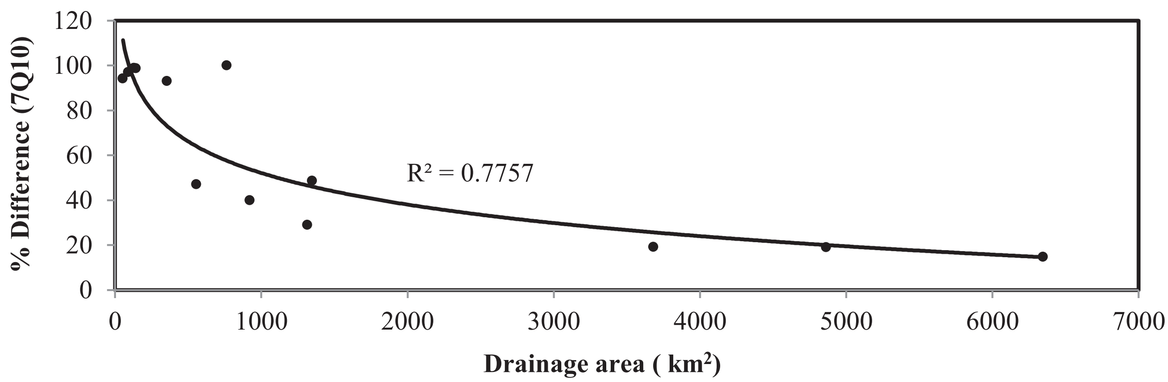

Figure 3.7 Percentage difference of 7Q10 between baseline and future scenario for future period.

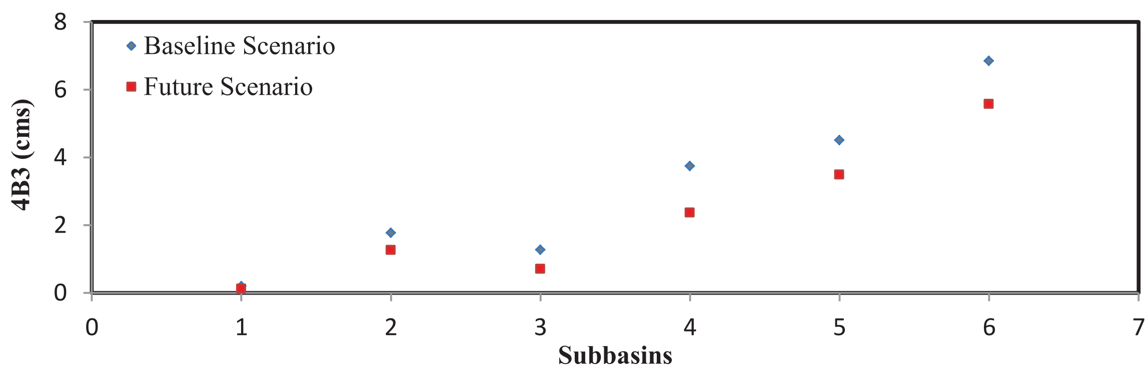

Figure 3.8 4B3 flows for baseline and future scenario for future period.

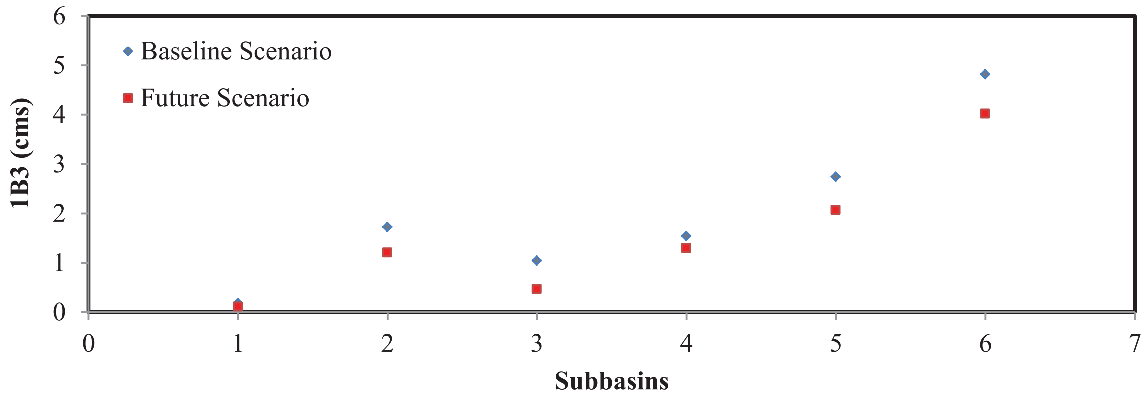

Figure 3.9 1B3 flows for baseline and future scenario for future period.

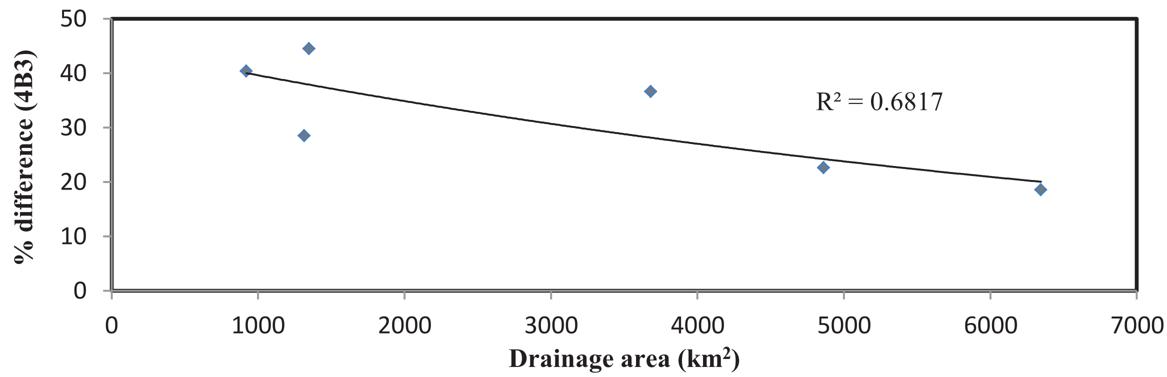

Figure 3.10 Percentage difference of 4B3 between baseline and future scenario for future period.

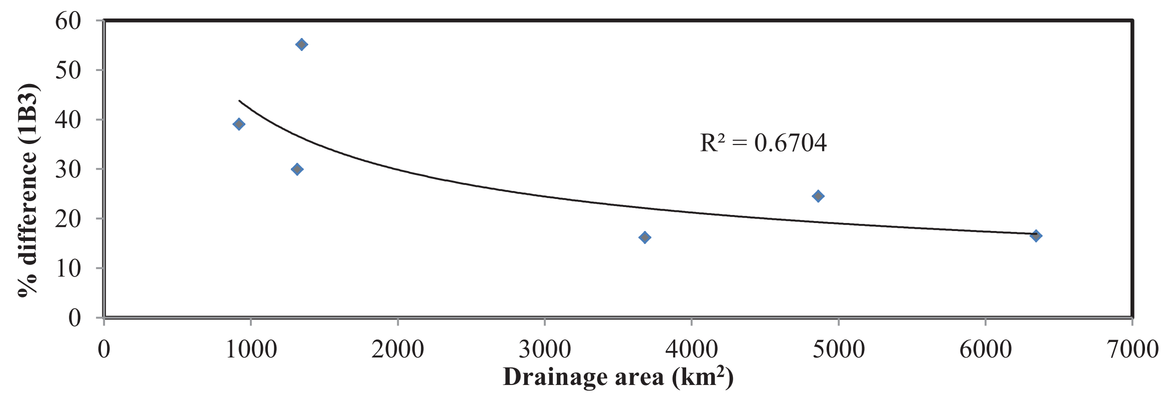

Figure 3.11 Percentage difference of 1B3 between baseline and future scenario for future period.

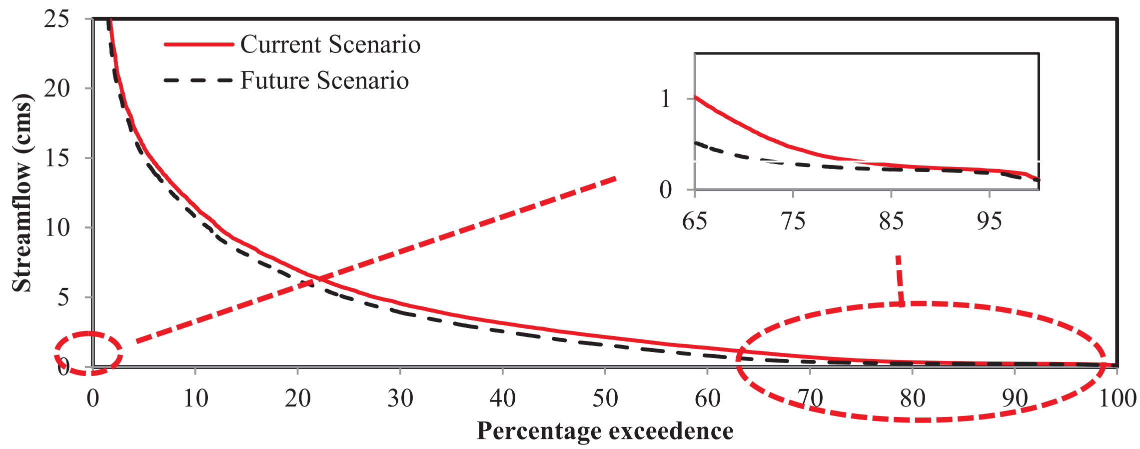

Figure 3.12 Flow duration curve for current and future scenario calculated over a 30 year period.

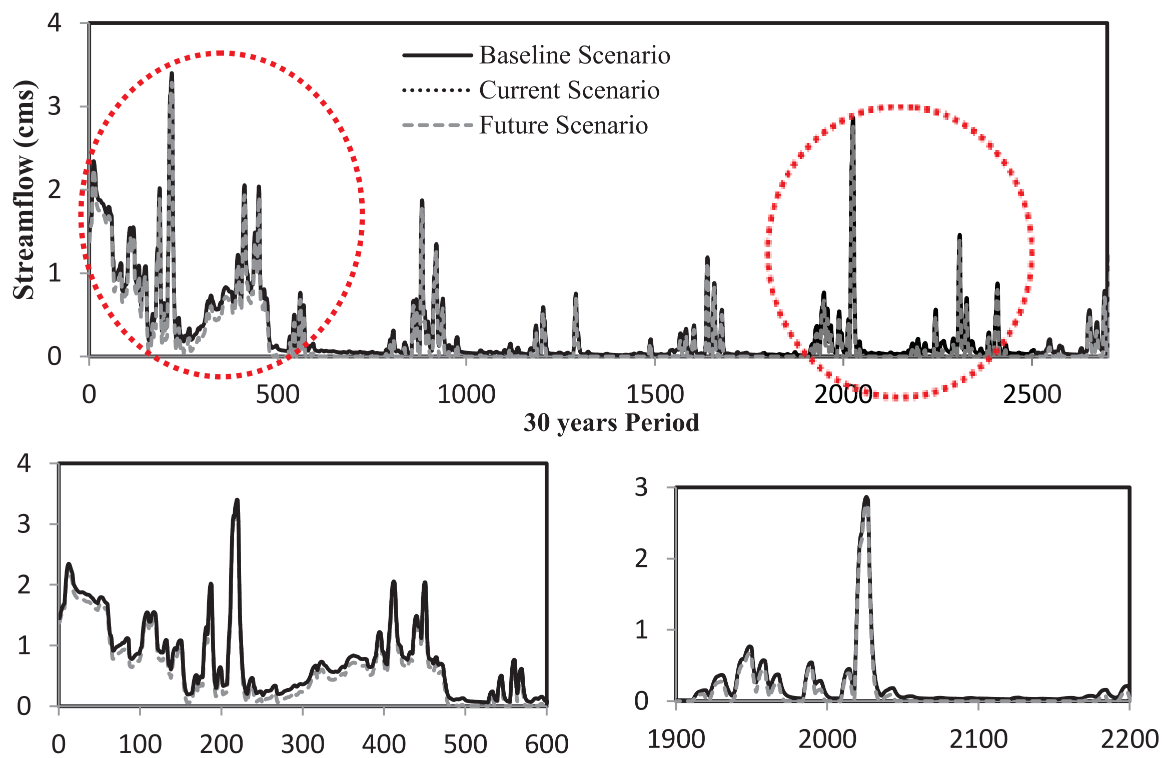

Figure 3.13 Time series of base flow on baseline, current and future scenario for future period.

Table 3.1 List of predictors used in SDSM Model to downscale NCEP reanalysis data.

Station Parameters	**Predictor Variable**	**Abbreviations**
Precipitation	Zonal velocity component at surface level	p_u
	Zonal velocity component at 850 Pa height	8_u
	Geostrophic airflow velocity at 850Pa height	8_f
	Vorticity at surface level	p_z
	Vorticity at 850Pa height	8_z
	Sea level pressure	slp
	Specific humidity at 500Pa height	s500
	Specific humidity at 850Pa height	s850
Temperature	Mean Temperature	temp
	Near surface specific humidity	shum

Chapter 4. Modeling Impact of Climate Change on Stream Low Flows in Muskingum Watershed.

Abstract

Water resources protection during low flows is always crucial when water resources scarcity occurs due to hydrologic drought. Additionally, the global climate change can exacerbate the conditions by directly reducing the streamflows, which can further worsen the surface water availability due to the large volume of water withdrawal for human consumption. Significant low flows can be experienced in the Muskingum watershed, where large amount of freshwater is utilized for hydraulic fracking by rapidly growing industries. Therefore, this study was conducted in order to assess the potential impact of future climate change on the hydrological regimes, especially during the low flow period. A widely accepted watershed model, Soil and Water Assessment Tool (SWAT) was used for watershed simulation using the climate output of Coupled Model Inter comparison Project (CMPI5). Precipitation and temperatures outputs from Max Planck Institute earth system model (MPI-ESM), assembled in CMPI5, and were used to evaluate the variation in streamflows during the 21st century. Three future periods namely, 2035s (2021-2050), 2055s (2051-2070) and 2085s (2070-2099) were set against the base condition (1995-2009). Climate model output such as maximum and minimum temperatures and precipitation during these three periods indicates the increasing trend in annual mean for all three periods. However, precipitations based on seasonal and monthly mean scale, revealed the decreasing trend in some periods. Lowest flow is projected to increase across the watershed during 2021-2050 period compared to remaining 50 years period, under the highest forced climate scenario; that is, Representative Concentration Pathways (RCP 8.5). Similarly, mean flows also can be expected to decrease during 2021 to 2050 in eastern, north-western and south western portion of the watershed. However, average annual flows are expected to increase substantially over 85% of the land surface over the 21st century. Additionally, the current fracking scenario was developed with 2035s climate output in order to assess the impact of withdrawal in current trend of fracking (2012). The effect of climate change on the stream low flows for the first 30 years of period was evaluated by comparing the result with and without considering hydraulic fracking. The effect of climate change on stream low flows was crucial when hydraulic fracking was considered. The results indicated the significant impact in 11 sources out of 32, with maximum difference up to 55% in 7 days minimum low flow even though there was negligible impact on mean streamflows. Similarly, the variation was significant in lower order streams, during low flow period indicating that low flow period was the most critical period, especially for small order streams.

Keywords: CMIP5, climate model, hydrologic analysis, MPI-ESM, SWAT, Low flow, and Drought.

Introduction

Scientist and water resources managers are always concerned about the streamflow variability, in order to protect and optimally utilize the freshwater resources, especially during low flows. Drought and low flow periods are the most crucial for flow variability and categorized as the most stressful events in the hydrological cycles. The hydrologic drought or low flow periods has become a particular interest of research topics among the scientist, recently, due to its characteristics of reducing the groundwater, lowering of the reservoir or lake level and declining in the streamflow discharge for consecutive years (Smaktin, 2000).

The temporal and spatial variation of the low flow considering the magnitude and frequency, are very essential for optimal allocation for water supply, recreation, wildlife conservation and reservoir flow regulation. Various natural factors are responsible for the low flow variation leading to the social and economic impacts. Economic losses related to the drought are so high that it is very difficult to measure and the mitigation measures have proven to be very costly (Riebsame et al. 1991). For example, the federal aid cost for mitigation activities of 1988 drought was about $7 billion and total cost associated with this drought was $39 billion. In addition to this, natural fluctuation to the low flows is affected by the anthropogenic impacts, which are causing supplementary severe conditions in the dry period. For example, large amount of water abstraction for industrial, irrigation, power generation and domestic water use reduces the downstream water volume (Benejam et al.2010). Similarly, several studies have stated that the agricultural practices may 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 flows and complications in optimal allocation of water resources. Consequently, the conflict of water resources management is mounting as the world population has been continuously increasing.

In addition to the conventional anthropogenic influence, water withdrawal for hydraulic fracking has been one of the critical issues especially for low flows period when severe drought occurs (Burton et al. 2014). Significant amount of water is withdrawn from the streams and reservoirs without considering rigorous analysis of potential impact to water environment and ecology. The future prediction of natural gas production in 2035 taking 49% share in shale gas accounts will clearly exceed the water withdrawal trend for fracturing (EIA 2012). While the fracking water volume is small in comparison with the total water availability in any area, the water withdrawal for drilling and fracturing activities over a short period of time might be stressful particularly during low stream flow. For example, it may create additional stress to the municipal water supplies and other direct human use including aquatic life in the low flow period. Spatially, this imbalance can be more consequential in specific small tributaries; and the alteration of flows can be more pronounced at the subbasin scale than at the large scale (Cothren et al. 2013).

This declining flow rates may be further stressed by decreasing trend of precipitation and increasing rise in global temperature (Vo¨ro¨smarty et al. 2000; Alcamo et al., 2003) due to the global climate change leading to the alteration in the hydrological cycle, water balance and water resource management. Therefore, there is a pressing need to explore the impact of future climate change in streamlows flows, especially for a watershed which is subjected to rapid hydraulic fracking.

Since GCMs data have to be downscaled to spatial and temporal scales to assess an impact over any affected area, downscaling technique requires very efficient expertise and computational skills. Therefore, in order to facilitate for the downscaled data at spatial and temporal scales, recently Climate model intercomparison project (CMIP5) dataset has been released by incorporating new GCM projections with more complete physical process and external forcing than previously published dataset CMIP3 (Knutti and Sedlacek 2013). Therefore, this study utilized the CMIP5 datasets to analyze the potential impact of future climate change in Muskingum watershed. This watershed is one of the major river watersheds of Ohio, where the development of oil and gas is emerging rapidly. Recently, several drilling companies are advancing to Ohio for oil and gas development leading to the water resources scarcity due to significant water withdrawal. Therefore, a widely used watershed model, Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998), was developed in order to simulate the impact of future climate change on stream low flows. While there are several publications regarding the application of CMIP3 dataset to assess the variability on hydrological regimes (Arnell et al. 2013, Van Viet et al. 2013), the application of the CMIP5 for hydrological study is ongoing research and relatively fewer articles have been published (Koirala et al., 2014; Ficklin et al., 2013). Author is not aware of any publication regarding the application of CMIP5 data for low flow evaluation in a watershed, which has a tremendous potential for hydraulic fracking. Additionally, the combined impact of climate change and fracking on stream low flows will be explored assuming current rate of fracking remains intact in the watershed.

Theoretical Background

SWAT Model

The description of SWAT model and its theoretical background have been provided in chapter 2.

CMIP5 Model

World Climate Research Program (WCRP) had developed the multi-model dataset through Coupled Model Intercomparison Project (CMIP) and made freely available through an archive at the Program for Climate Model Diagnosis and Intercomparison (PCMDI) (Brekke et al. 2013, Taylor et al. 2011). All over the world, scientists and researchers are assessing various climate related studies and also evaluating the CMIP5 output for the evaluation in Intergovernmental panel on climate change (IPCC) fifth assessment report (AR5) (Taylor et al. 2012). CMIP5 dataset incorporates newly developed four new set of climate forcing scenarios called representative concentration pathways (RCPs). RCP8.5, RCP6.0, RCP4.5 and RCP2.6 (Moss et al. 2010, Vuuren et al. 2011) are the scenarios with concentration, emission and land-use trajectories (Janssen 2013). Among these scenarios, RCP8.5 is the highest emission scenario, including greater greenhouse gas concentrations and warming effect than RCP6.0 and RCP4.5. Similarly, RCP6.0 is considered as midrange emission scenario and RCP4.5 as low range emission scenario. RCP2.6 is considered as strong mitigations scenario, which includes the increase of greenhouse gas and temperature changes to the first part of the 21st century and decreasing trend for both features on the second half of century (Maurer et al. 2014; Taylor et al. 2012). CMIP5 incorporates as the first time in CMIP project with Earth System Models (ESMs), atmosphere-ocean general circulation models (AOGCMs) and Earth System Models of Intermediate Complexity (EMICs) which helps to study extensively the impact of carbon responses on climate change (Taylor et al. 2012). Specially, it is the integration of the recent development in the integrated assessment modeling with a more comprehensive assessment of climate change than CMIP3.

Max Planck Institute earth system model (MPI-ESM)

Max Planck Institute earth system model (MPI-ESM) is the new revised earth 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 coupled model for the atmosphere is called as European Center-Hamburg (ECHAM6) for ocean as Max Planck Institute Ocean Model (MPIOM), for land and vegetation as Jena Scheme for Biosphere Atmosphere Coupling in Hamburg (JSBACH), and for the biogeochemistry as Hamburg Ocean Carbon Cycle Model (HAMOCC5) (Giorgetta et al. 2013). The new inclusion of carbon cycle has allowed research scientists to study the response of climate change on the carbon cycle. Depending on the resolution and setup of orbit and vegetation, 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).

Materials and Methodology

Study Area

The study was conducted in the Muskingum watershed, which was located in the eastern part of the Ohio. The study areas have been already described in chapter 2.

Data

The data needed for the watershed modeling including elevation, land cover, soil, climate, reservoir outflows, daily streamflows and current water use are reported in chapter 2 under the heading “Swat Model Input”. Model input and watershed delineation are borrowed from chapter 2. In order to analyze the future impact in the fresh water resources under climate change, the latest daily time scale of climate data (precipitation, minimum and maximum temperature) were downloaded, from publicly available archive for CMIP5 climate data, based on 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 needed: one for the evaluation of various climate model performances, and second for the future climate change. Since several climate models exist with the different climate forcing function, it is essential to evaluate the performance of 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). In order to conduct future climate change study, RCP 8.5 forced scenario was 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 hydrological simulations. Similarly, in order to assess the current impact of fracking for 2035s period, the data needed for current hydraulic fracking and source for fracking are described in chapter 2.

Model Calibration and Validation

The SWAT model calibration and validation procedure using SUFI-2 program has been described in Chapter 2 under heading "Model Calibration and Validation". The calibrated and validated model was used to simulate the streamflows from 1995 to 2009.

Model Evaluation Criteria

Similarly, the performance of the model was assessed using widely used four objective functions such as NSE, RMSE, PBIAS and R^2, which are described in the chapter 2 under heading "Model Evaluation Criteria".

Model Simulation

The SWAT model performance is thoroughly described in chapter 2.

Climate Modeling

The performance of climate models was examined by comparing downscaled model projected data for a historical period with observed data using squared correlation coefficient. For this, CMIP5 dataset using BCCA downscaling methods was 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 from Figure 4.1 to Figure 4.3. Out of the 19 models, the performance of MPI-ESM-LR was superior, which was evaluated based on the squared correlation coefficient (Figure 4.1). Both the configurations: MPI-ESM-LR and MPI-ESM-MR performed well for RCP 8.5 and RCP 4.5 at station 00014891 (Figure 4.2 and Figure 4.3). However, performance of MPI-ESM-MR model with RCP 8.5 and 4.5 were relatively better at station 00014891 (Figure 4.2 and Figure 4.3). As the MPI-ESM-LR configuration fitted well with the observed output in all the correlation tests and used with wide range for the CMIP 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 hydrological cycle at three different time periods: 2035s (2021-2050), 2055s (2051-2070) and 2085s (2070-2099). Similar periods were also adopted by the climate assessment report from NOAA (Kunkel et al. 2013). In the next step, climate dataset for three periods were integrated with SWAT model in order to simulate the streamflows for future climate change. For simplicity, point sources and water use data were not incorporated in the model in this analysis, as the future point sources and water use data are unpredictable.

Similarly, the current fracking condition, set as 2012 fracking activities, was applied in calibrated and validated SWAT model for the evaluation of climate change effect over a period of 2021-2050. This analysis would provide the climate change impact of early 21st century on stream low flows when current trend of hydraulic fracking remains intact.

Monthly fracking water use was provided in the model as constant values for 30 years period from the water use input file. Since the continuous lake outflow data was not available, 50 percentile of the available data from USACE was applied for a period 1995 to 2009 in order to best represent lake Outflow for 2035s period. The simulated flow for current fracking scenario was compared with the flows without fracking conditions, which is referred in this study as baseline scenario (2035s).

Result and Discussion

Climate outputs recorded from the model were assessed at one precipitation station (GHCN: USW00014891). The average monthly maximum temperature depicted that there may be generally increasing trend with the increase in period (Figure 4.4a & Figure 4.5). The monthly maximum temperature averaged over the period 2051 to 2070 is the warmest period among three periods, where it increases by nearly 7 ^{o}C in September. The changes are ranging from 1.4 ^{o}C in March to 3.6 ^{o}C in September for 2035s, 2.2 ^{o}C in March to 5.1 ^{o}C in October for 2055s, and 2.8 ^{o}C in March to 6.9 ^{o}C in September for 2085s (Figure 4.4a & Figure 4.5). Regarding seasonal changes, summer has more distinct change in monthly maximum temperatures than other seasons except for 2055s, in which, more change in autumn was realized than summer (Figure 4.4b). The mean annual precipitation also showed similar trend as the monthly average for the 2035s, 2055s and 2085s, respectively (Figure 4.4c).

Figure 4.6a & Figure 4.7 also showed the warmest period based on the monthly minimum temperatures averaged over a period of 2051-2070. The variations in these periods range from 1.8 ^{o}C in March to 3 ^{o}C in September for 2035s, 2.9 ^{o}C in March to 4.4 ^{o}C in February for 2055s, and 3.6 ^{o}C in March to 6.2 ^{o}C in August for 2085s. The study indicated that summer season would have higher increase in minimum temperature than other seasons (Figure 4.6b). Similarly, the annual minimum temperature showed an increasing trend for all three periods (Figure 4.6c). The overall analysis for temperatures from 2021 to 2099 illustrated that the watershed may be warming in the coming future based on highest forced scenario RCP 8.5. As the hydrological variation depends largely on the precipitation, future precipitations were compared with the historical observed one in Figure 4.8 & Figure 4.9. The monthly and seasonal mean scales were showing decrease in percentage change in precipitations (Figure 4.8a & b). However, all three periods showed the increasing trend in precipitations based on annual mean precipitations (Figure 4.8c). Seasonally, precipitations might be increasing at all seasons except summer and spring season in 2035s (Figure 4.8b). Therefore, mean monthly percentage change for 2035s in May, June, July and August were also showing decreasing pattern in precipitations compared to baseline precipitations. Interestingly, the highest percentage increase in 2035s (39%) can be experienced in October (Figure 4.8a & Figure 4.9). Similarly, period 2055s may encounter reduced precipitations in July, August, September, November and December. However, February might have the highest increase in precipitations in 2055s (49%) and 2085s (48%).

Hydrological cycle is mainly influenced by temperatures and rainfall pattern. The assessment was performed for the similar future periods against the baseline periods. Percentage exceedance flow taken at the outlet of the watershed indicated the chances of the occurrence of low flows are higher in 2055s than 2035s and 2085s (Figure 4.10). The percentage change in the annual mean, seasonal mean and monthly mean flows at the outlet of the watershed is presented in Figure 4.11. The monthly mean percentage change showed the September might be the stressful months in all three periods as the study showed 12.2%, 12.8% and 21.6% reduction in the streamflow indicating that water withdrawal in September month in 21st century has to be considered seriously for the water resources management (Figure 4.11a & Figure 4.12). Early period of 21st century (2035s) was crucial for water resources management as the reduction of flows by -5.4% in January, -14.2% in June, -1 %in July and -12 % in September could be expected.

On seasonal scale, mean seasonal flows showed an increase for all periods except summer in the 2035s period (Figure 4.11b), which was consistent with the precipitations trend of the period. The increasing trend was revealed in the annual mean streamflows in three consecutive future periods, which was consistent with the increasing trend of mean annual precipitations (Figure 4.11c). 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 baseline annual mean flow. The average annual streamflows depicted an increase of approximately 15%, 18.2% and 19.3% in the 2035s, 2055s and 2085s, respectively. However, the variation on some period might be due to the catchment and lag time effect in groundwater. The increment of flows for low flow period showed the positive signal for hydrological management for the 21st century.

In order to evaluate the impact of climate change on hydrological cycle for entire watershed, streamflows outlets from all the subbasins (406) for three future time periods were compared against a baseline scenario. The comparisons were based on two hydrological measures: annual percentage change on mean flow, and annual percentage change on minimum flows. Similarly, thematic map was used to explain the variation on streamflows in terms of percentage change for similar three future periods against baseline. While the watershed can experience the low flows for early 21st century (2035s) for specific months, the annual percentage mean change in streamflows showed that the watershed would be in wet conditions in 2021 to 2050 period (Figure 4.13). Yet, the eastern portion of the Tuscarawas subwatershed, eastern and western portion of Muskingum watershed, and western portion of Mohican subwatershed remain drier than other watersheds portions in this period (Figure 4.13). During 2051 to 2070 period, drier portions can be expected on eastern portion of Tuscarawas subwatershed region as in 2021 to 2050 periods but the percentage of wet zone will be decreased than first 30 years (Figure 4.14)

During 2070 to 2099, wet zone can be expected to increase to the large extent in the watershed (Figure 4.15). The drier region remains only in eastern portion of the Tuscarawas subbasin, smaller regions than previous periods. Research concluded the drier regions remain larger in first 30 years than other 50 years periods, and the watershed would get wetter in the progressive future periods.

The annual percentage minimum flows across the watershed remains fairly dry across the watershed in the first 30 years than remaining 50 years (Figure 4.16) as some portion of watershed experienced high flow in this period. Conversely, the larger wetter regions were experienced for the second 20 year period (2051-2070) (Figure 4.17). Similarly, last 30 years period showed progressively larger portion of wetter area with increased percentage difference in minimum flows (Figure 4.16). 2055s showed the major dry portion in the 1st and 2nd order streams (Figure 4.17), whereas 2085s showed the dry portion in the major stream regimes (Figure 4.18).

Similarly, the impact of the fracking scenario with the future climate change (2021-2050) was evaluated over 32 subbasins as the sources for current fracking withdrawal existed on those locations. Result revealed that the impact is insignificant in yearly mean flows as compared to current and baseline scenario (Figure 4.19). However, some impact was detected in 7 days monthly minimum flows (Figure 4.20) in 13 subbasins out of 32 subbasins, and the difference with greater than 2%. Variations were detected at all the subbasins with variable drainage area. Interestingly, all these changes were found in 1st order streams. Similarly, significant percentage changes in 7 days monthly minimum flows for baseline and current scenario with the increase in drainage area are displayed in Figure 4.21. Maximum changes up to 55% in streamflows was observed in watershed indicating that the low flow period was most crucial in climate changed condition if the hydraulic fracking is intact. However, the result varied from 3% to 55% on all affected subbasins. Similarly, the result also indicated that the change was minimum in large drainage area. In general, current fracking conditions showed the significant impact on 34% of the total sources with more than 5% change in 7 days minimum low flows. The effects are spatially critical over the lower order streams.

Conclusion and Discussion

The study analyzed the potential impact of climate change on the streamflows of the Muskingum watershed using the MPI-ESP-LR model with RCP 8.5 scenario for 21st century. The SWAT model was utilized to simulate the future streamflows using bias corrected downscaled data. Additionally, the correlation coefficient was used to evaluate the performance of various climate models which suggested that MPI-ESM model better harmonized with the observed precipitations with a satisfactory performance. Study suggested that the temperature (annual mean monthly) would increase by +2.5 ^{o}C in 2035s, 3.8 ^{o}C in 2055s and 5.3 ^{o}C in 2085s. Similarly, annual mean precipitation would increase by +3.5 % for 2035s, +7.1% in 2055s and +14% in 2085s as compared with baseline period.

The variation in the streamflows is expected to occur based on change in temperatures and precipitations. The result 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 monthly scale depicted that the coming decade has critical reduction on flows during September (low flow period). Similarly, the assessment on regional scale across the watershed suggested that 2035s is the worst period among three periods with reduction in streamflows in terms of annual percentage change, monthly mean and minimum flows.

Similarly, the assessment on the streamflows using current rate of fracking revealed that the low flow period is the crucial period over the year as 7 days minimum monthly flows indicated large variation when compared the lowest flow with and without fracking; this effect is significant in small order streams than bigger order streams.

While climate change study has uncertainty associated with the future emission of the greenhouse gasses, land cover changes and energy fluxes in the future, the research constitutes a complete framework for the systematic variation of streamflows in response to future climatic conditions. Since analysis indicates the possible change in hydrological cycle due to climate change, study provides an invaluable insight to decision makers for the water resources constraints in the watershed, especially due to water withdrawal for hydraulic fracking. More specifically, the water withdrawal in early 21st century is more crucial as the monthly low flows for summer season is expected to reduce despite increase in average annual mean flow. Therefore, planners need to devise a policy framework to incorporate the appropriate adaptation and mitigation measures to protect water resources against the future climate change impacts.

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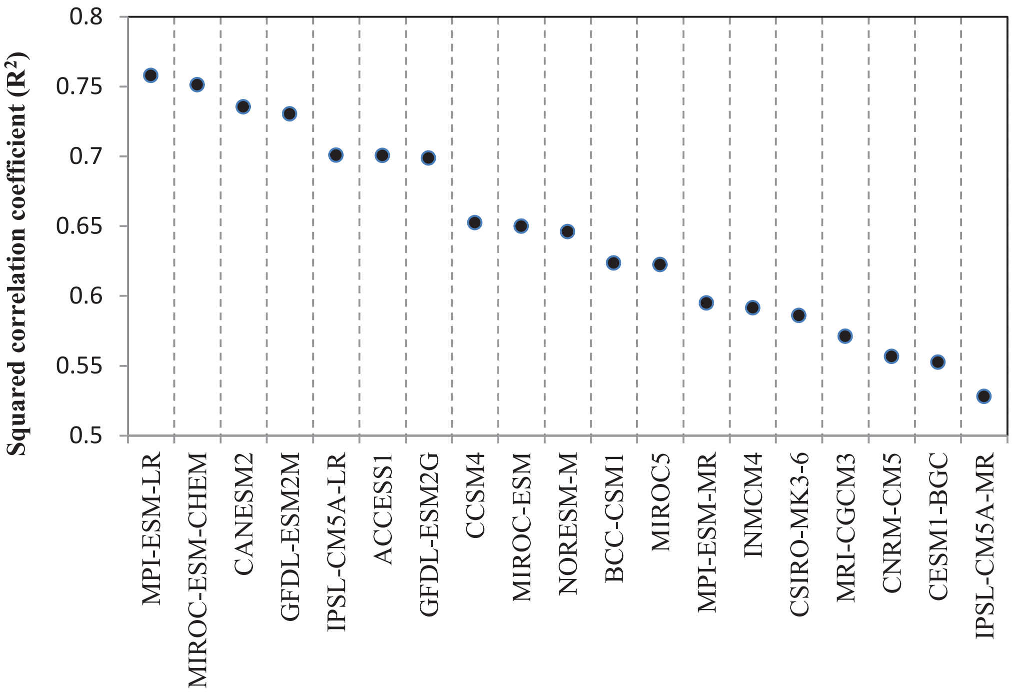


Figure 4.1 Squared correlation coefficient for 19 BCCA models under RCP 4.5 scenario of CMIP5 at precipitation station 00335747.

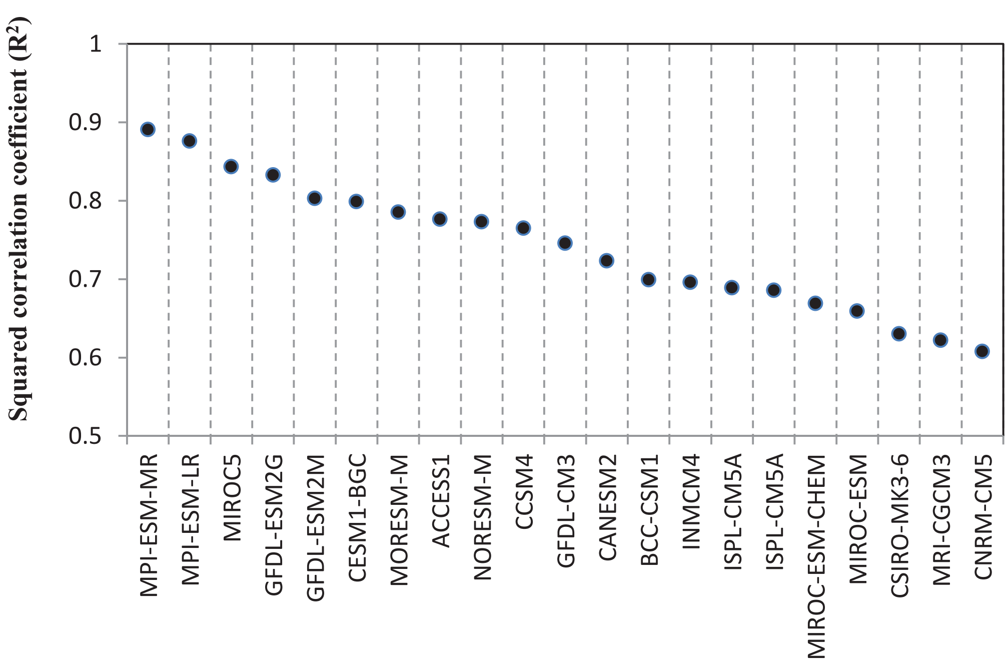


Figure 4.2 Squared correlation coefficient for 19 BCCA models under RCP 8.5 scenario of CMIP5 at precipitation station 00014891.

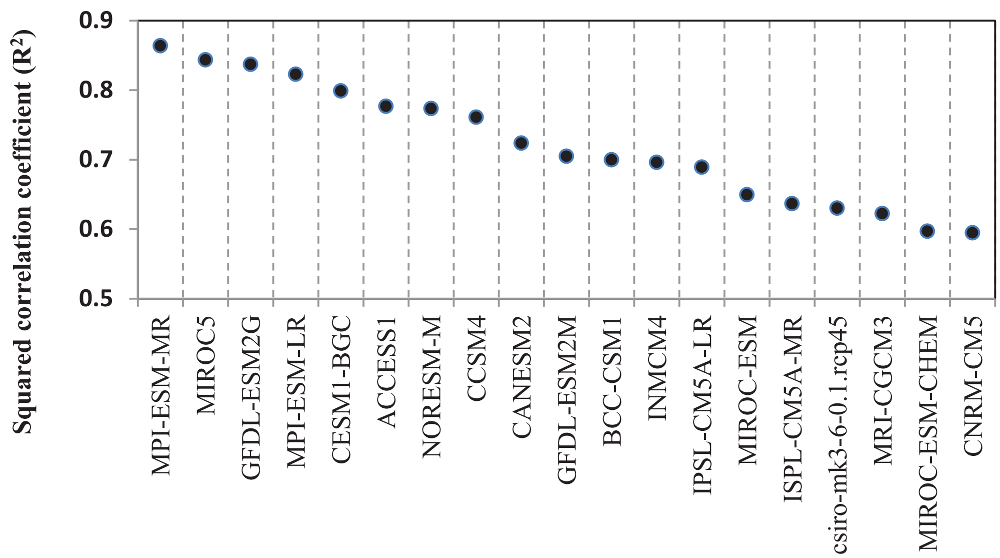


Figure 4.3 Squared correlation coefficient for 19 BCCA models under RCP 4.5 scenario of CMIP5 at precipitation station 00014891.

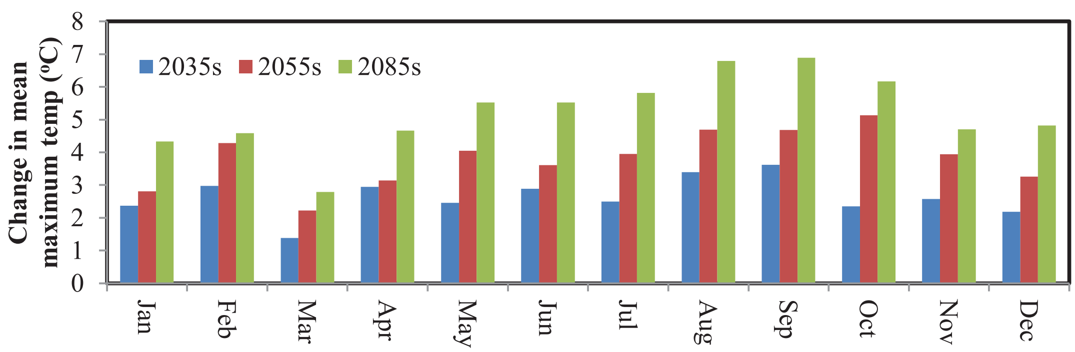
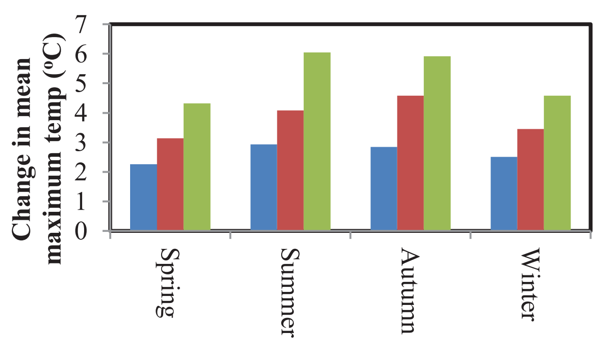


Figure 4-4 (a)



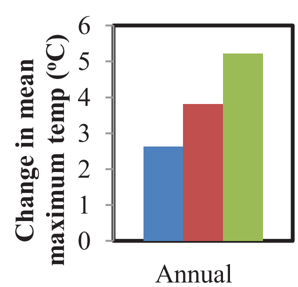


Figure 4-4 (b) Figure 4-4 (c)

Figure 4.4 a) Change in average monthly maximum temperatures predicted by MPI-ESM-LR for three future periods (2021 to 2050, 2051 to 2070 and 2070 to 2099) against the baseline period (1995-2009) at the Mansfield Lahm municipal airport station (GHCN: USW00014891), b) average changes in maximum seasonal temperatures, and c) average changes in annual maximum temperatures for three similar periods.

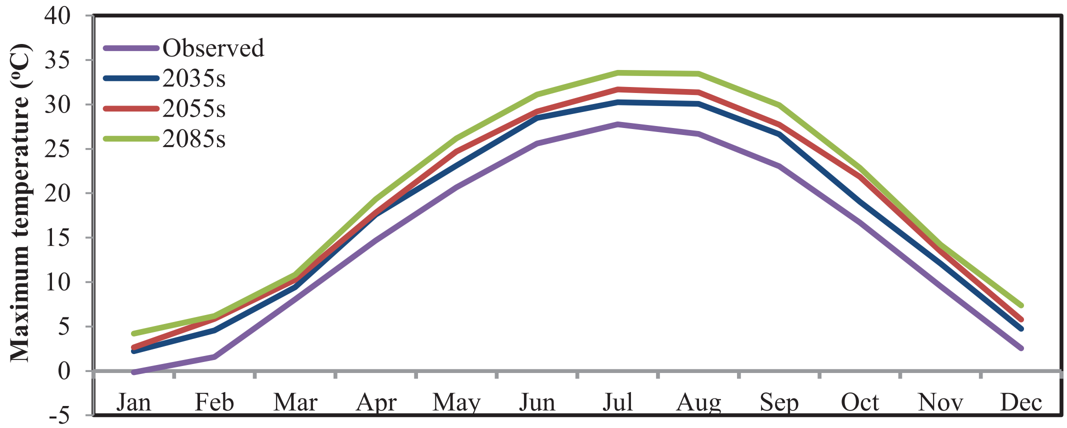


Figure 4.5 Average monthly maximum temperatures predicted by MPI-ESM-LR for three future periods (2021 to 2050, 2051 to 2070 and 2070 to 2099) & observed period (1995-2009) at the Mansfield Lahm municipal airport station (GHCN: USW00014891).

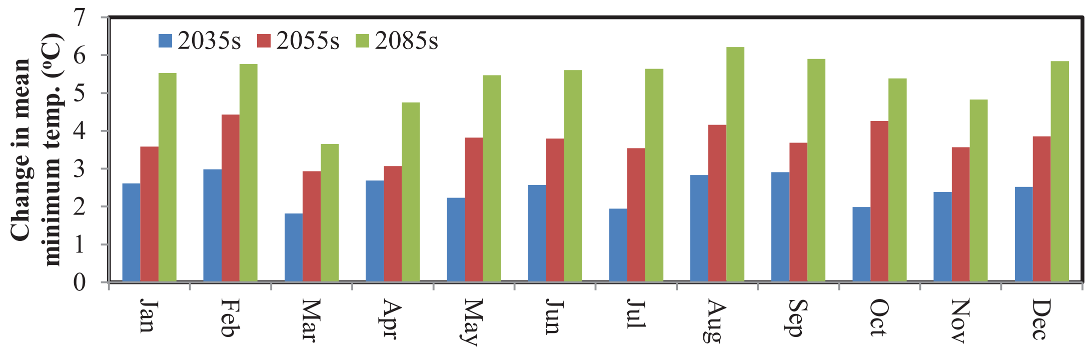
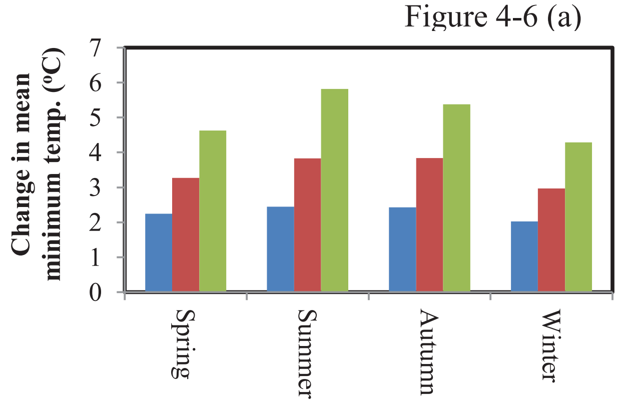


Figure 4-6 (a)



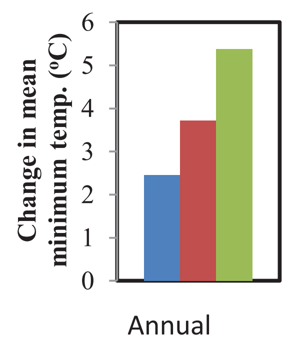


Figure 4-6 (b)

Figure 4-6 (c)

Figure 4.6 a)Change in average monthly minimum temperatures predicted by MPI-ESM-LR for three future periods (2021 -2050, 2051 to 2070 and 2070 to 2099) against the baseline period (1995-2009) at the Mansfield Lahm municipal airport station (GHCN: USW00014891), b) average changes in minimum seasonal temperatures, and c) average changes in annual minimum temperatures for three similar periods.

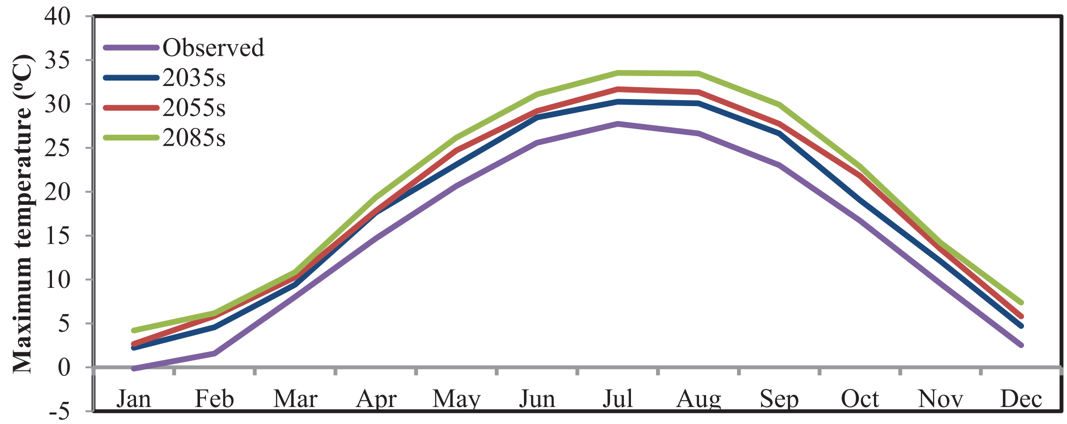


Figure 4.7 Average monthly minimum temperatures predicted by MPI-ESM-LR for three future periods (2021 -2050, 2051 to 2070 and 2070 to 2099) & observed period (1995-2009) at the Mansfield Lahm municipal airport station (GHCN: USW00014891).

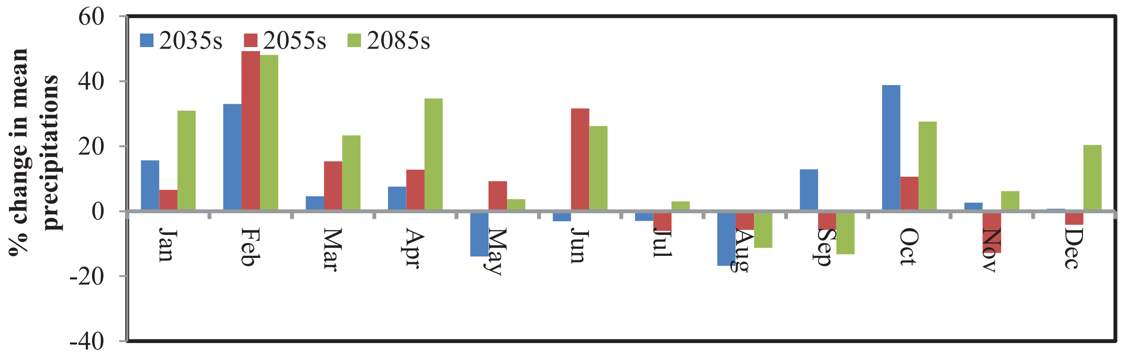


Figure 4-8(a)

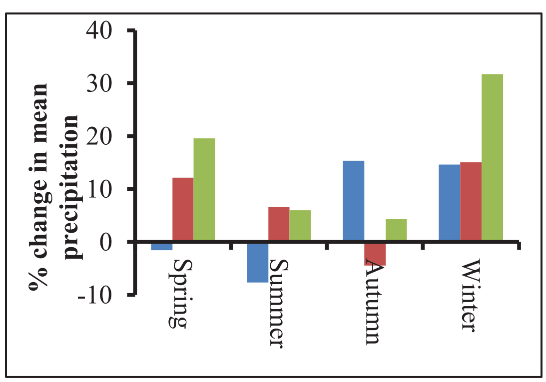


Figure 4-8(b)

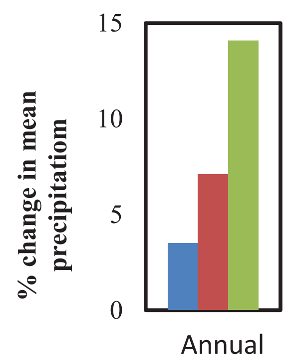


Figure 4-8(c)

Figure 4.8 a) Percentage changes in average precipitation predicted by MPI-ESM-LR for three future periods (2021 –2050, 2051 to 2070 and 2070 to 2099) against the baseline period (1995-2009) at the Mansfield Lahm municipal airport station GHCN: USW00014891, b) average changes in seasonal precipitation, and c) average changes in annual precipitations for three similar period.

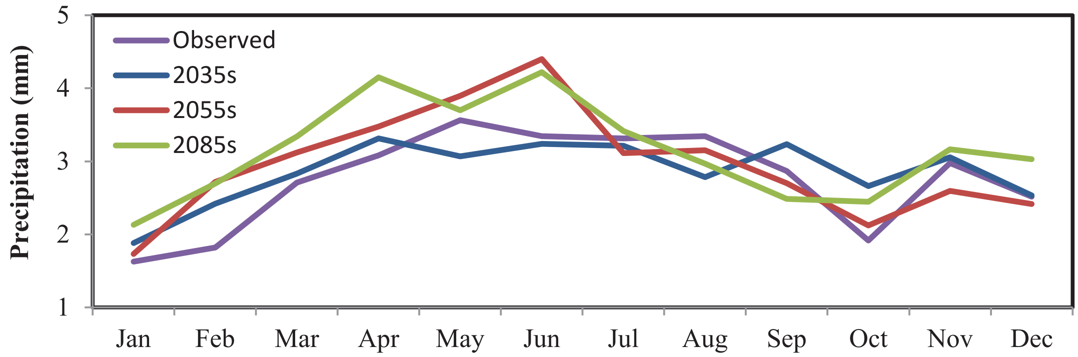


Figure 4.9 Average monthly precipitation predicted by MPI-ESM-LR for three future periods (2021 –2050, 2051 to 2070 and 2070 to 2099) & observed period (1995-2009) at the Mansfield Lahm municipal airport station GHCN: USW00014891.

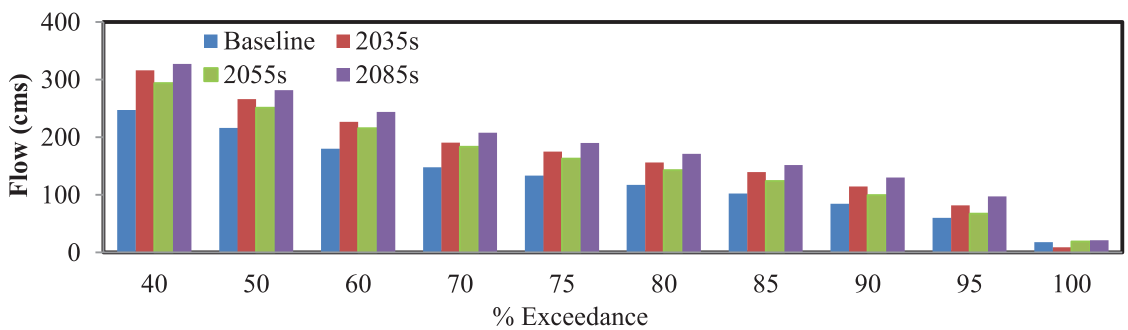


Figure 4.10 Percentage exceedance for mean flows volume for three future periods (2021-2050, 2051 to 2070 and 2070 to 2099) as compared to baseline period (1995-2009) at the outlet of the watershed.

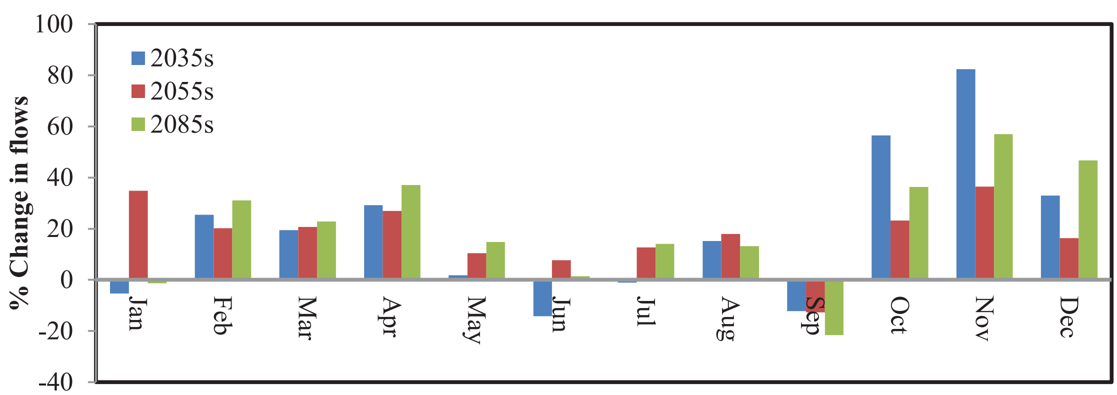


Figure 4-11 (a)

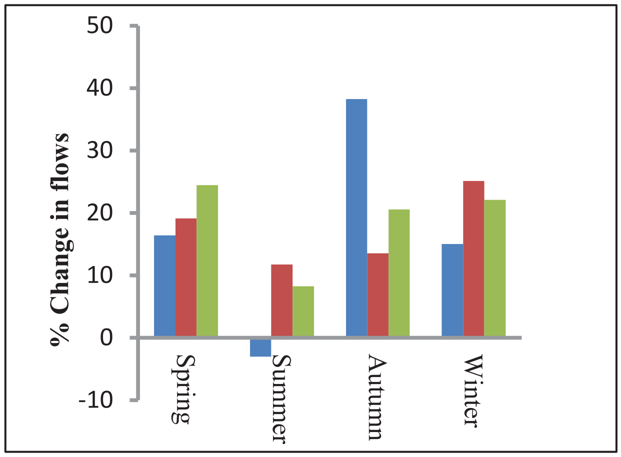


Figure 4-11 (b)

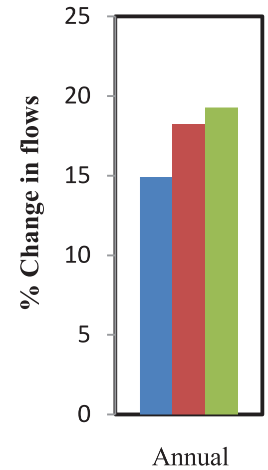


Figure 4-11 (c)

Figure 4.11 a) Percentage change in monthly mean flows 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 flows, and c) average annual flows for similar three periods.

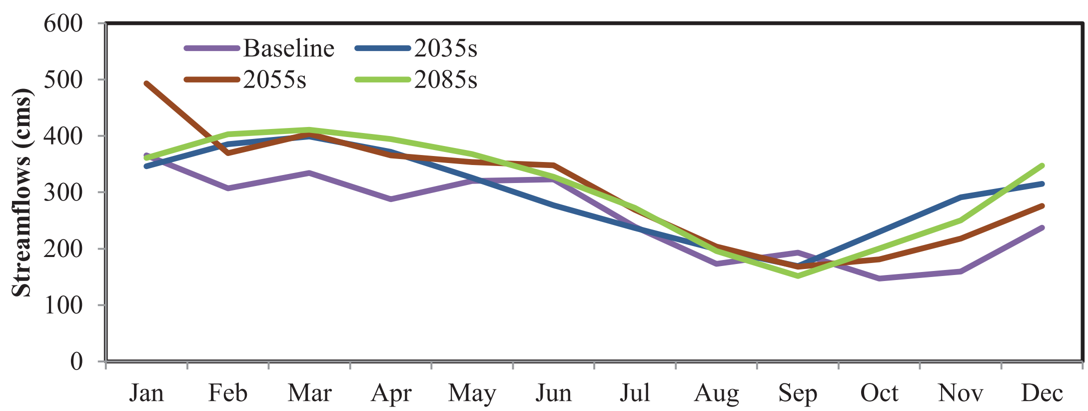


Figure 4.12 Monthly mean flows volume for three future periods (2021 -2050, 2051 to 2070 and 2070 to 2099) and baseline period (1995-2009) at the outlet of the watershed.

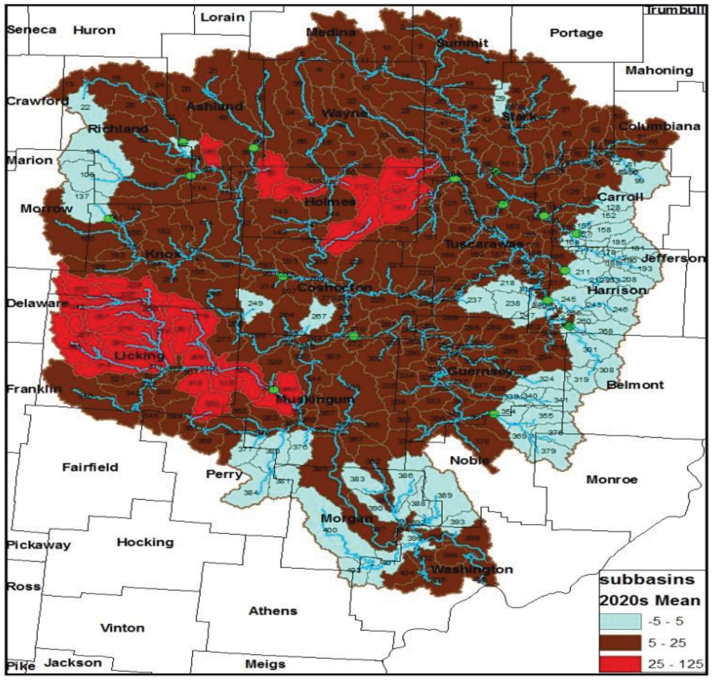


Figure 4.13 Percentage change in annual mean streamflow for future 2021 – 2050 period against base (1995-2009).

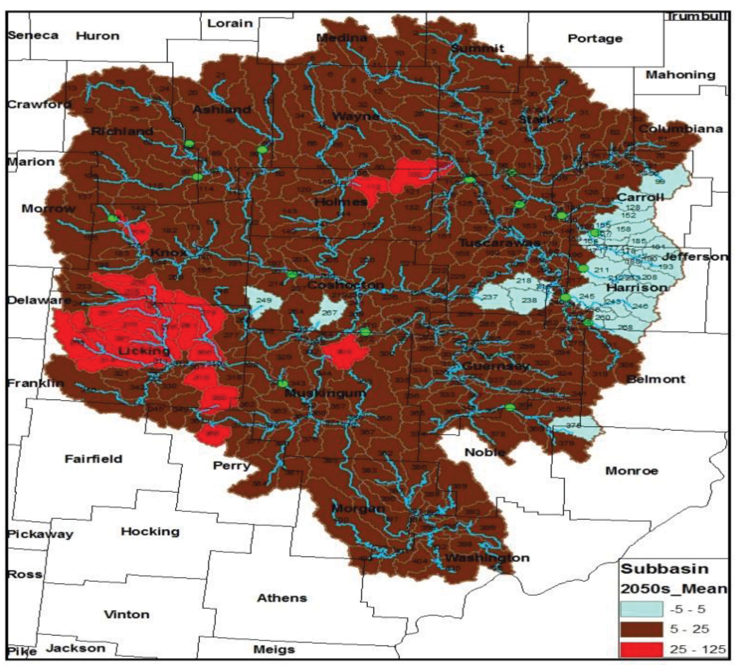


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Figure 4.14 Percentage change in annual mean streamflow for 2051 – 2070 against baseline period (1995-2009).

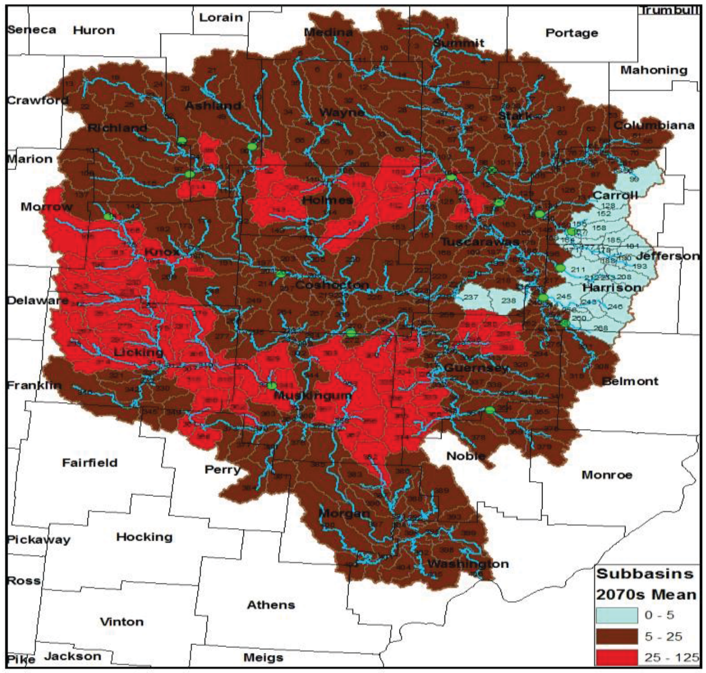

Figure 4.15 Percentage change in annual mean streamflow for 2070-2099 against baseline period (1995-2009).

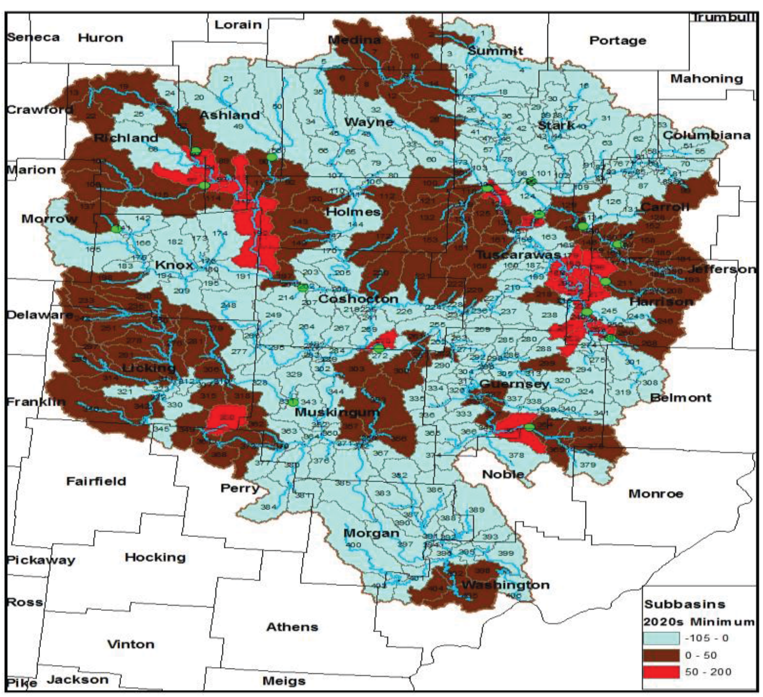

Figure 4.16 Percentage change in annual minimum streamflow for 2021 – 2050 against baseline period (1995- 2009).

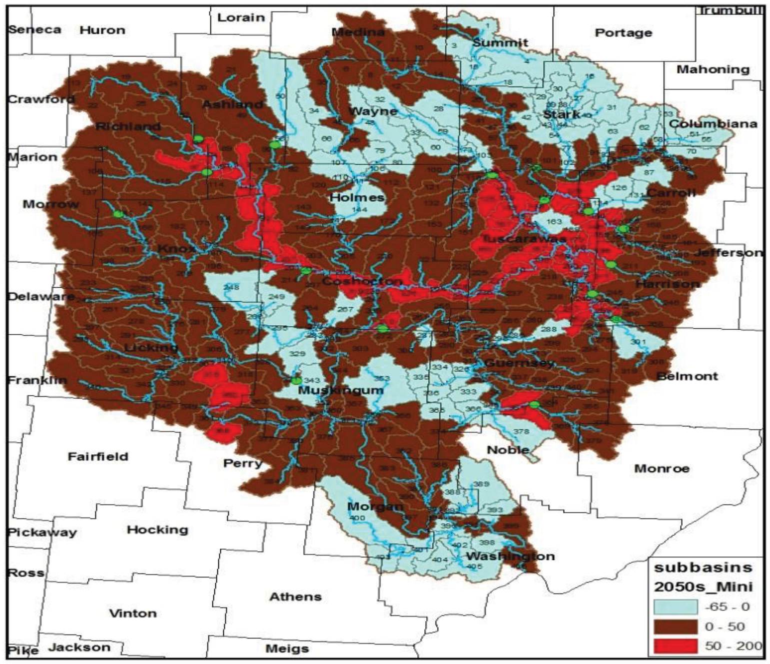

Figure 4.17 Percentage change in annual minimum streamflow for 2051 – 2070 against baseline period (1995 - 2009).

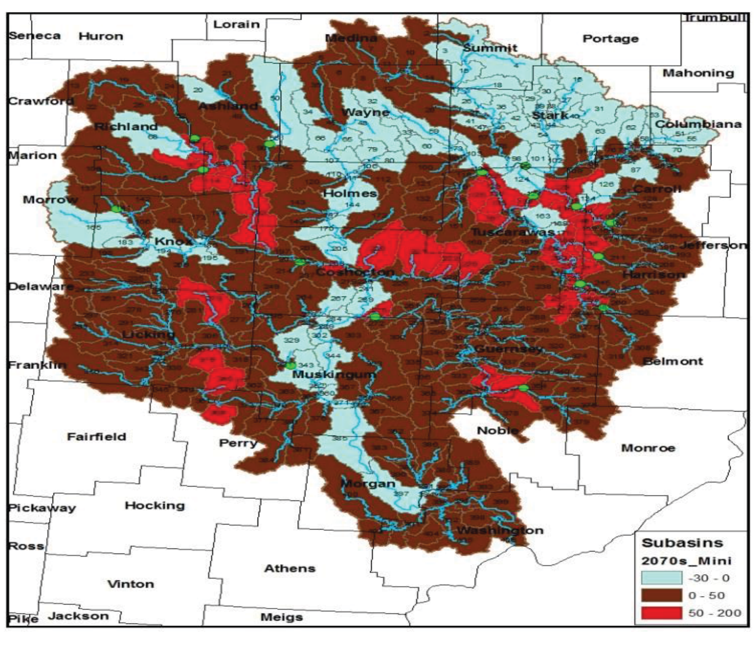

Figure 4.18 Percentage change in annual minimum streamflow for 2070 – 2099 against base (1995- 2009).

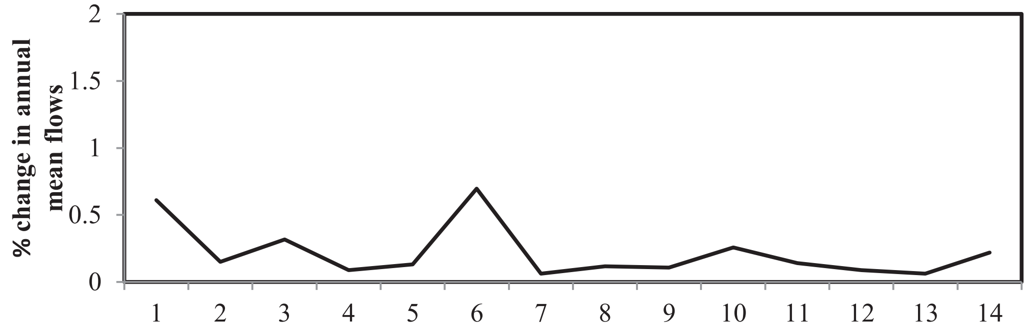

Figure 4.19 Percentage change in annual mean flows for current and baseline scenario during 2021 – 2050 periods.

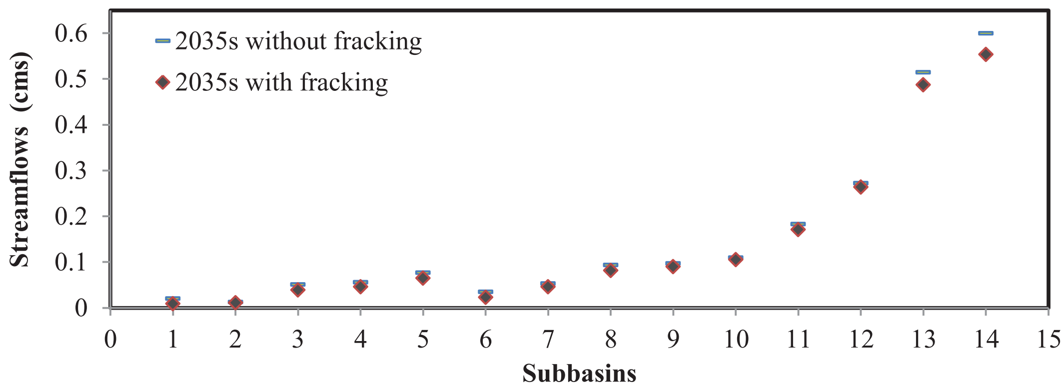

Figure 4.20 7 days monthly minimum flows for current and baseline scenario during 2021 -2050 period.

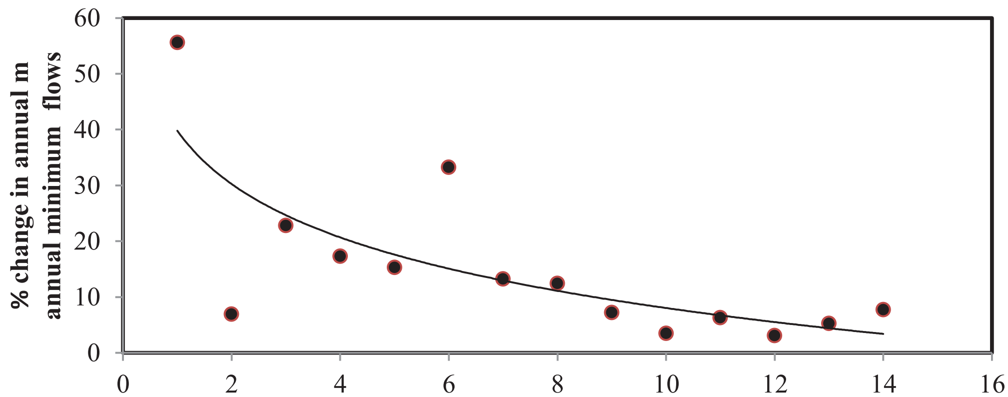

Figure 4.21 Percentage change in 7 days minimum flows for current and baseline scenario during 2021-2050 periods.

Chapter 5. Conclusions and Recommendations

The study initiates with the systematic review and documentation of the existing watershed models in order to select appropriate model for the assessment of potential impact of hydraulic fracking in watershed. Based on current literature, 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. Then, the model was calibrated and validated using multisite model calibration and validation technique in Muskingum Watershed. Calibration and validation were performed for the period from 2002 to 2009 and 1995 to 2001, respectively using observed daily flow at nine various USGS stations. The model captured the spatial and temporal pattern of stream flow satisfactorily with reasonable accuracy.

Simulated flows in ungauged locations were used to generate baseline and current scenarios with and without fracking for 2012 in order to assess the potential impact of water withdrawal for hydraulic fracking on water resources. Baseline scenario represents year 2012 simulation without hydraulic fracking and current scenario represents with hydraulic fracking for same year (2012). Analysis showed that water withdrawal due to hydraulic fracking had localized impact on the water resources, especially during low flow period. Greater alterations were found in seasonal mean (high flow) than the yearly mean flow. 30% of the withdrawal locations showed more than 5% changes in 7 days minimum monthly flows between baseline and current scenario. However, the impact is significant in small order streams.

Similarly, statistical downscaling model (SDSM) was used to generate thirty years of plausible future daily weather series based on occurrence of 25 percentile of historical dry period. Future flows were simulated to generate the baseline, current scenario (with current level of fracking) and future scenario (with future projected fracking). Significant differences were detected on future scenario with respect to baseline for the environmental low streamflows such as 7Q10, 4B3 and 1B3. However, impact of fracking was in the decreasing trend with the increase in drainage area. Flow duration curve for baseline, current and future scenarios also suggested that the low flow was affected as the alteration was noticeable below 85 % flow exceedance. As the low flow is supported by the ground discharge into the streams, the base flow for future scenario was varied.

Additionally, the future climate change was assessed by using the precipitation and temperatures output for the period from 2021 to 2099 from Max Planck Institute earth system model (MPI-ESM-LR) under the highest forced climate scenario (RCP 8.5), assembled in CMPI5. Three future periods namely, 2035s (2021-2050), 2055s (2051-2070) and 2085s (2070-2099) were set against the base condition (1995-2009). Results revealed the increasing trend in temperatures and precipitations in annual mean for all three periods. The monthly maximum temperature averaged over the period 2051 to 2070 is the warmest period among three periods, where it increases by nearly 7^{o}C in September. Summer has more distinct change in monthly maximum temperatures than other seasons except in 2055s with autumn showing slightly more change than summer. Similarly, summer season would have higher increase in minimum temperature than other seasons. Similarly, for precipitation, the seasonal and monthly mean scales were showing decrease in percentage change. However, annual mean precipitations are in increasing trend for all periods.

Lowest flow is projected to increase across the watershed during 2035s period as compared to remaining 50 years period. The monthly mean percentage change showed that September might be a stressful month in all three periods. Similarly, mean seasonal flows showed an increase for all periods except summer in the 2035s period. Mean flows also can be expected to decrease. During 2035s, the eastern, north-western and south western portion of the watershed might remain drier than other watershed portions. However, during 2055s period, drier portions can only be expected on eastern portion of Tuscarawas subwatershed region. Similarly, during 2070 to 2099, wet zone can be expected to increase to the large extent in the watershed.

Similarly, the impact of current fracking scenario was assessed with first 30 years of future climate change (2021-2050) setting two scenarios: baseline and current scenarios. Result revealed that the impact was insignificant in yearly mean flows as compared to current and baseline scenario. The low flow period was concluded to be crucial period over a year as 7 days minimum monthly flows indicated large variation in streamflows and these variations are only significant in small order of streams.

This research successfully applied the SWAT model for the study related with hydraulic fracking and its impact on water balance, even though uncertainties exist on the complex watershed model associated with the input data, model development and various hypothetical scenarios and climate model,. Results might be valuable to planners and decision makers to manage water resources against fracking, especially during low flow period. Similarly, necessary policy framework are suggested to be changed in order to incorporate the appropriate adaptation and mitigation measures to protect water resources against the future climate change impact and hydraulic fracking.