Appendix D.

Model Setup, Calibration, and Validation

1. Model Selection and Setup

The Loading Simulation Program in C++ (LSPC) was selected to address the modeling needs for the lower Grand River watershed TMDL. LSPC is a version of the Hydrologic Simulation Program FORTRAN (HSPF) model that has been ported to the C++ programming language to improve efficiency and flexibility[1]. LSPC integrates modern data storage and management capabilities, the original HSPF algorithms, and a data analysis/post-processing system into a convenient PC-based windows interface. LSPC's algorithms are identical to a subset of those in the HSPF model. LSPC is currently maintained by Tetra Tech and the U.S. EPA Office of Research and Development in Athens, Georgia. Advantages of choosing LSPC for this application include its ability to simulate both rural and urban land uses and its sophisticated algorithms for simulating watershed hydrology. LSPC is also free and publicly available. This is advantageous for distributing the model to interested stakeholders and amongst government agencies.

Due to the nature of the TMDL, the primary parameter of concern in the lower Grand River is flow. Therefore, although LSPC is able to simulate other parameters, the model was only setup and calibrated to simulate flow within the watershed. The LSPC model is driven by precipitation and other climatologic data (e.g., air temperature, cloud cover, wind speed). Of these, the most critical inputs are precipitation, air temperature, solar radiation, and potential evapotranspiration. Appropriate representation of these variables is therefore required to develop a valid model. Daily rainfall and temperature data from the weather station at Chardon (331458) were used, with other climatologic data taken from the weather station at Cleveland Hopkins Airport (14820).

The LSPC model was setup using hydrologic response units (HRUs). An HRU is defined as a watershed area assumed to be homogeneous in hydrologic response due to similar land use and soil characteristics. Additional details on the HRUs developed for the lower Grand River watershed are presented in Section 6.1 of the main report.

2. Calibration Process

Standard operating procedures for hydrologic calibration of a watershed model are described in Donigian et al. (1984), Lumb et al. (1994), and U.S. EPA (2000). During hydrology calibration, land segment hydrology parameters are adjusted iteratively to achieve agreement between simulated and observed stream flows at specified locations. Agreement between observed and simulated stream flow data is first evaluated on an annual and seasonal basis using quantitative and qualitative measures. Specifically, annual water balance, ground water volumes and recession rates, and surface runoff and interflow volumes and timing are evaluated, along with composite comparisons (e.g., average monthly stream flow values over the period of record).

Hydrologic predictions from the model are most sensitive to external forcing by precipitation, followed by potential evapotranspiration (PET). These weather inputs are typically not adjusted during calibration.

[1] Hydrologic Simulation Program FORTRAN (HSPF) is a comprehensive, public domain, watershed and receiving water quality modeling framework that was originally developed in the mid-1970s and is supported by U.S. EPA and USGS. During the past several years it has been used to develop hundreds of USEPA-approved TMDLs and it is generally considered one of the most advanced hydrologic and watershed loading model available. The hydrologic portion of HSPF is based on the Stanford Watershed Model, which was one of the pioneering watershed models developed in the 1960s. The HSPF framework is developed in a modular fashion with many different components that can be assembled in different ways, depending on the objectives of the individual project. A detailed discussion of HSPF simulated processes and model parameters are available in the HSPF User's Manual.

Within the model, the annual water balance is usually most sensitive to the specification of the lower zone nominal storage (LZSN) and the lower zone ET factor (LZETP), both of which control the amount of water lost to evapotranspiration. The distribution of runoff between storm and non-storm conditions is usually most sensitive to the infiltration index (INFILT) and ground water recession rate (AGWRC).

The hydrologic model is calibrated by first adjusting model parameters until the simulated and observed annual and seasonal water budgets are in good agreement. Then, the intensity and arrival time of individual events is calibrated. This iterative process is repeated until the simulated results closely represent the system and reproduce observed flow patterns and magnitudes. Sensitivity analyses for model input parameters can help guide this effort. Below is a more detailed description of the step-by-step process.

1. **Annual water balance**. In this step, the total average annual simulated flow volume is compared with the observed data. The input precipitation and evaporation data set, along with the calibration parameters LZSN, LZETP, and INFILT are the main factors influencing the annual water balance. Other factors include anthropogenic water inputs and outputs and ground water exchanges.
2. **Low flow / high flow distribution**. The low flows are usually matched first by adjusting the INFILT and AGWRC parameters. Low flows are also dependent on the accurate representation of point source discharges, irrigation applications, water withdrawals, and ground water exchanges. High flows were matched by adjusting the following model parameters: infiltration (INFILT), LZSN, interflow parameter (INTFW), and interflow recession (IRC). These high flows are also affected by physical characteristics of the land that affect runoff velocity and the timing of high flows in the stream: slope and manning's n.
3. **Seasonal adjustments**. Adjustments related to seasonal differences were made to vegetal interception storage capacity (CESPC), LZETP, and upper zone nominal soil moisture storage (UZSN). Updates to KVARY (variable ground water recession) and the fraction of remaining evapotranspiration from baseflow (BASETP) were also made.
4. **Storm peaks and hydrograph shape**. Simulated storm event peaks were compared to available storm hydrograph and storm peak data for selected storms. The storm flow is largely dependent on surface runoff and interflow volumes and timing. Changes were made to the infiltration (INFILT), UZSN, interflow parameter (INTFW), interflow recession (IRC), and the overland flow parameters (LSUR, NSUR, and SLSUR (slope of overland flow)), among other upland parameters.

After the model was configured, model calibration and validation were performed. The hydrologic calibration process involved a comparison of observed data to modeled in-stream flow and an adjustment of key parameters. Modeling parameters were varied within generally accepted bounds and in accordance with observed temporal trends and soil and land cover characteristics. The calibration was especially sensitive to the parameters for infiltration (INFILT), lower zone nominal storage (LZSN), and upper zone storage nominal (UZSN). The model was also very sensitive to the simulation of snow melt, and the SNOWCF parameter was varied to account for poor snow catch efficiency of the weather gage.

All hydrologic parameters for LSPC were selected to remain within the guidelines for parameter values set out in *BASINS Technical Note 6* (U.S. EPA 2000). The time period of 1986 through 2006 was selected for modeling because sufficient data from all necessary input datasets were available during this time period. The period of record was split into halves for calibration and validation. The calibration time period was selected as 1986 to 1995.

3. Calibration Results

The hydrology calibration results are shown below. The flow within the lower Grand River watershed was simulated by LSPC and added to an estimate of the drainage area weighted flow for the upper Grand River watershed. This combined flow was then used to compare to the observed flow at the USGS gage at Painesville. Figure D-1 through Figure D-4 show the graphical comparisons used to assess model performance. For a quantitative comparison, modeled and observed flows and rainfall were summarized by average monthly values over the simulation period. Comparisons of average monthly conditions (top chart) and daily flow conditions (bottom chart) are depicted graphically in Figure D-1. The model closely matches the observed data during this time period.

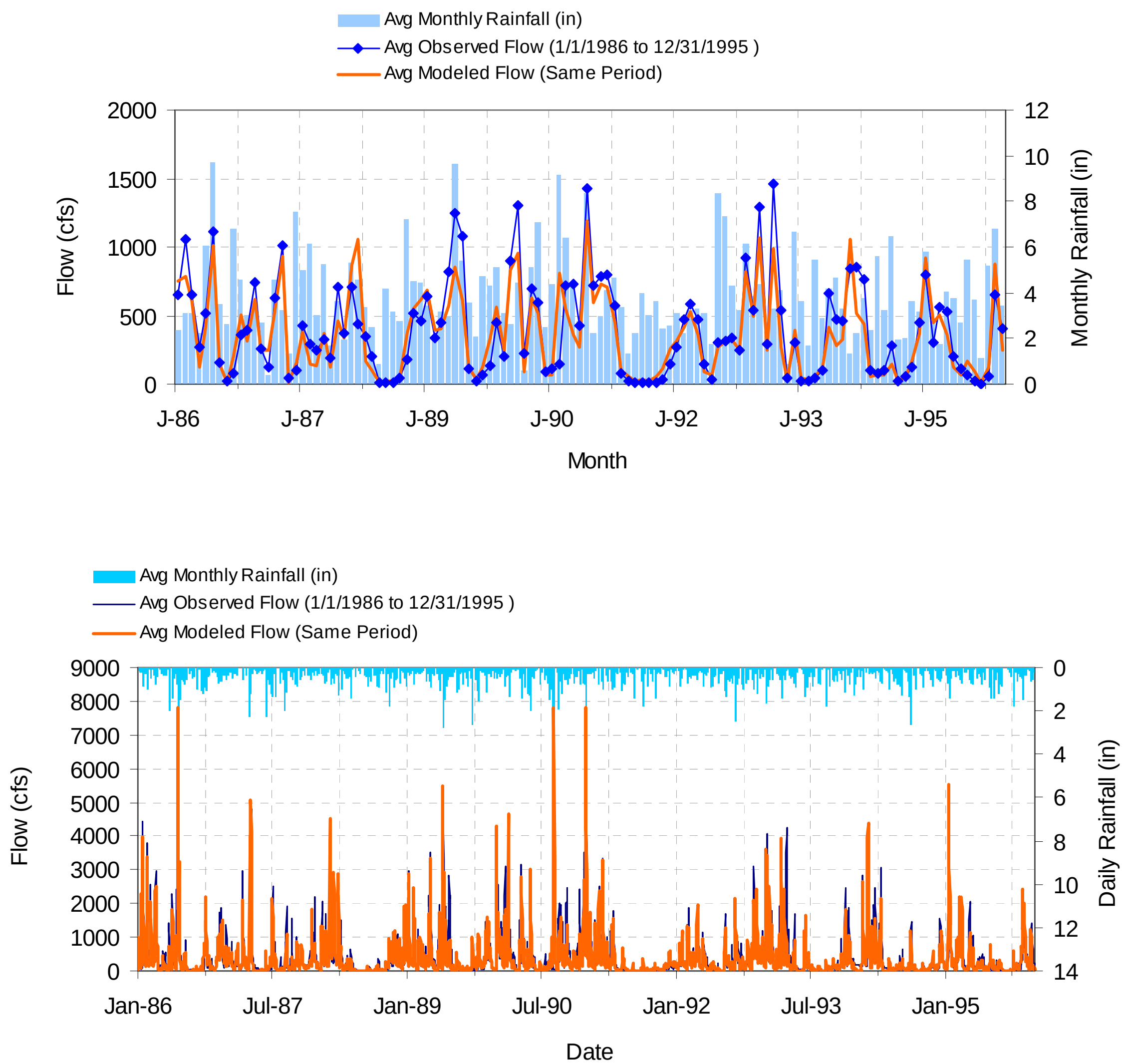


Figure D-1. Comparison of modeled and observed monthly (top chart) and daily flows (bottom chart) during calibration.

To provide a measure of model accuracy, average monthly model-predicted and observed flows were compared through a regression analysis shown in Figure D-2. The regression analysis indicates that the closer the data comes to the 45° angle line, the better the two data sets match. The analysis suggests that most of the flows are well correlated, with the modeled higher flows slightly under predicted. Certain months have been over- or under-predicted, but overall the model appears to predict stream flow at a frequency and magnitude similar to the observed data.

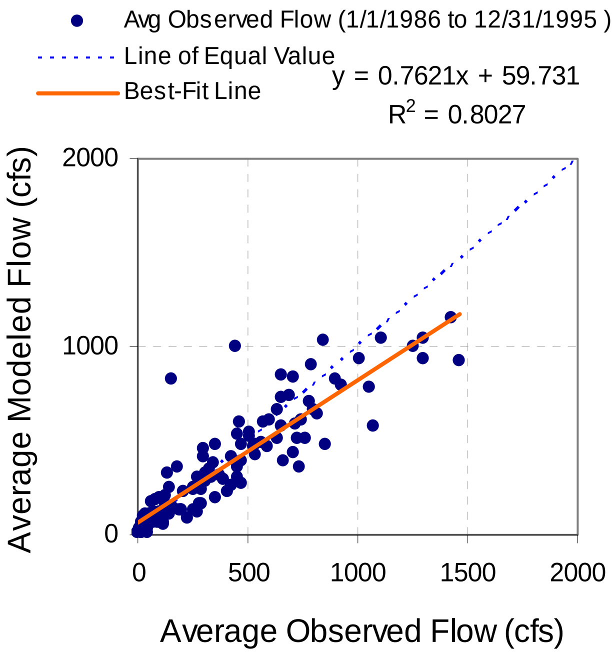


Figure D-2. Regression analysis of modeled and observed average monthly flows during calibration.

Another useful measure is an evaluation of model performance with respect to seasonal variations. Figure D-3 illustrates the average annual performance by month. These graphs indicate that the model slightly over-predicts stream flow during the summer months and under-predicts flow during spring months; however, the regression analysis shows a good predictive relationship for seasonal variation between modeled and observed flows. Some of the error in the model may be due to channel processes not accounted for with the use of the HRU approach (e.g., increased time of travel associated with artificial drainage).

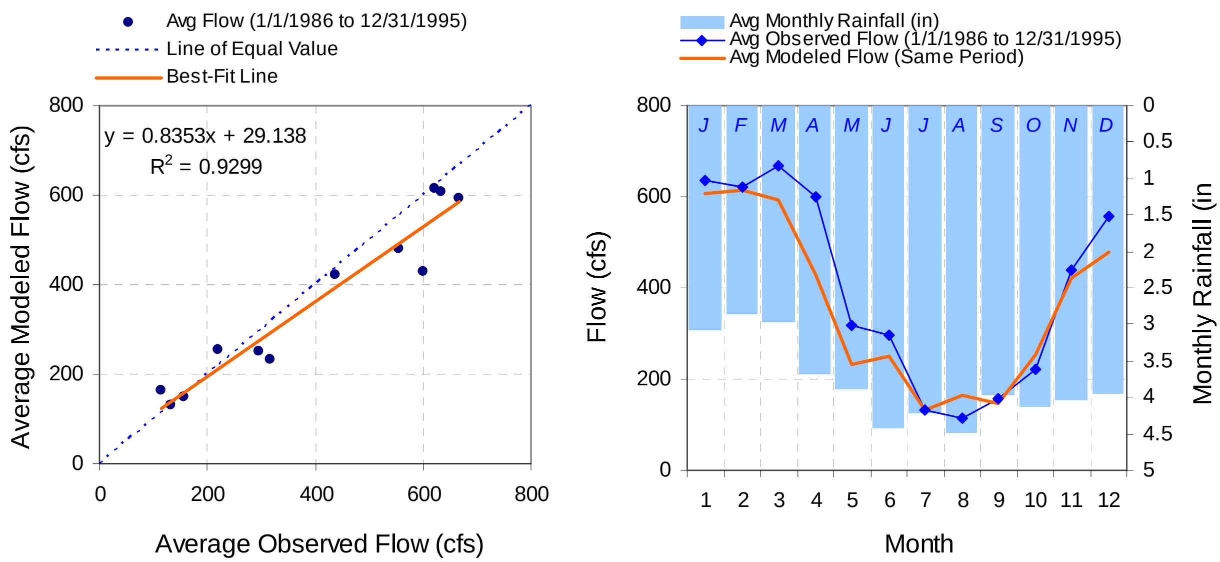


Figure D-3. Regression analysis and seasonal variation of average modeled and observed flows during calibration.

In addition to monthly and seasonal variations, the observed flow duration curve was compared to the modeled flow duration curve to ensure all flow regime trends were captured in the model. Figure D-4 shows that the modeled flow duration curve follows the trends of the observed flow duration curve during most flow regimes. Modeled low flows (lowest two percent) are slightly over-predicted, potentially due to water withdrawals that are known to occur but for which no data are available.

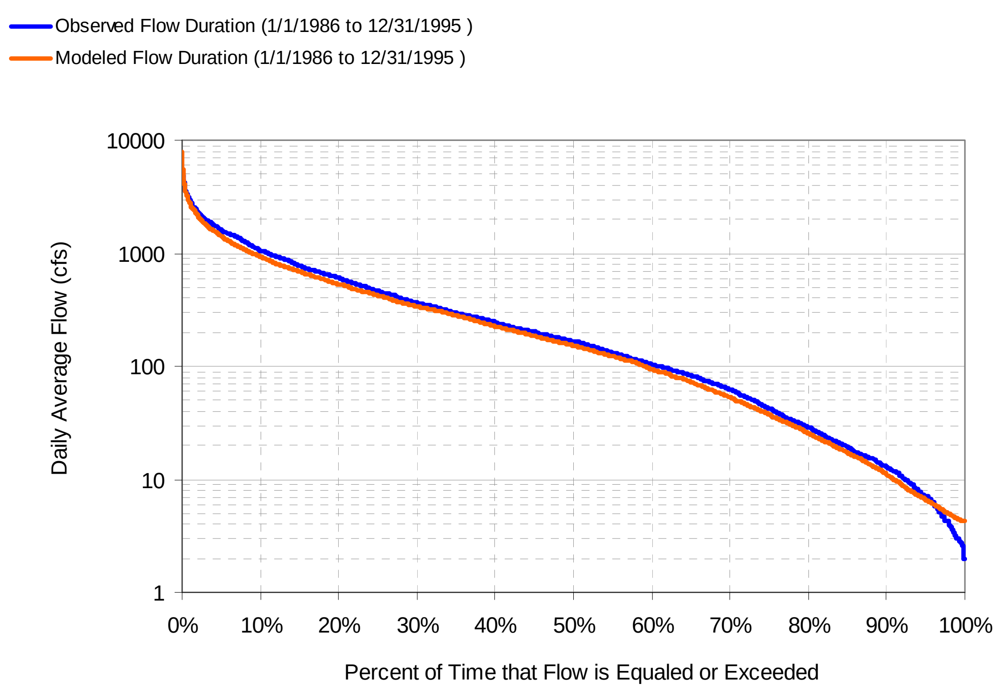


Figure D-4. Comparison of modeled versus observed flow duration curves during calibration.

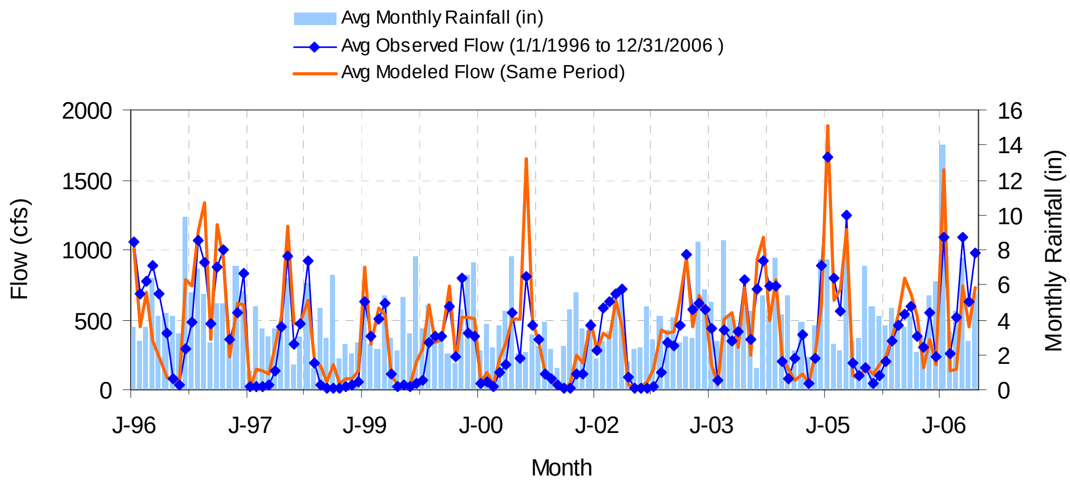
The volume of water transported through the system is one of the most important factors in assessment of model performance and applicability in TMDL development. For the hydrology calibration analysis, an assessment was performed to determine the relative error of model-predicted storm volumes with various hydrologic and time-variable considerations. Table D-1 reports the results of the analysis performed during model calibration. Specifically, volumes were compared under different flow regimes and seasonal periods. For higher flows (highest 10 percent), the model performs well in predicting storm volumes, with an error of -8.15 percent. The model also performs well for lower flows (lowest 50 percent), with an error of -9.99 percent. The overall error in volumes is -9.14 percent. The overall accuracy of the model was determined by comparing these relative errors in model performance to the recommended criteria (Lumb et al. 1994). In all cases the errors were within the recommended criteria, thus indicating the model is predicting flow and volumes well during various hydrologic and seasonal conditions. The largest source of model error is likely due to applying the point measurement of precipitation across such a large watershed. A discussion of precipitation across the watershed is presented in Section 5.1.

Table D-1. Volumes and relative error of modeled versus observed flows during calibration

LSPC Simulated Flow		**Observed Flow Gage**		
REACH OUTFLOW FROM SUBBASIN 4 10-Year Analysis Period: 1/1/1986 - 12/31/1995 Flow volumes are (inches/year) for upstream drainage area		**OBSERVED FLOW** 10-Year Analysis Period: 1/1/1986 - 12/31/1995 Flow volumes are (inches/year) for upstream drainage area		
Total Simulated In-stream Flow:	**18.26**	Total Observed In-stream Flow:		**20.10**
Total of simulated highest 10% flows:	**8.82**	Total of Observed highest 10% flows:		**9.61**
Total of Simulated lowest 50% flows:	**1.32**	Total of Observed Lowest 50% flows:		**1.47**
Simulated Summer Flow Volume (months 7-9):	**1.90**	Observed Summer Flow Volume (7-9):		**1.73**
Simulated Fall Flow Volume (months 10-12):	**4.93**	Observed Fall Flow Volume (10-12):		**5.19**
Simulated Winter Flow Volume (months 1-3):	**7.60**	Observed Winter Flow Volume (1-3):		**8.07**
Simulated Spring Flow Volume (months 4-6):	**3.84**	Observed Spring Flow Volume (4-6):		**5.12**
Total Simulated Storm Volume:	**10.55**	Total Observed Storm Volume:		**10.72**
Simulated Summer Storm Volume (7-9):	**1.12**	Observed Summer Storm Volume (7-9):		**1.13**
Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	-9.14	10		
Error in 50% lowest flows:	-9.99	10		
Error in 10% highest flows:	-8.15	15		
Seasonal volume error - Summer:	10.02	30		
Seasonal volume error - Fall:	-5.11	30		
Seasonal volume error - Winter:	-5.74	30		
Seasonal volume error - Spring:	-25.04	30		
Error in storm volumes:	-1.57	20		
Error in summer storm volumes:	-0.67	50		

4. Validation Results

Following model calibration, model validation was performed from 1996 to 2006 to test the calibrated parameters for a second time period, without further model adjustment. Model validation confirmed the applicability of the watershed-based hydrologic parameters derived during the calibration process. Validation results were assessed in the same manner as calibration: graphical comparison, regression analysis, and relative error in volume of model results and observed data. Figure D-5 through Figure D-7 present average monthly, daily flows, seasonal variation, and flow duration graphs and regression analyses for the validation time period.



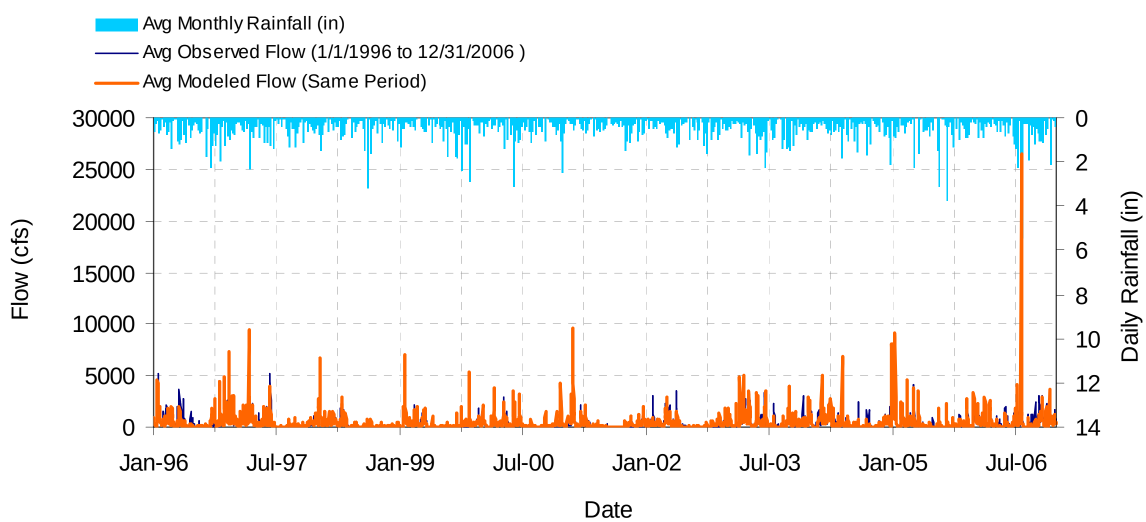


Figure D-5. Comparison of modeled and observed monthly flows during validation.

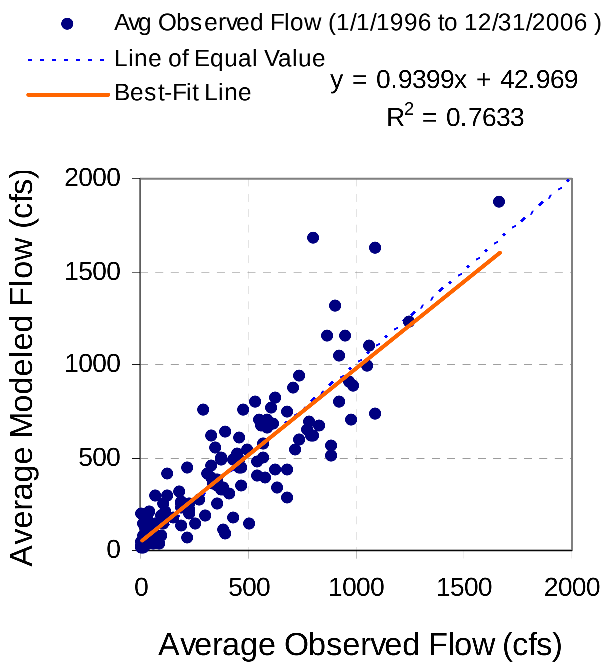


Figure D-6. Regression analysis of modeled and observed average monthly flows during validation.

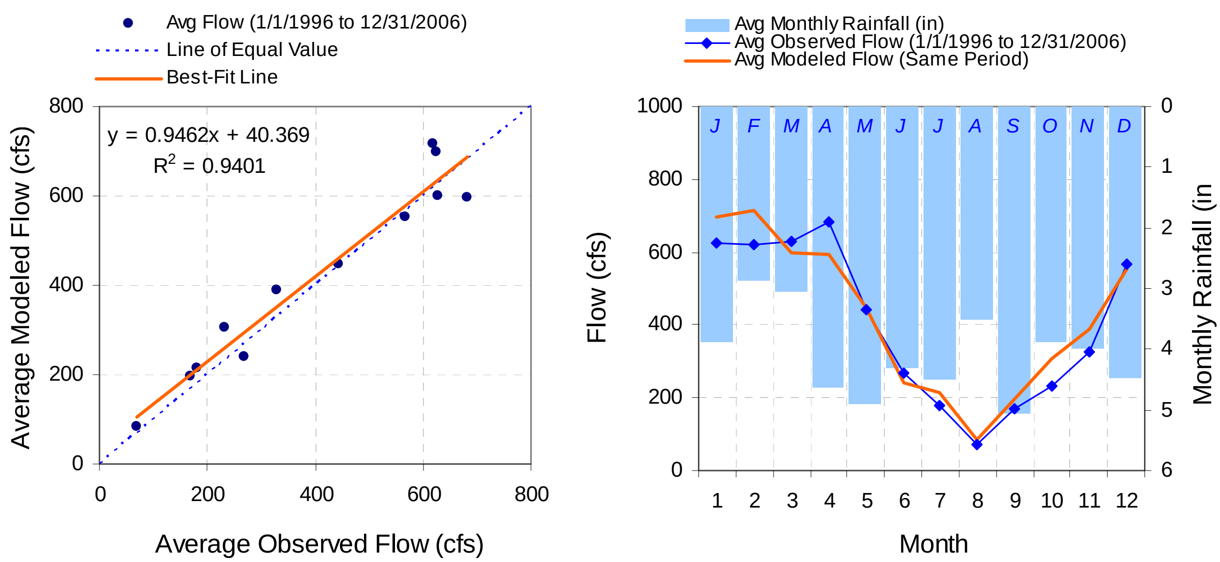


Figure D-7. Regression analysis and seasonal variation of average modeled and observed flows during validation.

Similar to the calibration results, the model generally predicts flow frequency and magnitudes within the observed range. The correlations presented in the validation regression analyses are almost as strong as those for the model calibration. Table D-2 presents the relative error analyses for the validation period. For higher flows (highest 10 percent), the model performs well in predicting storm volumes, with an error of 9.57 percent. The model also performs well for lower flows (lowest 50 percent), with an error of 9.61 percent. The overall error in volumes is -3.81 percent. In all cases the errors were within the recommended criteria, thus indicating the model is predicting flow and volumes well during various hydrologic and seasonal conditions. Overall, the validation results are similar to the calibration results, thus confirming the applicability of the watershed-based hydrologic parameters derived during the calibration process.

Table D-2. Volumes and relative error of modeled versus observed flows during validation

LSPC Simulated Flow		Observed Flow Gage		
REACH OUTFLOW FROM SUBBASIN 4 11-Year Analysis Period: 1/1/1996 - 12/31/2006 Flow volumes are (inches/year) for upstream drainage area		OBSERVED FLOW 11-Year Analysis Period: 1/1/1996 - 12/31/2006 Flow volumes are (inches/year) for upstream drainage area		
Total Simulated In-stream Flow:	**21.13**	Total Observed In-stream Flow:		**20.35**
Total of simulated highest 10% flows:	**10.61**	Total of Observed highest 10% flows:		**9.68**
Total of Simulated lowest 50% flows:	**1.47**	Total of Observed Lowest 50% flows:		**1.34**
Simulated Summer Flow Volume (months 7-9):	**2.12**	Observed Summer Flow Volume (7-9):		**1.79**
Simulated Fall Flow Volume (months 10-12):	**5.53**	Observed Fall Flow Volume (10-12):		**4.83**
Simulated Winter Flow Volume (months 1-3):	**8.78**	Observed Winter Flow Volume (1-3):		**7.85**
Simulated Spring Flow Volume (months 4-6):	**4.69**	Observed Spring Flow Volume (4-6):		**5.88**
Total Simulated Storm Volume:	**12.83**	Total Observed Storm Volume:		**11.31**
Simulated Summer Storm Volume (7-9):	**1.45**	Observed Summer Storm Volume (7-9):		**1.26**
Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	3.81	10		
Error in 50% lowest flows:	9.61	10		
Error in 10% highest flows:	9.57	15		
Seasonal volume error - Summer:	18.61	30		
Seasonal volume error - Fall:	14.60	30		
Seasonal volume error - Winter:	11.84	30		
Seasonal volume error - Spring:	-20.23	30		
Error in storm volumes:	13.44	20		
Error in summer storm volumes:	14.98	50		

5. Model Limitations and Assumption

The lower Grand River model is capable of representing only processes that are captured from the model input data. Events that are unknown to the model, such as undocumented flow alterations, cannot be replicated. Therefore, limitations in the input data drive the limitations, error and uncertainty in the LSPC model outputs. The following sections summarize the known limitations in the model input data, and how these data limitations potentially affect model output.

5.1. Weather Data

Weather data (e.g., temperature, precipitation, potential evapotranspiration) are critical for running the LSPC model. Precipitation data are ultimately the source for all modeled flows, while other weather data control temperature and evaporation processes. Therefore, the accuracy of modeled flows tends to increase as the number of weather gages increases. The quality of the weather data also affects the accuracy of the modeled flow. Only one daily precipitation data set was used for the Lower Grand River watershed because of the availability and reliability of the data. Daily Chardon (331458) rainfall and temperature data were used as well as climate data from the Cleveland WSFO AP station at Cleveland Hopkins Airport (14820).

5.2. Physiographic Characteristics

LSPC is driven by the basic physiographic characteristics that make up a watershed (e.g. slope, elevation). Therefore, physiographic data must be accurate and complete for each watershed. Potential errors were introduced into the model because several of these physiographic characteristics were simplified to facilitate modeling. Such potential error is typical. For example, most models will use an average elevation across a simulated watershed. It is impractical to model a continuously changing property (e.g., elevation) across a watershed. Generally, modeling is performed with “average” or “typical” data that is assumed to be representative. Also, physiographic characteristics change over time, and they might or might not be represented by the available data and the chosen calibration period. However, this process most likely introduces less significant modeling error when compared to the other potential sources of error.

5.3. Hydrology Calibration Data

One flow gage was available to represent the lower Grand River watershed with current and historical data. Ideally, the calibration should be conducted with more gages. However, the hydrology is well represented on a larger watershed scale in the lower Grand River watershed. Calibration of the modeled flow data was completed after subtracting the area weighted flow estimates being contributed by the upper Grand River from the monitored flows at the Painesville gage. This step also introduces uncertainty into the model. Due to the lack of flow data across the watershed, and notably in the upper Grand River, it is not possible to quantify the error for estimating flow from the upper Grand River.