ASSESSING THE PERFORMANCE OF BROOKVILLE FLOOD CONTROL DAM

by

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To my beloved parents, who supported me and wish me the best every second.

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ABSTRACT

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In this study, the performance of a flood control reservoir called Brookville Reservoir located in the East fork of the Whitewater River Basin, was analyzed using historic and futuristic data. For that purpose, USEPA HSPF software was used to develop the rainfall runoff modelling of the entire Whitewater River Basin up to Brookville, Indiana. Using uncontrolled flow data, the model was calibrated using 35 years of data and validated using 5 years by evaluating the goodness-of-fit with R^2, RMSE, and NSE. Using historic data, the historic performances were accessed initially. Using downscaled daily precipitation data obtained from GCM for the considered region, flows were generated using the calibrated HSPF model. A reservoir operation model was built using the present operating policies. By appending the reservoir simulation model with HSPF model results, performance of the reservoir was assessed for the future conditions.

1. INTRODUCTION

The term "Flood control" can be defined as the effort to prevent, minimize or even eliminate the damage of flood water. Due to the necessity of water, major cities were located near water resources such as lakes, rivers etc. Natural flood disasters often endanger the lives and cause severe damages to the properties. Hence, flood control became a significant topic of civil and environmental engineering.

Floods of natural rivers happen when high intensity rainfall occurs in a short time. It can also happen during long spells of rainfall. It can be controlled using structural and nonstructural measures. Structural measures include reservoirs and levees constructions. Nonstructural measures involve the best management practices, flood plain development and management. Construction of the reservoirs became the most commonly used method of flood control because they can serve multiple purposes. Most reservoirs were created by constructing dams on rivers. They were used for single or multiple purposes, for instance, flood control and flow balancing, hydroelectricity generation, water supply, and recreation.

Literature review indicates numerous studies which were done in the past for reducing the effects of floods, multipurpose optimizations and reservoir operations. The purpose of this research is to analyze the benefits derived from a flood control reservoir located on the East Fork of Whitewater River in southeast Indiana called Brookville Dam. This study focus is on the assessment of the flood control effectiveness.

Brookville Lake Dam is located just upstream of Brookville Township, Franklin, Indiana. The dam is designed and constructed by the U.S. Army Corps of Engineers in 1974. This dam is 181 feet high and 2800 feet long. Brookville Lake is the largest reservoir in Whitewater River Watershed system. The lake has a water surface of 8.2 square miles. Maximum capacity of this reservoir is 359,600 acre-feet. Brookville Lake is mainly used for flood control and recreation. Based on the historical research which was published in 1988, the construction of the dam prevented more than 2.5 million dollars in flood damage since 1974 (DNR).

In order to accomplish the objectives mentioned above, a HSPF (Hydrological Simulation Program – FORTRAN) model was built by using EPA BASINS (Better Assessment Science Integrating Point and Non-Point Sources) as the initial interface. HSPF is commonly used software for watershed and water quality studies such as TMDLs (Total Maximum Daily Loads). In this study, an attempt is made to use HSPF in reservoir studies. All factors which affect the watershed rainfall runoff, such as infiltration, base flow recession, routing were calibrated using historic data.

For assessing the flood control reservoir effectiveness in the futuristic scenario, future precipitation data generated by GCM (General Circulation Model) was used for simulation. GCM is a type of climate model which is used for weather forecasting by using physical, fluid-dynamical, chemical and even biological equations (NOAA). For two different representative emission pathways (2.6 and 8.6), future precipitation data were downloaded and analyzed.

A HEC HMS (Hydrologic Modeling System) was also built for the same purpose.

2. LITERATURE REVIEW

2.1. U.S. EPA BASINS and HSPF

For the considered objective, a rainfall runoff simulation model is needed. To select an appropriate model, initially the literature review was focused on rainfall runoff models (Hromadka II, 1990, Yapo *et al.*, 1996, Devia *et al.*, 2015, Jakeman and Hornberger, 1993). Pool *et al.*, (2017) examined the models to predict flow in ungagged sites.

Several rainfall runoff models were used in the field successfully in the past (Devia et al 2015). In this research study, HSPF model developed by USEPA with BASINS interface was used. Main advantage of this modeling approach is that the model is compatible to water quality modeling too. Further, several tools available with HSPF provides flexibilities to handle the pre and post processing. In this section, HSPF model related publications were reviewed.

Shirinian-Orlando and Uchrin (2007) developed a rainfall runoff model using HSPF modeling with the Upper Maurice River watershed, New Jersey, USA. They calculated the water budget in order to predict the total runoff form the land segment using the climate data for water quality modeling proposes. Imhoff et al. (2007) studied the significance of climate change and land use change of watersheds by using EPA BASINS 4.0 and HSPF mode. Twenty land use types in the 1900 km^2 watershed (Monocacy River Watershed, Maryland) was considered in that case study. Luzio et al. (2002) used HSPF model for the Upper North Bosque River watershed in Central Texas, USA. They considered data from January 1993 through July 1998 and used daily flow. Zhang and Wen (2003) developed watershed rainfall runoff model for Spring Creek watershed (HUC 03130010) with HSPF. They examined the specific parameters which need to be calibrated and developed calibration indices.

All these studies using HSPF modeling indicate the suitability and practicality of using BASINS and HSPF for creating the rainfall and runoff model for a watershed with integrated weather data available with BASINS WDM files. Whittemore and Beebe (2000) studied the usefulness of EPA BASINS. They summarized the advantages and disadvantages of the software and also provided the proposals for the future BASINS enhancements and additions. Recent versions of USEPA BASINS were updated significantly with several such suggestions provided by the end users. Lee et al. (2009) used EPA BASINS and the HSPF model for seven watersheds in the Chesapeake Bay area in order to assess the watershed performance of the EPA's nonpoint source water quality assessment decision support tool. NLDAS (North American Land Data Assimilation System) data was used as an alternative to NOAA NCDC (National Climatic Data Center)'s station data in this study. 1/8 hourly NLDAS precipitation and evapotranspiration data were imported to HSPF model for assessing the improvement of streamflow prediction. NSE (Nash-Sutcliffe model efficiency coefficient) was calculated and used to analyze the datasets. Xie and Lian (2011) compared and evaluated SWAT and HSPF using Illinois River Basin as the focusing watershed. NSE was used as the major criteria of comparison and evaluation for two models. The study indicates that the accuracy that the HSPF model can achieve in a modeling exercise have more reliance on the efficacy of the calibration.

2.2. HEC-HMS

Oleyiblo and Li (2009) created a HEC-HMS model for Misai and Wan'an catchments in China based on DEM data and precipitation data. This model was successfully used in flood forecasting. Meenu et al (2013) used HEC-HMS and SDSM for assessment of climate change impacts in Tunga-Bhadra river basin, India. The method comparing calibration period and validation period by using R^2 coefficient and NRMSE for streamflow analysis was introduced. Choudhari et al. (2014) developed HEC-HMS model and indicated the parameters which can be calibrated and optimized for model development process. They used the Balijore Nala watershed, Odisha, India. The application of RMSE in flow analysis was successful done and the equations are provided.

Considering the unique location and size of the East Fork Whitewater River Watershed, similar researches were reviewed for literature review. Zhang and Bakir (2008) studied Xinanjiang watershed which has the similar catchment area of 1369.89 square miles. Rainfall runoff model was created and calibrated for that watershed and the performance of HEC-HMS was evaluated by comparing with historical data. Abushandi and Merkel (2013) created rainfall runoff model of arid region with elevation difference of 800 meters in Jordan using HEC-HMS. Flow was analyzed by comparing observed flow and simulated flow. Nash-Sutcliffe model efficiency coefficient was used to quantify the goodness-of-fit between observed and simulated flow.

2.3. GCM

Global Climatic Models (GCM) are popularly used for examining the futuristic scenarios. Detailed documentation of GCM are available in the Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections website as the link:
https://gdo-cp.ucllnl.org/downscaled_cmip_projections/#Projections:%20Subset%20Request

These resources are available in public domain and users can download them and scale them down to use to their region. Many successful applications were presented in literature. In this section, few of them were reviewed. Ma *et al.,* (2014) studied the prediction of the anomalous precipitation for the summer of 1998 in China. The entire China was separated into 8 regions and JJA (June, July, and August) mean precipitation and JJA mean precipitation increment were developed. General Circulation Model (GCM) was introduced in that research paper, and the practicability of GCM in climate prediction was illustrated specifically. Giorgi (1990) studied the regional climate simulation results using a Limited Area Model (LAM) nested in a General Circulation Model. GCM was used to model the atmospheric behavior on a larger scale in that study. Kite *et al.,* (1994) successfully simulated streamflow in a macroscale watershed with the basin area over 61,000 square miles using GCM data. Mackenzie River Basin in northwestern Canada was studied for model development. 2 years of data (1986-1987) were used for calibration and 3 years (1988-1990) were used for validation in that study.

Bartman et al. (2003) successfully recalibrated the GCM output to austral summer rainfall over Southern Africa and mentioned the significance of continual data collection to modify the model. Crane and Hewitson (1997) specifically indicated that “the models are not effective and producing accurate short-term spatial and temporal simulations for several important climate variables – temperature and rainfall.” “The models have yet to achieve a viable skill level at the scales necessary for assessing climatic impacts on human societies.” Due to the uncertainty of the future climate data, the predicted future flow needs to be calibrated timely.

Based on previous studies, GCM output can be applied to future streamflow predictions. Downscaled GCM precipitation data were used for this research.

3. SYSTEM CONSIDERED

3.1. Brookville Dam – Basic Details

Brookville Lake Dam (National ID #IN03017) located near the southeastern part of Indiana State, around 65 miles away from Indianapolis and 35 miles from Cincinnati. The dam was constructed by the United States Army Corps of Engineers in 1974 in Brookville Township, Franklin County, Indiana. The coordinates of Brookville Lake Dam are presented below:

Table 3.1 Coordinates of Brookville Lake Dam

Name	Latitude	Longitude
Brookville Lake Dam	39.4395	-85.000

Brookville Lake dam has a height and length of 181 feet 2800 feet respectively. It impounds the East Fork Whitewater River. The primary propose of the dam is for flood control and water management. The aerial photograph of the dam site and its side view are given in Figures 3.1 and 3.2 (Thanks to Google Maps and Wikipedia).

Figure 3.1 Satellite Planform of Brookville Dam from Google Maps

Figure 3.2 Side View of Brookville Dam

After the construction of the dam, a riverine reservoir was created and named as Brookville Lake. The reservoir has the controlled surface elevation of 740 feet (in winter time December 1st to March 15th) to 748 feet (in summer time May 1st to October 15th), normal water surface area of 8.2 square miles, and the normal storage of 184,900 acre-feet for 748 feet in summer time. The lake is designed to have the maximum capacity of 359,600 acre-feet and the water surface level is designed to be maximum 775 feet during flood periods. The lake is also used for recreation, includes boating, hunting, fishing, and hiking. Adjacent recreation facilities include Mounds State Recreation Area and Whitewater Memorial State Park. The Figure.3.3 shows the location of Brookville Lake:

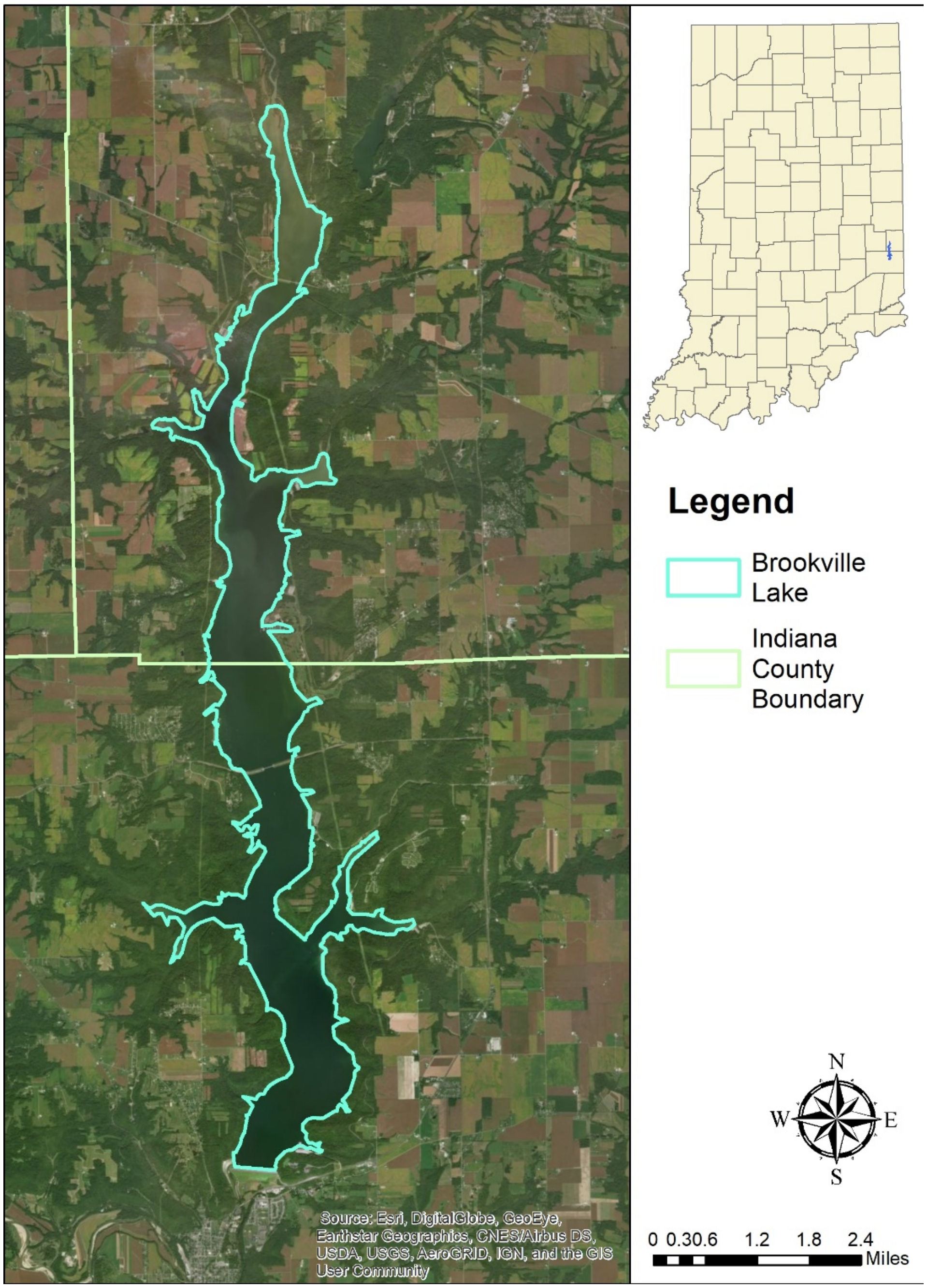


Figure 3.3 Brookville Lake

Whitewater River has the length of approximately 101 miles, it is formed by two forks, the west fork and the east fork. The channel length of west and east fork are 69.5 miles and 56.7 miles respectively. The average slope of the river is 1.1 m/km. Brookville Lake Dam is constructed on the east fork for the flood control propose to manage downstream of the Whitewater River and the Ohio River.

The dam is operated by the Louisville District, Great Lakes and Ohio River Division of the US Army Corps of Engineers. 6 hourly water surface elevation, inflow, outflow and precipitation data were recorded since January 1st, 1983 to the present day can be used for research proposes. This data is available on US Army Corps of Engineers website, Brookville Lake Yearly Lake Reports data set from 1983 to 2017. The data can be downloaded using the link below: http://www.lrl-wc.usace.army.mil/reports/yearly/Brookville%20Lake.html

This reservoir is operated historically with summer pool level (May 1st to Oct 15th) and winter pool level (December 1st to March 15th) at 748 ft and 740 ft respectively (Figure 3.4). Appropriate releases were made in the transition period to build the water level or lower the water level as shown in the figure:

DATE / TIME	ELEV	FLOW	FLOW-RES OUT	PRECIP-INC
	INST-VAL	INST-VAL	INST-VAL	PER-CUM
	FEET	CFS	CFS	INCHES
2016/1/1 6:00	747.22	876	3182	0
2016/1/1 12:00	747.06	1265	3432	
2016/1/1 18:00	746.83	1038	3428	
42371	746.58	939	3424	
2016/1/2 6:00	746.36	1082	3421	0
2016/1/2 12:00	746.13	1029	3417	
2016/1/2 18:00	745.88	935	3413	
42372	745.64	996	3409	
2016/1/3 6:00	745.4	944	3405	0
2016/1/3 12:00	745.15	891	3400	
2016/1/3 18:00	744.8	401	3396	
42373	744.65	1408	3392	
2016/1/4 6:00	744.38	729	3063	0
2016/1/4 12:00	744.14	714	2530	
2016/1/4 18:00	743.96	750	2529	
42374	743.79	810	2527	
2016/1/5 6:00	743.59	611	2525	0
2016/1/5 12:00	743.4	659	2523	
2016/1/5 18:00	743.21	658	2521	
42375	743.02	657	2519	
2016/1/6 6:00	742.83	682	2517	0
2016/1/6 12:00	742.63	636	2210	
2016/1/6 18:00	742.47	673	2019	
42376	742.33	674	2018	
2016/1/7 6:00	742.19	672	2017	0
2016/1/7 12:00	742.05	672	2016	
2016/1/7 18:00	741.91	680	2015	
42377	741.76	638	2014	

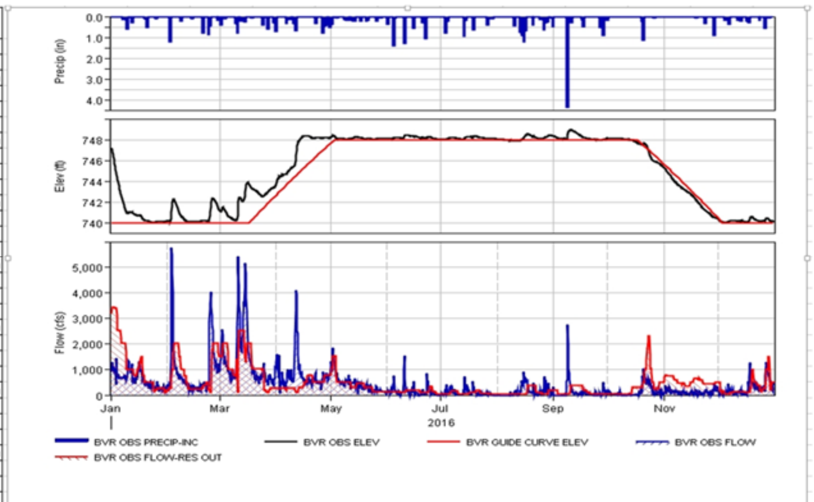


Figure 3.4 Sample of Brookville Lake Operation Data

3.2. Historic Flow Observations

Two gaging stations were operated by USGS in this system. One station is located at the downstream of Brookville Lake and the other one was located after the confluence of east and west forks. Gaging station (USGS 03276000 and USGS 03276500) location details are given in the Table 3.2.

Table 3.2 Coordinates of USGS Hydraulic Stations

Station ID	Latitude	Longitude
3276500	39.43389	-85.0033
3276000	39.40747	-85.0129

Flow data for these gaging stations are available through the USGS website. However, the one located on East Fork Whitewater River (03276000) records the flow data only from October 27^{th}, 2016 to March 6^{th}, 2018. Due to the lack of data, the station after the intersection of East and West fork (03276500) is considered for this study. Water channel daily discharge data is available on that station from October 1^{st}, 1915 to the present day. The dataset can be downloaded on the link below:

https://waterdata.usgs.gov/in/nwis/dv/?site_no=03276500&agency_cd=USGS&referred_module=sw

The above-mentioned dam operation data and gaging station flow data were used for model calibrations.

3.3. Data Downloaded from U.S. EPA BASINS

U.S. EPA BASINS was used to handle the preliminary geospatial data consolidation and data downloads. EPA BASINS provides automated download facilities for different datasets. By selecting the major watershed (Eight Digit HUC 05080003), several data were downloaded by software automatically. More data can be downloaded from the menu File/Download Data option. All data are displayed bellow:

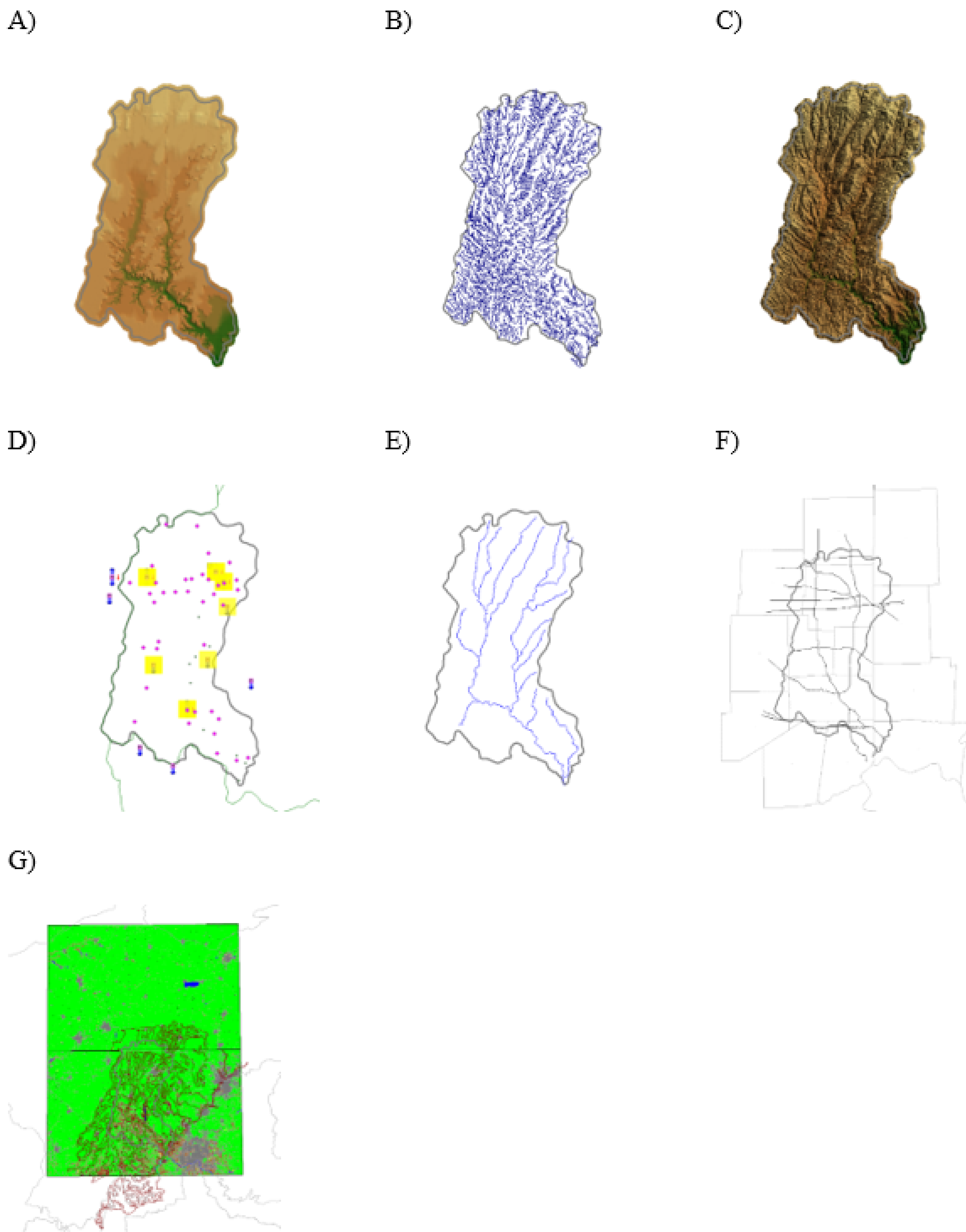


Figure 3.5 U.S. EPA BASINS Data

(Note: A. Digital Elevation Model, Grid. B. National Hydrography Dataset. C. National Elevation Dataset. D. Observed Data Stations, Point Sources and Withdrawals. E. Reach File, V1. F. Transportation and Political. G. Soil, Land Use and Cover.

After the data download, climate data were downloaded as WDM file format which is unique database format for HSPF modeling. 23 datasets were downloaded which includes hourly rainfall, daily temperature, potential evapotranspiration, wind speed, sunshine hours, dew point temperature, cloud cover. After downloading the required data, through BASINS, HSPF model was initiated. BASINS software runs in MAPWINDOW GIS platform and helps in geospatial data consolidation and this data were used to initiate the HSPF model.

The WDM rainfall data were updated with field specific precipitation data. The watershed covers 4 counties (Fayette, Franklin, Union, and Wayne counties). 7 weather stations covering this region were downloaded from USDA SWAT website. Indiana is grouped under Region 5 which includes Illinois, Indiana, Kentucky, Michigan, Missouri, Ohio, and Wisconsin State. Precipitation data from January 1st, 1950 to December 30th, 2010 were downloaded using the links:
https://www.ars.usda.gov/plains-area/temple-tx/grassland-soil-and-water-research-laboratory/docs/region-5-illinoisindianakentuckymichiganmissouriohiowisconsin/

Coordinates and identification codes of these 7 climate gaging stations are listed on the following table:

Table 3.3 Coordinates of Climate Gaging Stations

Station ID	Latitude	Longitude
C121229	39.8667	-85.1833
W03846	39.7667	-84.8333
C127362	39.8500	-84.8500
C127370	39.8833	-84.8833
C125050	39.5833	-84.9167
C121030	39.4167	-85.0167
C120132	39.5667	-85.1667

Daily precipitation data of these stations were averaged and used in the model development.

All the above-mentioned data and methods were used for historical data analysis and watershed rainfall runoff model calibration. For futuristic reservoir operation analysis, GCM precipitation data was used as the input of calibrated models. GCM model is available online from Scripps Institution of Oceanography on the link:
https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/#Projections:%20Subset%20Request

Time period, domain, spatial extent selection method, projection set, and output format can be specified on that website and results can be received by requester as an .nr file for different representative concentration pathways. Time period was selected as 2018 to 2099. Downloaded file can be opened with Arc MAP as a point shape file and read through the attribute table. Daily data was further disaggregated to hourly precipitation data.

This dataset was converted from Excel to WDM file and imported to HSPF model for future analysis. The above-mentioned data resources were used in historical data analysis as well as for the future scenario reservoir analysis.

4. HISTORICAL DATA ANALYSIS

4.1. Flow Data

Whitewater river basin is located in the southeast Indiana near Cincinnati. Its tributary is East Fork White Water River. To prevent the flooding, US Army Corps built a flood control dam in this tributary called the Brookville Dam. East Fork watershed drains approximately 380 square miles in Wayne, Union, Fayette, and Franklin counties. Two USGS gaging station located after the confluence of the Whitewater River and the East Fork White water tributary (03276500) (Figure 4.1) was used for this study. At this gaging station, the watershed drainage area is 1224 sq. miles.

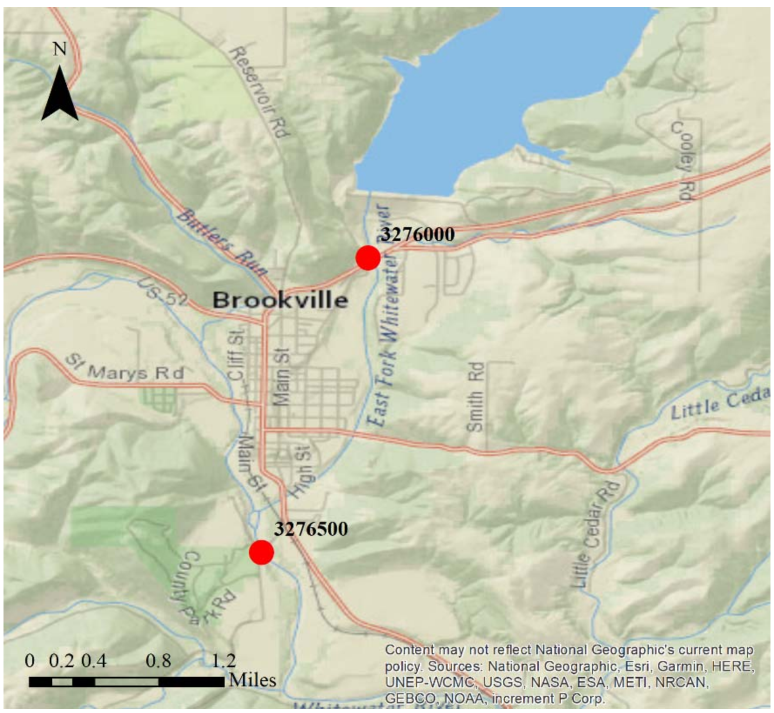


Figure 4.1 Locations of Hydraulic Monitoring Stations

Daily discharge data has been recorded by USGS from October 1st, 1915 to the present day. The period of record covers over 100 years includes the dam construction in 1974, which is appropriate for this research proposes.

Another USGS gaging station 03276000 is located on the East Fork, approximately 2000 feet on the downstream of the dam. At this site, hydraulic data, including discharge (mean), gage height, pH, dissolved oxygen and etc., is recorded by USGS and uploaded to the official website. However, for daily discharge of the stream, the period of record is only from October 27th, 2017 to March 6th, 2018. Due to the lack of data, this site was used only for reference.

Due to the dam construction in East Fork River, after 1974, the flow at this station has been controlled by the flood control reservoir operation. Historic inflow data, outflow data, stage data and precipitation of Brookville Lake were used as East Fork data. Inflow to dam was used as the East Fork flow data.

It is 6 hourly data from 1983 to 2017. A sample data is attached as figure below:

8	DATE / TIME	ELEV	FLOW	FLOW-RES OUT	PRECIP-INC
9		INST-VAL	INST-VAL	INST-VAL	PER-CUM
10		FEET	CFS	CFS	INCHES
11	2017/1/1 6:00	740.08	324	420	0
12	2017/1/1 12:00	740.05	202	346	
13	2017/1/1 18:00	740.05	303	346	
14	42737	740.03	212	346	
15	2017/1/2 6:00	740.01	168	153	0
16	2017/1/2 12:00	740.01	163	99	
17	2017/1/2 18:00	740.02	183	99	
18	42738	740.03	183	99	
19	2017/1/3 6:00	740.05	455	99	0.14
20	2017/1/3 12:00	740.1	593	99	
21	2017/1/3 18:00	740.18	731	99	
22	42739	740.26	731	99	
23	2017/1/4 6:00	740.32	686	492	0.35
24	2017/1/4 12:00	740.35	745	736	
25	2017/1/4 18:00	740.35	729	736	

Figure 4.2 Sample of Reservoir Data

After the initial data were downloaded, historic data analysis was conducted to study the benefits obtained from the flood control reservoir operations. Using the historical flow data observed by USGS gaging station 03276500, yearly peaks were captured for the 103 years (1915 to 2017). Figure 4.3 gives the data plot in chronological order. This figure shows a significant peak reduction after the dam construction. In the first 59 years (1915-1974) before dam construction, 7 peaks went above 40000 cfs. During 1959 flood level reached a stage of 27.78 ft on 01/21/1959. At this stage

Advanced Hydrologic Prediction Service web site indicates a flooding of "Water reaches the top of the levee that protects low-lying areas of Brookville. The business district at Brookville behind the levee is threatened. Major flooding continues along the river from Stavetown to New Trenton and West Harrison in Indiana to Harrison in Ohio. Lowland roads are flooded along the river and homes and businesses are affected." But, after 1974, in the last 44 years, peak flow did not go beyond 40000 cfs. These data can be found though the website below:
https://water.weather.gov/ahps2/hydrograph.php?wfo=iln&gage=brki3

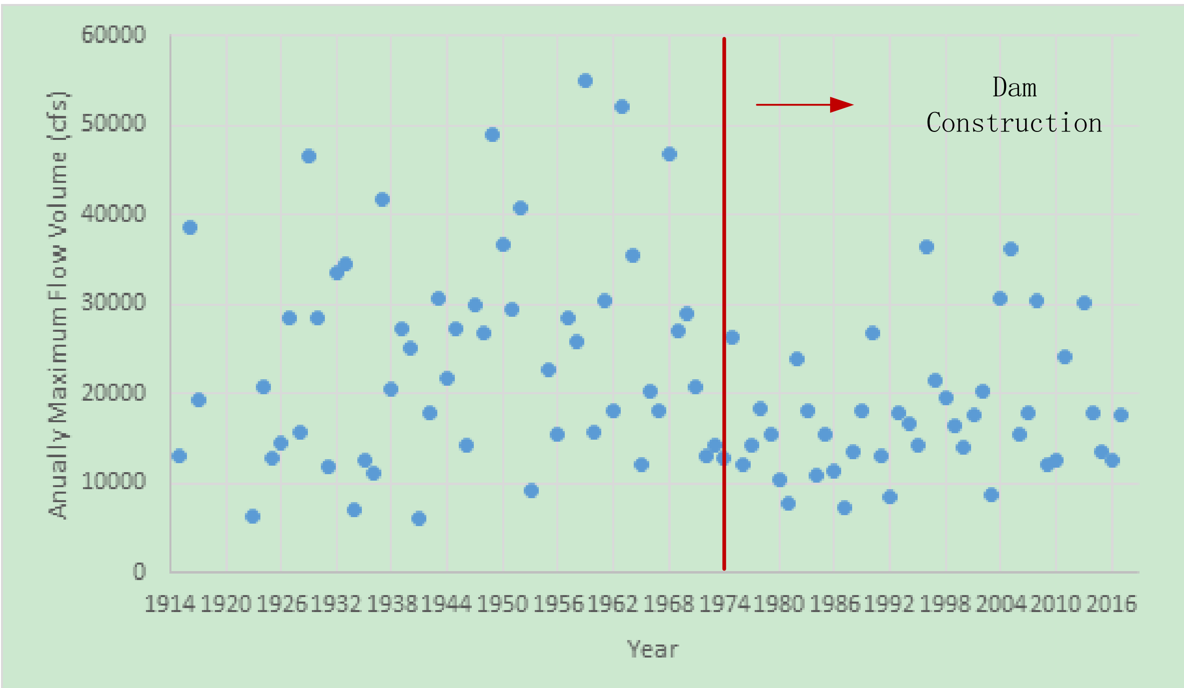


Figure 4.3 Whitewater at Brookville Yearly Peaks

Apart from larger peaks, this dam operation resulted in low peak reduction too. In past 44 years from 1974 to 2017 after dam construction, only 15 peaks over 20000 cfs were occurred in the Whitewater River. However, prior to dam, 74 peaks over 20,000 cfs were observed. After dam construction, 162 peaks under 20000 cfs were observed. Likewise, low peaks (5000 to 20000) were also examined. After 1974, 624 peaks were observed but only 672 of peaks were observed prior to dam. Low peaks are not destructive, so the reservoir operation benefitted the downstream flooding area by minimizing the floods. The detailed number of peak appearances, average annual peak appearance and percentage of peak reduction is presented in Table 4.1.

Table 4.1 Detailed Peak and Peak Reduction Conditions

Peak Stream Volume Range (×1000 cfs)	Before Dam Construction 1915-1974		After Dam Construction 1974-2017		Percentage of Peak Reduction (%)
	Number of Appearances	Average Annual Peak Appearance	Number of Appearances	Average Annual Peak Appearance	
5-10	479	8.12	477	10.84	-33.53
10-15	140	2.37	110	2.50	-5.36
15-20	53	0.90	37	0.84	6.39
20-25	36	0.61	7	0.16	73.93
25-30	19	0.32	3	0.07	78.83
30-35	7	0.12	3	0.07	42.53
35-40	4	0.07	2	0.05	32.95
40+	8	0.14	0	0.00	100.00

Based on the Brookville Dam operation data, in the past 44 years, inflow went beyond 5000 cfs for 441 times. Two storms resulted in an inflow greater than 20000 cfs. If the same rainfall occurred over the entire Whitewater River basin, it might have resulted in a flood peak of 65207 cfs in 1983 and 65213.5 cfs in 1990 at the USGS 03276500 by simple proportion. Inflow characteristics were examined in the next stage. Number of inflow peaks more than 5000, 10000, 15000 and 20000 cfs in the last 44 years were presented in Figure 4.4:

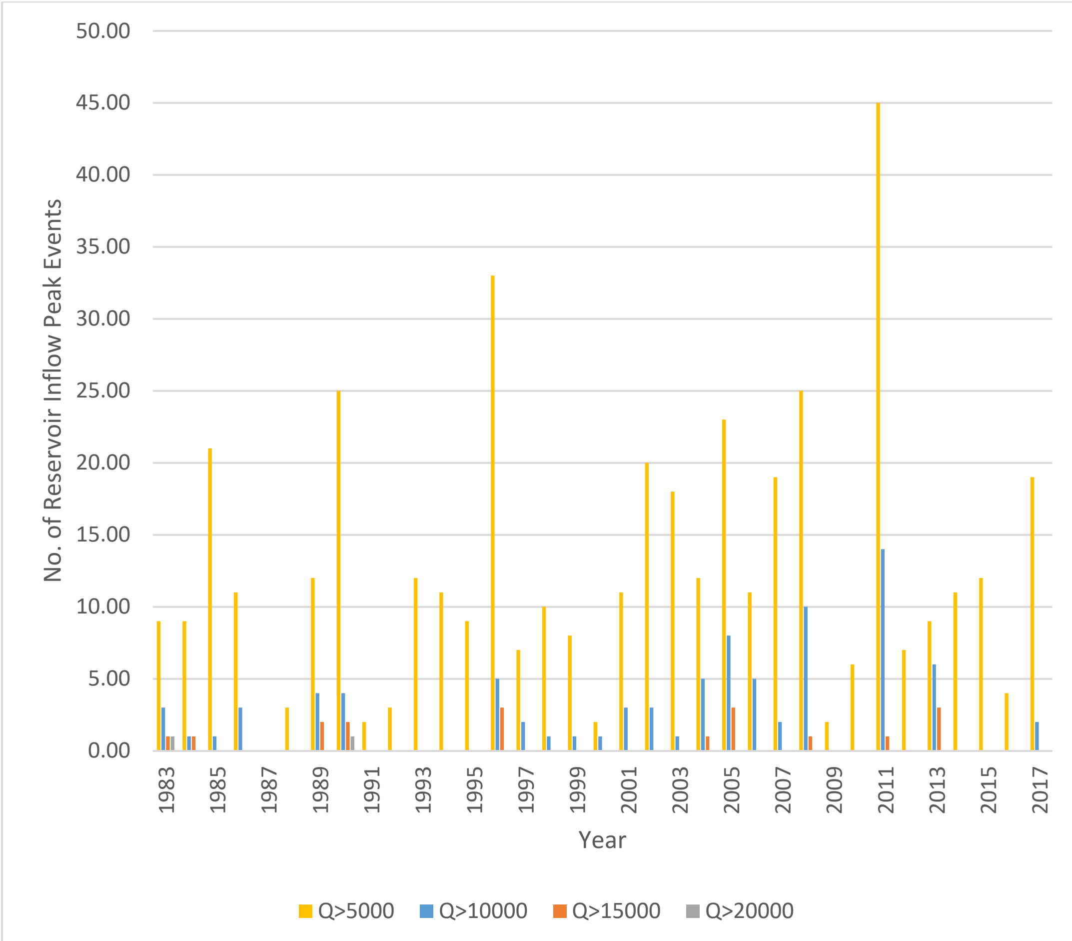


Figure 4.4 Number of Reservoir Inflow Peaks after Dam Construction

During the same period, outflows were also analyzed. Outflow peaks more than 5000, 10000, 15000 and 20000 were captured (Figure 4.5). While comparing Figure 4.4 and Figure 4.5, it was observed that the peak outflows were reduced substantially.

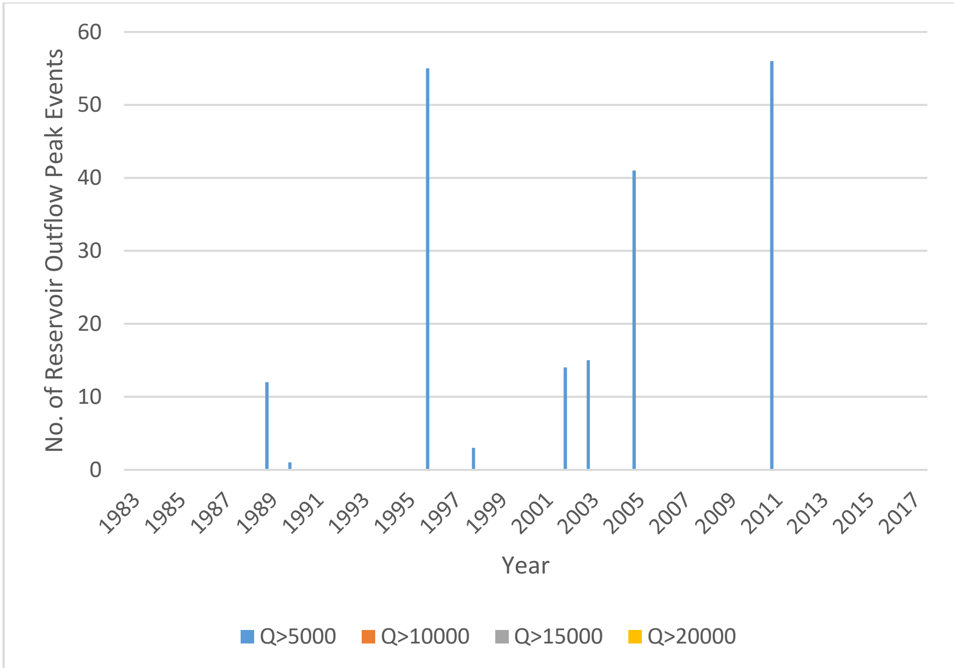


Figure 4.5 Number of Reservoir Outflow Peaks after Dam Construction

By focusing on the inflow peaks, the reservoir inflow was compared with reservoir outflow for the times when inflow peaks occur, the annual percentages of peak reductions which conducted by the reservoir are presented as Figure 4.6 below:

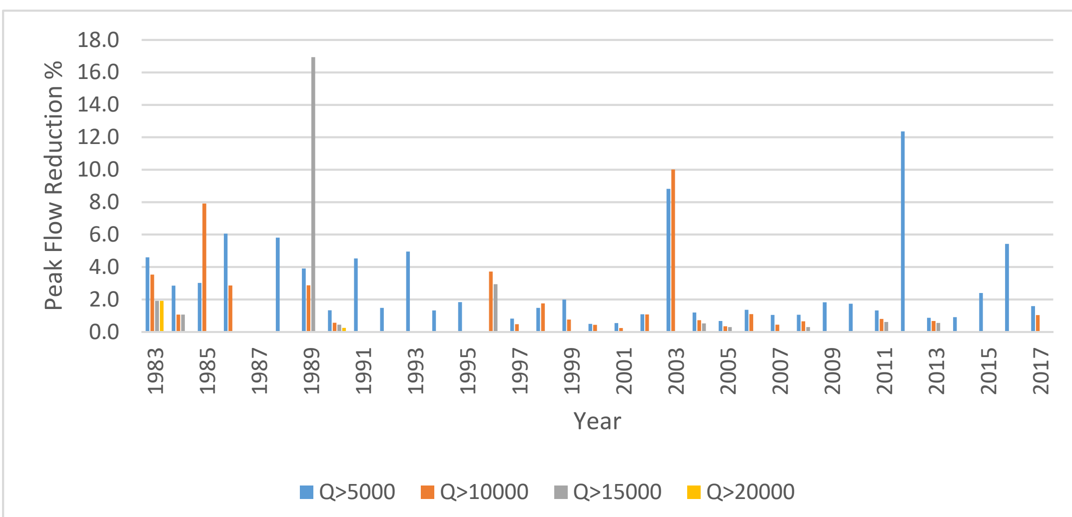


Figure 4.6 Annual Percentage of Peak Reduction

In this research work, future performance of the flood control reservoir analysis was taken as the main objective. To examine the performance, a simulation model was developed using HSPF modeling approach. To implement the present reservoir operations (as shown in Figure 3.4), a simulation model needs to be constructed externally. This operation model will be combined with HSPF results to analyze the benefits of reservoir operation.

To construct that, Storage-Stage and Area-Stage relationship was needed. Table 4.2 shows the three data points available for Brookville dam.

Table 4.2 Storage, Stage, and Water Surface Area Data

	Water Surface Elevation (feet)	Water Surface Area (Acres)	Storage (Acre-feet)
Winter	740	4513	144944
Summer	748	5260	184008
Flood	775	7788	359633

These data can be found though the link provided below:
https://www.lrl.usace.army.mil/Portals/64/docs/Engineering/Water_Management/Lake%20Area%20Capacity%20chart%202.pdf

Since only three data points were available, the following verification was done by setting up an exponential relationship with the available data (Figure 4.7 and 4.8) and the relationship derived is given in Equation 4.1, Equation 4.2, and Equation 4.3.

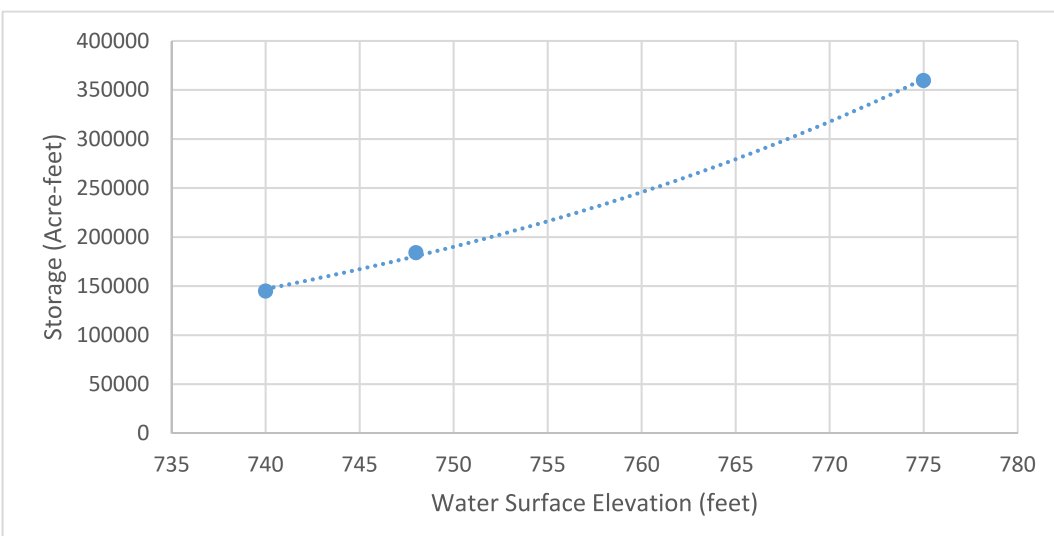


Figure 4.7 Storage-Stage Relationship

$$y = 0.0008e^{0.0257x} \tag{4.1}$$

Where,

y is the reservoir storage in Acre-feet,

x is the water surface elevation in feet.

The equation was reversed for final water surface elevation calculations as Equation 4.2:

$$x = \frac{\ln(\frac{y}{0.0008})}{0.0257} \tag{4.2}$$

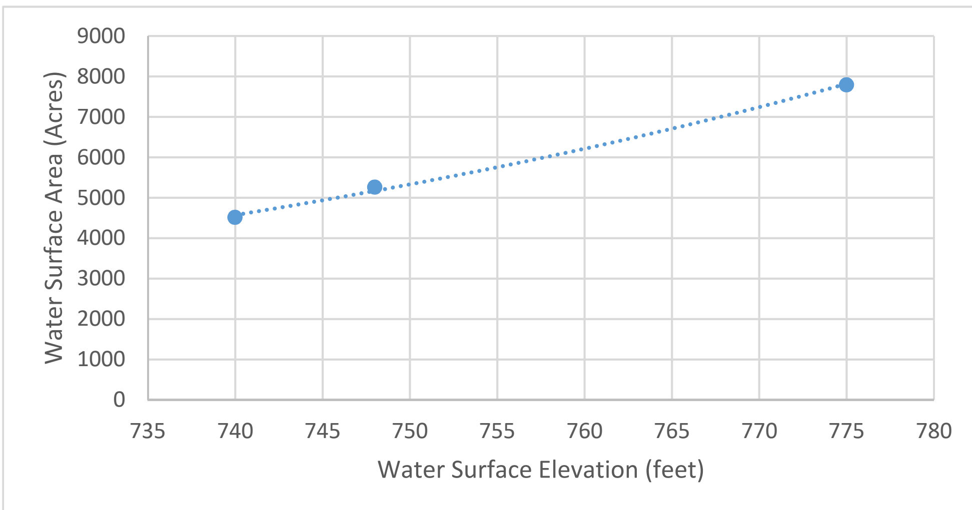


Figure 4.8 Area-Stage Relationship

$$z = 0.0545e^{0.0153x} \tag{4.2}$$

Where,

z is the water surface area in Acres,

x is the water surface elevation in feet.

To verify this data fit, a simulation was run for a year and the obtained stages and published stages were compared (Figure 4.9 and Figure 4.10). Based on the previous data and equations, 5 years of operation data (2012-2016) were used for validation. By plotting the actual water surface elevations and simulated surface elevations (Figure 4.9 and 4.10), the elevations were compared. Since the results were satisfactory, these relationships were used to build the simulation model.

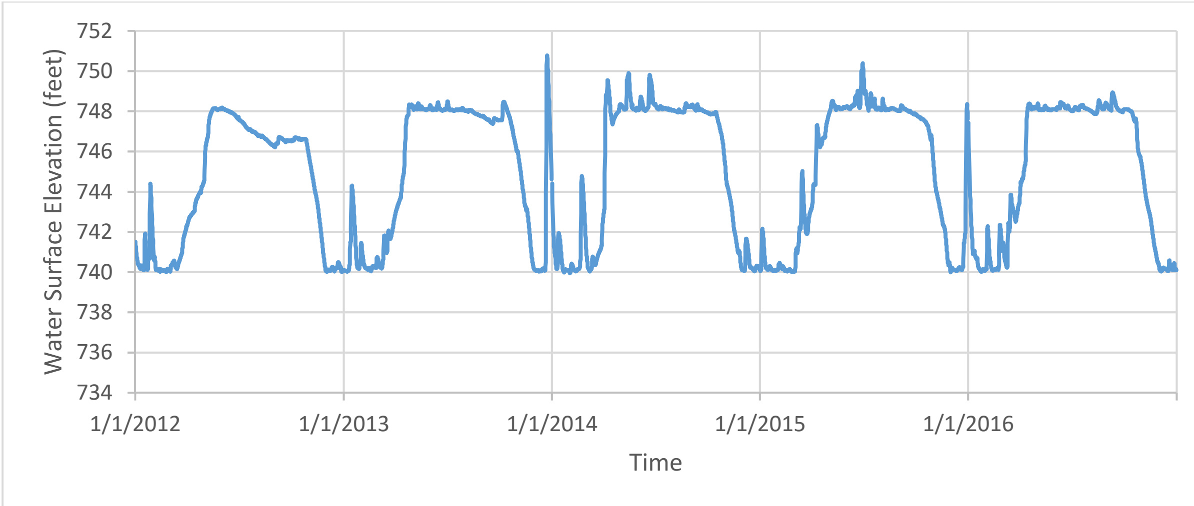


Figure 4.9 Actual Water Surface Elevation for 2012-2016

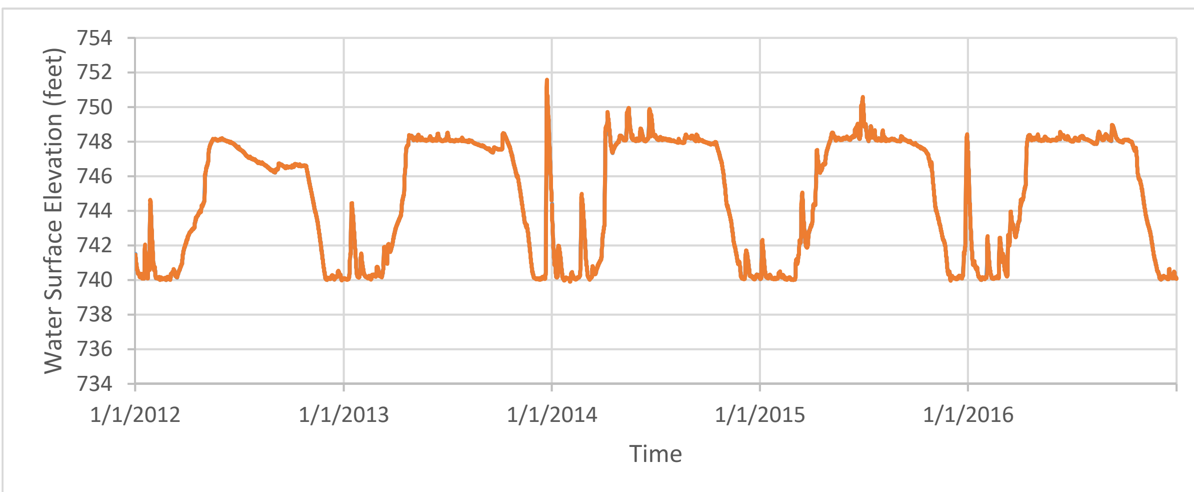


Figure 4.10 Simulated Water Surface Elevation for 2012-2016

The simulation model was developed by using these equations (Equation 4.1 and Equation 4.3). However, the operation rules were modified. The Brookville Lake is treated as an independent reservoir by not considering the downstream conditions. The original operating rule indicates that the summer pool level and winter pool level were maintained as 748 ft and 740 ft respectively. The modified operating rule lowers the summer pool level by 2 ft to 746 ft. However, the winter pool level was maintained as the same in order to analyze the recreation area closures due to water level raise during summer. Instead of releasing water by following the original operating rule, a new releasing rule was used as shown in Figure 4.11.

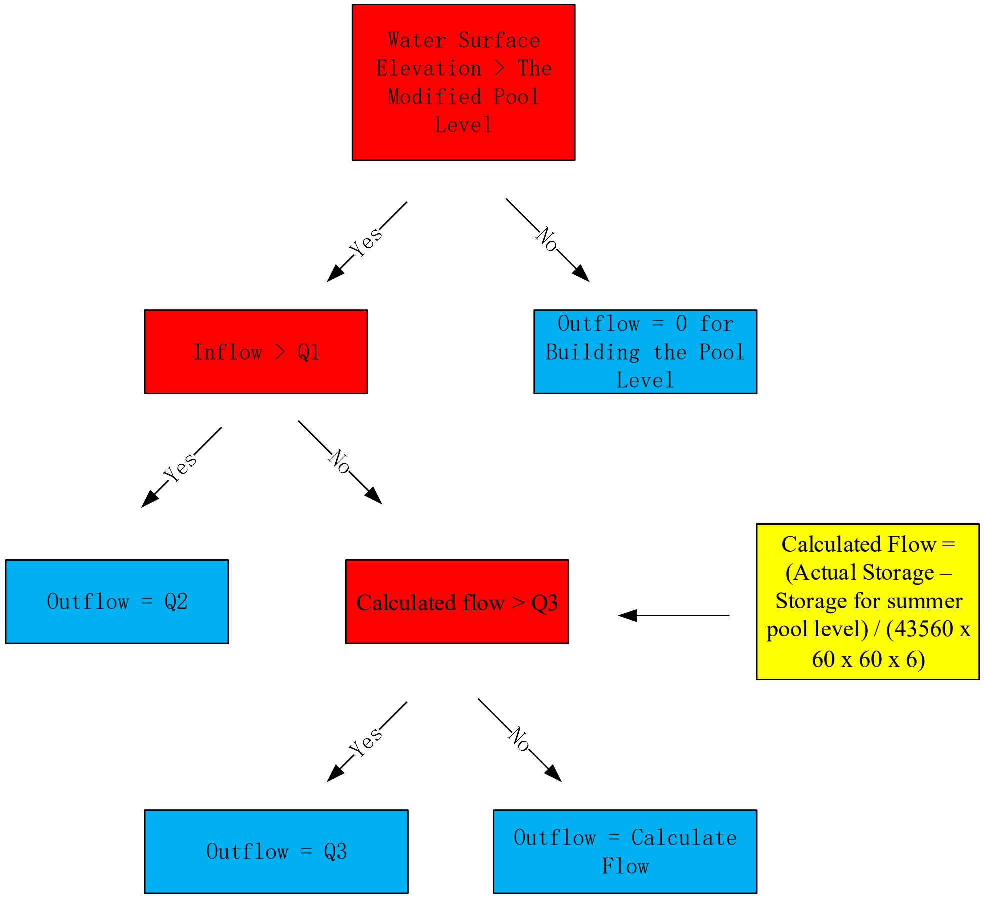


Figure 4.11 Modified Releasing Rule

In this case, the flow criteria are listed on Table 4.3:

Table 4.3 Flow Criteria for Case 1

	Flow Criteria in cfs
Q1	1000
Q2	750
Q3	2500

Recorded reservoir inflow and elevation data were used as the inputs in the simulation model. Equations developed from the Storage-Stage Relationship and the Area-Stage Relationship were used in the mass balance to find the optimal release (Equation 4.4).

$$\begin{aligned} &Final\ \ Storage\ \ Volume \\ &\quad = Initial\ \ Storage\ \ Volume + Inflow\ \ Volume - outflow\ \ Volume \end{aligned} \tag{4.4}$$

(Here seepage loss and evaporation loss were not considered.)

With the modified reservoir outflow, the pool levels can be calculated by the simulation model. Based on the reservoir data published by US Army Corps of Engineers, suitable elevations of most of the recreation facilities were available. The only two beaches within the recreation area, Mounds Beach and Quakertown Beach have the highest elevation as 751 ft above sea level. This data can be downloaded though the link:

https://www.lrl.usace.army.mil/Portals/64/docs/Engineering/Water_Management/Resevoir_Impact/Brookville.pdf

According to this data, any pool level greater than 751 ft may cause closures of recreation area. Original water pool level with the simulated water pool level were compared for five years where the extreme inflow peaks were encountered (1983, 1995, 1996, 2005, and 2011). Number of times the pool level went above 751 ft were presented for each year in Table 4.4.

Table 4.4 Case 1 Number of Appearance of Water Pool Elevation Greater Than 751 ft

Number of Appearances	1983	1995	1996	2005	2011
Historical	42	33	156	100	114
Simulated	43	35	152	101	114

In this case, by following the flow criteria, the number of 6 hourly closure appearances increased with revised operating rule (Table 4.5).

Table 4.5 Flow Criteria for Case 2

	Flow Criteria in cfs
Q1	4000
Q2	50
Q3	6000

The recorded historical maximum flow released by Brookville Lake Dam is 6224 cfs, and the minimum flow released during inflow peaks is 47 cfs. Therefore, these values are approximated as 6000 cfs and 50 cfs in case 2 simulation for pool level simulation. The number of appearances of pool level went above 751 feet for case 2 is presented on Table 4.6.

Table 4.6 Case 2: Number of Appearance of Water Pool Elevation Greater Than 751 ft.

Number of Appearance	1983	1995	1996	2005	2011
Historical	42	33	156	100	114
Simulated	43	31	144	100	114

The numbers of high water-level appearances are changed by modifying the flow criteria but not significantly. Which indicates that by following the historical flow releasing rule with the same outflow range, recreation closures due to water level raise is not reduced obviously.

4.2. HSPF Model Development

For developing HSPF Model, precipitation data is available with the flow data for Brookville Lake from 1983 to 2017; however, this precipitation data cannot represent the entire watershed with 1224 square miles of area. So, this data was used together with the USDA data discussed in chapter 3Totally 7 met stations are location in four counties covered by the watershed area, numbered as C121229, W03846, C127362, C127370, C125050, C121030, and C120132 were considered. Daily precipitation data were downloaded for these met stations from January 1st, 1950 to December 30th, 2010. Average of the precipitation data were used for final model.

For HSPF model, precipitation was used in inches. HSPF simulation model was developed as an hourly model. Due to the lack of hourly historical precipitation data, the average daily data were disaggregated to hourly by using NRCS Method (Appendix. A).

5. METHODOLOGIES AND RESULTS

5.1. USEPA BASINS and HSPF

BASINS (Better Assessment Science Integrating Point and Non-point Sources) is a multipurpose environmental analysis system. It is developed by USEPA to model watershed- water quality studies. BASINS is a GIS based software runs in MAPWINDOW GIS and helps in preliminary geospatial analysis. HSPF model can be initiated using BASINS interface. HSPF is capable of simulating a large watershed rainfall runoff modeling and can calculate the discharges at different nodes of the watershed. In this research, for the considered Whitewater River watershed, rainfall runoff model was developed using BASINS HSPF interface and was calibrated using historic data. Calibrated watershed model was then used to simulate the future simulations using GCM data.

The latest version of US EPA BASINS, 4.1, is used for watershed model creation because of the significant improvements made with this version. They include improvements like automatic watershed delineation tools updates with TauDEM (Terrain Analysis Using Digital Elevation Models) version 5, inclusion of functional tools like GenScn and WDMUtil in the main model itself (USEPA, 2018). For starting model creation, the eight-digit Hydrologic Unit Code (HUC) Whitewater River Watershed (HUC 05080003: Whitewater. Indiana. Ohio), was selected as shown in Figure 5.1.

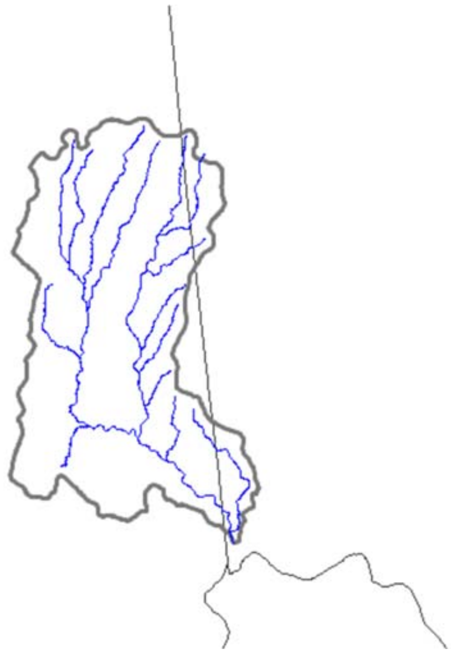


Figure 5.1 Whitewater River Watershed Image with Default Settings

For developing the watershed model using HSPF, BASINS interface was used to download different datasets. Using the "Download Data" menu, NHD (National Hydrography Dataset), DEM (Digital Elevation Model), NED (National Elevation Dataset), and soil and land use data were downloaded. In addition, meteorological data, and transportation data were imported to facilitate the model development. Detailed steps were given in the Appendix B.

For the Whitewater River System, daily flow observations measured by USGS were used (USGS stations ID3276500 and 3276000). Location coordinates (Table 1) of these stations were used to create a point theme shape file. This station location was used as a point of interest to perform watershed delineation.

Location details of flow and rainfall gage stations in this watershed (Table 3.2 and Table 3.3) were used to create a point theme shape file. They were used for delineating the watershed.
Automatic watershed delineation was done using the tool provided in BASINS using Digital Elevation Model and NHD (National Hydrology Dataset) dataset. Based on flow gaging station locations, a focusing mask was drawn manually by treating flow observation station 3276500 as the outlet (Figure 5.2). Delineated watershed is shown in Figure 5.3.

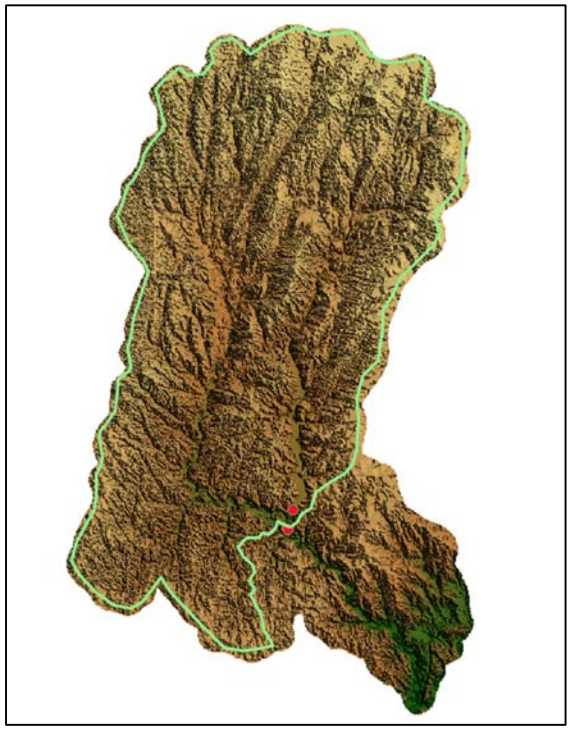


Figure 5.2 Focusing Mask

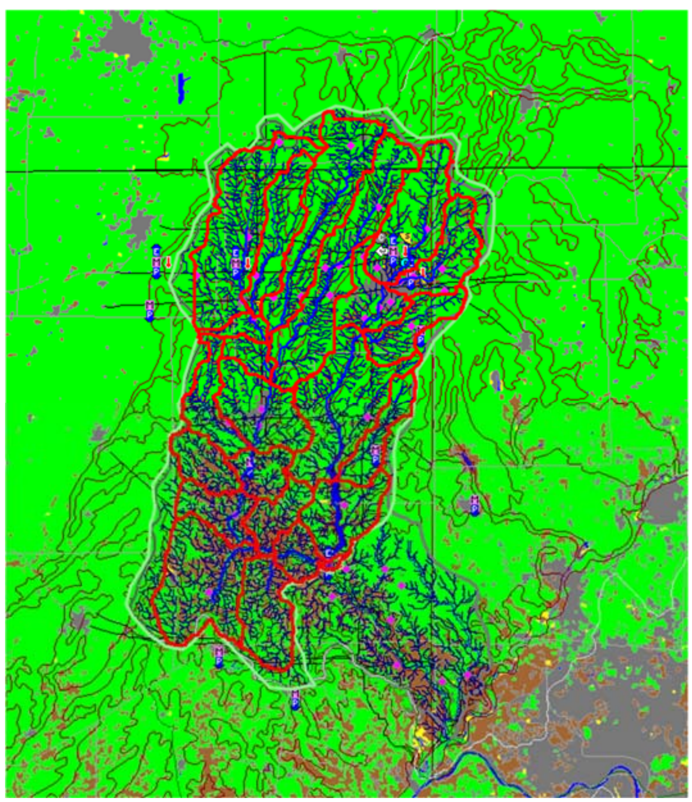


Figure 5.3 Delineated Model

After the successful delineation of the watershed, HSPF (Hydrological Simulation Program-Fortran) model was initiated with the rainfall gage datasets with WDM files. Initial data preparation steps were given in Figure 5.4. Entire sequence of steps followed in HSPF model development is given in Figure 5.5.

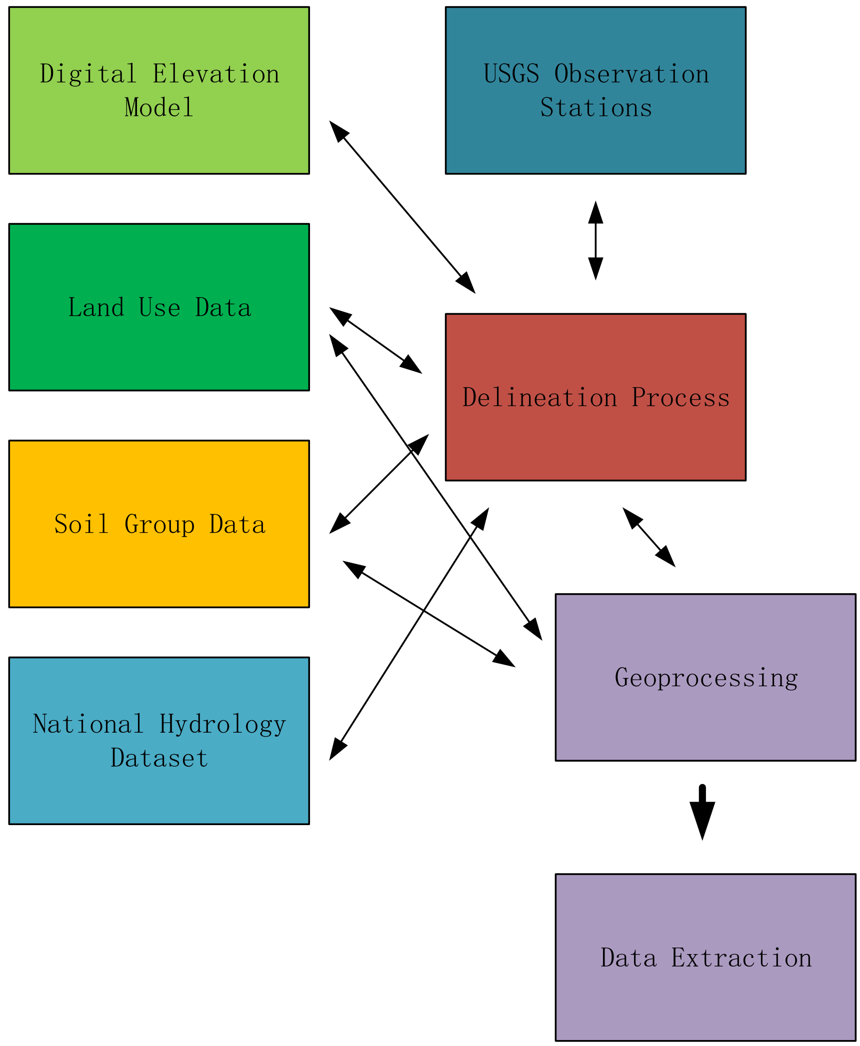


Figure 5.4 Initial Data Preparation

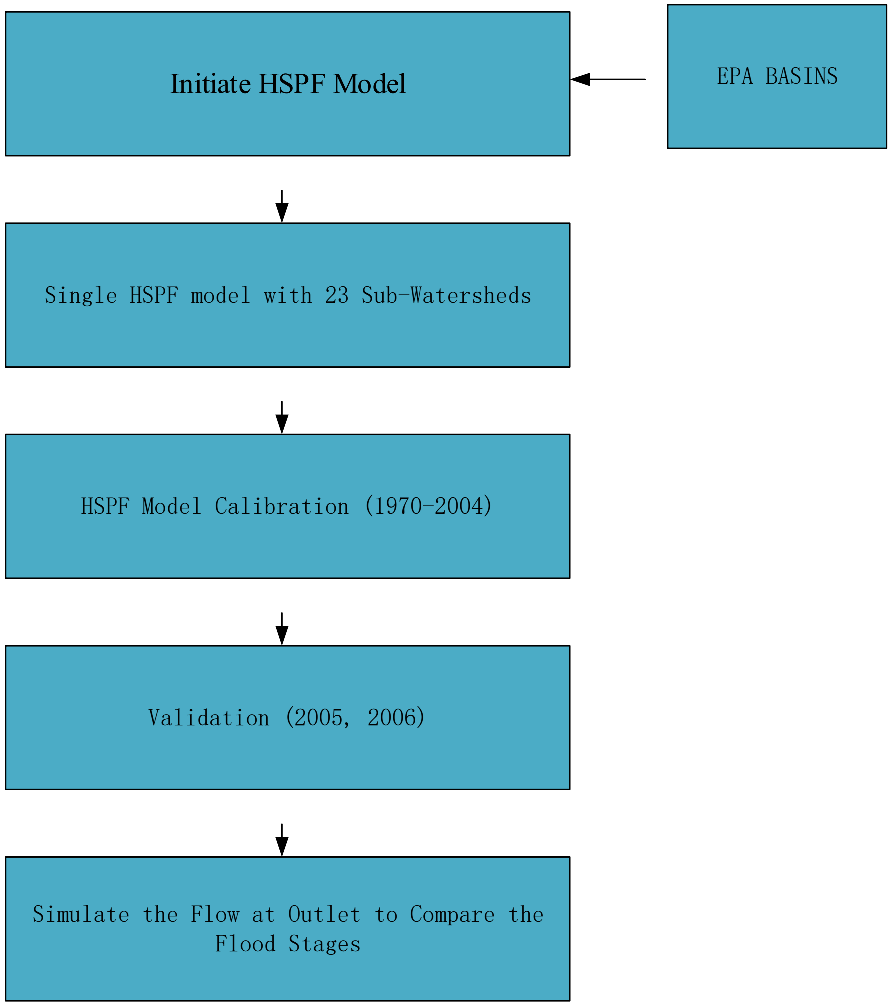


Figure 5.5 HSPF Modelling Steps

After the delineation is complete, necessary files required for HSPF construction is also created by the BASINS software. Subsequently, HSPF model building was done using HSPF add on facility in BASINS. The initial HSPF model for the watershed gets stored in the BASINS/model out folder. The initial raw HSPF model comes with an output WDM file (Weather Data Management file). When HSPF run is completed, the data gets stored in that WDM file. As a preliminary step, a weather data WDM file is also introduced during BASINS-HSPF initialization process. The initial HSPF model built with HSPF interface are shown in Figure 5.6.

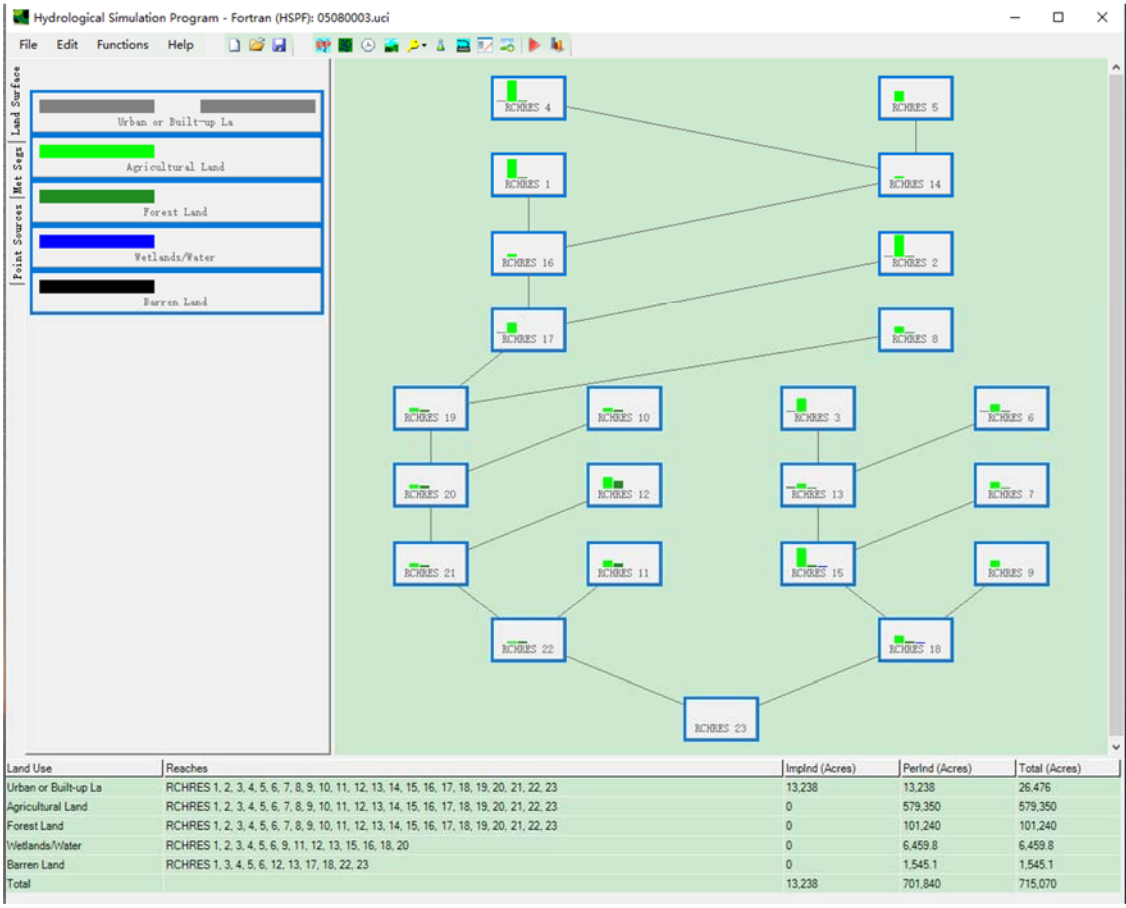


Figure 5.6 HSPF Model User Interface

Based on soil and land cover data, two main categories called impermeable and permeable land were created. In total, 23 sub-watershed reaches were created during this automated process. The land use was divided into 5 major types (Urban or Built-up Land, Agricultural Land, Forest Land, Wetlands/Water, and Barren Land). The HSPF lumps the land cover data to different sub-categories with details as shown on Table 5.3. Land use table indicates that this watershed is dominated by agricultural land cover.

Table 5.1 Land Use Details (Acres)

Land Types	IMPLND	PERLND	Total
Urban or Built-up Land	13238	13238	26476
Agricultural Land	0	579350	579350
Forest Land	0	101240	101240
Wetlands/Water	0	6460	6460
Barren Land	0	1545	1545
Total	13238	701840	715078

The weather data from downloaded WDM file was modified using the precipitation data downloaded from USDA website. 7 stations precipitation data daily average obtained from USDA website were disaggregated to hourly rainfall as indicated in Chapter 3 was used to run the preliminary simulation. HSPF model was fine-tuned by adjusting FTables (Figure 5.7) which is instrumental in lumped flow routing in HSPF model. Other parameters such as infiltration rate, baseflow controlled parameters were adjusted systematically based on the recommendation given in BASINS Technical Note 5 (Chandramouli et al., 2010).

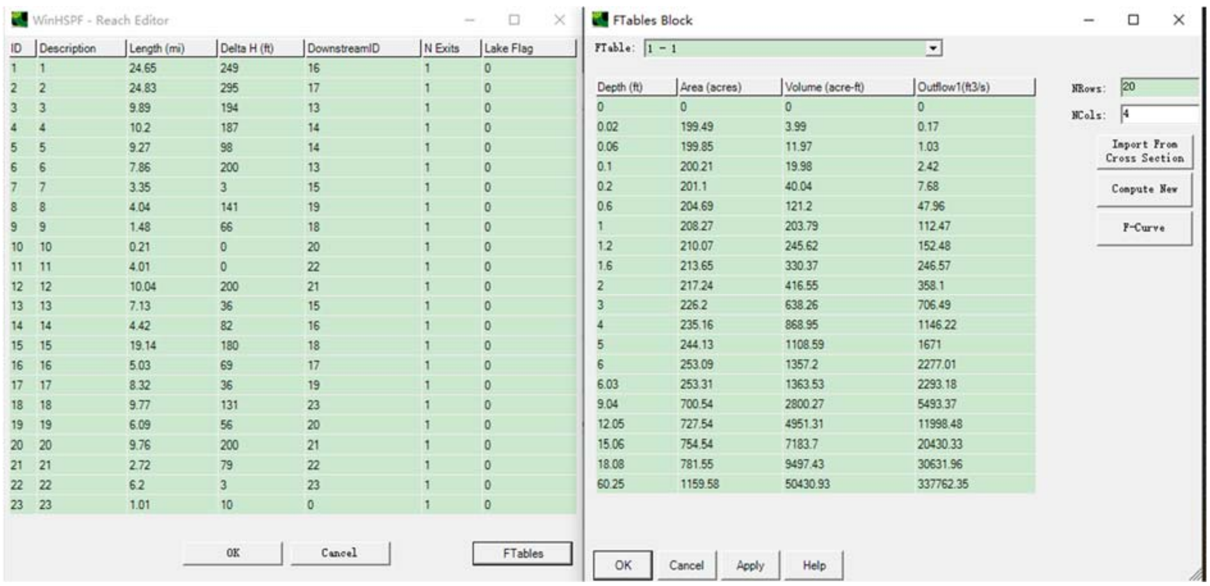


Figure 5.7 Details of Sample Flow Table

HSPF model calibration was done using data from 1970 to 2004. The HSPF model simulated flow was compared with observed data at USGS gaging station 03276500 as shown in Figure 5.8. USGS flow data at Gaging station 03276500 were revised by adding the actual reservoir inflows to Brookville dam to generate the uncontrolled flow data at the confluence point of East and West Forks of White Water River. This synthesized data was used for model calibration. The infiltration rate for each sub-watershed was fine-tuned during flow calibration.

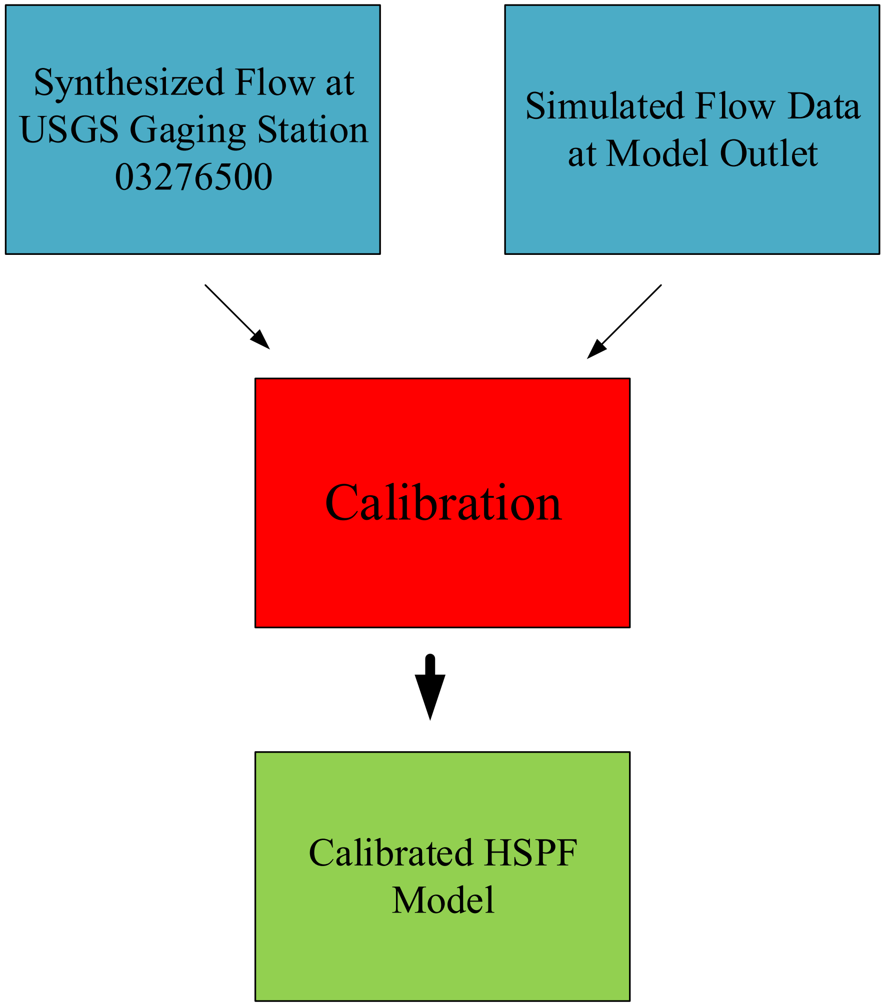


Figure 5.8 Calibration Process

Simulated and observed flows were captured and compared using high flow, low flow, and medium flow regimes. After examining coefficient of determination (R^2), root mean square error (RMSE), and Nash-Sutcliffe model efficiency coefficient (NSE), the calibrations were finalized. Equations of R^2, RMSE, and NSE calculation are shown as Equation 5.1, 5.2, and 5.3.

$$R^2 = \left(\frac{n(\sum xy)-(\sum x)(\sum y)}{\sqrt{[n\sum x^2-(\sum x)^2][n\sum y^2-(\sum y)^2]}}\right)^2 \quad (5.1)$$

Where,

R^2 is the coefficient of determination,

x is the observed flow,

y is the simulated flow,

and, n is the size of dataset.

$$\text{RMSE} = \sqrt{\frac{\sum_{t=1}^{T}(Q_m^t - Q_o^t)^2}{T}} \tag{5.2}$$

$$\text{NSE} = 1 - \frac{\sum_{t=1}^{T}(Q_m^t - Q_o^t)^2}{\sum_{t=1}^{T}(Q_o^t - \overline{Q_o})^2} \tag{5.3}$$

Where,

RMSE is the root mean square error,

NSE is the Nash-Sutcliffe model efficiency coefficient,

Q_o is the mean of observed discharges,

Q_m is modeled discharge,

and, Q_o^t is the observed discharge at time t.

By applying the above-mentioned equations with the help of Excel, R^2 for 1970 to 2004 data set was calculated as 0.7453 as shown in Figure 5.9. The R^2 value is close enough to 1 which indicates a good fit of model output flow data to actual flow data.

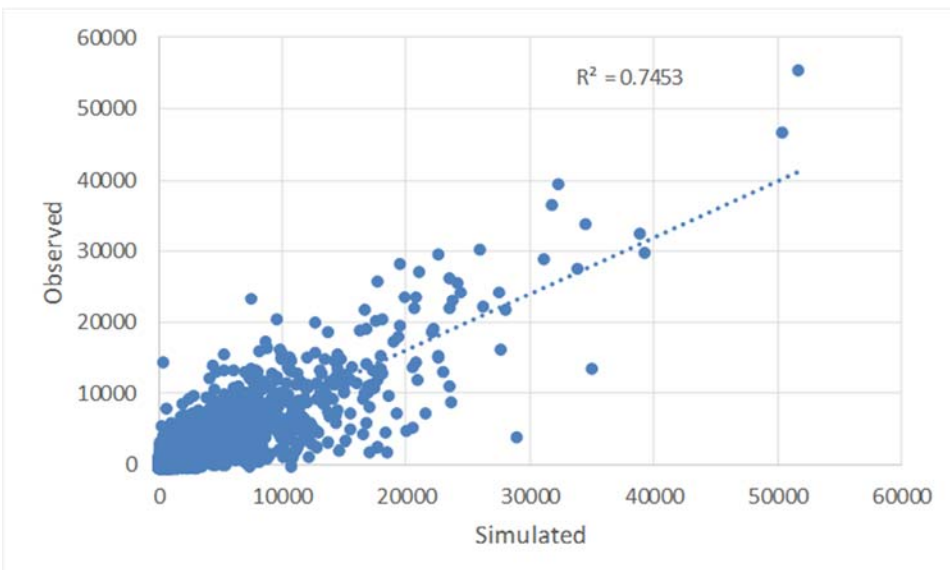


Figure 5.9 Observed vs. Simulated Flow

RMSE for different flow regimes were also analyzed for 1970 to 2004. Total 12794 days of daily flow data was separated sorted to low flow regime (Q<1000 cfs), medium flow regime (1000 cfs≤Q≤10000 cfs), and high flow regime (Q≥10000 cfs) based on the observed flow. The results are shown on Table 5.4.

Table 5.2 RMSE for Calibration

	Range (cfs)	Number of Data	RMSE	Percentage Derivation
Low Flow Regime	<1000	7778	527.70	-18.52
Medium Flow Regime	1000-10000	4841	1353.32	10.39
High Flow Regime	>10000	175	6776.48	21.16

Based on these results, data of 2005 and 2006 were used for validation. 730 days of flow data was analyzed and RMSE were calculated for the same 3 flow regimes as shown on Table 5.5.

Table 5.3 RMSE for Validation

	Range (cfs)	Number of Data	RMSE	Percentage Derivation
Low Flow Regime	>1000	279	585.65	-13.67
Medium Flow Regime	1000-10000	435	1347.80	25.89
High Flow Regime	<10000	16	6604.96	20.21

By comparing Table 5.4 and Table 5.5, RMSE and percentage derivation values for the same flow regime are similar which also proves the validation of the model.

NSE is only used hydrological model predictive model assessment which is the most valuable perimeter to check the usability of HSPF model. NSE for model calibration and validation were calculated and compared as Table 5.6. Both NSE values for calibration and validation are close to 1 which indicates the good performance of the calibrated HSPF model.

Table 5.4 NSE for Calibration and Validation

	Calibration	Validation
NSE	0.73	0.81

Observed and simulated flows for year 2004, 2005, and 2006 were given in Figure 5.10 to 5.12.

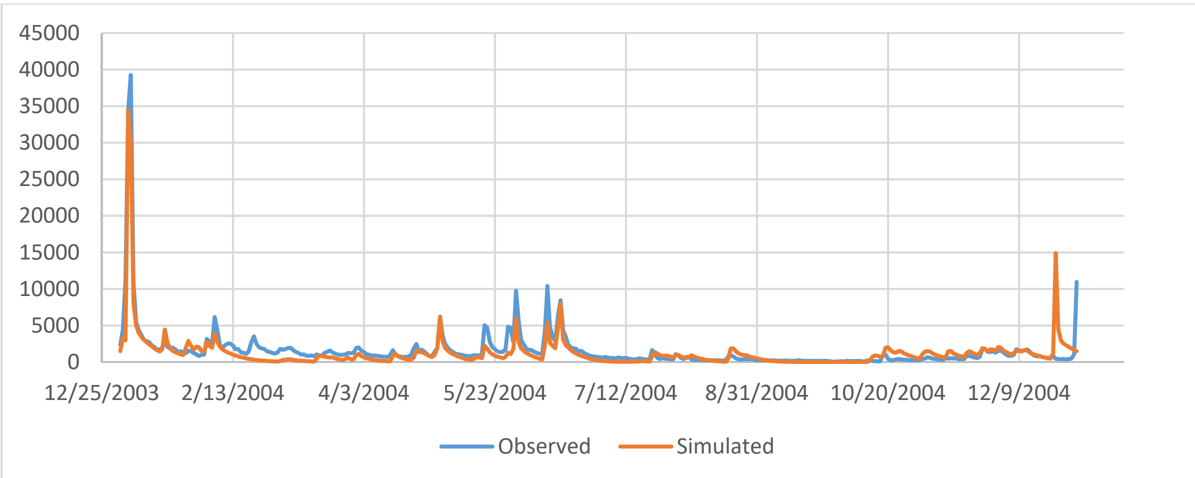


Figure 5.10 2004 Flow Data

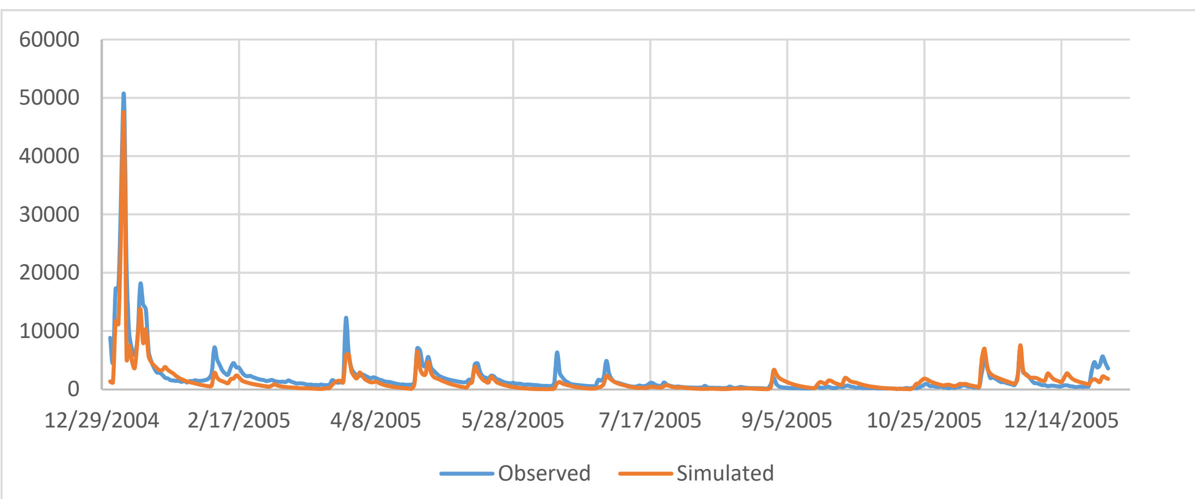


Figure 5.11 2005 Flow Data

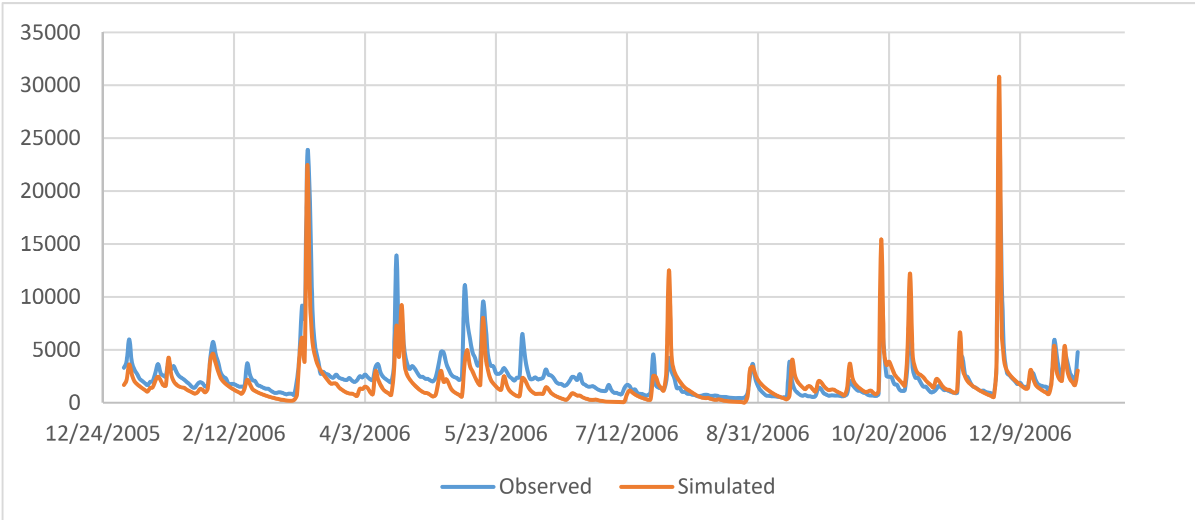


Figure 5.12 2006 Flow Data

After successful calibration of the HSPF model, the calibrated model was used to simulate futuristic scenarios. For futurist scenario analysis, global climatic model results were used. Downscaled CMIP5 was available for different HUCs through this link on a daily scale:
https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/#Projections:%20Subset%20Request
This website is developed and supported by Lawrence Livermore National Laboratory, National Energy Technology Laboratory, and other universities, laboratories, and organizations.

PCMDI (Program for Climate Model Diagnosis & Intercomparison) provides CMIP (Coupled Model Intercomparison Project) data. PCMDI is at Lawrence Livermore National Laboratory and funded U.S. Department of Energy. PCMDI continuously improve the methods and various tools used in the global circulation model (GCM). CMIP5 (Coupled Model Intercomparison Project Phase 5) data is on a global scale. For hydrologic analysis, regional level or HUC level data are needed. Through the above-mentioned web link, downscaled daily rainfall data are available as a geospatial data compatible to Arc GIS platform. Users can select required time frame and location specifics through a user-friendly interface. This global climatic projection is available for different carbon emission scenarios such as RCP 2.6, 4.5, 6.0, and 8.5. Here RCP stands for Representative Concentration Pathway. 2.6 or 4.5 here represents radiative forcing values compared to pre-industrial values to that of the year 2100. In that scale RCP 2.6 has minimal CO_2 emission in 2100 where as RCP 8.5 is for worst CO_2 emission scenario. For this study, RCP 2.6 and RCP 8.5 CMIP5 data for Whitewater River region was used to analyze the future inflow conditions. Daily precipitation data was downloaded from January 1st, 2018 to January 1st, 2099.

The cumulative annual of precipitation was plotted and analyzed as Figure 5.13 below. The annual precipitation volumes of RCP 2.6 are greater than the volumes of RCP 8.5, which indicates that in the study area of Whitewater River Basin, as the CO_2 emission increases, the precipitation volume decreases. This leaded to the assumption of the extreme flow will occur in the future with low CO_2 emission and RCP 2.6 precipitation data was initially used as model input.

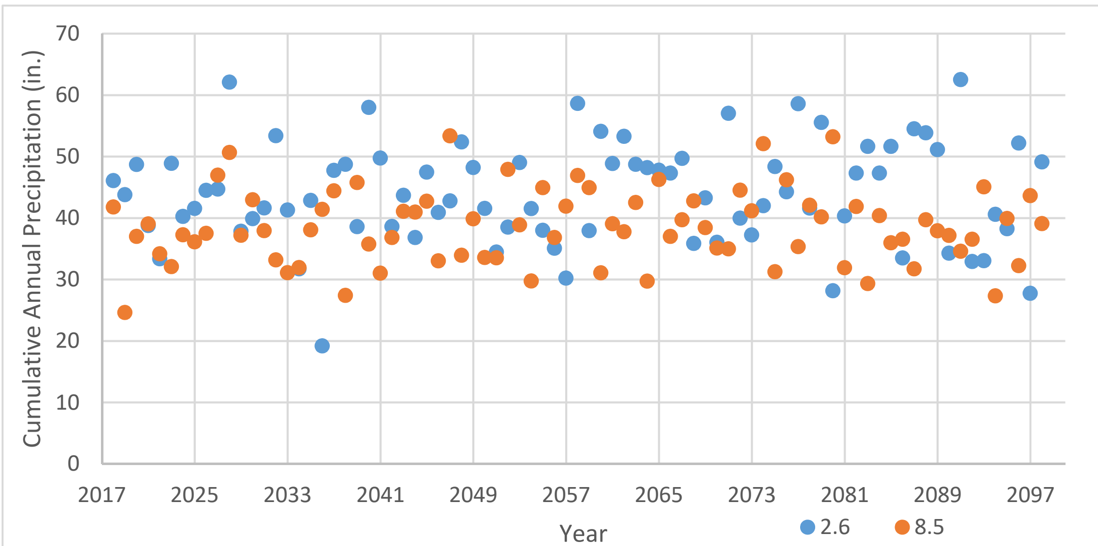


Figure 5.13 Cumulative Annual Precipitation for 2018 to 2098

Future daily precipitation data from January 1st, 2018 to January 1st, 2099 was disaggregated to hourly by using NRCS method and saved as a WDM file using EPA BASINS. With the future precipitation data as input, the future flow was simulated using HSPF model. Due to memory handling issues, 48 years (2018-2065) of flow data were simulated. This time span covers the predicted maximum precipitation day of the 81 year-span on July 28th, 2061.

Figure 5.14 shows daily flow forecasting data and Figure 5.15 shows the annual peak volume of Whitewater River at USGS station 03276500:

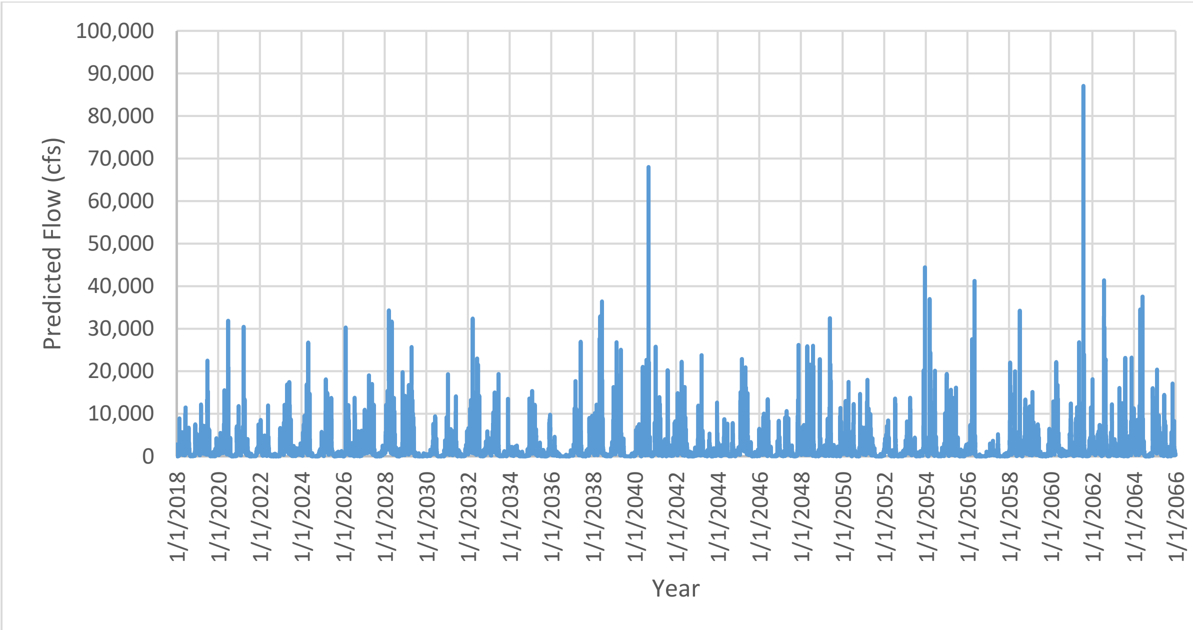


Figure 5.14 Flow Forecasting Data

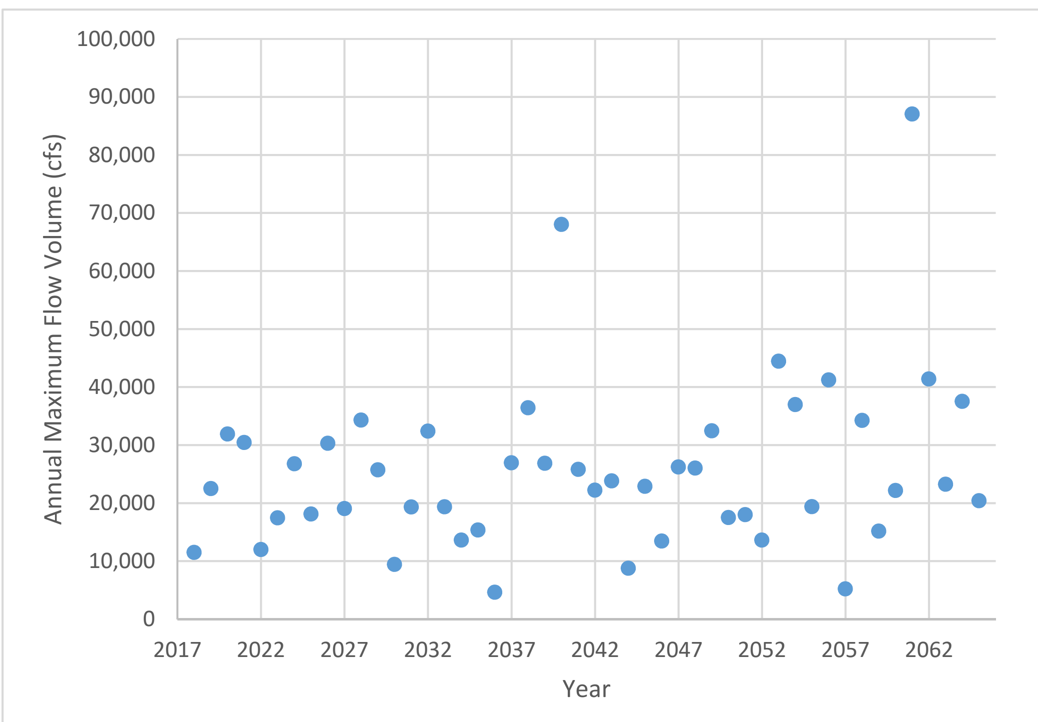


Figure 5.15 Simulated Annual Peak Volume for 2018 to 2065

For the predicted 48 years of flow data, 910 days of flow went above 5000 cfs and 20 days went above 40000 cfs. 2 obvious peaks were captured over 50000 cfs which is greater than the maximum peak in historical records. The number of peak appearance and average annual peak appearance is analyzed on Table 5.7.

Table 5.5 Detailed Future Peak Flow Conditions

Peak Stream Volume Range (×1000 cfs)	Number of Appearance	Average Annual Peak Appearance
5-10	633	13.188
10-20	214	4.458
20-30	43	0.896
30-40	15	0.313
40+	5	0.104

In the HSPF model, Brookville Dam is located at the outlet of sub-watershed R18. It represents the East Fork outflow. R23 is the USGS gaging station (outlet of the model). R22 is the outlet of West Fork The dam operation rule controls the outflow from sub-watershed R18 to R23. By combining the reservoir outflow using a reservoir simulation model (which will be R18) and outflow from sub-watershed R22, the HSPF model results with reservoir operation can be found at R23. This will represent the flow at White Water River after the East and West Fork Confluence. The flow data of R18 can be imported as the inflow for reservoir operation simulation model case 1 as explained in Chapter 4. A six-hourly time scale was used for this analysis. HSPF simulated flow data for R23, R22, and R18 were exported on 6-hour time interval for this purpose. R18 data was used in the simulation model case 1 and the outflow were captured. By adding the outflow data from reservoir simulation model with the flow data of R22 from HSPF, the reservoir controlled future outflow of the entire watershed was found. The above-mentioned procedures are illustrated on Figure 5.16.

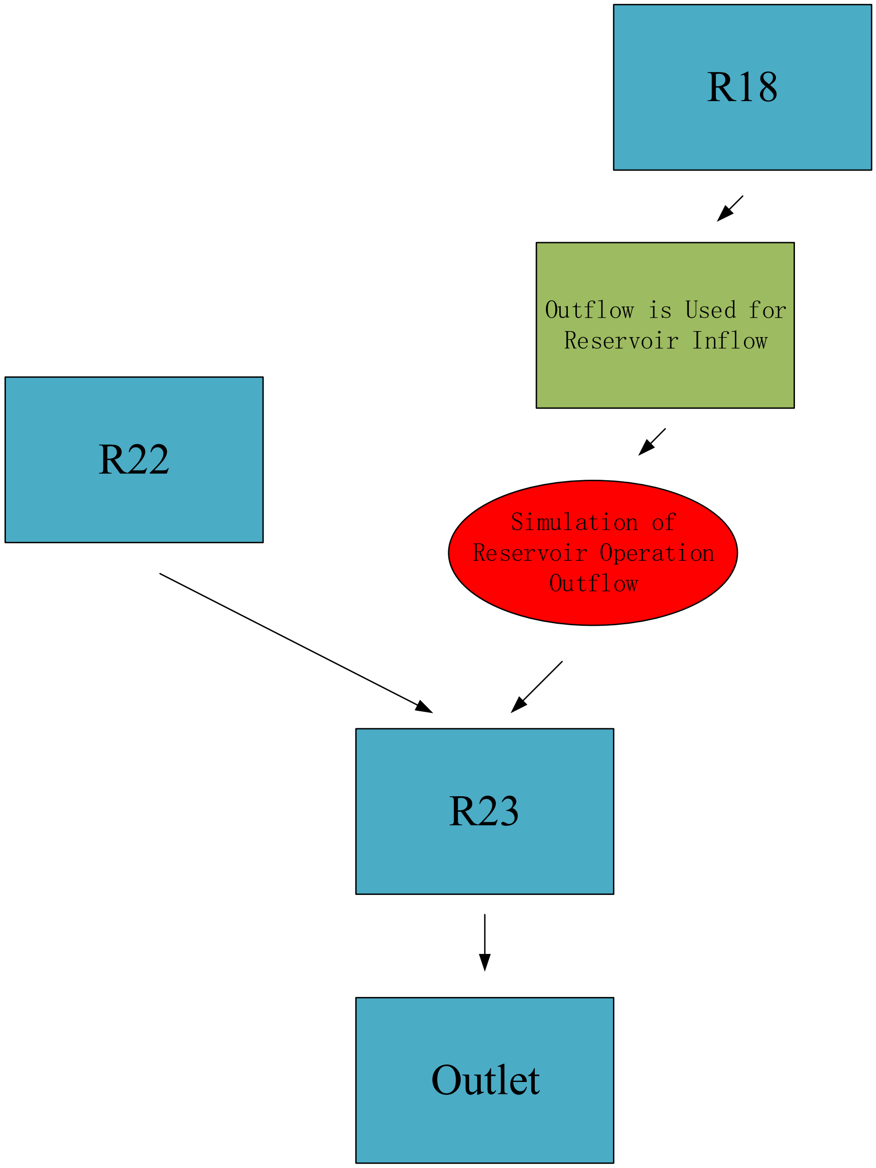


Figure 5.16 Produce of Reservoir Controlled Outflow Calculation

According to IPCC Expert Meeting Report-Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies, CO_2 concentrations for different RCPs will have very small differences before year 2030 (Moss et al. 2007). 11 years (2030-2040) flow data were used for reservoir-controlled outflow calculation and analysis. The results are shown in Figure 5.17 and Figure 5.18.

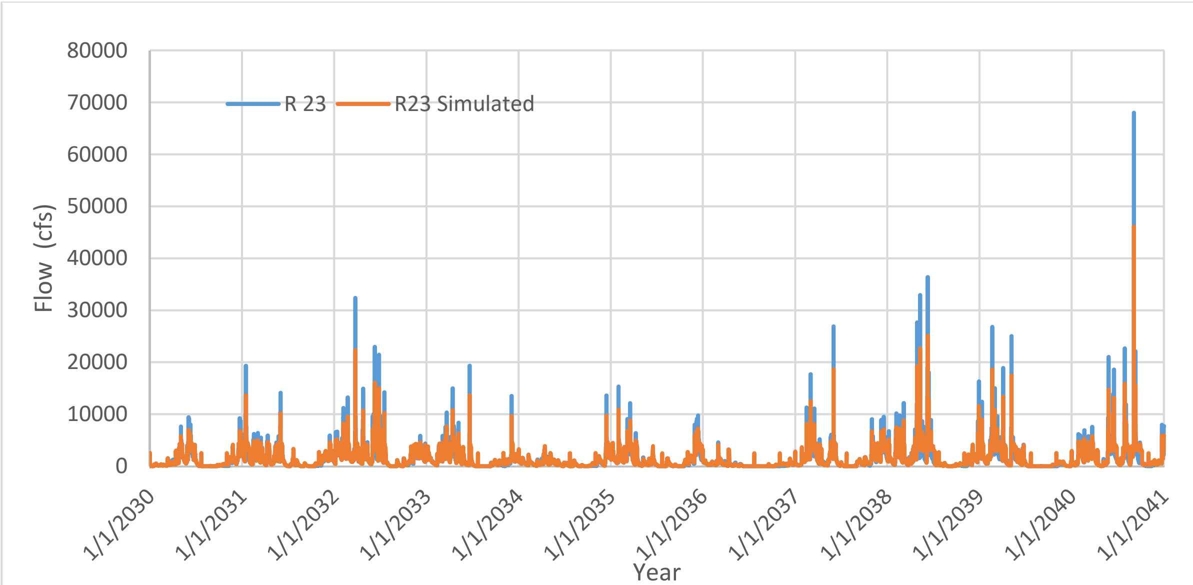


Figure 5.17 HSPF Outflow vs. Simulated Model Outflow for R23

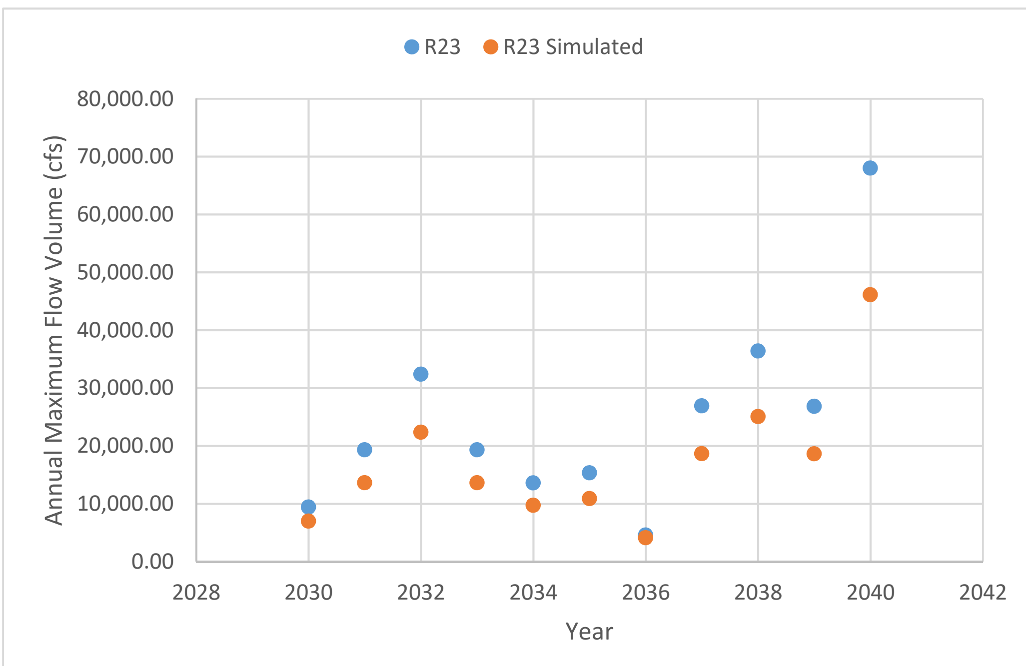


Figure 5.18 Annual Maximum Flow Volume

For these years, 808 and 509 times of 6 hourly peak flow greater 5000 cfs were captured from uncontrolled HSPF model outflow and simulation model outflow data respectively. From Figure 5.17, peak reduction can be observed and further examined as shown in Table 5.8.

Table 5.6 Detailed Peak and Peak Reduction Conditions for 2030-2040

	HSPF Output		Simulation Model Output Using HSPF		
Stream Flow Range (×1000 cfs)	Number of Appearances	Average Annual Peak Appearances	Number of Appearances	Average Annual Peak Appearances	Peak Reduction %
30+	20	1.82	8	0.73	60
20-30	32	2.91	8	0.73	75
10-20	148	13.46	114	10.36	22.97
5-10	608	55.27	379	34.46	37.66
0-5	15264	1387.64	15573	1415.73	-2.02

Outflows more than 30000 cfs flow were reduced from 20 to 8 times (60% reduction) due to reservoir operation which will save severe flood damages in future. Further, the reservoir operation reduces lower peaks (20 to 30000 cfs) by 75%.

Years with extreme precipitation (2040 and 2061) was also analyzed in Figure 5.19 to 5.20. The HSPF model maximum outflow for 2040 is 68010 cfs on September 4th, 2040 and the simulation model reduced that flow to 46130 cfs. Moreover, for 2061, the HSPF model maximum outflow is 87046 cfs on July 28th, 2061 and the simulation model reduced that flow to 29494 cfs.

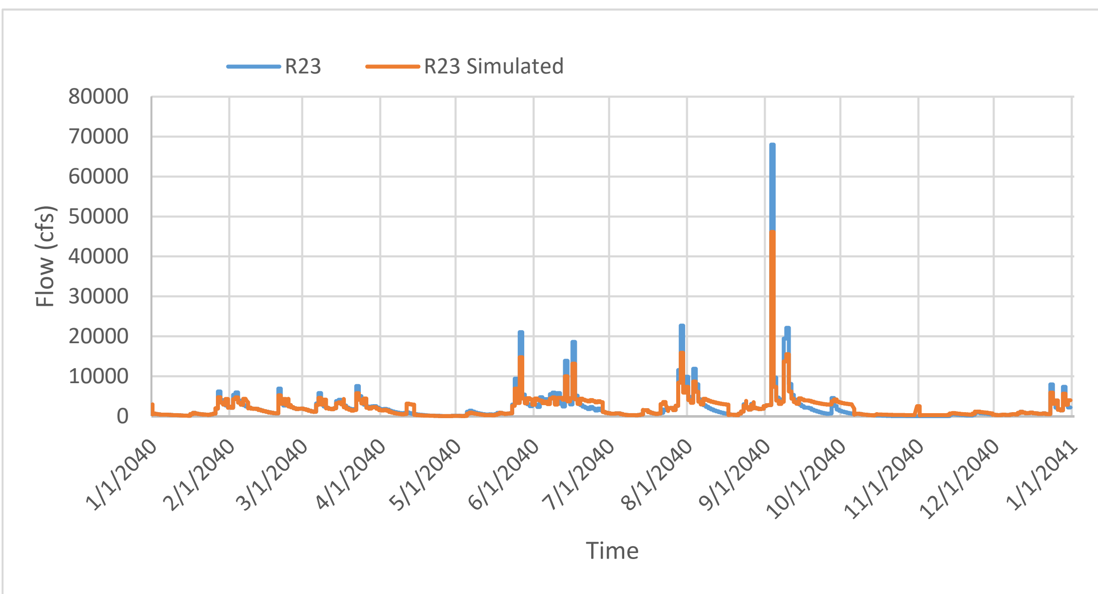


Figure 5.19 2040 Flow Data

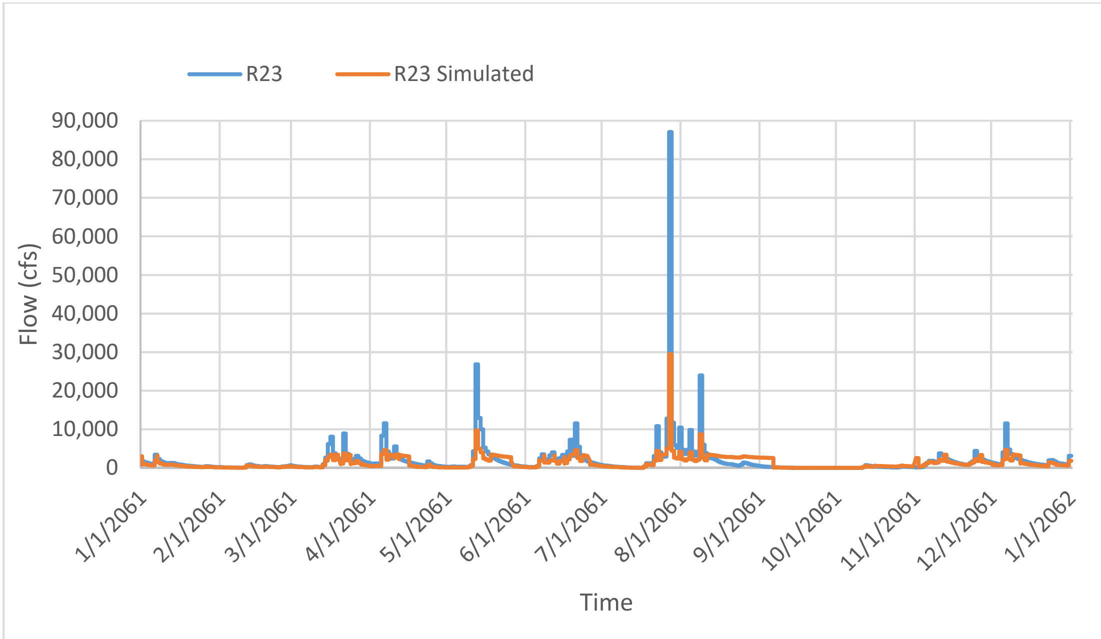


Figure 5.20 2061 Flow Data

The peak reduction rate, as on Table 5.9, for 2040 and 2060 maximum flow is 32.12% and 66.12% respectively. An outflow of 87046 cfs is not recorded at White Water River in 100 plus years of historic observations. Even the worst flood in 1913, reached about 60,000 cfs only which resulted in very severe damages at downstream cities such as Harrison, OH. An outflow of 87046 cfs would be causing extreme damages to those cities. However, Brookville Dam operation will reduce the peak by 66 % and avoid the flooding.

Table 5.7 Peak Reduction Rates for Two Extreme Precipitation Years

	HSPF Output Maximum Flow (cfs)	Simulation Model Output Maximum Flow (cfs)	Peak Reduction %
2040	68010	46130	32.17
2061	87046	29494	66.12

The same methodology was applied for RCP 8.5 which has the maximum CO_2 emission. Precipitation data was downloaded from January 1st, 2018 to January 1st, 2099 and disaggregated to hourly scale and used in the HSPF simulation. 48 years of flow data (2018-2065) were simulated by HSPF and analyzed (Figure 5.21 and Figure 5.22).

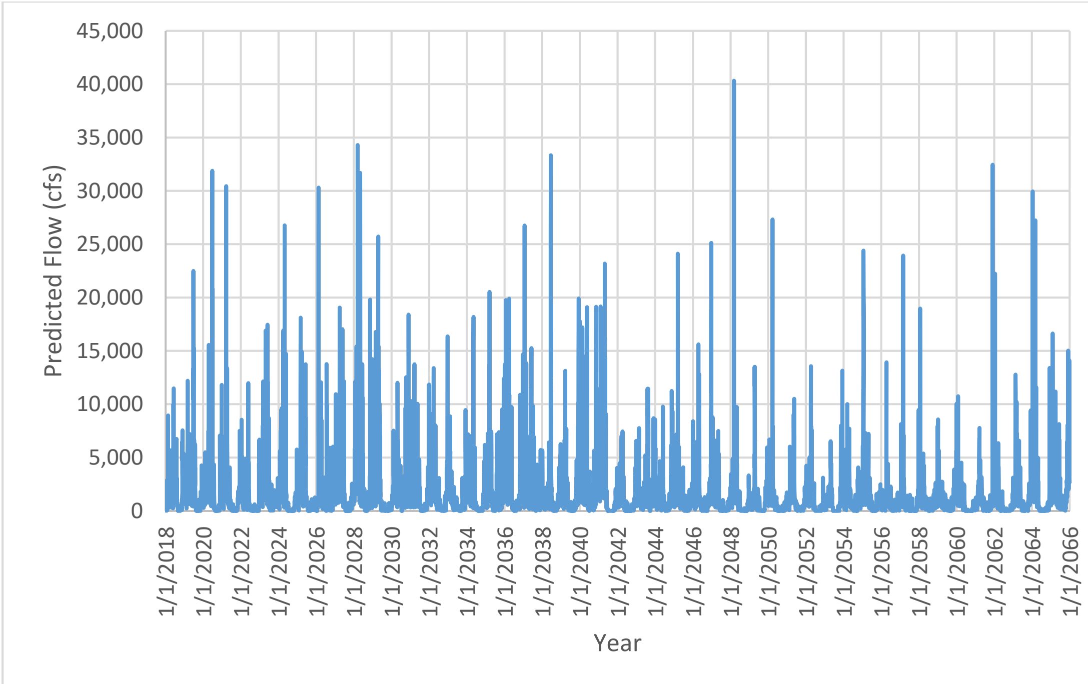


Figure 5.21 Flow Forecasting Data for RCP 8.5

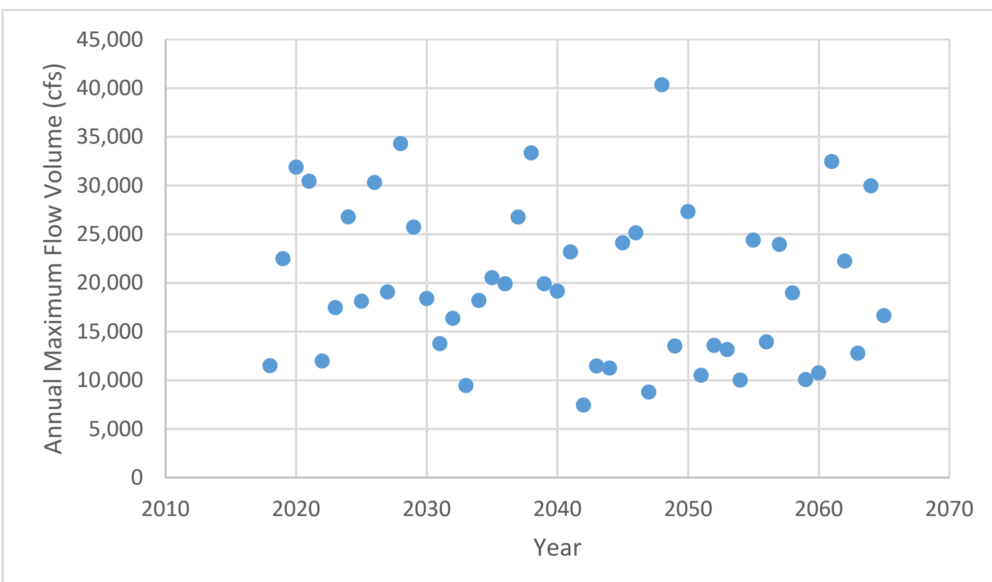


Figure 5.22 Simulated Annual Peak Volume for 2018 to 2065 for RCP 8.5

Simulated future flow and simulated reservoir operated flows were compared in Figure 5.23 and 5.24. As the precipitation decreases with CO_2 emission in this region, only one peak with more than 35000 cfs (year 2048) was observed.

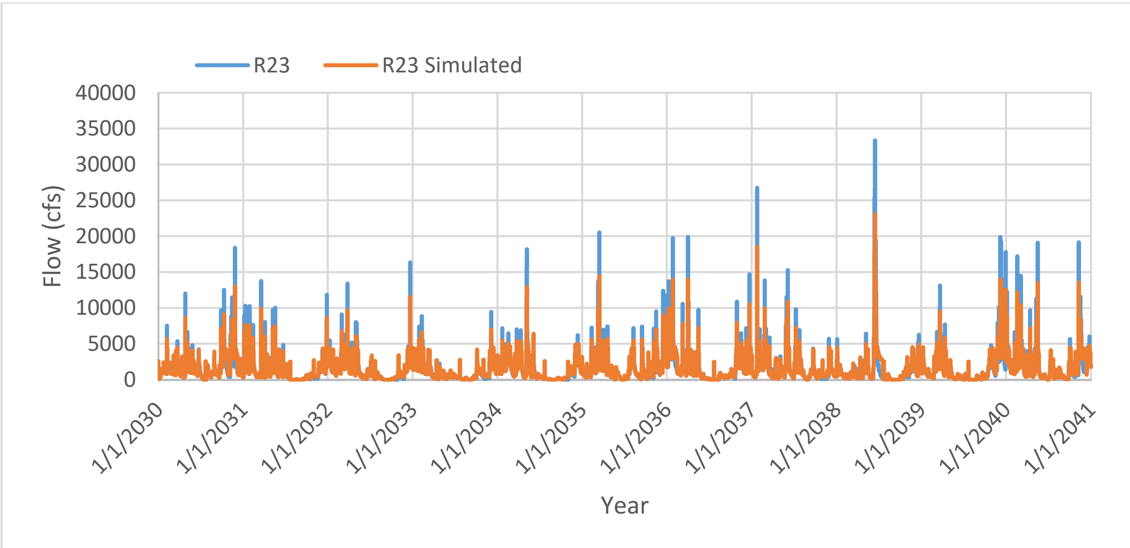


Figure 5.23 R23 HSPF vs. Simulated Model Outflow for RCP 8.5

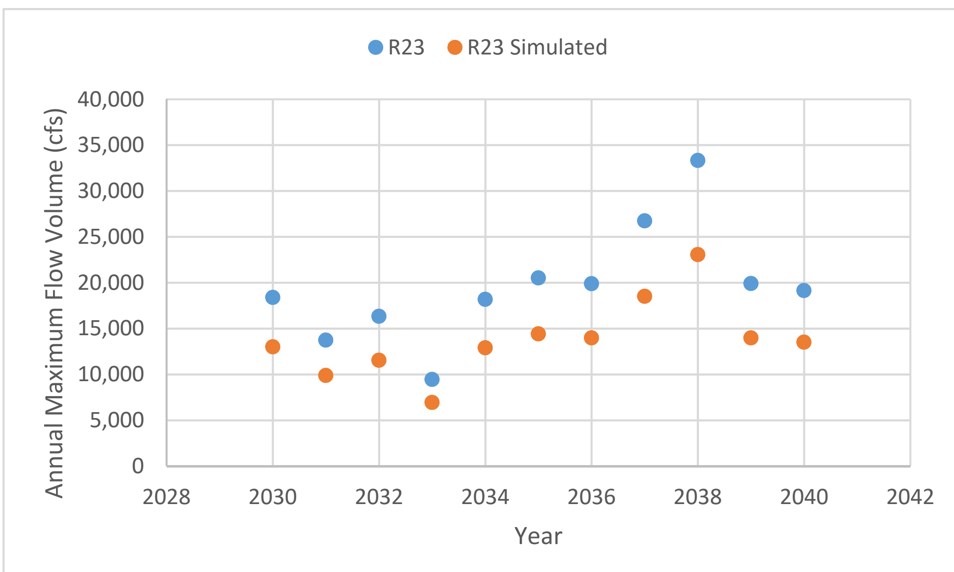


Figure 5.24 Annual Maximum Flow Volume for RCP 8.5

Differences between reservoir regulated flows and uncontrolled flows were compared in Table 5.10. Reservoir operation results in decreasing all the flood peaks more than 30000 cfs (100% reduction).

Table 5.8 Detailed Peak and Peak Reduction Conditions for 2030-2040 for RCP 8.5

	HSPF Output		Simulation Model Output Using HSPF		
Stream Flow Range (×1000 cfs)	Number of Appearances	Average Annual Peak Appearances	Number of Appearances	Average Annual Peak Appearances	Peak Reduction %
30+	4	0.36	0	0.00	100.00
20-30	16	1.45	4	0.36	75.00
10-20	200	18.18	92	8.36	54.00
5-10	520	47.27	386	35.09	25.77
0-5	15332	1393.82	15590	1417.27	-1.68

The extreme flow for RCP 8.5 scenario was simulated during 2048. The extreme of that year will be reduced from 40325 cfs to 27630 cfs (peak reduction rate of 31.48%) (Figure 5.25).

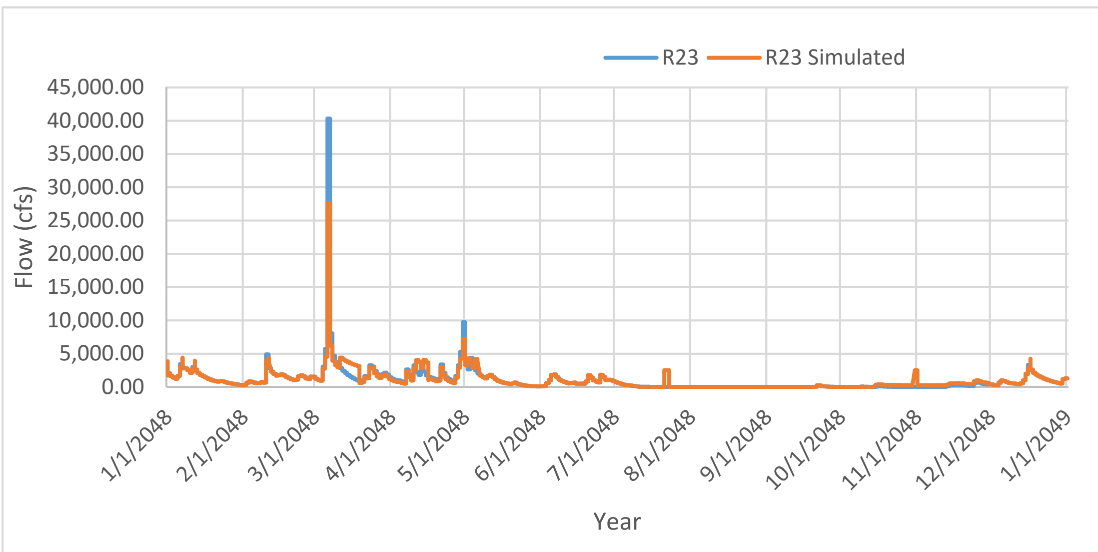


Figure 5.25 2048 Flow Data for RCP 8.5

Table 5.11 compares the results of RCP 2.6 and RCP 8.5 simulations with reservoir operation. In both cases, the flood control benefits of Brookville reservoir are substantial.

Table 5.9 Peak Reduction Rate for Both RCPs

Stream Flow Range (×1000 cfs)	Peak Reduction %	
	RCP 2.6	RCP 8.5
30+	60	100
20-30	75	75
10-20	22.973	54
5-10	37.664	25.77
0-5	-2.024	-1.68

5.2. HEC-HMS

Apart from the BASINS-HSPF model, for modelling watershed rain runoff, U.S. Army Corps of Engineers HEC-HMS software was also used for developing watershed rainfall runoff model. It is a user-friendly software which is often used for hydrological modelling. HEC-HMS model was also calibrated using historical flow data. It also yielded similar results to that of HSPF model. The reason for developing HEC-HMS model was the flexibility to include a reservoir in the modelling scheme. BASINS model needed an external simulation model for reservoir operation as shown in Figure 5.14. Since both results were very similar, HSPF model results were presented in this research thesis.

6. CONCLUSION

The objective of assessing the performance of Brookville flood control dam is achieved by combining the HSPF Model with a reservoir operation model. Using historic flow data, the performance of the flood control done by the Brookville dam was examined first. It indicates substantial benefits due to the dam construction, the peak flow at Whitewater River never exceeded 40000 cfs. Calibrated and validated HSPF model was used to examine the future benefits of this flood control reservoir.

Futuristic scenario analysis was done with downscaled CMIP5 GCM precipitation data. The data are downloaded for different CO_2 emission as RCP 2.6 and RCP 8.5. Both precipitation data are imported to the validated model for simulating the futuristic uncontrolled and controlled flow. The results are analyzed for flood prediction.

Despite difficulties and uncertainties associated with searching data and predicting future climate conditions, the study is finished with optimistic results. Reservoir operation results in substantial reduction of flow peaks for both scenarios. Few future peaks were very large for less carbon emission case and the dam operations reduces them by 60%. The frame work used in this research is easily extendable to other watersheds.

REFERENCES

Abushandi, Eyad and Broder Merkel. "Modelling Rainfall Runoff Relations Using HEC-HMS and IHACRES for a Single Rain Event in an Arid Region of Jordan." 5 February 2013.

Bartman, A. G., W. A. Landman and C. J. De W. Rautenbach. "Recalibration of General Circulation Model Output to Austral Summer Rainfall over Southern Africa." 7 July 2003.

Chandramouli, Chandramouli Viswanatha, Madhusudhan Narayana and S. V. T. Ramesh. "Developing Fecal TMDLs for Watershed Management Using Fuzzy Based Approach." *Watershed Management Conference*. 2010.

Choudhari, Kishor, Balram Panigrahi and Jagadish Chandra Paul. "Simulation of Rainfall-runoff Process Using HEC-HMS Model for Balijore Nala Watershed, Odisha, India." *International Jornal of Geomatics and Geosciences* 2014: Volume 5, No. 2.

Crane, Robert G. and Bruce C. Hewitson. "Doubled CO2 Precipitaion Changes for the Susquehanna Basin: Down-Scaling from the Genesis General Circulation Model." *International Jornal of Climatology* 1998.

Devia, Gayathri K., Ganasri B. Pa and Dwarakish G. Sa. "A Review on Hydrological Models." *International Conference on Water Resources, Coastal and Ocean Engineering (ICWRCOE 2015)*. 2015.

DNR. "Water Whitewater River Basin, Indiana-Executive Summary." 1988.

Giorgi, Filippo. "Simulation of Regional Climate Using a Limited Area Model Nested in a General Circulation Model." 26 March 1990.

Hromadka II, T. V. "Rainfall-Runoff Models: A Review." *Environmental Software* June 1990: Volume 5, Issue 2, Pages 82-103.

Imboff, J. C., et al. "Using the Climate Assessment Tool (CAT) in U.S. EPA BASINS Integrated Modeling System to Assess Watershed Watershed Vulnerability to Climate Change." February 2007.

Jakeman, A. J. and G. M. Hornberger. "How Much Complexity is Warranted in A Rainfall-Runoff Model?" *Water Resources Research* August 1993: Volume 29, Issue 8, Pages 2637-2649.

Kite, G. W., A. Dalton and K. Dion. "Simulation of Streamflow in a Macroscale Watershed Using General Circulation Model Data." May 1994.

Luzio, Mauro Di, Raghavan Srinivasan and Jeffrey G, Arnold. "Integration of Watershed Tools and SWAT model into BASINS." *Journal of the American Water Resources Association* August 2002.

Ma, Jiehua, Huijun Wang and Ke Fan. "Dynamic Downscaling of Summer Precipitaion Prediction over China in 1998 Using WRF and CCSM4." May 2015.

Meenu, R., S. Rehana and P. P. Mujumdar. "Assessment of Hydrologic Impacts of Climate Change in Tunga-Bhadra River Basin, India with HEC-HMS and SDSM." 11 May 2012.

Mohamad, Bakir; Zhange, Xingnan;. "GIS-Based Hydrological Modeling: a Comparative Study of HEC-HMS and the XInanjiang Model." *Twelfth International Water Technology Conference*. Alexandria, Egypt, 2008.

Moss, Richard, et al. *Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies.* Geneva: Tnergovernmental Panel on Climate Change, 2008.

NOAA. *NOAA 200th Top Tens: Breakthoughs: The First Climate Model*. 12 May 2017. 19 November 2018.

Oleyiblo, James Oloche and Zhijia Li. "Application of HEC-HMS for Flood Forecasting in Misai and Wan'an Catchments in China." 2010.

Pool, Sandra, Daniel Viviroli and Jan Seibert. "Prediction of Hydrographs and Flow-Duration Curves in Almost Ungauged Catchments: Which Runoff Measurements are Most Informative for Model Calibration?" *Jornal of Hydrology* Novemeber 2017: Volume 554, Pages 613-622.

Shirinian-Orlando, Anne A. and Christopher G. Uchrin. "Modeling the Hydrology and Water Quality Using BASINS/HSPF for the Upper Maurice River Watershed, New Jersey." 31 Janurary 2007.

Storm Rainfall Depth and Distribution. Natural Resources Conservation Service-United States Department of Agriculture, 2015.

Whittemore, Ray C. and John Beebe. "EPA's BASINS Model: Good Science or Serendipitous Modeling?" *Journal of the American Water Resources Assocition* June 2000: Vol. 36, No. 3.

Yapo, Patrice O., Hoshin Vijai Gupta and Soroosh Sorooshian. "Automatic Calibration of Conceptual Rainfall-Runoff Models: Sensitivity to Calibration Data." *Journal of Hydrology* June 1996: Volume 181, Issues 1-4, Pages 23-48.

Zhang, Yi and Menghong Wen. "Watershed Modeling and Calibration for Spring Creek Sub-basin in the Flint River Basin of Georgia Using EPA BASINS/HSPF Modeling Tool." 2003.

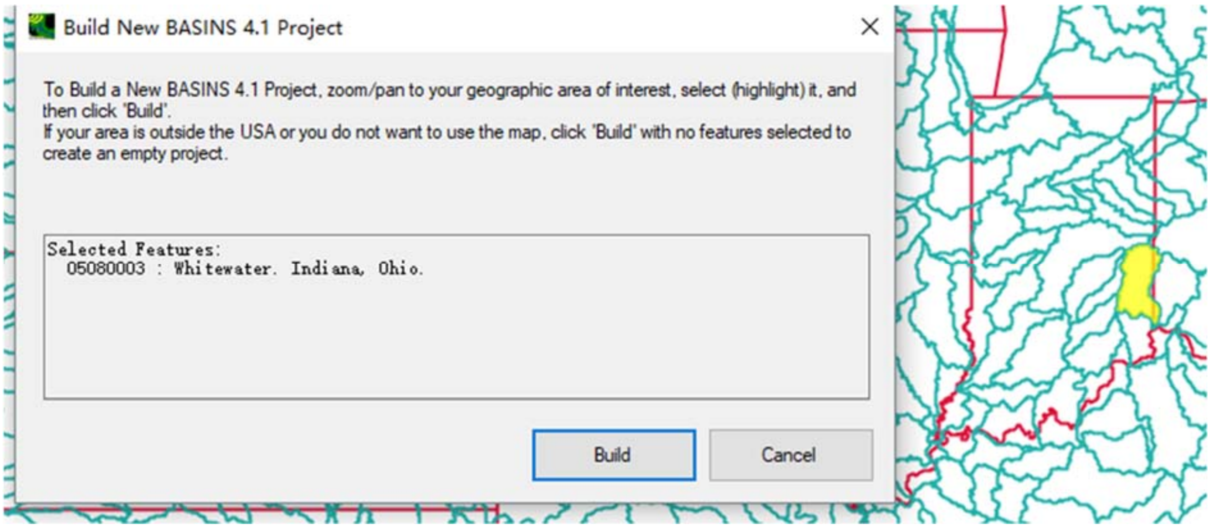
APPENDIX A. NRCS METHOD

Time hr	Cumulative 24-hr rainfall ratio	Time hr	Cumulative 24-hr rainfall ratio
0	0	12.5	0.7288
0.5	0.0031	13	0.7943
1	0.0064	13.5	0.8307
1.5	0.01	14	0.8546
2	0.0139	14.5	0.8741
2.5	0.018	15	0.8892
3	0.0224	15.5	0.9013
3.5	0.0271	16	0.9122
4	0.032	16.5	0.9222
4.5	0.0372	17	0.931
5	0.0427	17.5	0.9388
5.5	0.0484	18	0.9456
6	0.0544	18.5	0.9516
6.5	0.0612	19	0.9573
7	0.069	19.5	0.9628
7.5	0.0778	20	0.968
8	0.0878	20.5	0.9729
8.5	0.0988	21	0.9776
9	0.1108	21.5	0.982
9.5	0.1259	22	0.9861
10	0.1454	22.5	0.99
10.5	0.1693	23	0.9936
11	0.2057	23.5	0.9969
11.5	0.2712	24	1
12	0.4763		

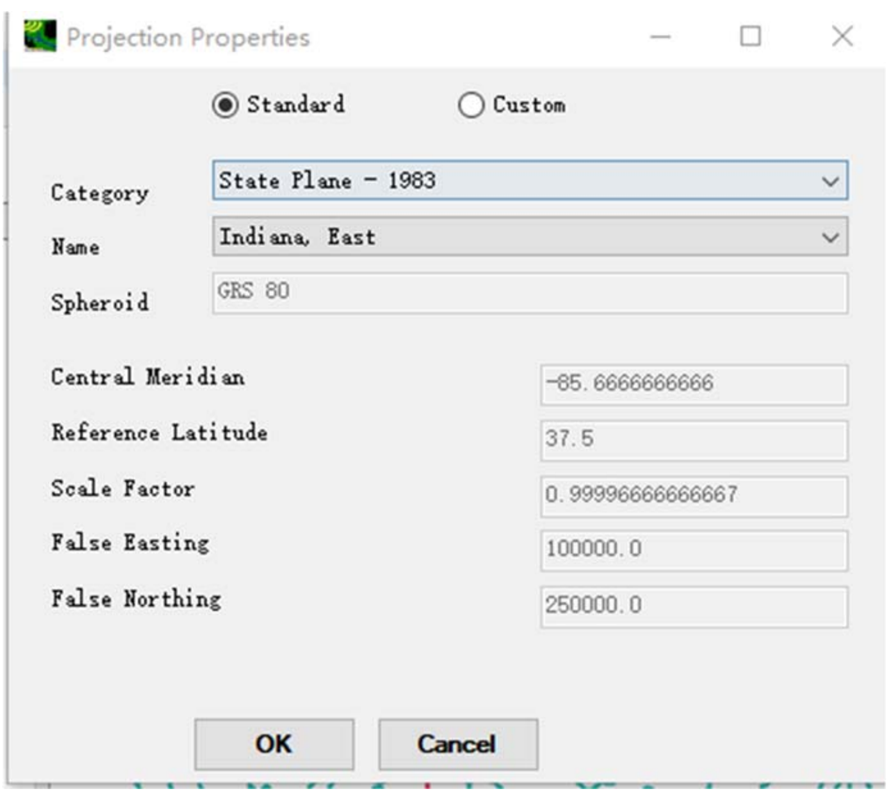
(Storm Rainfall Depth and Distribution)

APPENDIX B. STEPS OF EPA BASINS/HSPF MODEL CREATION

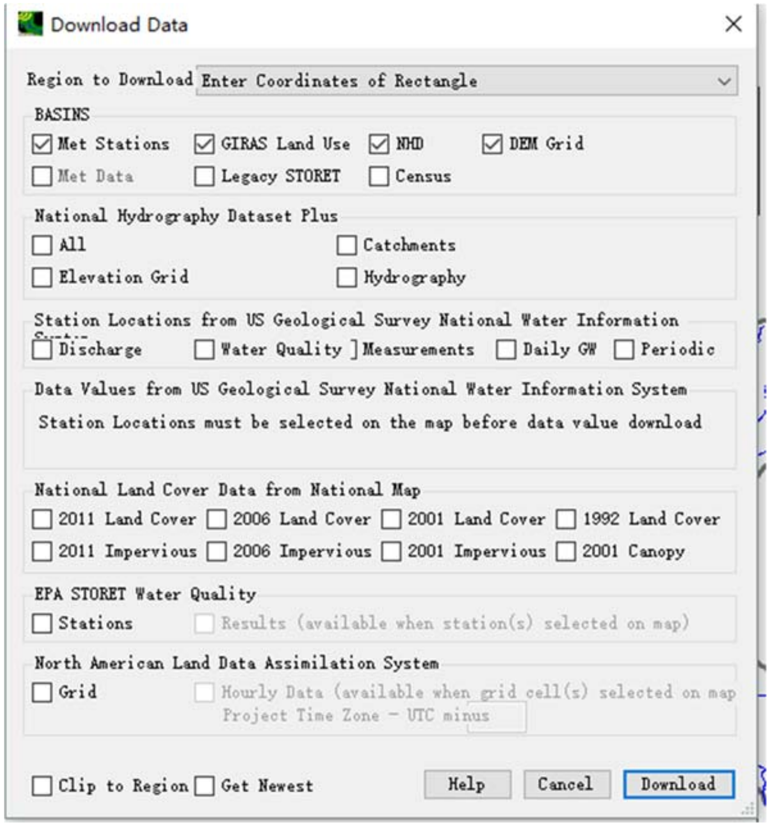
1. EPA BASINS Version 4.1 is used for this research. In Build New Project, the corresponding watershed (05080003: Whitewater. Indiana, Ohio) was selected and build as an empty watershed model and saved.

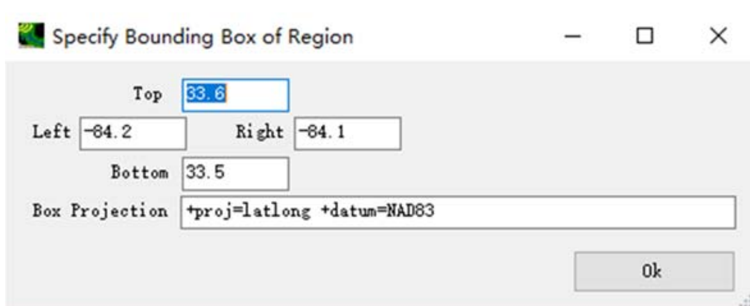


2. Projection Properties is selected as Standard, State Plane-1983, Indiana, East.

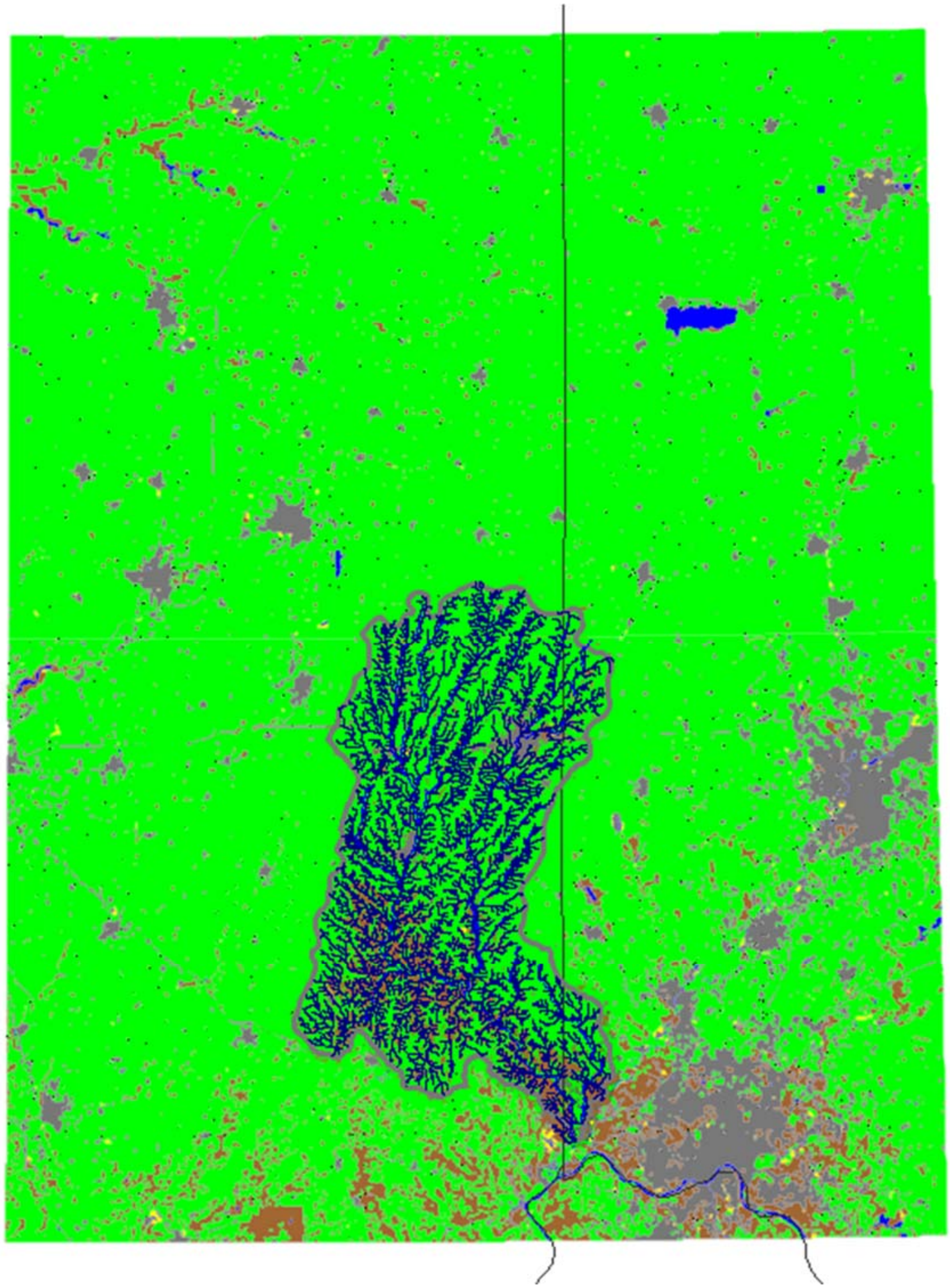


3. Watershed property data is downloaded under File-Download Data, the required data set options are selected for downloading including Met Stations, GIRAS Land Use, NHD, and DEM Grid. The Specify Bounding Box of Region stays as default.

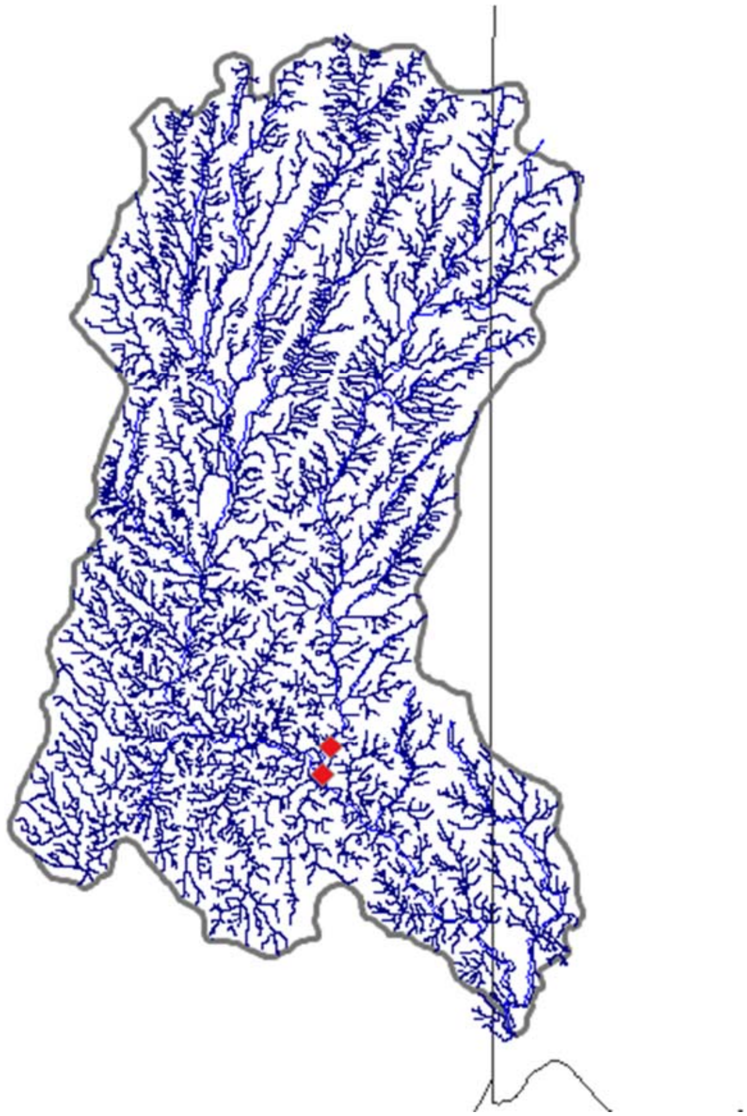




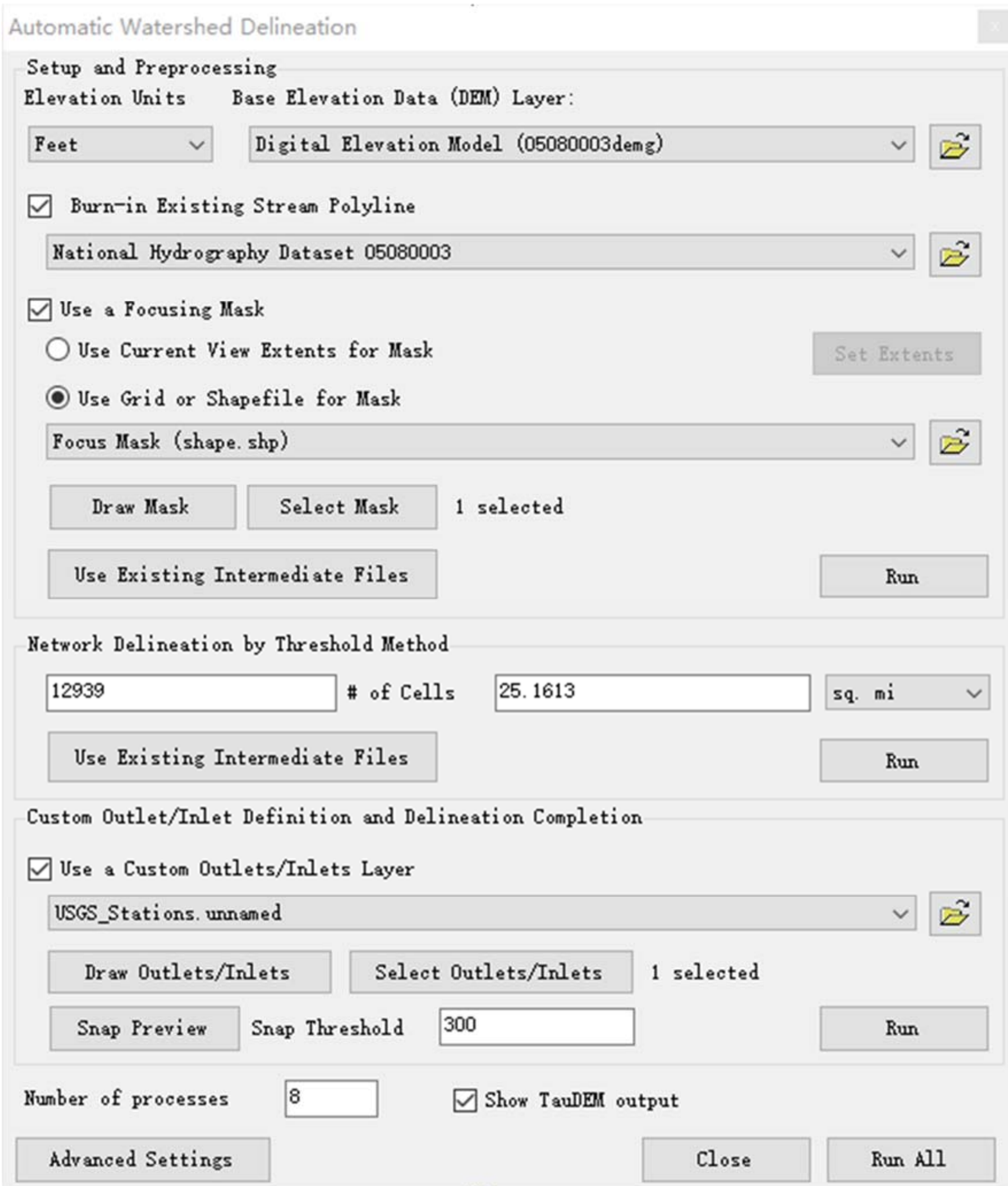
4. With all downloaded data, click Download, the watershed model is set with elevation, land use, soil type and hydrology data set.



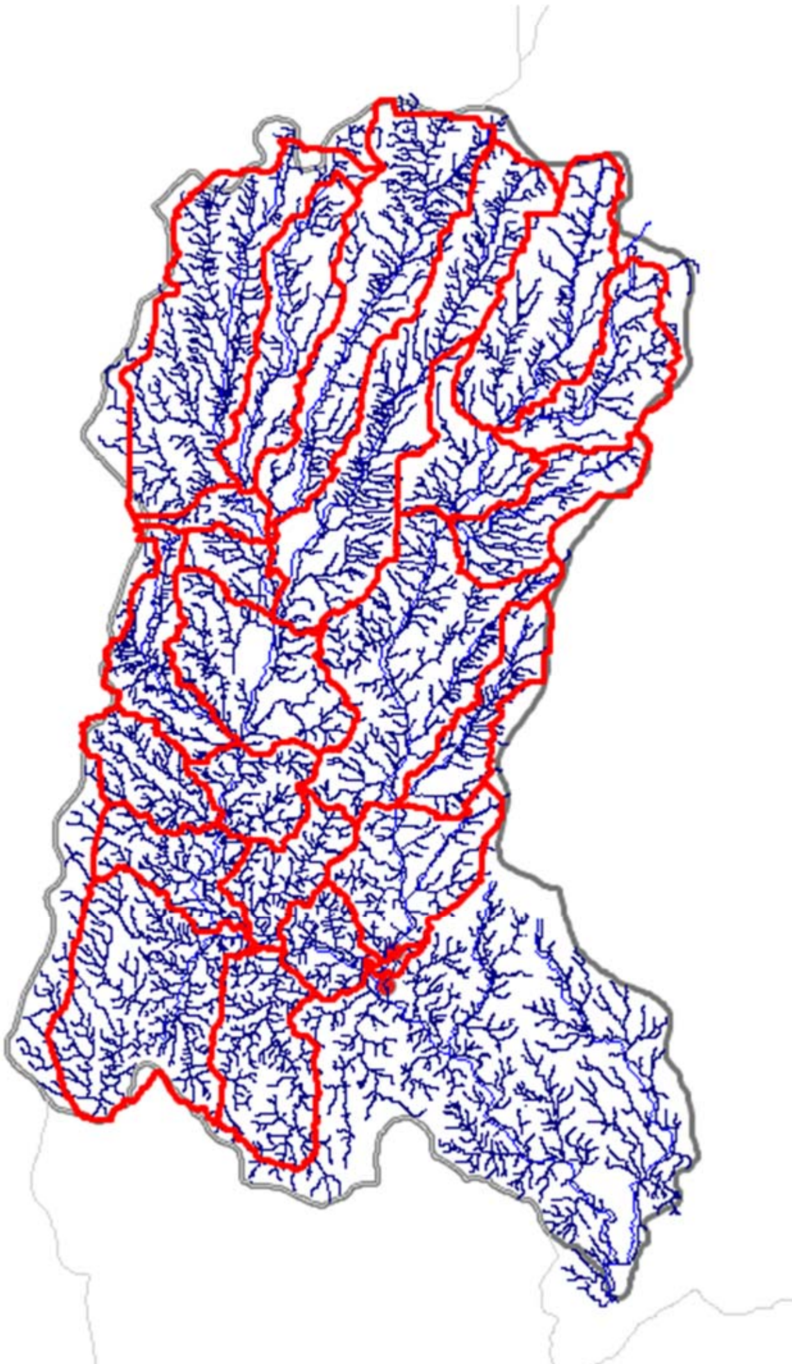
5. Layers can be displayed or hided by users for convenience under Legend-Layers window on the left. Coordinates of USGS hydraulic gaging stations 03276000 and 03276500 are inserted as a shapefile created by ARC GIS for further development.



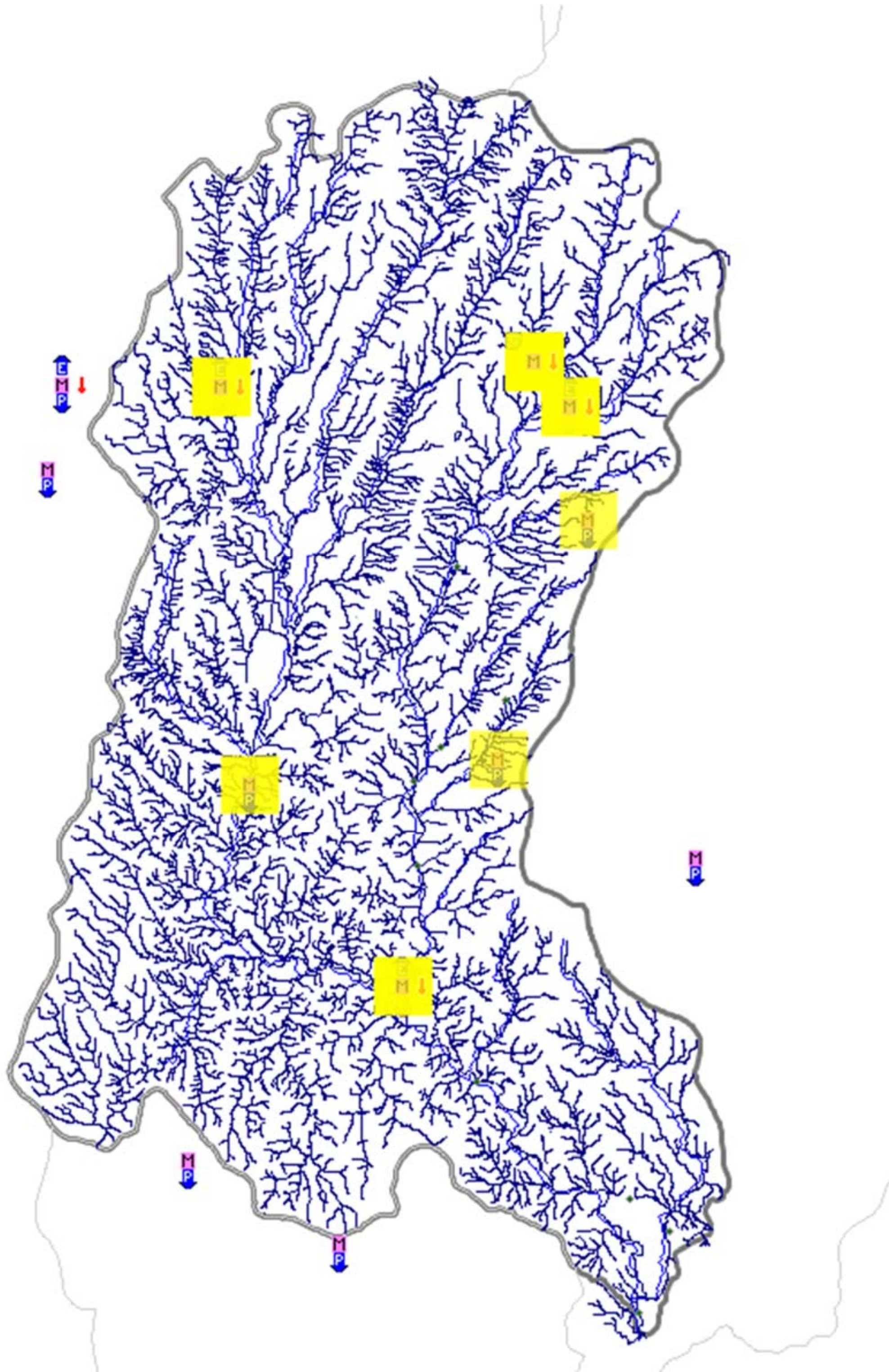
6. By using the lower station as the starting and ending point, a Focus Mask is drawn carefully by following the watershed boundary under Watershed Delineation-Automatic. Elevation Units is selected as Feet and Base Elevation Data layer is selected as Digital Elevation Model (05080003demg) which is downloaded. The outlet is selected under USGS gaging station shapefile. Burn-in Existing Stream Polyline is selected as National Hydrography Dataset 05080003. Other values stay as default.



7. By click Run All, the watershed shapefile is created automatically by the software. 23 sub-watersheds are developed and separated, the outlet is located on the 23rd sub-watershed. The model is saved data analysis.



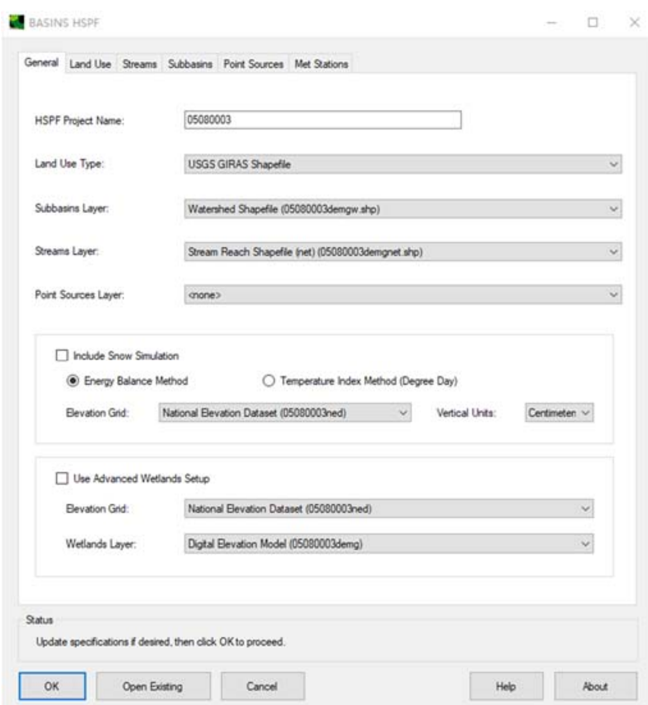
8. By displaying the Observed Data Stations-Weather Station Sites 2009, 7 types of met data is measured by 12 Met Stations. There are 7 met stations located within the area of the selected watershed. These data is used for further data analysis and HSPF model development.



9. Layers data can be observed by right click the layer and selected Attribute Table Editor. All these data can be modified based on reality and used for future watershed analysis. For example, lengths of reaches.

SHAPE__ID	FNODE_	TNODE_	LPOLY_	RPOLY_	LENGTH
0	6674	6646	0	0	0.034941
1	6646	6379	0	0	0.426409
2	6646	6489	0	0	0.300747
3	6489	6348	0	0	0.203189
4	6489	6445	0	0	0.109884
5	6445	6373	0	0	0.08525
6	6373	6305	0	0	0.125279
7	6373	6308	0	0	0.080353
8	6308	6167	0	0	0.22415
9	6308	6270	0	0	0.06478
10	6270	6123	0	0	0.225119
11	6270	6095	0	0	0.226851
12	6095	6021	0	0	0.226674
13	6095	6011	0	0	0.108389
14	6011	5807	0	0	0.305665
15	6011	5765	0	0	0.301567
16	6445	6417	0	0	0.178
17	6417	6283	0	0	0.238522
18	6283	6182	0	0	0.124414
19	6182	5778	0	0	0.498184
20	6182	6122	0	0	0.075709
21	6122	5748	0	0	0.491605
22	6122	6079	0	0	0.0693
23	6079	5799	0	0	0.334036
24	6079	5776	0	0	0.319871
25	6283	6121	0	0	0.26751
26	6417	6503	0	0	0.173733

10. By clicking Models-HSPF, an uci. file can be created by relating all the data downloaded.

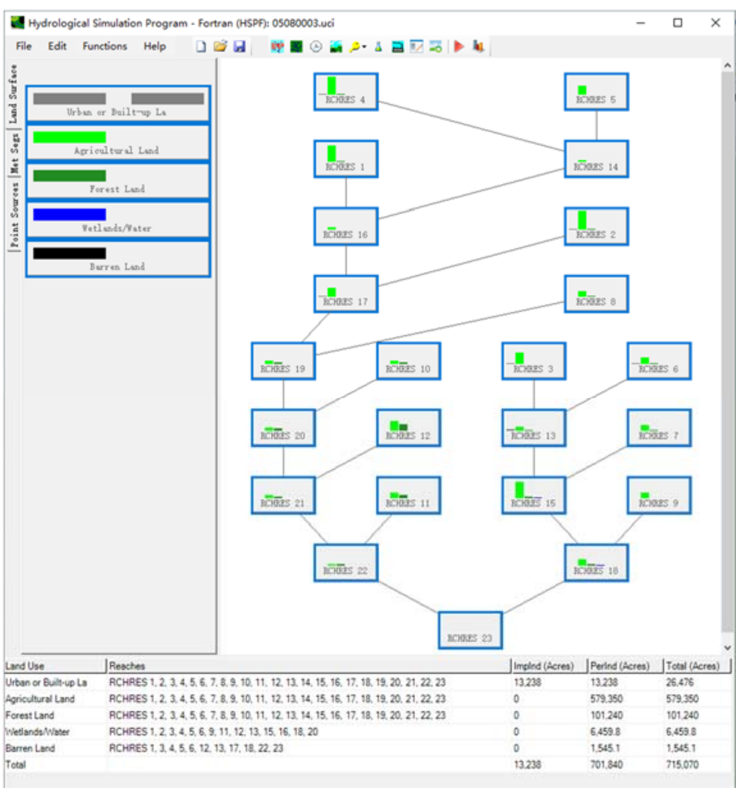


11. The HSPF is named as 05080003, and saved in an empty folder. Met data is also copied and pasted onto the same folder for convenience. The HSPF model is run for the first time in order to get results for further development.

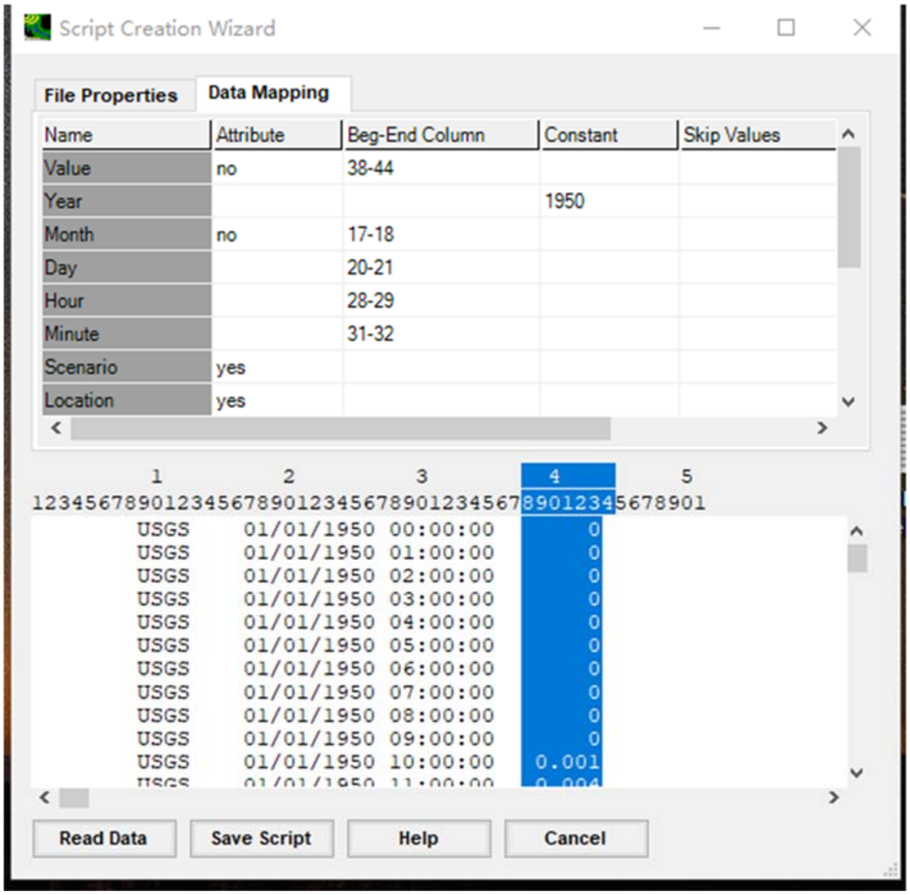
12. The .uci file can be open by WinHSPF 3.0 and also Notepad. Met data can be opened and edited by WDMUtil. Based on the latest release note, most of the functions of WDMUtil is concluded by EPA BASINS. The load path is changed as met.wdm, which load directly from the same folder where the .uci file contains.

```
FILES
<FILE>  <UN#>***<----FILE NAME------------------------------------------------->
MESSU     24   05080003.ech
          91   05080003.out
WDM1      25   05080003.wdm
WDM2      26   met.wdm
BINO      92   05080003.hbn
END FILES
```

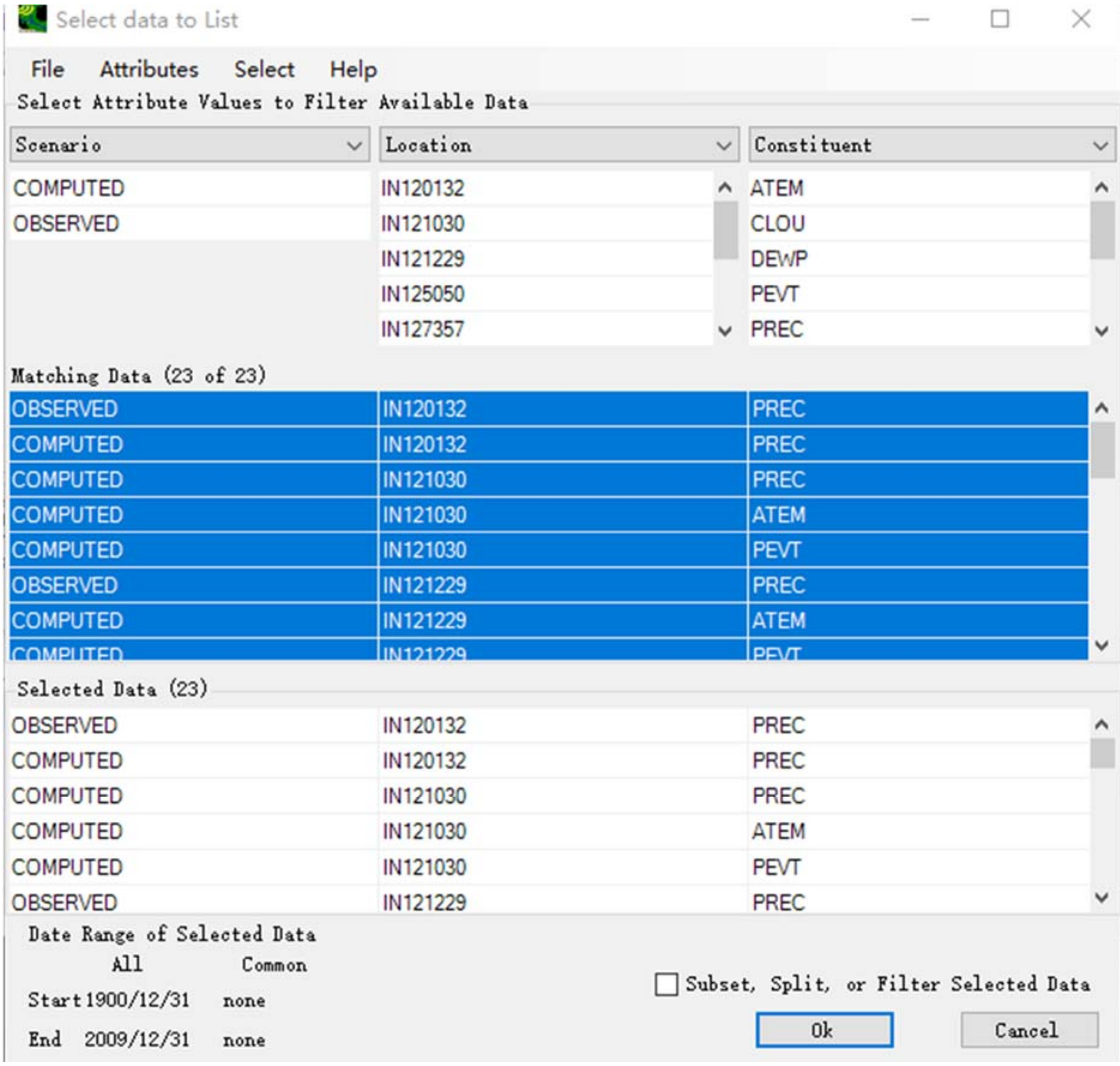
13. By changing the code in the .uci file which is opened by Notepad, different load path can be applied for data input.



14. Precipitation data for daily time interval downloaded from USDA official website is used for replacing the precipitation data downloaded automatically by BASINS. The new precipitation data is disaggregated to hourly and imported to Excel. The Excel worksheet can be saved as .prn file and read as WDM file under File-Open Data-Read Data with Script. Under Data Mapping, the script is modified manually.



15. After the precipitation data is updated and numbered, the new WDM data is saved and added to the existing WDM file under File-Save Data In. and the data can be observed under File-Manage Data, Analysis-List.



16. By clicking Ok, all Time-Series data can be listed on a table. These values can be changed for model development, also, can be exported by simply copy and paste for data analysis.

Time Series List

File Edit View Analysis Help

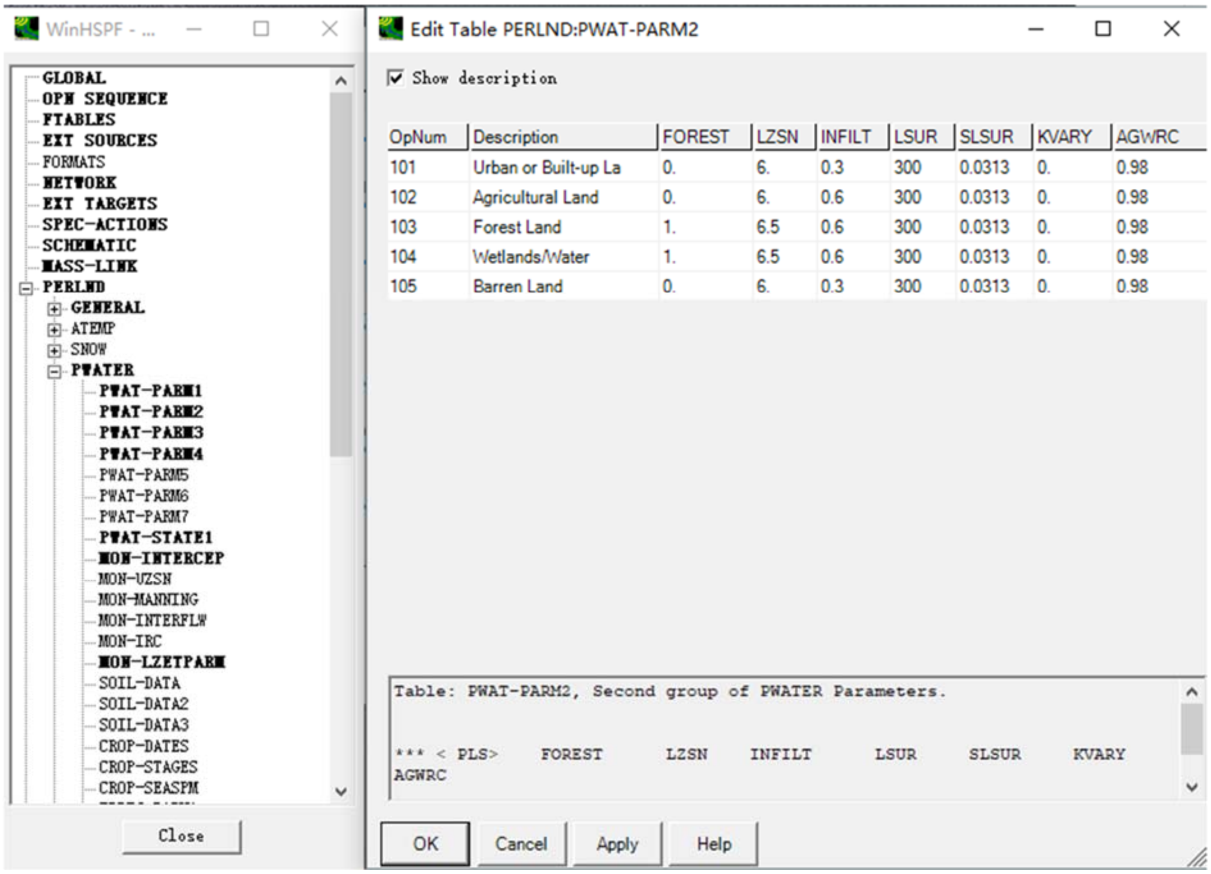
History 1	from met.wdm	from met.wdm	from met.wdm	from met.wdm	from met.wdm	from met.wdm	from met.wdm	from met.wdm	from met.wdm	from met.wdm	from met.wdm	from met.wdm	from met.wdm	from met.wdm	from met.wdm	from met.wdm
Constituent	PREC	PREC	PREC	ATEM	PEVT	PREC	ATEM	PEVT	PREC	PREC	PREC	PREC	ATEM	PEVT	PREC	PREC
Id	1	10	11	13	16	21	23	26	30	31	41	51	53	56	60	61
Min	0	0	0	-31	0	0	-31	0	0	0	0	0	-26	0	0	0
Max	2.6	2.68	3.015	104	0.022984	2	102	0.022548	2.349	2.86	2.28	10.03	103	0.024917	1.744	4.6058
Mean	0.0046835	0.0044737	0.0048102	51.535	0.0032032	0.0043705	49.665	0.0030451	0.0046847	0.0048121	0.0044134	0.00447	50.256	0.0030674	0.004375	0.0044999
1900/12/31 19:00															0	
1900/12/31 20:00															0	
1900/12/31 21:00															0	
1900/12/31 22:00															0	
1900/12/31 23:00															0	
1900/12/31 24:00													Missing	Missing	0	
1901/01/01 01:00													11.15	0	0	
1901/01/01 02:00													10.1	0	0	
1901/01/01 03:00													9.26	0	0	
1901/01/01 04:00													8.63	0	0	
1901/01/01 05:00													8.21	0	0	
1901/01/01 06:00													8	0	0	
1901/01/01 07:00													11.36	0	0	
1901/01/01 08:00													14.51	0.00031391	0	
1901/01/01 09:00													17.45	0.00082296	0	
1901/01/01 10:00													20.39	0.0011751	0	
1901/01/01 11:00													22.91	0.0011751	0	
1901/01/01 12:00													25.01	0.0011751	0	
1901/01/01 13:00													26.69	0.0011751	0	
1901/01/01 14:00													27.95	0.0011751	0	
1901/01/01 15:00													28.79	0.00082296	0	
1901/01/01 16:00													29	0.00031391	0	
1901/01/01 17:00													26.25	0	0	
1901/01/01 18:00													23.5	0	0	
1901/01/01 19:00													20.75	0	0	
1901/01/01 20:00													18.25	0	0	
1901/01/01 21:00													15.75	0	0	
1901/01/01 22:00													13.5	0	0	
1901/01/01 23:00													11.25	0	0	
1901/01/01 24:00													9.5	0	0	
1901/01/02 01:00													7.75	0	0	

17. These previous steps from 14 to 16 can also be done with WDMUtil for old version of EPA BASINS.

18. New precipitation data can be used for HSPF model by changing the load path of WDM data in the .uci file which is opened by Notepad. Other load path stays as default.

```
WDM2     5 PREC     ENGL          SAME PERLND 101 105 EXTNL  PREC
WDM2     6 ATEM     ENGL          SAME PERLND 101 105 EXTNL  GATMP
WDM2    12 DEWP     ENGL          SAME PERLND 101 105 EXTNL  DTMPG
WDM2     8 WIND     ENGL          SAME PERLND 101 105 EXTNL  WINMOV
WDM2     9 SOLR     ENGL          SAME PERLND 101 105 EXTNL  SOLRAD
WDM2     7 PEVT     ENGL          SAME PERLND 101 105 EXTNL  PETINP
*** Met Seg IN120132
WDM2     5 PREC     ENGL          SAME IMPLND 101     EXTNL  PREC
WDM2     6 ATEM     ENGL          SAME IMPLND 101     EXTNL  GATMP
WDM2    12 DEWP     ENGL          SAME IMPLND 101     EXTNL  DTMPG
WDM2     8 WIND     ENGL          SAME IMPLND 101     EXTNL  WINMOV
WDM2     9 SOLR     ENGL          SAME IMPLND 101     EXTNL  SOLRAD
WDM2     7 PEVT     ENGL          SAME IMPLND 101     EXTNL  PETINP
*** Met Seg IN120132
WDM2     5 PREC     ENGL          SAME RCHRES   1  23 EXTNL  PREC
WDM2     6 ATEM     ENGL          SAME RCHRES   1  23 EXTNL  GATMP
WDM2    12 DEWP     ENGL          SAME RCHRES   1  23 EXTNL  DEWTMP
WDM2     8 WIND     ENGL          SAME RCHRES   1  23 EXTNL  WIND
WDM2     9 SOLR     ENGL          SAME RCHRES   1  23 EXTNL  SOLRAD
WDM2    14 CLOU     ENGL          SAME RCHRES   1  23 EXTNL  CLOUD
WDM2     7 PEVT     ENGL          SAME RCHRES   1  23 EXTNL  POTEV
```

19. By opening the .uci file with WinHSPF 3.0, input data can be managed under Input Data Editor. In this case, infiltration rate is leading parameter for adjustment.



20. By modifying the infiltration rates for different land cover types, the simulated flow is behaving similar as the actual flow data.