Chapter 1

Watershed Flow Regime Restoration Evaluation Process

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CH2MHILL

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CHAPTER 1

Watershed Flow Regime Restoration Evaluation Process

Introduction

This chapter is one of a series of related documents[1] developed under a study to address Great Lakes flow regime-based ecosystem improvement projects. Together, this series of chapters includes an accounting system to quantify ecosystem improvements based upon flow regime restoration and a process to facilitate ecosystem improvement transactions. The system defines repeatable steps to determine flow regime restoration opportunities on a watershed basis and provides example flow regime restoration best management practices (BMPs). This facilitated ecosystem improvement process envisions the need for private contracts to facilitate the ecosystem improvement transaction. Examples of private contracts between the entity in need of an ecosystem improvement (that is, project sponsor) and the entity with an ecosystem improvement opportunity (that is, project owner) are provided.

These chapters are presented individually because different applications are anticipated depending upon end users' goals. Chapters may be useful to users individually or collectively[2].

The Need for Flow Restoration

Flows in our watersheds serve many purposes. Water flow provides habitat for aquatic communities, quenches our thirst, grows our agriculture and economy, and creates recreation opportunities. These benefits are limited by the ability of water, as it flows through a watershed, to provide beneficial services. It is possible to better manage water to obtain more of the desired services it provides, since creating more water in itself is not possible (absent climate change or artificial augmentation). For example, while more water cannot be provided, more services from water can be obtained with proper management, such as providing the aquatic habitat needed to augment fisheries production, or improving groundwater recharge to allow replenishment of groundwater supplies.

With purposeful management, water flow changes occur to watershed resources and additional benefits can be mitigated to offset reductions in beneficial uses that would otherwise occur. Studies have shown that flow changes affect the water-dependent natural resources that have come to depend upon them (Doyle et al. 2005, Bunn and Arthington 2002).

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[1]Executive Summary, Chapter 1: Watershed Flow Regime Restoration Evaluation Process, Chapter 2: Developing Stormwater BMP Quality Gallon Metric, Chapter 3: BMP Evaluation Process, Chapter 4: Quality Gallon Accounting System Protocol, Chapter 5: Facilitating and Funding Stormwater Management for Ecosystem Improvement, Chapter 6: Ecosystem Improvement Transaction Example Contracts, Chapter 7: Study Evaluation, Chapter 8: Study Communication Summary

[2] The project team members (CH2M HILL in association with The Conservation Fund, Cook and Franke, Public Sector Consultants, and Stormtech) acknowledge the generous support from the Great Lakes Protection Fund as part of their Growing Water suite of research projects.

Consequently, resource changes result from flow alteration associated with land use changes such as development and agriculture, or surface and groundwater pumping. These resource changes can be offset and even improved upon if appropriate management actions are taken. Decision makers have the ability to control the water flow within a watershed through purposeful management and create higher beneficial uses than would otherwise occur.

This study acknowledges that, in addition to flow, water quality changes, invasive species, physical alterations, and other development-related factors in a watershed also have an important influence upon the aquatic community and other beneficial uses of water. The effects of these factors not withstanding, if healthy flows do not occur, then, even with no other impairments, beneficial uses will not be met. Nevertheless, control measures must be implemented to mitigate other impacts.

Older, urbanized watersheds that developed without the benefit of stormwater BMP implementation are areas where flows have obviously changed. Urbanized areas face many challenges to flow restoration, one of which is the lack of space to implement stormwater controls; however, small measures implemented broadly across watersheds have the potential to improve the beneficial uses provided by these waters. Because flows in urbanized watersheds have been most dramatically affected by development, they also offer strong potential for restoration. For this reason, this study focused upon flow restoration opportunities within two urbanized watersheds: the Rouge River near Detroit, Michigan, and the Menomonee River near Milwaukee, Wisconsin. The methodology and results are transferable to watersheds in other eco-regions.

Potential Drivers for Watershed Restoration

There are many reasons for watershed restoration that vary from region to region. Other regions have had more direct and specific reasons for watershed restoration than what has been experience to date in the Great Lakes. The following list presents some example restoration drivers from other regions within the U.S. Similar drivers may one day trigger restoration in the Great Lakes as well.

- Atlanta Region: water and watershed planning have become a focal point due to rapid growth and potential drinking water scarcity because there are no large rivers or lakes for a water supply source. The combination of several factors has led to an emphasis on watershed resource protection, including: a legal ruling addressing total maximum daily load (TMDL) issues that required the State of Georgia to study and solve water quality impacts; support within the business community to resolve water issues in order to aid economic growth; and a concern over water scarcity. These factors coalesced into a program to study watersheds and determine the potential aquatic biota and water quality impacts that would occur from land use changes, and to require stormwater BMPs to treat impacts. Stormwater utility implementation on a county basis provided a funding source for BMP maintenance, stream restoration, and flood control projects. The efforts focused upon better water management by using water more effectively from water supply and watershed aquatic resource perspectives. Large-scale retrofits of urbanized areas or watershed restoration were not the program focus.

- Chesapeake Bay: EPA's Chesapeake Bay Program was a strong driver for implementing a variety of watershed protection measures with the primary goal of reducing nutrient loadings to the Bay. As a result, jurisdictions in Maryland and Virginia have implemented stormwater management programs to reduce nutrient loads that encourage the use of low impact development (LID) stormwater management practices. Several municipalities have also conducted stream assessments to inventory stream conditions and identify restoration opportunities to reduce erosion and nutrient loads, and better manage aquatic resources. In many instances, stormwater utilities have been implemented to provide funding for BMP maintenance and implement stream restoration projects. Some older BMPs have been retrofitted, but large-scale retrofits of existing urbanized areas have not occurred.
- Florida Everglades: the Florida Everglades restoration focused upon better water management to protect and restore ecosystem services with water supply and agricultural pressures. Water was treated to reduce nutrient loadings from agricultural runoff and to bring flows closer to natural conditions to protect and restore the ecosystem as well as to better manage water supply sources. A combination of state and federal funding was used for implementing the restoration efforts.
- Coastal Louisiana: the value of maintaining natural flow processes extends not only to providing natural resource value, but also value to physical property. The 2005 Hurricane Katrina destruction in Louisiana and Mississippi brought to the forefront some of the natural processes that were altered over time and caused coastal wetlands to sink and erode, reducing natural barriers to storm surges.
- Endangered species: in the Washington and Oregon area, endangered species concerns led to flow management changes at hydropower facilities and influenced stormwater management practices. Practices that mimic natural processes of infiltration by using LID techniques to reduce runoff volume, improve water quality, and help streams maintain important flow characteristics for endangered species. The improved flow management seeks to mimic the natural hydrology to protect ecological resources.

In addition to these large-scale examples, flow management directly addresses combined sewer overflows (CSO) and separate sewer overflows (SSO), TMDLs, source water protection, and flood damage. These examples illustrate how better water management can be used to provide improved conditions for natural resources and social and economic benefits.

Relationship to Great Lakes Regional Collaboration, Great Lakes Compact, and Other Great Lakes Initiatives

Great Lakes policy makers, regulators, and stakeholders representing federal, state, First Nations, cities, environmental organizations, and interested people have been very active in Great Lakes management issues. The flow regime restoration principles presented in this paper were developed in the context of these ongoing efforts. A Presidential Executive Order in May 2004 started the Great Lakes Regional Collaboration (GLRC) (www.glrc.us), which developed a comprehensive restoration strategy focusing on eight issues, including several where flow regime played an important role. The Annex to the Great Lakes Compact addresses water supply management and conservation measures. Example conservation measures go beyond drinking water conservation to include watershed and stormwater management practices that better manage flows. Other important flow-related management efforts include fisheries restoration programs mandated for the U.S. Army Corps of Engineers (USACE). USACE is exploring methods to restore Great Lakes fisheries through flow management opportunities.

Each of these Great Lakes management efforts contains goals consistent with the flow regime restoration principles contained in this chapter. Better flow management can provide improved water conservation as required in the Great Lakes Charter Annex, help restore fisheries as provided in the USACE program, improve in-stream water quality, and provide watershed restoration with resulting downstream benefits to the Great Lakes. The flow regime restoration approach provides principles and examples of how better water management can have multiple benefits to the Great Lakes themselves and achieve multiple objectives of various Great Lakes management programs.

Ecological Flows

Flow Restoration in the Context of Watershed Restoration

Many communities are currently mitigating flooding and erosion problems caused by urbanization in watersheds. Reduced infiltration from compacted soil, pavement, and roofs increases runoff volumes and peak flows, which can lead to property loss, structural damage, and safety hazards for communities located near rivers and streams. Increased runoff can also degrade aquatic habitat and destabilize streambanks in receiving waters.

Ecosystem restoration and rehabilitation projects are often completed for the mutual benefit of humans and the environment. The human benefit is directly achieved by decreasing flooding, erosion, and property loss. The environmental benefit to the river and indirect human benefits include stabilizing streambanks, creating fish habitat, and improving water quality. When restoration projects are conducted, they are often completed to achieve a human benefit, but also improve the river for fish and other animals. Because the health of the river directly affects the animals that inhabit it, protecting and restoring the river system is an important component of watershed management.

Fisheries in river systems depend on many factors. Fish, like humans and other animals, require adequate environmental factors for their survival. These environmental factors include habitat (homes), food, environmental quality (that is, water quality, air quality, etc.), movement barriers, predation, and recruitment. The environmental factors for a healthy fishery include stable rivers with natural flow (habitat), aquatic plants and insects (food), and clean water in the rivers (environmental quality). If any of these environmental factors are impaired the stream becomes less able to support the fishery.

The flow regime of a river is one of the environmental factors required to support a healthy river ecosystem (Doyle et al. 2005, Bunn and Arthington 2002). The flow regime of a river includes more than just the quantity of water in the river. Instead the flow regime includes statistical information about the flow in a river over a period of time. For example, the recurrence intervals of flow rates in a river may change over time or may have seasonal variations. These natural changes in flow are part of a river's flow regime (Poff et al. 1997). Studies have shown that the aquatic-life community changes as development increases the amount of imperviousness in a watershed. Significant changes can occur when imperviousness reaches between 8 and 12 percent imperviousness (Wang 2001). However, impacts are watershed-specific and can appear at lower or greater impervious fractions.

The changing flow rates over time are a natural cycle for rivers; however the increase in imperviousness and stormwater runoff rates can change the flow regime in a river from a ″natural″ condition to an unhealthy or unstable condition. If the flow regime of a river is significantly altered, the river may not be able to support a healthy fish community (Bunn and Arthington 2002, Wiley et al. 1998, Dyson et al 2003). Therefore, a fishery with a natural flow regime is expected to be healthier than a one where the flow regime has been significantly altered.

Flow Characterization Methods

A range of methods has been developed in various countries that can be employed to define ecological flow requirements and to help determine target flow regimes that improve the river ecosystems. Each of these methods may involve input from experts, hydraulic or hydrologic characterization, habitat assessments, and biological sampling. The methodologies may address all or parts of the river system (that is, flow, habitat, water quality, fisheries, etc.). Example methods include:

- Indicators of Hydrologic Alteration (IHA—Richter Method)
- In-stream Flow Incremental Methodology (IFIM)
- Downstream Response to Imposed Flow Transformation (DRIFT)
- Catchment Abstraction Management Strategies (CAMS)
- Tennant Method
- Lotic Invertebrate Index for Flow Evaluation (LIFE)
- Building Block Methodology (BBM)

Most of the evidence gathered to date has focused on fish and macroinvertebrate habitat requirements, with recent emphasis on the relation between stream flow and woody riparian vegetation and recreation. Water management problem solving has matured from setting fixed minimum flows with no linkage to a specific aquatic habitat benefit, to incremental methods in which aquatic habitats are quantified as a function of discharge. Brief descriptions of several methods are summarized in Table 1-1 as reviewed by the International Union for Conservation of Nature and Natural Resources (IUCN 2003).

TABLE 1-1
Existing Methodologies to Measure the Effects of Flow on River Ecosystems

Methodology	Description	References	Link between Methodology and Aquatic Ecosystem
Indicators of Hydrologic Alteration (IHA-Richter Method)	The IHA-Richter Method defines benchmark flows for rivers where the primary objective is the protection of the natural ecosystem. The method identifies the components of a natural flow regime, indexed by magnitude (of both high and low flows), timing (indexed by monthly statistics), frequency (number of events), duration (indexed by moving average minima and maxima), and rate of change. It uses gauged or modeled daily flows and a set of 32 indexes. Each index is calculated on an annual basis for each year in the hydrological record, thus concentrating on interannual variability in the indices. An acceptable range of variation of the indices is then set, for example ±1 standard deviation from the mean or between the 25th and 75th percentiles.	Richter et al. 1996	There has not been adequate research to relate the calculated flow statistics to specific elements of the ecosystem. Research relating the IHA-Richter methodology with the flow regime targets developed by Wiley (1998) is currently underway.
In-stream Flow Incremental Methodology (IFIM)	The IFIM was designed by a multidisciplinary U.S. Fish and Wildlife Service team of biologists, hydrologists, engineers, and computer scientists in the 1980s to address impacts on river ecosystems from changing river flow regimes. The IFIM was originally developed to assess impacts from dams and abstractions. The methodology involves the development of several computer models that are used to define the relationship between flow and fish habitat. The four types of models used are a hydraulic model, a biological model, a habitat model and a water quality model. The models are combined to assess the impacts (positive or negative) that flow regime modification has on available habitat and water quality, and biology of the river.	Bovee et al. 1998, Stalnaker et al. 1995	Direct link between hydrology and available habitat. Assumes that if habitat is available, aquatic animals will inhabit the areas.
Downstream Response to Imposed Flow Transformation (DRIFT)	The DRIFT is a scenario-based framework for providing decision makers with options of future flow regimes for a river of concern. DRIFT has four modules to determine a number of scenarios and their ecological, social, and economic implications. DRIFT has a strong socioeconomic module that describes the predicted impacts of each scenario on subsistence users of a river's resources. Within the constraints of a project, scientific studies are conducted of all aspects of the river ecosystem: hydrology, hydraulics, geomorphology, water quality, riparian trees and aquatic and fringing plants, aquatic invertebrates, fish, semiaquatic mammals, herpetofauna, and microbiota. All studies are linked to flow, with the objective of being able to predict how any part of the ecosystem will change in response to specified flow changes.	King et al. 2003	Direct link between land use changes and the effects on the hydraulics and ecosystem in a river.
Catchment Abstraction	The U.K. Environment Agency has developed CAMS to assist in managing water	Environment	Direct link between land use

TABLE 1-1
Existing Methodologies to Measure the Effects of Flow on River Ecosystems

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Management Strategies (CAMS)	abstractions in England and Wales. The CAMS process includes participation of interested parties through catchment stakeholder groups and a Resource Assessment and Management (RAM) framework. The first step is to calculate the environmental weighting that determines a river's sensitivity to a reduction in flow by assessing physical characterization, fisheries, macrophytes, and macroinvertebrates. Once a score for each of the four elements has been defined through the RAM process, the scores are combined to categorize the river into one of five Environmental Weighting Bands, where Band A (5) is the most sensitive (average score of 5) and E is the least sensitive (average score of 1). In a separate part of the RAM framework, a flow duration curve for natural flows is produced. The RAM framework then specifies allowable abstractions at different points of the curve for each weighting band producing an ecologically acceptable flow duration curve.	Agency 2002	and the effects on the hydraulics (flow duration curve) of the river.
Tennant Method	The Tennant Method was developed for Midwestern states to specify minimum flows required to protect a healthy river environment. Percentages of the mean annual flow are specified that provide different quality habitat for fish. This method can be used elsewhere, but indexes would need to be recalculated for each region. In the Midwestern states, the indexes have been widely used in planning at the river basin level, however they are not recommended for specific studies and where negotiation is required.	Tennant 1976	Direct link to hydrologic and river hydraulics; however annual flows may not reflect improvements to flow regimes more frequent than annual flows.
Lotic Invertebrate Index for Flow Evaluation (LIFE)	The LIFE method was developed in the U.K. and designed to be based on routine macroinvertebrate monitoring data. An index of perceived sensitivity to water velocity was assigned to all U.K. taxa. The index value is then modified by the abundance of the observed taxa to calculate a composite "score." The method measures the effect of the flow velocity on the abundance of macroinvertebrate taxa. For monitoring sites close to flow gauging stations, the relationship between the LIFE score and preceding river flow may be analyzed. Moving averages of preceding flow have shown good correlation with LIFE scores over a range of sites. Procedures for using this information in the management of river flows are still under development.	Extence et al. 1999	Direct link to water velocity; however the process may not reflect changes with land use changes and the resulting flow duration curve of the river.

TABLE 1-1
Existing Methodologies to Measure the Effects of Flow on River Ecosystems

Methodology	Description	References	Link between Methodology and Aquatic Ecosystem
Building Block Methodology (BBM)	The BBM was developed in South Africa to analyze the functional links between all aspects of the hydrology and ecology of the river system. This method uses hydrologic analysis, hydraulic rating information, and biological data. It also makes significant use of scientific experts. The basic premise of the BBM is that riverine species are reliant on basic elements (building blocks) of the flow regime, including low flows and floods that maintain the sediment dynamics and geomorphologic structure of the river. An acceptable flow regime for ecosystem maintenance can thus be constructed by combining these building blocks. The BBM revolves around a team of experts that follow a series of steps, assess available data, use model outputs, and apply their combined professional experience to come to a consensus on the building blocks of the flow regime. The BBM has a detailed manual for implementation, which is now routinely used in South Africa. It has also been applied in Australia and the U.S.	King et al. 2000	Includes a holistic approach for a direct link to changes in land use and the effects on river hydraulics and watershed hydrology.

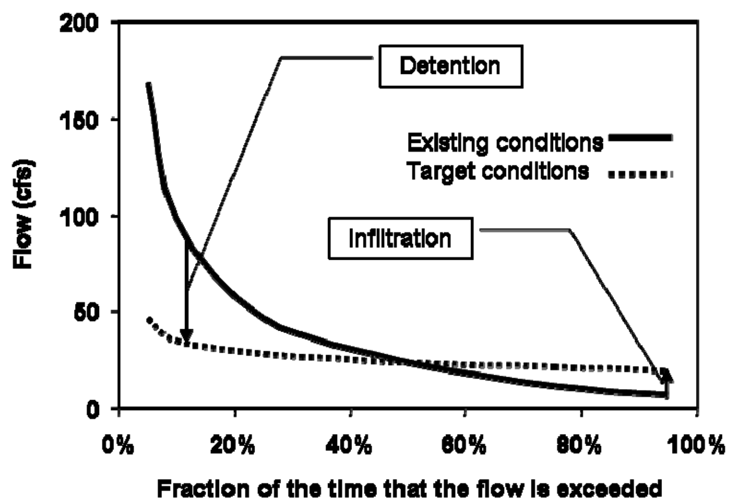
Flow Duration Curves for Watershed Flow Restoration

The methodology chosen for this study uses a flow duration curve to develop desired reference flow conditions in a watershed. This methodology, developed by Wiley, et al. (1998), correlates watershed characteristics, such as tributary area, watershed slope, land use, surficial geology, precipitation, and other factors to estimate a flow duration that represents a flow regime supportive of selected target fish species. Because the fish species live within a spectrum of flow conditions, it is assumed that maintaining or restoring the overall reference flow duration curve will also be beneficial for the fish species. The reference flow duration curve can then be used as an ecological target flow for the watershed.

The reference flow duration curve can be compared with the actual flow conditions in the watershed to evaluate the ability of the flow regime to support the desired species. If the reference condition is different from the actual flow condition, the reference condition can be used as a target for flow restoration through stormwater BMP implementation.

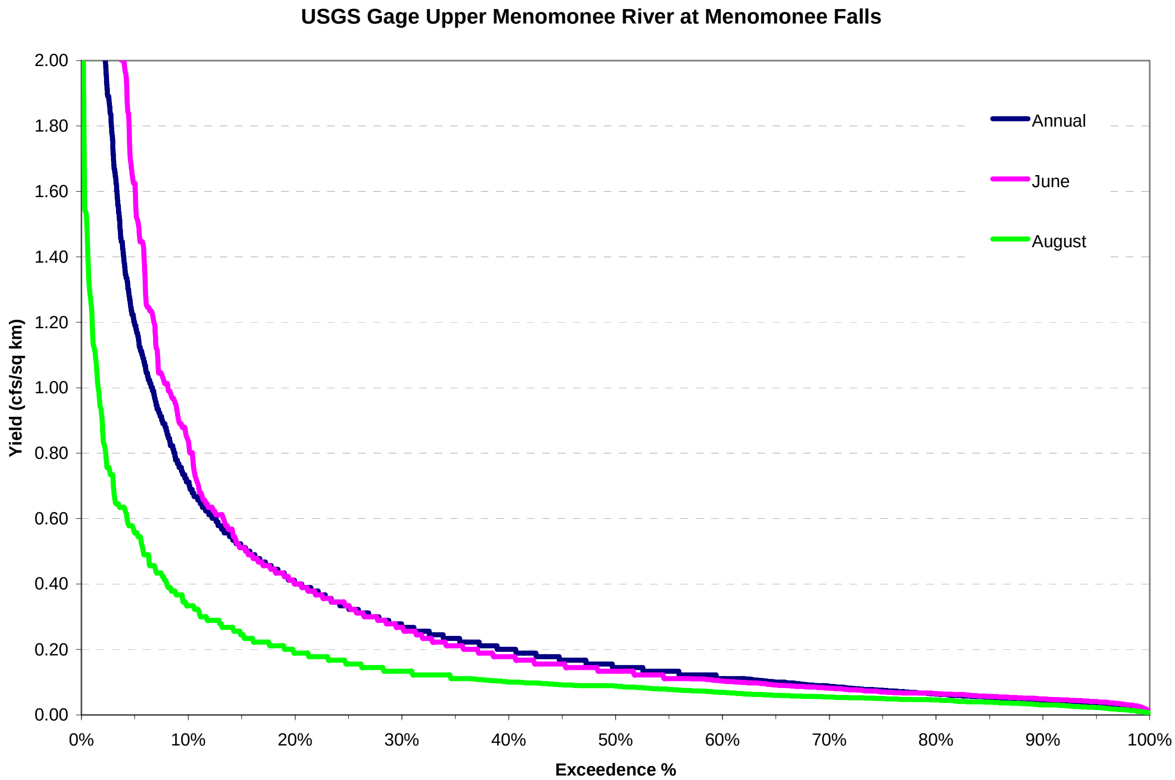
A conceptual graphic depicting the existing and reference or target ecological flow condition is shown in Figure 1-1.

FIGURE 1-1
Existing and Reference Target Ecological Flow Condition
Conceptual depiction of the effect of stormwater management BMPs in matching the ecological target flow duration curve by reducing peak flows and increasing baseflow.



Flow duration curves correspond to a time span. The time span can be annual, seasonal, or monthly. Different flow duration curve shapes result depending upon the time of year that is used. An example of how the flow duration curve varies by season is shown in Figure 1-2.

FIGURE 1-2
Example of Flow Duration Curve Variation by Season
Seasonal Variations in Flow Duration Curves for the Upper Menomonee River Subwatershed



For the purposes of this study, the flow duration curve of interest corresponds to the time at which flow increases would most significantly affect the life cycle of the target fish species. After consultation with fisheries biologists in the upper Midwest, the month of June was selected as a critical period for warm water species because they hatch during that time of year.

For example, it has been shown that there is a correlation between higher flows and higher hatchling mortality (Bovee, 1994). Consequently, when higher flows occur from increased urbanization, additional hatchling mortality is expected. The flow duration curve at a reference condition can provide the ecological target for stormwater design criteria to minimize hatchling mortality.

The reference condition is one in which target fish species are known to thrive. Because fisheries data have been collected during recent decades, the reference flow condition takes into account existing human influences. Thus the reference condition in this study is not an unachievable pre-settlement condition, but rather a realistic, operational goal.

Watershed Evaluation Process

Knowledge of the principles and relationships between flows and the aquatic systems that depend upon them allows development of a watershed evaluation to support management decisions. Many watershed analysis methods have been developed and it is not the intention of this study to duplicate those efforts. For example, the U.S. Environmental Protection Agency (USEPA) recently published a *Handbook for Developing Watershed Plans to Restore and Protect Our Waters* (USEPA 2006), and the Center for Watershed Protection has published numerous articles on watershed management, including *The Smart Watershed Benchmarking Tool* (Center for Watershed Protection 2006).

This study approaches the watershed evaluation process by starting on a watershed scale to make management and policy decisions. The decisions can then be translated to a smaller, project-by-project scale where the policy is implemented. This chapter discusses a watershed evaluation process that can be supported by data collected from the watershed, hydrologic modeling, or both.

Flow Regime Restoration: What to Look For?

The following two principles were followed when evaluating flow regimes for potential restoration in urbanized settings:

- Determine the peak flow timeframe that is critical for fish species.
- Combine flow restoration with streambank stabilization.

The rationale for including each of these principles in the flow regime restoration and watershed evaluation approach is provided below.

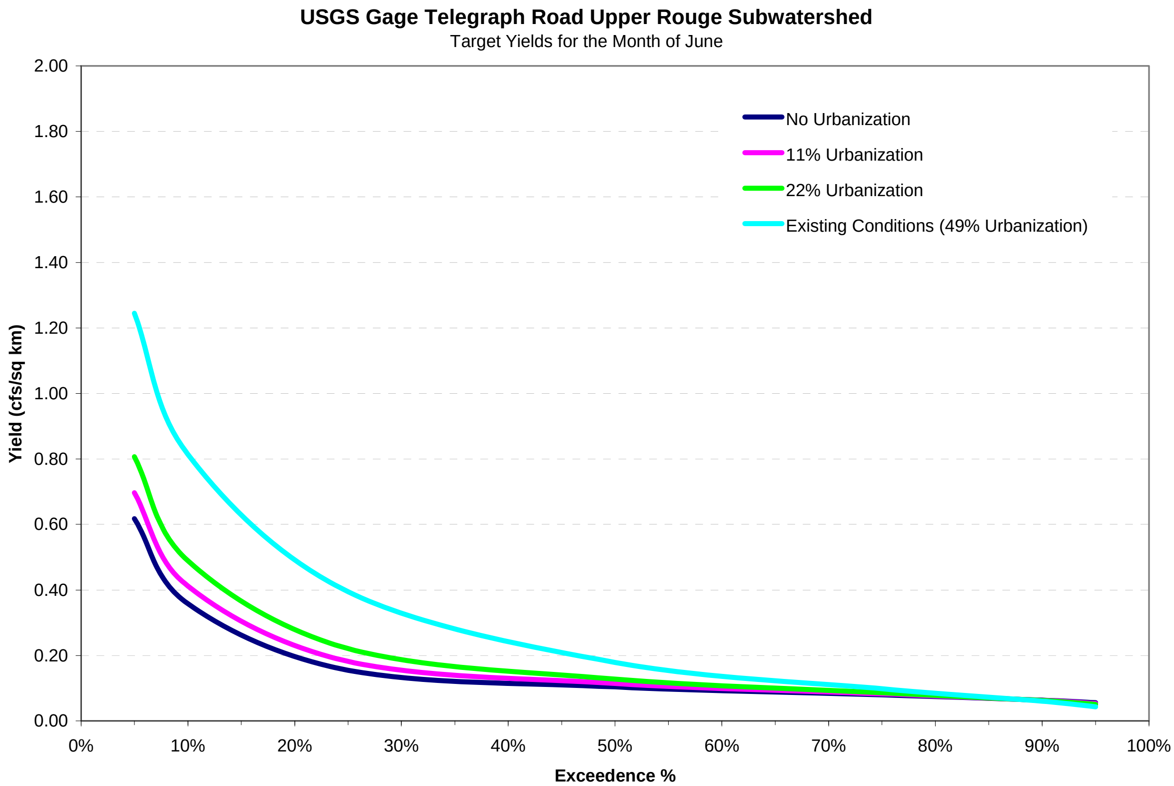
Determine the flow timeframe that is critical for fish species.

Increases in peak flows will most directly affect fish communities when they are most susceptible to peak flows, which is when the fish are hatching and just after they have hatched. For the Rouge River near Detroit, Michigan, and the Menomonee River in Milwaukee, Wisconsin, which are warm water streams, this critical period occurs during the month of June. Consequently, if the effects of urbanization are apparent in a June flow duration curve as shown in Figure 1-3, a target curve for that month provides a good basis for flow regime restoration criteria. Urbanization effects can also result in lower base flows; however, controlling peak flows through the use of infiltration-based BMPs can also benefit base flow conditions.

Combine flow restoration with streambank stabilization.

Peak flows can have multiple effects on the stream, such as causing changes to physical habitat. In urbanized settings, channel geomorphic changes are often evident. Consequently, a watershed restoration approach in an urbanized watershed would require both controlling the peak flows to levels tolerable by the aquatic community and stabilizing stream geometry to support physical habitat. For the purposes of this study, it has been assumed that stream channel restoration will also be required in urban streams and, consequently, flow control should focus on restoring flows that directly affect fish communities and providing a stable channel geomorphology. It is important to combine the hydrologic restoration with streambank stabilization to achieve overall restoration goals in an urbanized watershed.

FIGURE 1-3
Predicted Changes to the June Flow Duration Curve with Urbanization for the Upper Rouge River Watershed

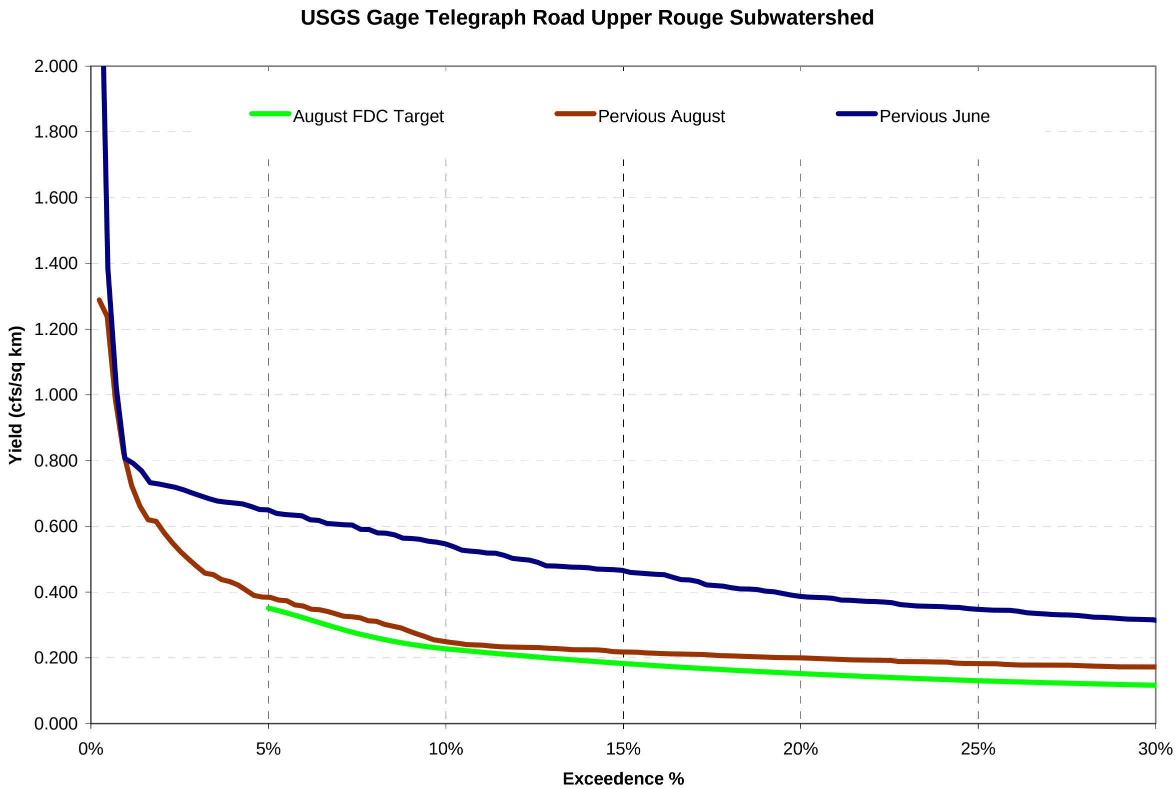


Flow Duration Curve Selection

Based upon the flow regime restoration evaluation principles, an appropriate flow duration curve was selected for watershed evaluation and analysis. As noted above, it is important to first select the period of time for the flow duration curve and ensure that data are available. A summary of findings is presented below. Appendix 1A contains details on seasonal factors that are observable through various flow duration curves, and methods and data requirements for flow duration curves calculated through stream gages and hydrologic modeling. Minimum data requirements depend upon the level of certainty needed for flow regime restoration and vary by flow duration curve calculation methodology. Information for the development of flow duration curves generally exists for making incremental progress in flow regime restoration.

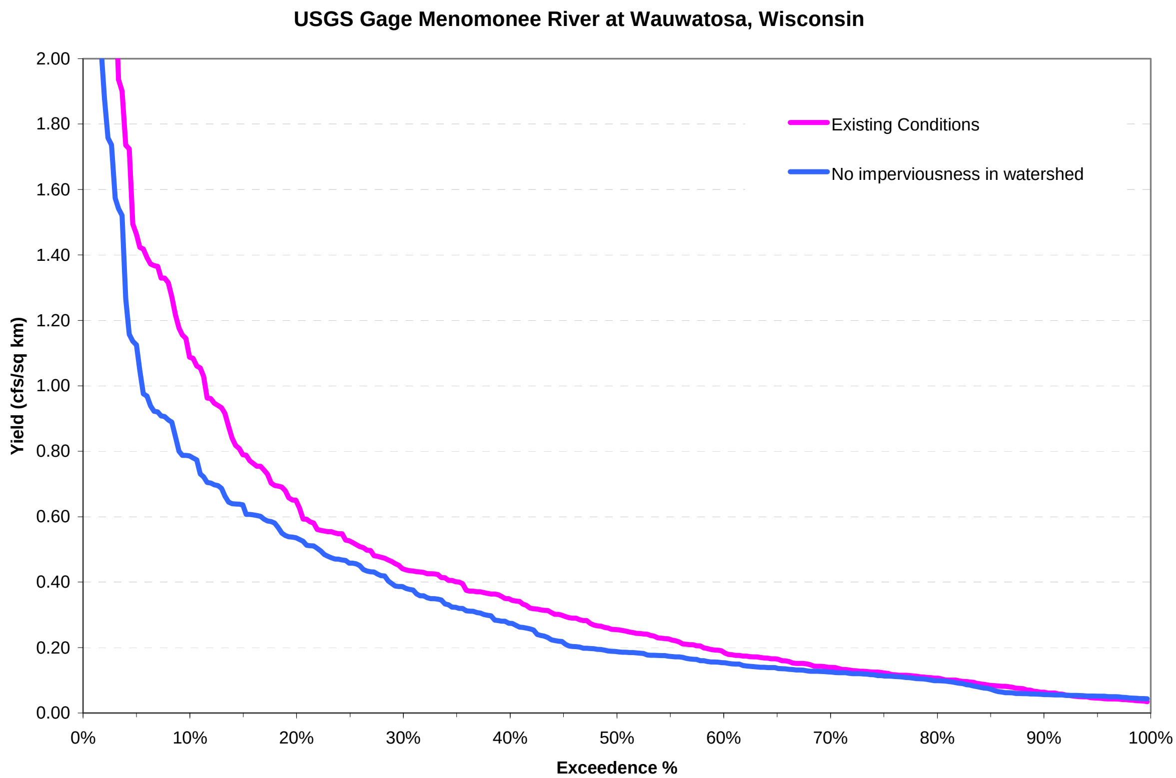
As stated earlier, through expert opinion, it was determined that changes to the June flow duration curve would most readily affect fisheries. However, Wiley et al. (1998) had developed ecological target curves for the month of August only. This curve was the result of regression equations based on watershed parameters. A similar curve could have been developed for the month of June using the same methodology, but it was not available at the time. Therefore, an alternate method based on hydrologic modeling was devised to generate the June curve. The computer program HSPF was used to develop a rainfall-runoff model of the watershed that was calibrated to reproduce the observed duration curve at the U.S. Geological Survey (USGS) gage. Following guidance from University of Michigan experts, the ecological target duration curve is expected to correspond to a watershed in its existing conditions but with minimal imperviousness. This theory was tested by applying a zero-imperviousness condition to the calibrated model and extracting the August curve. The results shown in Figure 1-4 indicate the validity of this assumption. Following this positive verification, the results of the hydrologic model were processed to obtain the ecological target duration curve for June. Figure 1-5 compares this curve with the observed curve for existing conditions. Additional modeling information is found in Appendix 1A.

FIGURE 1-4
Comparison between the Ecological Target for August and the Simulated Flow Duration Curve Assuming no Imperviousness (Pervious August)
The simulated pervious June curve serves as ecological target for that month.



As Figure 1-5 indicates, the effect of urbanization is readily observable for the month of June. Therefore, it is surmised that designing BMPs that attempt to restore the flow regime to match the June target flow duration curve provides a strong link to protecting fisheries during their most vulnerable stage. As a result, the month of June was selected as a basis for flow regime restoration in an urbanized setting.

FIGURE 1-5
Comparison between Observed Existing Conditions and the Simulated June Flow Duration Curve that Serves as Ecological Target



Design Criteria Development

To move a watershed from an impaired flow regime to a restored flow regime, specific design criteria have to be developed so decision makers can determine "how much" restoration is required in a watershed, and also "how much" is provided by individual restoration efforts. Biologists, engineers, planners, and other stakeholders need to know how large a BMP needs to be to achieve the desired flow restoration results. This section explores the development of design criteria to facilitate watershed planning as well as evaluate specific BMPs.

Mechanisms for Flow Regime Restoration

Flow regime restoration is needed where natural processes have been altered, usually due to anthropogenic effects. Consequently, implementing a restoration philosophy that focuses on mimicking the natural processes that have been altered provides the greatest chance of success. The goal is to match the ecologic target duration curve described earlier. Such a philosophy is not new to water management and is found in practices such as stormwater LID and conservation design principles.

To restore altered flow regimes, the following implementation process is suggested:

1. **Maximize infiltration.** Infiltration is reduced when land is developed and the land cover changes from a pervious to an impervious surface. Reduced infiltration can lower aquifer levels and reduce baseflow to streams. As a result of lower infiltration rates, more water leaves the watershed through surface runoff and less is available for groundwater recharge. This change has important ramifications for aquatic species that depend on groundwater-fed streams, and for humans who depend on aquifers for water supply.

   Consequently, the first step in flow regime restoration for areas that have had increased impervious area should be to focus upon opportunities to reduce the amount of surface runoff through the creation of additional infiltration opportunities. Infiltration can be implemented by reducing imperviousness, disconnecting imperviousness, reducing turf cover in favor of diverse native landscaping, and incorporating grass swales, pervious pavement, rain gardens (bioretention), and other similar BMPs that retain runoff onsite and encourage infiltration.

2. **Provide detention**. After infiltration opportunities have been maximized, detention may still be required to approach the target flow duration curve. Providing stormwater detention reduces the speed at which stormwater runs off the land by holding back the water and slowly draining it over time. Stormwater runs off impervious areas much faster than pervious areas. In addition, development typically directs runoff to storm drains that allow the water to move fast. Detention storage can reduce stream velocities during storms by holding the water in an impoundment and metering stormwater discharge slowly over time.

   Some BMPs, such as bioretention, can incorporate both infiltration and detention aspects. Bioretention facilities are designed to include a shallow ponding depth for storage. Larger storage facilities in the form of detention ponds, regional online storage, or floodplain storage are also potential BMPs for implementing detention storage.

3. **Control channel forming flow.** Natural channels are formed by a range of flows that are influenced by land use, geology, sediment transport, and vegetation. The channel-forming flow is commonly associated with a flow frequency near a 1- or 2-year return period. When land use changes yield greater impervious areas in a watershed, the flow associated with the channel forming flow can increase. This results in bank erosion as the channel tries to reach equilibrium with the additional runoff. Bank erosion can cause an increased channel size, deepening of the channel, disconnection of the channel to the floodplain, and the potential for aquatic habitat and property loss. Therefore, controlling the channel-forming flow provides for a stable channel that is beneficial to aquatic habitat and private property.

   Restoring the channel-forming flow may not be practical in areas that have experienced urbanization. Even after implementation of infiltration and detention measures as described above, the channel-forming flow may be reduced, but could remain at levels that continue to cause channel instability. Therefore, it is expected that streambank stabilization may be required in addition to hydrologic controls to allow the channel to function with the range of flows present in the channel after BMPs have been installed. It should be noted that flow restoration is a process that can take time to fully implement due to socioeconomic and political factors. In addition, the geomorphic processes controlling stream channel changes are dynamic and respond to additional development as well as to stormwater retrofits in older development. Therefore, selection of the design target for stream stabilization needs to consider these time-dependent changes.

Other considerations

In addition to restoring processes that have been affected by anthropogenic changes in a watershed, flow regime management should also consider the protection of public and private infrastructure. Consequently, flood control may be needed as part of an overall watershed flow regime management plan. Future planning for development should focus upon allowing the development of areas that are not prone to flooding, with appropriate stormwater management BMPs using an approach that reproduces the natural processes.

Target Flow Duration Curve Conditions: What do they represent?

The target flow duration curves developed for a given location have the following characteristics:

- They do not represent presettlement conditions; rather, they represent an average landscape condition influenced by anthropogenic factors, possibly including mechanisms to mitigate these influences.
- Maintaining this flow condition is expected to be beneficial for desirable fish species that thrive under these conditions and are expected to be present.
- Other factors, such as habitat, water quality, and fish barriers, could limit the presence of expected species. Separate efforts may be needed to address these issues.

Design Criteria

BMP designers need a practical, easy-to-understand design method, preferably presented in a manner similar to other stormwater management design requirements. One characteristic of commonly used design criteria is to establish a set of rainfall depths of given return periods, which are transformed into runoff hydrographs using a rainfall-runoff model that can be as simple as an equation or as complex as a sophisticated hydrologic model. The rainfall depths selected are aimed at meeting several management goals such as water quality control, groundwater recharge, channel protection, and flood control. This approach is convenient because rainfall records can be considered spatially uniform and are readily available. The procedure suffers from known shortcomings. The first is the assumption that the probability of exceedence of the rainfall event is equal to that of the resulting flow, which in general is not true. The second is the use of synthetic storms that have no resemblance to the actual rainfall record. The third is the assumption of a constant antecedent soil moisture condition at the beginning of rainfall. These three issues are significant, but typically ignored during design. Moreover, the resulting designs are rarely checked against actual rainfall records to evaluate performance.

For the purposes of this study, a design procedure needs to be expanded to represent the target flow duration curve rather than individual storm events. However, it should be noted that in a real-world flow duration curve, there is no one-to-one relationship between precipitation depth and flow. A given precipitation depth can produce various flows at different times depending on antecedent moisture conditions. Therefore, it is necessary to apply a continuous simulation approach rather than a discrete-storm approach to BMP design.

The following sizing procedure is suggested:

1. Select a rainfall depth such that 80 to 90 percent of the annual rainfall volume occurs in storms smaller than that depth. For most humid locations in the United States, this value is about 1 inch. For arid locations, the threshold is roughly 0.5 inch or less.
2. Size the BMP to capture the runoff resulting from this rainfall depth and release it over 72 hours.
3. Run the actual continuous rainfall record for the BMP and derive the flow duration curve for average daily flows.
4. Compare with the target flow duration curve and modify the geometry of the BMP outlet to attempt to match the target curve (see scale discussion below).

This iterative process is not as time-consuming as it appears at first glance. After the designer acquires experience with the shifts in the flow duration curves in response to geometric modifications, the process is straightforward (Pomeroy et al., 2007; Phalegy, 2007). The design procedure can be streamlined with the development of watershed-specific design curves that allow sizing of several BMP types, depending on soils and land use. For example, for a given BMP type, a chart can provide an estimate of the area required as a function of the drainage area to the BMP.

For the Menomonee River watershed it was found that the target flow duration curve was best approximated by releasing a 24-hour precipitation depth of 1.1 inches over 72 hours. A similar estimate of the Upper Rouge River yielded a precipitation depth of 0.8 to 0.9 inches.

Discussion

In the typical design process, a BMP is sized and its outlet designed for a specified release rate. The flow duration curve provides insight into an appropriate BMP release rate because, for a given exceedence probability, the watershed yield (average daily flow per unit watershed area) is known. Consequently, both the volume needed to control the threshold rainfall depth and the release rate are known and the BMP can be designed to meet these criteria. This ecological flow criterion would be layered with additional requirements appropriate for the watershed such as groundwater recharge, channel protection, and flood control.

Matching the target flow duration curve needs to take into account issues of relative scale between the various drainage areas and the control point where ecosystem improvements are desired. An approximation to the target flow duration curve may be impossible if the drainage area to the BMP is small. On the other hand, the effect of this small area on the overall effect at the point of interest further downstream may be negligible. In cases where the flow duration curve scale and BMP catchment scale do not correspond, the BMP should be designed to control the flow duration curve to the extent possible for the above referenced storm while also meeting applicable water quality, groundwater recharge, and channel protection criteria to prevent localized impacts. A "catchment" approach encompassing several BMPs and covering a scale similar to that used in developing the target flow duration curve needs to be considered to match the target flow duration curve. If a hydrologic model is used to aid the development of the target flow duration curve, a scale of several hundred acres to several square miles may be possible. When stream gage data is used to develop the target flow duration curve, the area draining to the gage will determine the scale range appropriate for the flow duration curve analysis.

By no means does this observation insinuate that in-line regional facilities intercepting runoff from large drainage areas are the solution. A dam on a live stream has deleterious consequences on many levels of the aquatic ecosystem that far outweigh any flow restoration benefits. However, an implication is that there is a great degree of flexibility in implementing BMPs at the catchment level, as long as the resulting flow duration curve at the observation point matches approximately the ecological target curve. It is important to note that the area of a watershed targeted for resource protection and the flow duration curve observation point should have the same catchment scale to avoid undesired flow regime management decisions. The numerical experiments indicate that the stormwater management strategy should start with maximization of infiltration opportunities, which requires BMP implementation in small catchment areas.

One issue that this approach does not address is the effect of peak flow magnitude and frequency on fish. These flow regime characteristics need measurements finer than daily average values. University of Michigan fisheries biologists indicated that extreme events are part of the natural cycle of fish species. Some of these events will flush young fish downstream, but they will be able to repopulate the stream in the same season. Other events will be so severe that the population may be decimated and take years to recover. If urbanization increases the frequency and magnitude of these events, the recovery may be difficult or impossible. Pomeroy et al. (2007) showed that these events had a significant effect on aquatic macroinvertebrates. The effect that matching the daily-flow ecological targets has on instantaneous peak flow distributions is a subject for further research.

BMP Retrofits

The study has envisioned flow regime restoration occurring where land use changes have already altered the flow regime. Consequently, restoration will occur primarily in the form of BMP retrofits, which could take the form of modifying existing detention facilities; implementing LID such as bioretention, green roofs, porous pavement, and other runoff-volume control techniques; providing off-line regional stormwater management; and floodplain detention.

As shown above, the flow duration curve approach to flow restoration results in a design standard that addresses frequent and, consequently, relatively smaller storms. This criterion requires a BMP footprint that has a chance of implementation in urbanized areas because of the limited space typically available.

Implications for New Development

Even though this flow regime restoration approach focuses on retrofits, the approach has implications for new development as well. If flow regime restoration is taking place in a watershed and new development does not incorporate stormwater management practices consistent with maintaining the flow duration curve, then these impacts may negate the improvements.

For example, if a watershed has an altered flow duration curve because of development in the lower reaches and retrofits for flow regime restoration are implemented, the restored regime will only be maintained as long as development occurring upstream in the watershed has appropriate control standards. Consequently, the flow regime restoration concepts must also be applied to create standards for new development consistent with maintaining the desired flow regime condition.

Other Potential Benefits

Besides flow regime restoration, other benefits are possible from stormwater BMP retrofits. Controlling the runoff quantity as well as providing water quality improvements for frequent storms has potential benefits in a variety of settings, including:

- Benefiting riparian property owners—property owners immediately adjacent to a stream often experience increased erosion and property loss due to the high velocity and streambank erosion associated with urban streams. Reducing runoff from frequent storms can reduce the rate of streambank erosion and property loss.
- CSO control—CSOs can be reduced by slowing down runoff and increasing infiltration with the use of stormwater BMPs. Controlling frequent storms can lower peak runoff rates and reduce overall runoff volume. Larger storms may still result in CSOs, but the frequency and volume of overflows can be reduced.
- Water quality improvement—treating stormwater runoff from urbanized areas for frequent storms will improve runoff water quality depending on how effective the BMP is at removing pollutants. In urbanized areas where no stormwater BMPs exist, there are significant opportunities to improve water quality. Various water quality issues, including meeting TMDL water quality standards, could be addressed through urban stormwater retrofits.
- Source water protection—treatment of stormwater can help protect and replenish drinking water sources. The stormwater BMPs can reduce the amount of pollutants reaching drinking water sources. In addition, infiltration-based BMPs can help to restore aquifers that rely on infiltration for groundwater recharge.

A specific example is the Chesapeake Bay restoration. Communities within the Chesapeake Bay watershed are encouraged to implement stormwater BMPs to reduce nutrient loadings to the bay. These implementation programs promote dispersed stormwater BMP (LID) as one of the watershed restoration and pollutant reduction techniques. Runoff from urbanized areas is one important component of the Bay's restoration.

The applicability of these various examples will depend upon the specific needs within a given watershed. Implementation of a large-scale watershed restoration program would require significant monetary investment and regulation. Opportunities also exist to provide incentives or market-based mechanisms for watershed restoration. Several potential stormwater BMP implementation incentives are discussed in Chapter 5, Facilitating and Funding Stormwater Management for Ecosystem Improvement.

Measuring Ecosystem Benefits of BMPs

Measurement of BMP implementation can help track implementation progress. The effect that a BMP has on the flow regime is measured by the volume that is required to preserve or restore the flow regime. For the purposes of accounting for BMP design size, the volume unit of gallons is used in this study. Other units of volume such as cubic feet or acre-feet could be used, but are often not easily visualized by the general public. A unit that the general public can picture is beneficial, especially when dispersed stormwater BMPs (such as rain gardens) are used on private properties.

The number of BMP gallons needed in a subwatershed can be determined through watershed planning and set as a goal for implementation. As BMPs are implemented, the progress made toward the overall subwatershed goal can be tracked. The BMP volume is calculated differently for a new stormwater BMP versus a retrofit of an existing BMP, as discussed below.

New BMPs

For new stormwater BMPs, the volume associated with flow regime restoration or preservation is calculated through the design process discussed above. Using the design criteria, a stormwater BMP is sized to determine the volume required to meet the design criteria. For a new BMP, the volume associated with meeting the design criteria is the volume the BMP provides towards restoring or preserving the flow regime. For example, a newly constructed BMP may have a total volume of 100,000 gallons, but only 50,000 gallons are required to meet the design criteria for a healthy flow regime (the additional 50,000 gallons may be required for channel protection criteria, such as controlling the 2-year flood). Although the BMP provides 100,000 gallons of storage, the BMP provides 50,000 gallons of benefit towards restoring or preserving the flow regime for the target conditions.

Retrofit Existing BMPs

Existing BMPs were not built using design criteria consistent with the flow regime target release rates. Most design criteria for existing BMPs allow stormwater to discharge at a higher release rate than the rate needed for a healthy flow regime. Therefore, additional volume is required to store water and release it more slowly. The additional volume required to meet the flow regime target release rates is the volume provided by the retrofit BMP towards restoring the flow regime. For example, if an existing BMP is retrofitted to increase the existing total volume from 100,000 gallons to 150,000 gallons to meet the flow regime target release rate, retrofitting the BMP provides 50,000 gallons of improvement towards a restored flow regime.

It is important to emphasize that additional design criteria may be required to recharge aquifers, protect stream channels and, avoid property losses. While the BMP in the above example provides 100,000 gallons of storage and only 50,000 gallons measure the benefit towards flow regime restoration, the total storage volume is important to meeting other management objectives.

Example Volume Calculation

Table 1-2 defines the volume for various BMP types. The definitions are for new BMPs. Volume calculation for BMP retrofits would subtract the existing volume already provided by the BMP as described above. Example volume calculations associated with BMPs are found in Chapter 3.

TABLE 1-2
Calculation Methods for the Volume Provided by Stormwater BMPs

BMP Categories	Calculation
Stormwater wetlands	The volume of captured and treated runoff for the design rainfall depth.
Bioretention	The volume of captured and treated runoff for the design rainfall depth.
Grassed swale	The volume of captured and treated runoff for the design rainfall depth (for example, storage volume behind check dam or increased infiltration due to engineered soil).
Sand filter	The volume stored in the filter bed for the design rainfall depth.
Offline wet detention basin	The storage volume of the basin for the design rainfall depth.
Inline wet detention basin	The storage volume of the basin for the design rainfall depth.
Dry detention basin	The storage volume of the basin for the design rainfall depth.
Rooftop runoff management	The volume of captured and treated runoff for the design rainfall depth.
Underground storage	The storage volume of the basin for the design rainfall depth.
Permeable pavement and infiltration devices	The volume of captured and treated runoff for the design rainfall depth.
Land use conversion	The decrease in runoff volume for the design rainfall depth.
Land preservation	One potential calculation approach is described below.
Floodplain enhancement	The decrease in runoff volume for the design rainfall depth.

Land Preservation

Land preservation in the form of open space, recreational land, and green space, introduces potential habitat and flow benefits by protecting the land from future flow regime impacts. However, the methodology described herein would not allow any credits to land preservation because the hydrology would remain the same. There is an inherent benefit in leaving the land undeveloped because development on the site would alter the hydrology to some degree. Consequently, it seems intuitive that benefits should be allowed and documented for preservation practices, even though these benefits need to be considered as damages avoided in the future. Therefore, the benefits of land preservation need to be valued differently from those of a constructed BMP, which actively provides flow restoration benefits.

The following approach was developed to calculate preservation gallons:

1. Determine the area preserved.
2. Subtract any regulatory required buffer widths adjacent to the stream.

3. Use the design rainfall depth to calculate the volume across the resulting area.
4. Use 50 percent of the calculated gallons.

The allowable BMP volume associated with preservation is assumed to be equal to that resulting from equating it to a hypothetical BMP that infiltrates 50 percent of the threshold rainfall depth. The 50 percent value does not have a scientific significance but could be adjusted depending on the infiltration properties of the soil. This adjustment would take into account that potential development over sandy soils is more detrimental than over clayey soils; therefore, more credit would be accrued by preserving land underlain by soils of high infiltration capacity. The main thrust of the credit though is to promote preservation while installing new or retrofitting old BMPs to restore the flow regime.

In summary, the gallon value associated with a preservation site is not directly tied to restoring a flow duration curve. However, it is associated with preserving the current flow regime. Setting gallon target numbers for flow regime restoration in a watershed should take into account any additional goals for preservation. These values are expected to vary from watershed to watershed.

Rouge River and Menomonee River Case Studies

The Rouge River near Detroit and Menomonee River near Milwaukee were used to compare flow regime restoration opportunities through the use of stormwater BMPs. The two watersheds contain similarities, but also differences in watershed management priorities and investment. Both watersheds are contained within the Great Lakes basin and both include older urban areas as well as first and second ring suburban developments. Both watersheds have had significant hydrologic alterations and the potential for ecological improvement is expected to be significant.

A summary of the case study findings and rational behind choosing these two watersheds is provided here with additional details in Appendix 1B.

Rouge River Setting

Study of the Rouge River has benefited greatly from the Rouge River National Wet Weather Demonstration Project funded through USEPA grants. The project demonstrates how a systematic watershed approach to pollution management can result in cost-effective and ultimately greater and faster achievement of designated uses in a water body (Rouge River Project 2007).

Initially, focus within the Rouge watershed was on controlling sewer overflows, however, the emphasis has transitioned over time to include nonpoint source pollution control and stormwater management implementation. The watershed focus has led to the development of a watershed-based organizational structure called the Alliance of Rouge Communities (ARC), which includes all governmental jurisdictions within the watershed. Through the National Wet Weather Demonstration Project, the watershed has been studied extensively with vast amounts of data collected through the course of the study effort. Although great strides in water quality improvement through sewage discharge control have been made in the Rouge watershed, it still does not have the expected fish communities of reference watersheds.

The focus of this study has been upon the subwatershed known as the Upper Rouge River. This subwatershed is nearly entirely developed and increases in peak flows have caused streambank erosion problems and private property damage along stream reaches. Through the National Wet Weather Demonstration Project, flow regime and fish assemblages within the watershed have been studied.

Menomonee River Setting

The Menomonee River has also been studied, but for different reasons and it has not benefited from significant USEPA grant funding as compared to the Rouge. Like the Rouge, the Menomonee is significantly developed, however the headwater areas still contain a significant amount of rural land use. Urban downstream reaches of the Menomonee River have also been plagued by sewage discharges, but the focus of pollution control has been limited to point source controls. The watershed has been studied extensively for the purposes of flood control and new initiatives are underway to better understand nonpoint source water quality impacts. There has been limited data collected to characterize flow regime and fish assemblages.

Together, these case studies provide an opportunity to compare flow regime restoration opportunities through stormwater BMP implementation between two watersheds that are in the Great Lakes basin, but vary in geographic location, local watershed management interests, and level of study.

Rouge River Results

The analysis of the effects of various BMP implementation scenarios focused on the change in the flow duration curve. Table 1-3 summarizes the scenarios that were evaluated.

TABLE 1-3
BMP Scenarios for Analysis

Scenario	Description
Base	Unmodified calibrated model for existing conditions.
Detention Basins 1.0 inch	Each subbasin has sufficient detention storage to hold 1.0 inch of runoff from all developed areas.
Detention Basins 0.5 inch	Each subbasin has sufficient detention storage to hold 0.5 inch of runoff from all developed areas.
Disconnect all imperviousness	Route flow from all impervious areas to adjacent pervious land to allow greater opportunity for infiltration.
Partially disconnect imperviousness	Route flow from 80 percent of commercial/industrial areas and 50 percent of residential areas to adjacent pervious land.
Rain gardens	Convert 10 percent of residential pervious area to new rain garden land use type, and route 50 percent of residential imperviousness to it.
Pervious pavement	Convert 50 percent of commercial/industrial impervious area to new pervious pavement.
Forested	Replace all land use with forest.
No imperviousness	Replace all impervious land with corresponding pervious (grassed) area. This scenario corresponds to the target flow condition.

Figure 1-6 shows the results that different BMP implementation scenarios produce on average daily flow yields greater than the 30 percent exceedence level at the Telegraph Road stream gauge. The flow durations are compared against target yields, which were developed from prior research linking flow and healthy fish communities (Wiley et al., 1998).

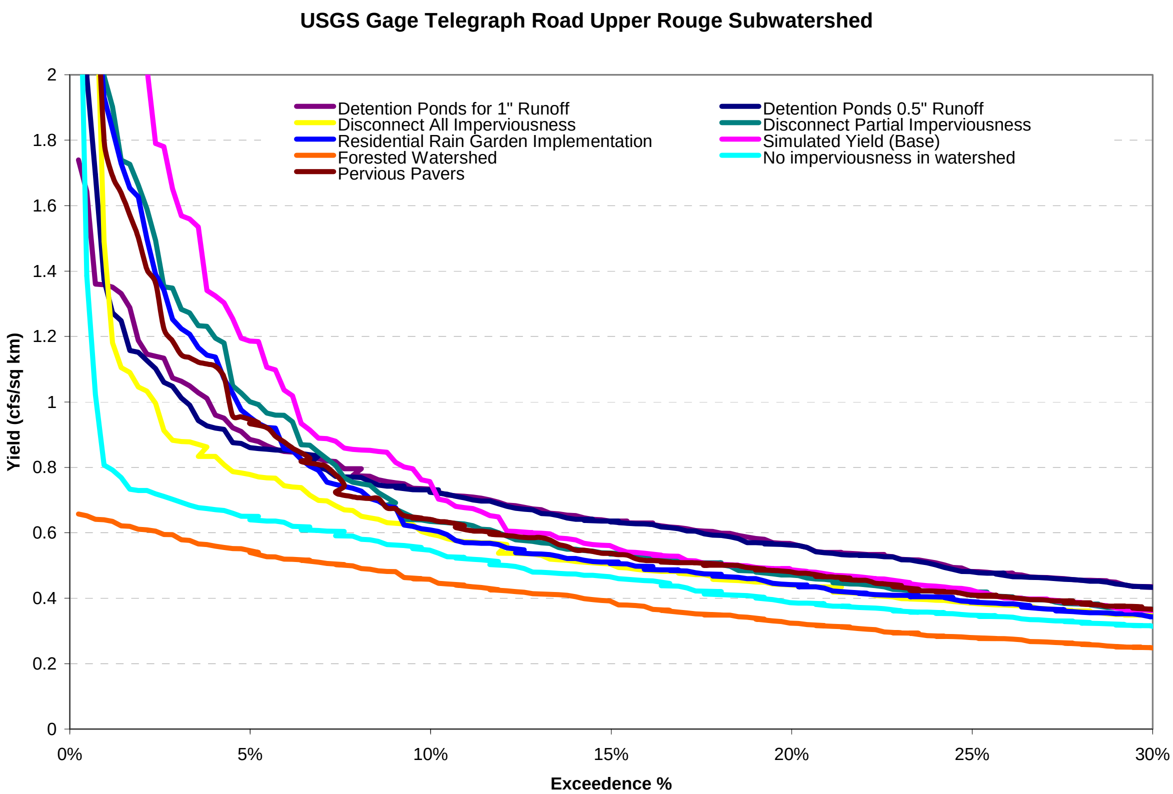
For storm flows above the 10 percent exceedence level, all BMP implementations have the positive result of reducing the watershed yield below base conditions, although to various degrees. Disconnection of imperviousness results in the greatest decrease in yield, followed by detention ponds. The implementation of detention ponds increases yields for storm events above the 10 percent exceedence level, resulting in a shift in the flow duration curve shape. This shift is caused by the extended drawdown time for ponds that continue to release water for 72 hours following a storm event. The peak flow reduction provided by detention ponds for large storms should be beneficial for fish because lower storm flows translate into lower velocities and conditions more survivable by fish. However, the detention ponds also result in increasing flows beyond the 10 percent exceedence flow, which may have the negative effect of increasing velocities and creating detrimental conditions for fish during some periods. For large storms (storm events of less than 1 percent exceedence), providing detention for 1 inch of runoff results in a greater yield reduction. Beyond the 6 percent exceedence level, both 0.5-inch and 1.0-inch pond storage capacities produce similar results.

Implementation of pervious pavement and rain gardens also produces a decrease in yield, with the modeled pervious pavement scenario performing slightly better than the rain garden scenario. The flow duration curve for infiltration-based BMPs (disconnection, pervious pavement, and rain garden) is the closest to the no-imperviousness target curve.

Figure 1-6 also compares the curve resulting from "pristine" forested conditions with that equivalent to removing imperviousness from the existing conditions. This comparison emphasizes that the ecological target does not reflect a pre-settlement condition but seeks to mitigate the effects of uncontrolled runoff.

The figure also shows that even this target may need to be adjusted upwards because of practicality reasons such as realistic levels of BMP implementation, ability to achieve the desired result, frequency and thoroughness of maintenance, performance, model input and output accuracy, and other factors affecting BMP effectiveness. These factors and other sources of variability insinuate that this study needs to be extended into a formal uncertainty analysis that bounds the lines in Figure 1-6 with confidence intervals. These probability estimates need to be translated in to the probability of having the desired fish species.

FIGURE 1-6
June Flow Durations at Telegraph Road
Storm flows greater than the 30 percent exceedence level.



Rouge Gallon Estimate from Example Implementation

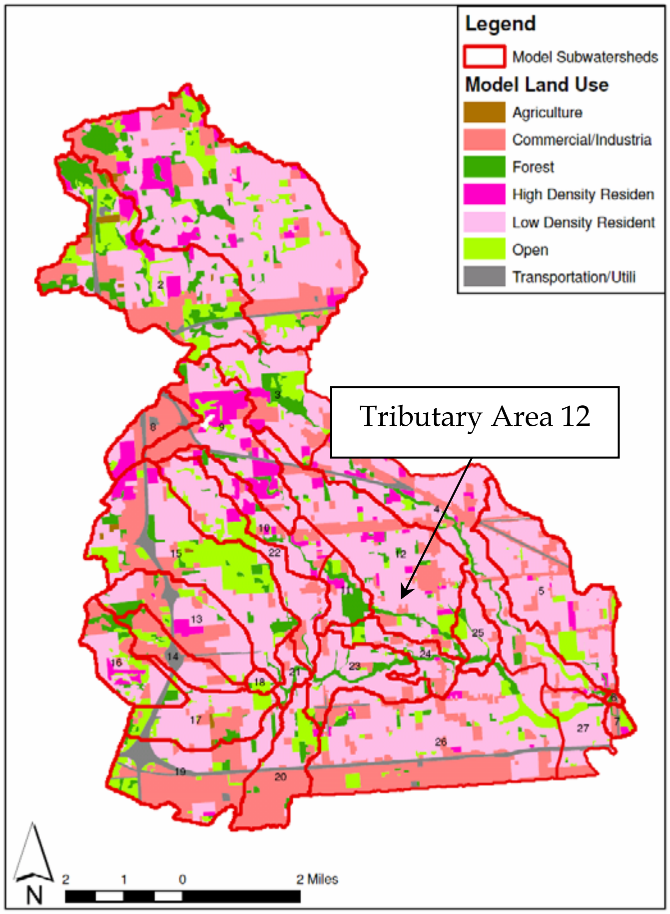
Besides the watershed wide response analysis for various BMPs, several of the BMP scenarios described above were examined more closely for a portion of the Rouge River watershed. As described below, rain gardens and permeable pavement were further analyzed for Tributary area 12, which is located in the middle reaches of the Upper Rouge River as shown in Figure 1-7. The tributary area is 4.8 square miles with 35 percent imperviousness. Additional details on the analysis can be found in Chapter 3, BMP Evaluation Process.

Rain Garden Implementation

Rain gardens are applicable to approximately 69 percent of the tributary area, or 2,143 acres of high- and low-density residential property. To treat 50 percent of the residential area, 74 acres of rain garden would need to be implemented. Assuming 6 inches of ponding depth, the rain gardens create 12 million gallons of flow restoration storage volume. Model results for the Rouge River subwatershed indicate that a 50 percent rain garden implementation provides one third of the yield reduction needed to meet the ecological target for the subwatershed.

A planning-level estimate of the cost for do-it-yourself installation materials is \$3–5 per square foot (ft^2), roughly \$13,000,000 for this implementation. Complete installation by a specialty contractor would increase the cost to \$10–12/ft^2.

FIGURE 1-7
Tributary Area 12 Location within the Upper Rouge River Watershed



Permeable Pavement Implementation

Commercial imperviousness accounts for more than a third (14 percent of the 35 percent) of imperviousness in tributary area 12. Of these 417 impervious acres, it is assumed that 50 percent of the imperviousness can be treated using 25 percent of the imperviousness converted to pervious pavers. To treat 50 percent of the commercial impervious area, 104 acres of permeable pavement would need to be installed. Assuming 6 inches of available storage depth, this creates 17 million gallons of flow restoration storage volume. As with the rain garden implementation, a 50 percent permeable pavement installation in the Rouge River subwatershed provides approximately one third of the yield reduction needed to meet ecological targets.

A planning level cost estimate of $\$4/ft^2$, yields roughly \$19,000,000, for this implementation.

Rouge River Conclusions

Of the BMPs analyzed, disconnecting all imperviousness achieved the best reduction in flows, although a close match was not attained. The results indicated that application of bioretention on 50 percent of the residential areas has virtually the same effect as deployment of permeable pavement on 50 percent of commercial areas, although neither one of these approaches by itself is sufficient to match the target flow condition equivalent to zero imperviousness. While disconnecting all impervious area in the watershed does have a dramatic affect upon the flow duration curve, it does not fully restore the flow to the target condition. This indicates that while significant flow restoration is theoretically possible in an urbanized watershed, fully restoring a watershed to a condition with no imperviousness is very difficult. In addition to analyzing these BMPs that restore the flow regime, the analysis could be expanded to incorporate rural land use preservation practices, as described above to preserve the flow regime.

Finally, the results indicate that a stormwater management approach based exclusively on ponds does decrease the high peak flows, but also produces the negative result of increasing the magnitude and frequency of lower-peak flows.

Menomonee River Results

Table 1-4 lists the scenarios that were evaluated in the Menomonee River watershed. The analysis of the effects of these scenarios focused on the change in the flow duration curve. June flow duration curves at Wauwatosa. The results are shown in Figure 1-8.

Detention ponds were very effective in reducing yields for the storm flows with exceedence levels less than 15 percent; however, at higher exceedence levels, detention ponds cause a yield increase. Implementation of rain gardens and pervious pavers also resulted in decreases in yield. Disconnection of imperviousness did not have a dramatic effect as was seen in the Rouge River. This may be because soils in the Menomonee River basin have lower infiltration rates than those in the Rouge River basin.

To better understand the effect of location in the watershed on BMP effectiveness, a smaller subset of infiltration-based BMP scenarios was analyzed at a smaller subwatershed scale. The results are shown in Figure 1-9. The Honey Creek watershed is more urban with 36 percent imperviousness and no agriculture.

TABLE 1-4
BMP Scenarios for Analysis in the Menomonee River Watershed

Scenario	Description
Base	Unmodified calibrated model for existing conditions.
Detention basins 0.5 inch	Each subbasin has sufficient detention storage to hold 0.5 inch of runoff from all developed areas.
Disconnect all imperviousness	Route flow from all impervious areas to adjacent pervious land to allow greater opportunity for infiltration.
Partially disconnect imperviousness	Route flow from 80 percent of commercial/industrial areas and 50 percent of residential areas to adjacent pervious land.
Rain gardens	Convert 10 percent of residential pervious area to new rain garden land use type, and route 50 percent of residential imperviousness to it.
Pervious pavement	Convert 50 percent of commercial/industrial impervious area to pervious pavement.
Full rain garden and pervious pavement treatment	Convert 20 percent of residential pervious area to new rain garden land use type, and route 100 percent of residential imperviousness to it. Convert 100 percent of commercial/industrial impervious area to new pervious pavement.
No imperviousness	Replace all impervious land with corresponding pervious, grassed area. This scenario corresponds to the target flow condition.

FIGURE 1-8
Effect of BMP Implementation on June Flow Duration Curves for the Menomonee River in Wauwatosa, Wisconsin
Storm Flows above the 30 percent exceedence level

USGS Gage Menomonee River at Wauwatosa, Wisconsin

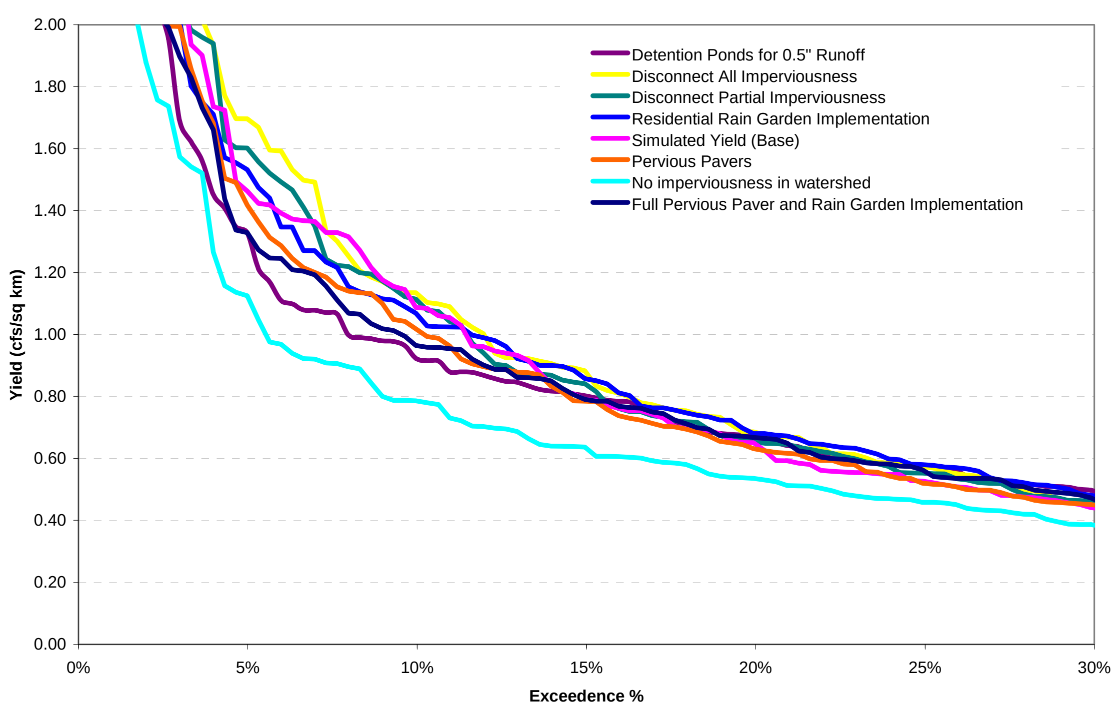
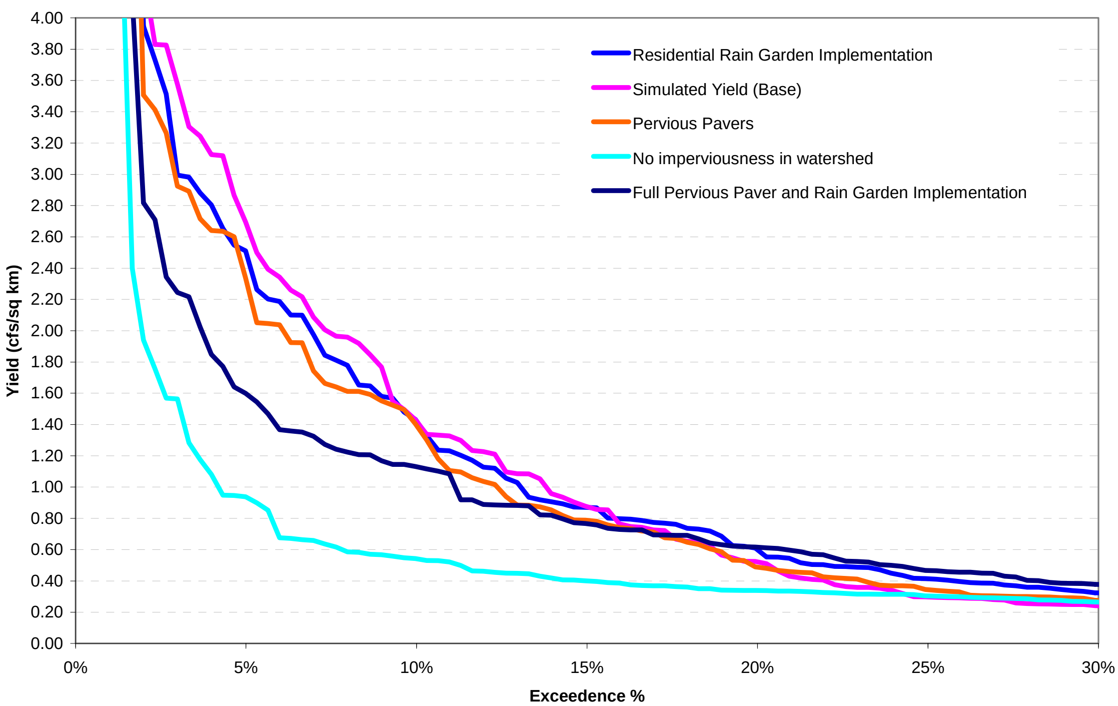


FIGURE 1-9
Effect of BMP Implementation on June Flow Durations for Honey Creek in Wauwatosa, Wisconsin

USGS Gage Honey Creek at Wauwatosa, Wisconsin

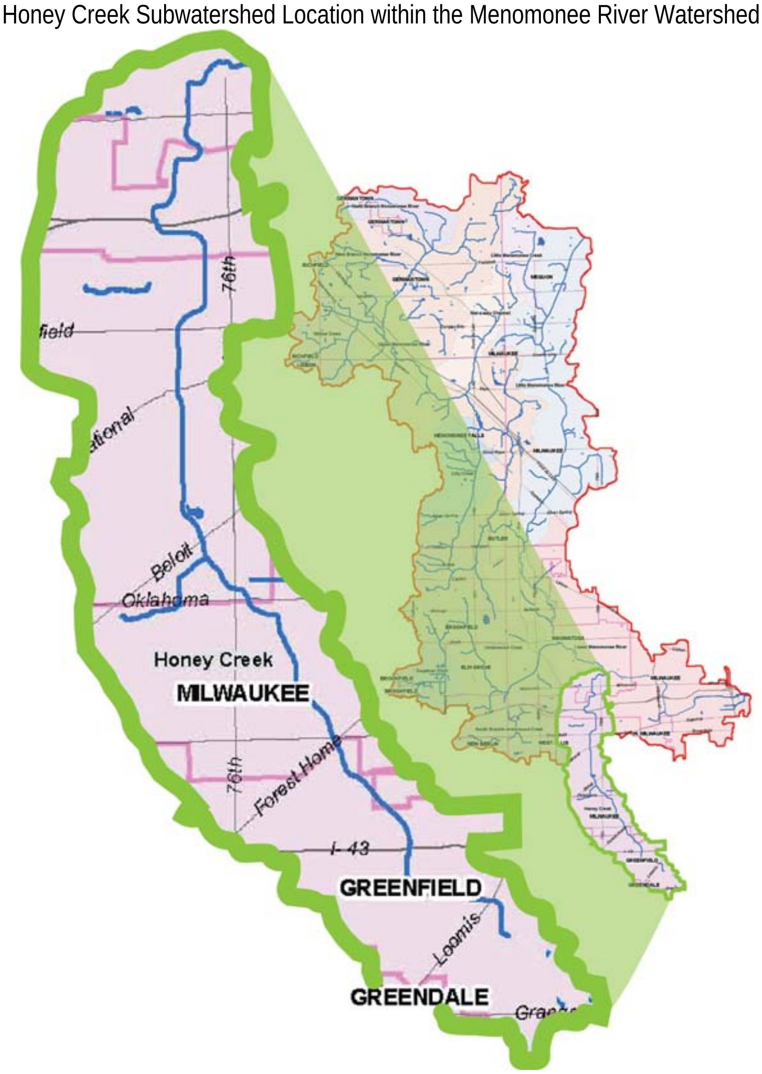


Infiltration-based BMPs had a noticeable effect in the urban Honey Creek subwatershed. Both pervious pavement and rain garden implementation resulted in decreases in yield. The combined effect of the full implementation of pervious pavement and rain gardens resulted in a substantial reduction in simulated yields for the Honey Creek watershed, even though the target flow condition was not fully reached. Even if a natural flow cannot be fully reached through BMP implementation, beneficial effects such as a reduction in the frequency of peak flows would still occur. The results of BMP implementation will vary from watershed to watershed with the control of frequent storms significantly influenced by the infiltration capacity of watershed soils.

Menomonee Gallon Estimate from Example Implementation

In addition to the watershed-wide response analysis for various BMPs, rain garden and permeable pavement BMPs were further analyzed for the Honey Creek subwatershed, which is located in the southwestern corner of the Menomonee River watershed and terminates in the lower reaches of the Menomonee River as shown in Figure 1-10. The subwatershed tributary area is 10.8 square miles with 36 percent imperviousness. Additional information on the analysis can be found in Chapter 3, BMP Evaluation Process.

FIGURE 1-10
Honey Creek Subwatershed Location within the Menomonee River Watershed



Rain Garden Implementation

Rain gardens are applicable to approximately 68 percent of the subwatershed, or 4,705 acres of high- and low-density residential property. To treat 50 percent of the residential area, an estimated 161 acres of rain garden would need to be implemented. Assuming 6 inches of ponding depth, the rain gardens provide 26 million gallons towards flow regime restoration. Model results for this installation show a drop in watershed yield for exceedence values below 15 percent, bringing the subwatershed closer to its ecological target flow.

A planning level estimate of the cost for do-it-yourself installation materials is \$3–5/ft^2, roughly \$29,000,000 for this implementation. Complete installation by a specialty contractor would increase the cost to \$10–12/ft^2.

Permeable Pavement Implementation

Commercial areas account for about a third (13 percent of the 36 percent) of imperviousness in the subwatershed. Of the 870 commercial impervious acres, it is assumed that 50 percent are treated with permeable pavement installation in 25 percent of the impervious area. To treat 50 percent of the available area, 217 acres of permeable pavement would need to be installed. Assuming 6 inches of available storage depth, the permeable pavement areas create 35 million gallons towards flow regime restoration. Model results for this installation demonstrate a drop in watershed yield similar to the rain garden implementation.

Using a planning-level cost estimate of \$4/ft^2 translates into roughly \$38,000,000 for this implementation.

Menomonee River Conclusions

The results show that the impact of BMP implementation varies by location within the watershed. Areas with higher imperviousness responded more dramatically to BMP implementation than areas with lower imperviousness. For the highest flows, the best match to the target flow regime is achieved through detention pond BMPs, although a close match is not obtained and while ponds decrease peak flows, they also increase the magnitude and frequency of low flows.

The results also show that application of bioretention on 50 percent of the residential areas or permeable pavement implementation has a relatively small impact upon the overall watershed; however more dramatic impacts are seen when significant BMP implementation occurs in more urbanized subwatersheds. The modeling results of disconnecting impervious area are not shown, but this practice fell in the middle of all the other alternatives and did not restore the flow regime to the degree that was observed in the Rouge River. In addition to analyzing these BMPs that restore the flow regime, the analysis could be expanded to incorporate rural land use preservation practices, as described above to preserve the flow regime.

Rouge River and Menomonee River Comparison and Flow Regime Case Study Conclusions

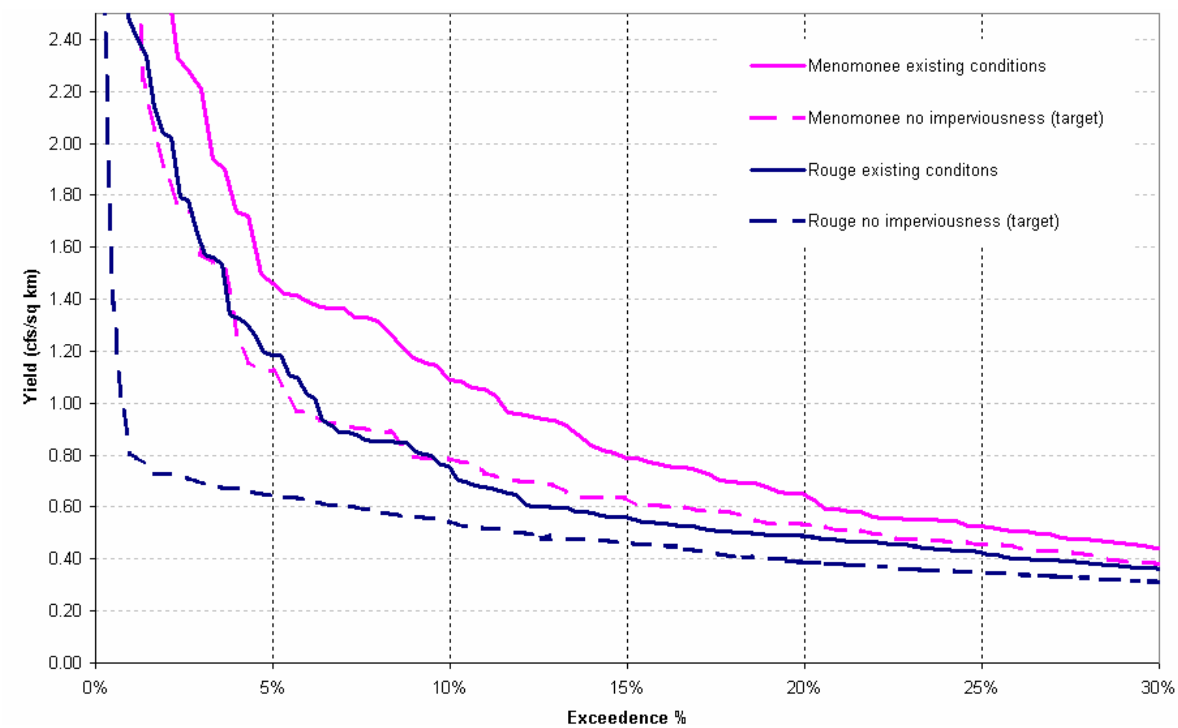
Implementing storage and infiltration-based BMPs in the Rouge and Menomonee River watersheds resulted in significant reductions in watershed yield for given flow exceedence frequencies. The simple approach of disconnecting imperviousness appears as a cost-effective approach to decreasing yields towards the flow target.

Several observations can be made between the characteristics of the two watersheds and the result of BMP implementation on flow regime restoration. The Upper Rouge River watershed flow regime responded more significantly to BMP implementation than the Menomonee River watershed. There could be several reasons for this. First, the infiltration potential of the Upper Rouge River watershed is higher than the Menomonee River watershed. As a result, simulation of infiltration-based BMPs indicates a better response in the Upper Rouge River watershed as compared to the Menomonee River watershed.

Second, the Upper Rouge River watershed is almost fully developed, while land use in 28 percent of the Menomonee watershed is agricultural. As a result, the Menomonee watershed has a significant portion that offsets the urban impact upon the flow duration curve.

A comparison of observed flow conditions indicated that, for the higher end of the flow duration curve, flows are naturally higher in the Menomonee watershed, while for the lower end of the flow duration curve, flows are naturally lower in the Menomonee watershed. This indicates that a higher runoff rate naturally occurs in the Menomonee. This finding is consistent with lower permeability soils in the Menomonee as compared to the Rouge. When examining the Menomonee watershed relative to the Rouge River watershed, the effect of implementing BMPs is not as dramatic. A comparison of the flows in the two watersheds is shown in Figure 1-11.

FIGURE 1-11
Menomonee River and Upper Rouge River Watershed Flow Duration Curve Comparisons for the Month of June



An important conclusion from these observations is that stormwater BMP retrofits in urbanized areas with high infiltration capacity soils will have a more dramatic restorative effect on the flow duration curve than BMP retrofits in watersheds with low permeability soils. Another observation is that it is more difficult to attain a target in a relatively impervious watershed, even though the natural soil conditions are closer to pavement, due to the limited capacity of the soils to absorb additional water that may run onto them from impervious surfaces.

Besides improving the flow regime within these watersheds, implementing these types of BMPs as urban stormwater retrofits would be expected to decrease property loss due to streambank erosion by reducing the frequency of peak flows and the resulting erosion. In addition, BMP implementation would also be expected to improve water quality and increase groundwater recharge. If implemented in areas where combined or separate sewer overflows were problematic, the BMPs could also serve to reduce overflows by reducing peak flows and directing some runoff into groundwater recharge.

Implementation of a large-scale watershed restoration program would require significant monetary investment and regulation. Opportunities exist to provide incentives or market-based mechanisms for watershed restoration. Several potential stormwater BMP implementation incentives are discussed in Chapter 5, Facilitating and Funding Stormwater Management for Ecosystem Improvement.

Results for other watersheds would be expected to vary depending upon the degree of development in the watershed and soil infiltration potential, but implementation of infiltration based BMPs would be expected to restore the flow regime at least in part to a healthier condition for natural fish communities. Detailed flow regime restoration predictions using flow duration curves may not always be necessary for other watersheds when stormwater BMP practices intended to restore flow regime, applicable BMP design standards, and potential for results become generally known. Consequently, as the flow regime restoration body of knowledge grows, the lessons are expected to be readily transferable to other watersheds.

Areas for Further Study

During the design standard development, some questions were raised where additional analysis and research could be useful. Additional analysis could be useful in the following areas:

- Rainfall associated with flow duration curve exceedence levels. Simplified sizing procedures should be developed to facilitate design of BMPs based on ecological criteria. These procedures would associate design rainfall depths with a release rate to arrive at a BMP size that approximately matches the target flow duration curve. Design procedures should also include a verification step using modeling and real rainfall records to understand the effect of the BMP on the flow regime.
- Release rate associated with flow duration curve exceedence levels. The release rate for a BMP associated with the flow duration curve restoration is difficult to determine. The data used to develop a target flow duration curve used a data set where the minimum catchment area was approximately 30 square kilometers. BMPs treat an area much smaller than this. Consequently, the flow duration curve does not translate directly into a release rate because of scale differences. Release rates with excessive drawdown periods are not practical in humid climates because of the high probability of successive rain events. Additional research is needed to investigate the effect of small drainage areas on the flow duration curve at a point downstream. It is very likely that the effects of a shorter drawdown will be diminished by routing effects as the water reaches a downstream observation point.
- Physical stream integrity and flow duration curve exceedence levels. The flow duration curves developed by the University of Michigan focused on stream biological conditions and did not incorporate any geomorphic conditions of the stream. Consequently, flows that control the channel geometry, such as the bankfull flow, are not included in the flow duration curve. Additional analysis to associate the flow duration curve to such physical

conditions may be beneficial. It may also be useful to extend the flow duration curve restoration concepts in this study to include the flows that directly affect the physical structure of the channel, in addition to flows that affect the biology of the stream. This is because, where the physical channel structure is changing, the resulting habitat and biological community will also be affected.

- The flow duration curve regression equations developed by the University of Michigan can be expanded to other states or ecoregions. Developing applied methods to utilize a target flow duration curve for restoration and stormwater management design standard development could be very useful. In addition, the identification of which percent exceedence flows most directly impact various fish species (for example, cold water or warm water) life-cycles could be beneficial to targeting restoration and preservation criteria and the most critical time of the year to focus design standard development.
- Developing guidance that addresses the identification of an appropriate flow duration curve target (when a target representing limited urbanization in a watershed cannot be achieved), or research showing at which threshold aquatic species become less abundant would be very beneficial. Uncertainty analysis will be beneficial in addressing the probability of attaining suitable flow regime targets and the probability that the desired species will be present.

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Appendix 1A
Flow Duration Curve Selection Details

APPENDIX 1A

Flow Duration Curve Selection Details

This appendix describes how the June flow duration curve was selected as an ecological flow target. The appendix includes discussion on seasonal factors observable through various flow duration curves as well as methods and data requirements for flow duration curves calculated through stream gages or hydrologic watershed modeling.

Flow Duration Curve Selection

Based upon the flow regime restoration evaluation principles, available flow duration curve tools were reviewed and data needs evaluated to determine an appropriate flow duration curve for watershed evaluation and analysis. It is important to first select the period of time for the flow duration curve and ensure that data is available.

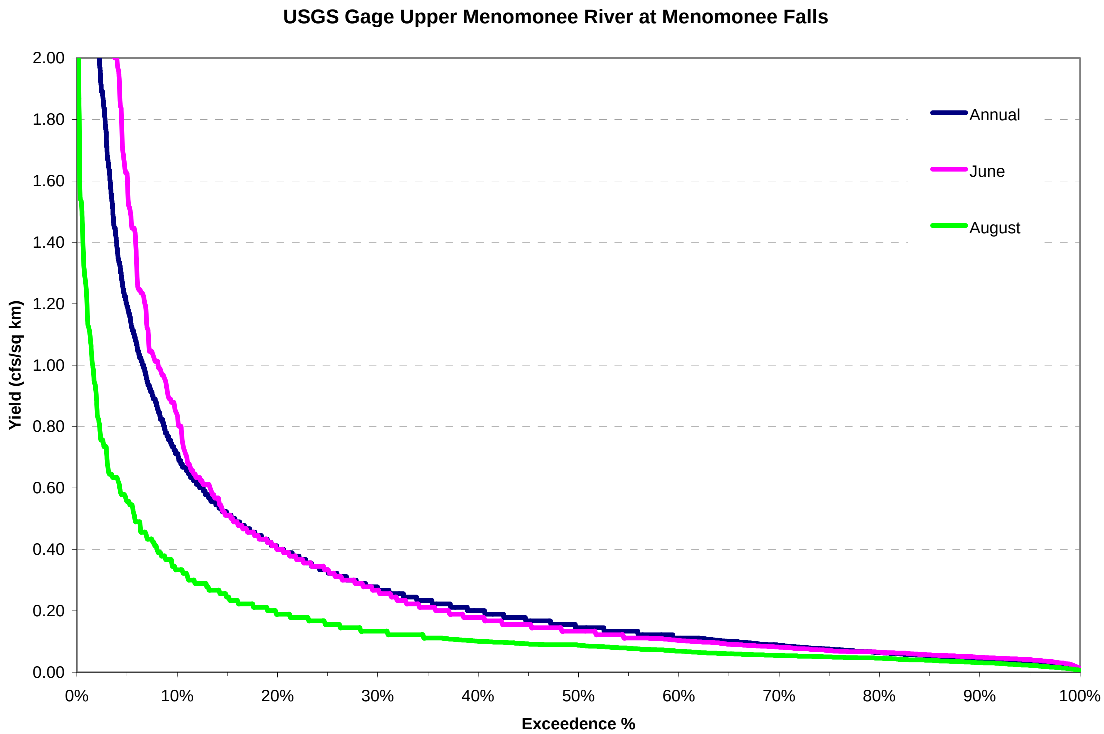
Annual, April, and August Flow Duration Curves

Wiley, et al. (1998), developed flow duration curves in Michigan for the entire year—an annual flow duration curve—as well as flow duration curves for the months of April and August. The study team reviewed the flow duration curves for applicability to flow management decisions in the Rouge and Menomonee River watersheds. The annual flow duration curve represents all flow conditions experienced in the river throughout the year. The April flow duration curve is representative of high flow spring runoff conditions. The August flow duration curve is representative of baseflow conditions when flows are generally the lowest during the year and high water temperatures associated with late summer conditions. Figure 1A-1 presents predicted flow duration curves using methods developed by Wiley, et al. (1998), for various timeframes

It is important to select a flow duration curve that can measure the flow regime change for which a fix is desirable. For example, with counteracting the affect of urbanization, changes in peak flows or baseflow conditions would need to be measured through the flow duration curve. Urbanization produces more runoff and higher peak flows from impervious areas because prior to urbanization, the precipitation could infiltrate into the ground. Consequently, selecting a flow duration curve to establish a target condition for the watershed should include a period of time where urbanization is present.

An April flow duration curve represents the seasonal time of year when the ground is saturated and runoff is unable to infiltrate. Consequently, most precipitation runs off into streams. The April saturated condition is not unlike an urbanized impervious condition in that water readily runs off and does not have an opportunity to infiltrate. Consequently, the month of April is not a good flow duration curve to use when analyzing for the effects of urbanization since saturated conditions and impervious conditions both cause all water to directly run off.

FIGURE 1A-1
Seasonal Variations in Flow Duration Curves for the Upper Menomonee River Subwatershed



The annual flow duration curve reflects all flow conditions throughout the year, including drought and wet periods. When analyzing the higher flows associated with the annual flow duration curve, most of the flows occur in the spring under conditions similar to April. In addition, the annual flow duration curve dampens the wet and drought period flows that occur over a year. For example, as seen in Figure 1A-2, a flow condition that assumes no imperviousness in the Rouge River watershed compared to the actual measured flows reflecting nearly 50 percent imperviousness shows little difference between the two curves. Therefore, for both of the above reasons, the annual curve is also not a good flow duration curve to analyze when evaluating the effects of urbanization and flow

The August flow duration curve reflects flow conditions when the watershed is generally hot and dry, groundwater levels are unsaturated, and baseflow conditions persist. The unsaturated condition in August is almost the opposite of the April condition. In August, the ground is unsaturated and has a higher infiltration capacity than April, when the ground is saturated and has a low infiltration capacity. The reduced infiltration capacity resulting from urbanization is most directly seen under August conditions. Consequently, the month of August is a good flow duration curve to analyze when looking for the effects of urbanization. Observed versus predicted flow duration curves shown in Figure 1A-3 clearly show the increases in peak flows associated with urbanization. However, August peak flows may not be as critical to aquatic species as peak flows at other times.

FIGURE 1A-2
Predicted Annual Flow Duration Curve without Urbanization and the Observed Annual Flow Duration Curve (with Urbanization) in the Upper Rouge River Watershed

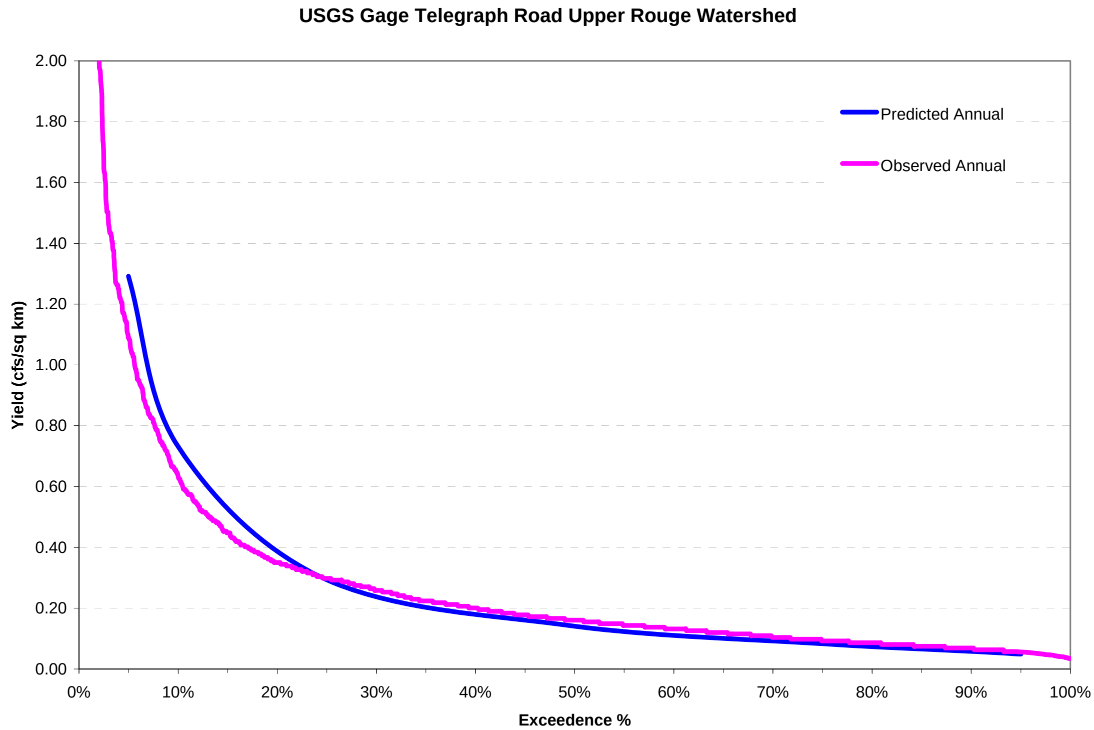
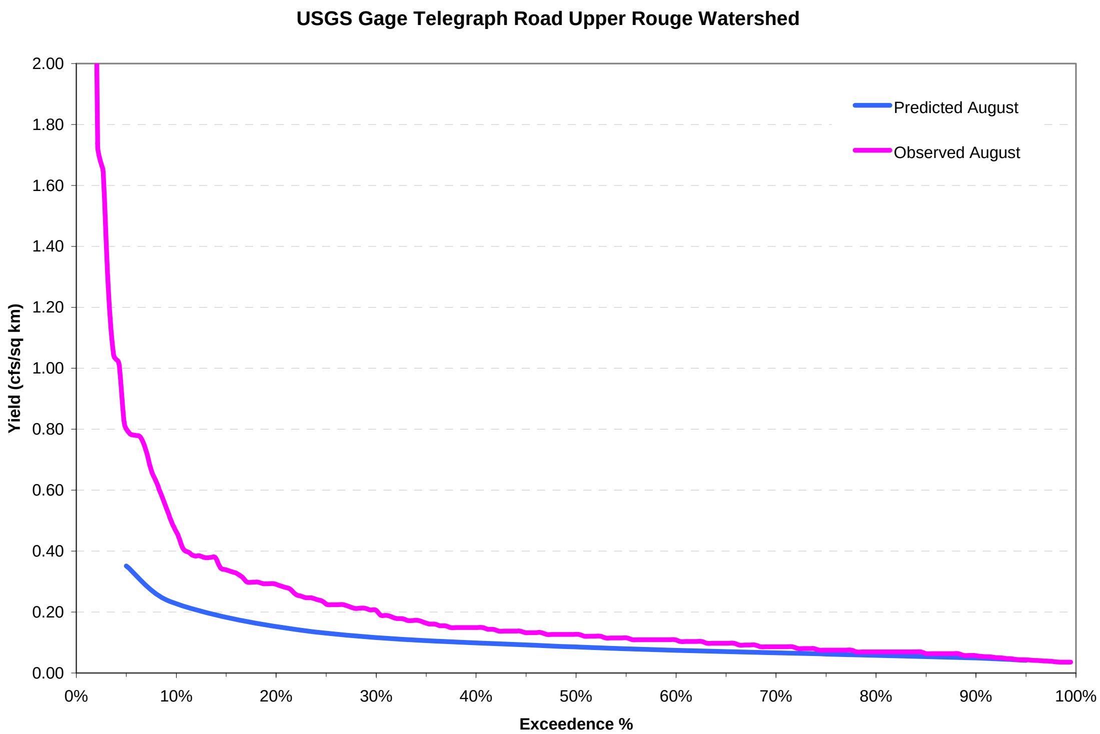


FIGURE 1A-3
August Flow Duration Curve without Urbanization and the Observed Curve (with Urbanization) for the Upper Rouge Watershed

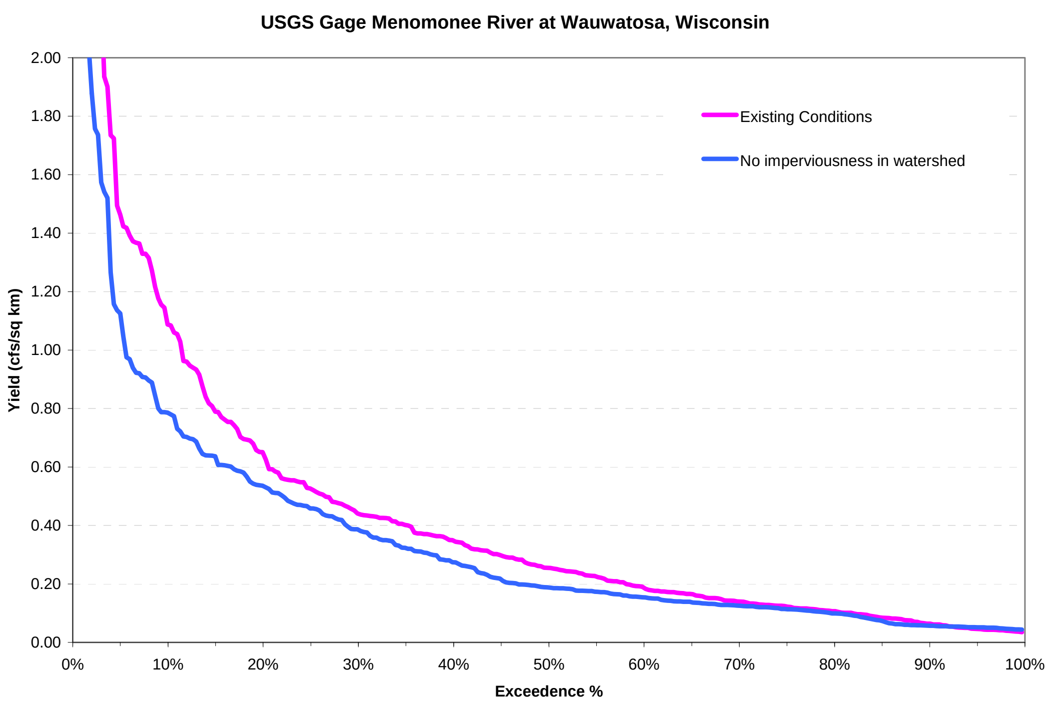


June Flow Duration Curve

Discussions with fisheries biologists indicated that while the month of August may most clearly illustrate the affects of urbanization, it may not be the month in which peak flow increases affect fisheries most directly. Documentation from more than 20 years indicates that warm-water fish are very vulnerable to peak flows when they first hatch (Bovee 1994). For warm water fisheries in the upper Midwest, June is the critical month for fish hatching.

Consequently, it was determined that changes to the June flow duration curve would most readily affect fisheries and would likely reflect a condition in between the April and August climate condition where the affects of urbanization could be seen in the flow duration curve, but would not be as dramatic of a difference as August. This theory was tested by developing an estimated flow duration curve through watershed modeling, the results of which are shown in Figure 1A-4. Additional modeling information is found in Appendix 1B. During the watershed modeling, the flow regime was calibrated for existing developed conditions and the imperviousness in the watershed was changed in the model to simulate an undeveloped condition. The results clearly showed a dramatic difference in developed versus undeveloped flow duration curve responses. A June flow duration curve could also be estimated through regression equations, similar to methods used by Wiley, et al. (1998).

FIGURE 1A-4
Effect of Imperviousness on the Simulated June Flow Duration Curve



As Figure 1A-4 indicates, the affect of urbanization is readily observable for the month of June. Designing best management practices (BMPs) to a June flow duration curve provides a strong link to protecting fisheries during their most vulnerable stage. It also reflects a condition where urbanization effects are readily observable. As a result, the month of June was selected as a basis for flow regime restoration in an urbanized setting.

Within this study, the goal of the flow regime restoration is to try to restore flow regime conditions beneficial to a fish community and to determine whether flow regime restoration through stormwater BMP implementation is possible to offset the affects of imperviousness.

Developing Flow Duration Curves

The existing flow conditions in a watershed are needed to determine the existing flow duration curves. Flow duration curves are developed from long-term continuous flow information from either observed or simulated data. The existing flow conditions can be determined by using existing flow gage information or, if flow gage information is not available, developing a continuous simulation hydrologic model. For either method of developing existing condition flow duration curves, the curves will allow for the comparison of the existing and target flow conditions. The target flow conditions can be obtained either from regression equations or through watershed simulations. Comparing existing and target flow conditions will determine the restoration and stormwater BMPs that are needed to move the existing conditions towards the target condition. This applies to watersheds that have experienced urbanization or changes to the hydrologic properties of the watershed.

Flow Duration Curve Evaluation by Flow Gages

The U.S. Geological Survey (USGS) and many other state and local governmental agencies have installed flow monitoring gages in many watersheds. The gages have been installed for water supply management, flood management, water quality studies, and for research through public and private entities. Flow gages are typically installed and maintained by the USGS, but universities, state departments of natural resources, and local governments have also monitored flow because of its importance to land and water resource management. For example, the Milwaukee Metropolitan Sewerage District and the Rouge River Program Office have installed flow gages in the Menomonee River watershed and the Rouge River watershed, respectively, to help the agencies with flood and management decisions. Flow gage monitoring is a relatively inexpensive process, but an essential part of the hydrology of a watershed and land and water resources management.

As discussed previously, flow duration curves are a statistical representation of river flow. Therefore historic flow gage information is required to develop an existing condition flow duration curve. A minimum of 5 years of average daily flow records could be used to develop a flow duration curve, but 10 years or more are preferred. In general, a longer period of flow gage information will produce a more statistically representative flow duration curve; however, the period of record used in developing a curve should consider significant watershed developments or changes to the hydrology of the watershed because they may affect the flow duration curve results. For example, if 20 years of flow data is available for a watershed and 15 years ago a significant development occurred that had an affect on the hydrology of the watershed, the period of record that should be used to develop a flow duration curve for the watershed should include the more recent 15 years and not the first 5 years. This is because the hydrology is significantly different over the first 5 years than it was for the more recent 15 years, and the first 5 years do not represent a flow condition that the watershed will experience again.

A flow duration curve is developed using flow gage information and by following standard statistical analyses. A curve similar to Figure 1A-1 can be used to compare the existing flow conditions to the target conditions. The comparison can then be used to establish goals to restore the flow in the watershed to the target condition.

Developing flow duration curves from gage data is relatively easy and straightforward. Because a flow duration curve can be very easily developed from flow gage data, flow gage data can be particularly useful in screening potential areas of flow regime impairment.

Data Requirements and Limitations

Long-term flow gage data must first be available if this methodology is used. The USGS and other entities maintain flow gage networks, but the gage locations are sometimes limited. Maintaining or expanding these networks allows for the use of the data in flow regime management decisions. If the data is unavailable, then only hydrologic modeling can be used. A simple flow duration curve analysis can be very easily performed if the data is available.

A flow gage only provides flow information for the specific location where the gage is located. Consequently, the usefulness of flow gage data is limited in that it is only for one location and information is not provided for other locations within the watershed. For more detailed analysis for multiple locations within a watershed involving tributaries and subwatersheds, a hydrologic model can be used to simulate flows at any location within a watershed. It should be noted that hydrologic modeling also requires flow gage data to calibrate the model.

Flow Duration Curve Evaluation by Hydrologic Modeling

Many watersheds and subwatersheds do not have sufficient flow gage data to develop flow duration curves through statistical means. Therefore an alternative method—such as a continuous simulation hydrologic model—can be used to model the watershed properties and develop a flow duration curve that would mimic the existing conditions. Hydrologic models that could be used include HSPF and SWMM.

A model can be used to develop a representative flow duration curve if flow gage data is available for calibration. After calibration, the model can also extrapolate from the period of time when flow data exists, to longer periods of time when other data—such as precipitation—exists to support the model. The extrapolation allows for a longer period of time to develop a representative flow duration curve or to simulate conditions under which flow data was unavailable (for example, presettlement, future land use conditions, etc.).

A model that is developed with data from a long period of record improves the statistical accuracy of the curves and increases the confidence of conclusions drawn from comparing an existing and target flow duration curve. For example, if flow gage data is available for a watershed, such as in areas with less than 5 years of data, the model could be calibrated and validated using the 5 years of flow data and extrapolated for other precipitation records. The extrapolated data could then be used to develop a flow duration curve for a period equal to the precipitation record.

A hydrologic model also has the flexibility of producing flow duration curves throughout a watershed, whereas a statistical analysis of flow gage data can only develop a flow duration curve at the gage location. The flexibility of the model may outweigh the greater accuracy of a flow gage analysis in some situations, such as if flow duration curves are required at multiple locations in the watershed to compare with target conditions.

A detailed discussion of creating and analyzing flow duration curves using a hydrologic model is included in Appendix 1B.

Data Requirements and Limitations

Developing an accurate model requires the software to run the model and significant watershed data to support and calibrate the model. Information such as land use classifications and areas, soil properties, river networks, topography, and precipitation records are required to develop a flow duration curve when flow gage data are not available.

A model is limited, though, in that if flow gage data is not present, the model cannot be calibrated. An uncalibrated model can still produce results; however, the results cannot be checked against observed conditions and there is less confidence in the results. An uncalibrated model may not provide an adequate level of confidence when comparing the curve produced from the model to a target curve. While this does not exclude an uncalibrated model from producing a representative curve, a model should be calibrated for making management decisions. An example of model calibration is provided in Appendix 1B.

Flow Duration Curve Evaluation by Watershed Statistics

It is possible to predict and estimate a flow duration curve by combining the watershed hydrologic modeling data or flow gage data with watershed characteristics information. A statistical relationship exists between flow and watershed characteristics such as: tributary area, surficial geology, precipitation, land slope, land use, and other factors. A statistical regression approach has been used for stream segments as part of an ecological classification of rivers in the upper Midwest (Michigan DNR, Unpublished 2006). Such an approach can develop well-correlated relationships between flows and watershed characteristics such that flows can be predicted for watersheds where no gage data are available.

Data Requirements and Limitations

Extensive flow and geospatial data are needed to correlate a flow duration curve relationship to watershed characteristics. Flow data and geospatial data are needed for all watersheds to be used in the development of the statistical relationship. For the State of Michigan, 75 flow gage sites were used to develop relationships for Michigan’s Lower Peninsula (Cooper 2006). In addition, all of the watershed characteristics must also be known for a watershed where the statistical information is to be applied.

Development of the statistical regression equations is limited by how well the watershed characteristics correlate to the flow data. Examples in Michigan have produced very well correlated results (r-squared values greater than 0.90) (Cooper 2006). Application of the method is limited by how similar the watershed characteristics of the study watershed are compared to the data set that has been used for the regression equation development.

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Appendix 1B

Rouge River and Menomonee River Case Studies

APPENDIX 1B

Rouge River and Menomonee River Case Studies

Introduction

The Rouge River near Detroit and Menomonee River near Milwaukee provide a good opportunity to compare and contrast flow regime restoration opportunities through the use of stormwater best management practices (BMPs). The two watersheds contain similarities and differences in watershed management priorities and investment. Both watersheds are in the Great Lakes basin and include older urban areas as well as first- and second-ring suburban developments. Both watersheds have had significant hydrologic alterations and the potential for ecological improvement is expected to be great.

Study of the Rouge River has benefited greatly from the Rouge River National Wet Weather Demonstration Project funded through U.S. Environmental Protection Agency (USEPA) grants. The demonstration project focuses on showing how a systematic watershed approach to pollution management can result in cost-effective, greater, and faster achievement of designated uses in a water body (Rouge River Project 2007).

Initially, focus within the Rouge watershed was on controlling sewer overflows; however, the emphasis has transitioned over time to include nonpoint source pollution control and stormwater management implementation. The watershed focus has led to the development of the Alliance of Rouge Communities (ARC), which includes all governmental jurisdictions within the watershed. Through the National Wet Weather Demonstration Project, the watershed has been studied extensively with vast amounts of data collected through the course of the study effort. Although great strides in water quality improvement through sewage discharge control have been taken in the Rouge, the watershed still does not have the expected fish communities of reference watersheds.

The focus of this study has been upon the upper subwatershed in the Rouge River. The upper subwatershed is nearly entirely developed. Increases in peak flows have caused streambank erosion problems and private property damage along stream reaches in the Upper Rouge River subwatershed. Flow regime and fish assemblages within the watershed have been studied through the National Wet Weather Demonstration Project.

The Menomonee River has also been studied, but for different reasons, and it has not benefited from significant USEPA grant funding as compared to the Rouge. Like the Rouge, the Menomonee is significantly developed; however the headwater areas still contain a significant amount of rural land use. Urban downstream reaches of the Menomonee River have also been plagued by sewage discharges, but the focus of pollution control has been limited to point source controls. The watershed has been studied extensively for the purposes of flood control and new initiatives are underway to better understand nonpoint-source water quality impacts. There has been limited data collected to characterize flow regime and fish assemblages.

Together, these watersheds provide an opportunity to compare flow regime restoration opportunities through stormwater BMP implementation for two watersheds—both are contained within the Great Lakes basin, but vary in geographic location, have different local watershed management interests, and have been studied to various degrees.

Modeling Analysis

Many watersheds and subwatersheds do not have sufficient flow gage data to develop flow duration curves through statistical means. Therefore an alternative method—such as a continuous simulation hydrologic modeling—can be used to model the watershed properties and develop a flow duration curve that would mimic the existing conditions. This document summarizes the hydraulic modeling completed as part of the Upper Rouge River and Menomonee River watershed case studies.

Data Summary

The data required to support a HSPF model includes geographic and climatic data. The purpose of modeling a watershed is to understand the current hydrologic regime and to evaluate alternatives for changing (that is, improving) the hydrologic regime. In some watersheds, HSPF models exist where additional data are not required to complete hydrologic modeling and the HSPF models can be directly used for developing target flow duration curves. In many watersheds however, a HSPF model will need to be updated, recalibrated, or developed from scratch.

If a model for a watershed needs to be updated, calibrated, or developed from scratch, specific data will be required. Much of the data is widely available from local, state, and federal sources. The data are used to model the watershed conditions and include parameters such as cloud cover, precipitation, land use, soil types, topography, and even information about historical stormwater management practices. A summary of the data required to develop a flow duration curve using a HSPF model is provided in Table 1B-1.

The data required for a HSPF model is generally available from federal, state, or local government agencies. The data are often available for download from the internet. Some data, such as U.S. Geological Survey (USGS) stream flow, is available for free from the USGS Web site, but not all data will be available for free or for all watersheds. Data such as hourly precipitation or meteorological data may be more difficult to locate compared to land use or soil data. Some data may be required to be purchased from universities, National Oceanic and Atmospheric Administration (NOAA), regional climate centers, or other similar organizations. Whether the data is purchased or acquired for free, a minimum amount of data is required to support a HSPF model as shown in Table 1B-1. Some of the data are used to calibrate the model, while some data are used instead of manually selecting modeling parameters. While manually selecting modeling parameters to calibrate the model is an acceptable approach, using the watershed data discussed above will reduce the effect required to calibrate the model to the watershed.

TABLE 1B-1
Watershed Data Requirements for a HSPF Model

Data for HSPF Model	Description	Availability	Required Data*
Geographical Data			
Land Use	Land use data provides information about the type and amount of imperviousness in watershed. The model uses land use data to help estimate the amount and rate of stormwater runoff.	Available through private companies, and state and local government agencies. Also available nationwide through the USEPA BASINS program.	Y
Soil Types	Soil information is required to model the physical properties of the soil, such as infiltration rates.	Available through private companies, and state and local government agencies. Also available nationwide through the USEPA BASINS program.	Y
Units of Government	Units of government data is used to relate stormwater management practices to specific areas in the watershed. Stormwater management requirements may differ between governmental units within a watershed. Incorporating the units of government and the stormwater management requirements in a model will support calibrating the model throughout a watershed.	Available through private companies, and state and local government agencies. Also available nation-wide through the USEPA BASINS program.	N
Hydrography	Network of streams and rivers in a watershed.	Available through private companies, and state and local government agencies. Also available nationwide through the USEPA BASINS program.	Y
USGS Stream Gage Sites	Locations of USGS stream gage sites in the watershed, where stream flow information is used to develop observed flow duration curves.	Available from the USGS.	Y
Watershed Delineations	Watershed delineations are used by the model to develop stream flow and stormwater runoff in the watersheds.	Available through private companies, and state and local government agencies. Also available nationwide through the USEPA BASINS program. Watersheds can also be delineated using standard geographic information system (GIS) software and topography data.	Y
Sub-watershed Delineations	Sub-watershed delineations are used by the model to develop stream flow and stormwater runoff in a smaller scale sub-watershed.	Available through private companies, and state and local government agencies. Sub-watersheds can also be delineated using standard GIS software and topography data.	Y

TABLE 1B-1
Watershed Data Requirements for a HSPF Model

Data for HSPF Model	Description	Availability	Required Data*
Topography	Provides information about the elevation and slope of the watershed and sub-watersheds. Topography is used by the model to estimate time of concentrations of the stormwater runoff.	Available through private companies, and state and local government agencies. Also available nationwide through the USEPA BASINS program. Watersheds can also be delineated using standard GIS software.	Y
Climatic Data			
Hourly Precipitation	Hourly records of all precipitation events, including rain and snow.	Available through regional climate centers, NOAA, and state climatologists. Also available from some local government agencies.	Y
Meteorological	Records of air temperature, dew point, solar radiation, wind speed, and the amount of cloud cover.	Available through regional climate centers, NOAA, and state climatologists. Also available from some local government agencies.	N
Stream Flow	Stream flow information is used to calibrate the model and to compare observed conditions with modeling results.	Available from the USGS and some state and local government agencies.	Y

* All data identified in this table is required for a HSPF model to simulate watershed conditions. However, a HSPF model could be developed without all of the data identified in this table by manually adjusting modeling parameters to simulate watershed conditions. The model may require additional calibration steps when parameters are input manually instead of acquiring all necessary watershed data.

BASINS =

Watershed Analysis Tools

The USEPA BASINS is a multipurpose environmental analysis computer model for use by regional, state, and local agencies in performing watershed and water-quality-based studies. The BASINS package includes: (1) national databases; (2) assessment and targeting tools to evaluate water quality at various scales; (3) programs to import local data such as land use, digital elevations, and soils; (4) tools for watershed delineation; (5) a suite of water quality models, including WinHSPF (Windows version of HSPF model); and (6) graphical postprocessing of simulated and observed data. The integrated GIS format of BASINS provides a platform for ready manipulation of land use/land cover information, while the incorporated WinHSPF model allows simulation of a range of parameters at a variety of time scales, from hourly and daily to seasonal.

HSPF is a mathematical computer model developed under USEPA sponsorship to simulate hydrologic and water quality processes in natural and man-made water systems. It is an analytical tool that has application in the planning, design, and operation of water resources systems. The model enables the use of probabilistic analysis in the fields of hydrology and water quality management. HSPF uses information such as time-series of precipitation, temperature, evaporation, and parameters related to land cover patterns; soil characteristics; and agricultural practices to simulate the processes that occur in a watershed. Data from BASINS can be used within HSPF. The initial result of an HSPF simulation is a time-series of the quantity and quality of water transported over the land surface and through various soil zones down to the groundwater aquifers. Runoff flow rate, sediment loads, nutrients, pesticides, toxic chemicals, and other quality constituent concentrations can be predicted; however this study only used the hydrology simulation capabilities of HSPF.

The model uses these results and stream channel information to simulate in-stream processes. From this information, HSPF can produce a time-series of water quantity at any point in the watershed. Therefore the model allows the calculation of flow rates in any subbasin for any span of time. The model can also run “what-if” scenarios that alter land use or implement various BMP practices to determine how the variations in watershed conditions influences the hydrology.

The successful application of this model requires building a BASINS project for the planning area and supplementing the BASINS data with additional data as available. Data and output from previous studies may also be needed. The HSPF application requires the following data:

- Meteorologic
- Land cover
- Point source flow (if the point source is a significant baseflow component)
- Soils
- Previous study calibration or finding information, if applicable
- Channel cross sections and profiles
- Observed flow (flow gage data)

The meteorological input data and units required for BASINS/HSPF simulations are shown in Table 1B-2. BASINS normally uses meteorological data defined at hourly intervals for modeling, although daily data for many parameters can be converted to hourly data (“disaggregated”) using WDMutil. WDMutil is a computer program for meteorological time series processing for BASINS/HSPF (USEPA 2001).

Besides BASINS/HSPF, there are other watershed hydrologic modeling tools that could be used, such as SWMM.

TABLE 1B-2
BASINS/HSPF Meteorological Input Data

Data Description	Units
Measured air temperature	Degrees Fahrenheit
Measured precipitation	Inches/hour
Measured dew point temperature (optional)	Degrees Fahrenheit
Measured wind movement (optional)	Miles/hour
Measured solar radiation (optional)	Langleys/hour
Measured cloud cover (optional)	Tenths of sky dome
Potential evapotranspiration (ET)	Inches/hour
Potential surface evaporation (optional)	Inches/hour

Upper Rouge River, Michigan

The following sections discuss the application of HSPF to the Upper Rouge River study area. The data collection, watershed characterization, calibration, and scenario results are presented in the following sections.

Data Summary

As part of the model database development, the necessary meteorological data was compiled for use in HSPF. The nearest sufficiently long hourly precipitation record was for Dearborn, Michigan (NCDC 202015), southeast of the study area. There was a daily precipitation record within the Upper Rouge River watershed at Farmington, but it covered only 2 years (2003–2004). A 2-year duration is not long enough for a reasonable hydrologic calibration. Additional hourly records were available at Detroit City and Detroit Metro Airports, but these were significantly farther from the study area.

Daily minimum and maximum air temperature were also available at Dearborn. The data was disaggregated to create an hourly time series using WDMutil. Potential evapotranspiration was computed from the Dearborn air temperature using the Hamon method, also available in WDMutil.

Observed flow was available at four locations within the study area. The Rouge River Program Office operates two hourly gages on Bell Branch; however the gages cover relatively short spans of time, and therefore the data sets were not used in calibration. The USGS maintains two daily stream flow gages at Farmington and Telegraph Road in Redford Township, located west of Detroit (see Figure 1B-1). The USGS gages were used for calibrating the HSPF model.

A summary of the temperature, precipitation, and flow data used for calibrating the HSPF model is shown in Table 1B-3.

TABLE 1B-3
Summary of Available Data for Upper Rouge River Modeling

Data Description	Station ID	Location	Period
Air temperature	NCDC 202015	Dearborn	1990 Jan–2004 Dec
Precipitation	NCDC 202015	Dearborn	1990 Jan–2004 Dec
Observed Flow	USGS 04166300	Upper Rouge River at Farmington	1997 Oct–2004 Sep
	USGS 04166470	Upper Rouge River at Telegraph Rd	1958 Apr–2004 Sep
	None	Bell Branch at Inkster Rd	1995 Jul–1996 Sep
	None	Bell Branch at Beech Daly Rd	1994 Apr–1994 Nov

Land use for the study area is shown in Figure 1B-2. The primary land use is low density residential (51 percent), commercial (22 percent), and other urban categories (8 percent). There are small portions of forest (8 percent) and open land (10 percent), with a very small amount of agriculture (0.4 percent).

Subwatershed boundaries were obtained from prior studies conducted by the Rouge River Program Office. Each subbasin is drained by a stream reach that was based on the USGS RF1 coverage, intersected by the subbasin boundaries. This process yields stream length and cross section data, which were used to create a set of function tables (FTABLES) that specify the geometric properties of the reach and the stage-discharge relationship. The stage-discharge relationships were based on Manning's equation for open-channel flow, and were used to simulate the watershed hydraulic conditions.

Calibration

The HSPF model was calibrated to best achieve a match between observed and simulated flows at the two USGS flow gage stations. The longer of the two records at Farmington encompassed 13 years (water years 1991–2003) and was used as the primary station for calibration. The record at Telegraph Road spans only 7 years (water years 1997–2003), and therefore it was used for validation.

The calibration results at Farmington are shown in Table 1B-4 and Figures 1B-3 through 1B-5. In all calibration and validation figures, the blue line represents the observed flows and the pink line represents the simulated flows. In general, the primary station shows a good agreement between simulated and observed values. The total runoff is within 2 percent of observed values, and both the sum of the highest 10 percent and lowest 50 percent are within 4 percent of the observed flows. Figures 1B-3 and 1B-4 show the hydrograph for the simulation period and a single simulation year. Because only one rainfall station was available for the entire calibration period and the measured station is located adjacent to the study area, it is expected that individual storm peaks will not perfectly match between measured and modeled data. However, the range of overpredicted and underpredicted flows should be similar. The flow duration curve in Figure 1B-5 shows that the model accurately predicts flow frequency, but the model slightly overpredicted the very largest storms and underpredicted the lowest base flows. Overall, the calibration was acceptable for the purpose of the study.

FIGURE 1B-1
Upper Rouge River Subwatersheds

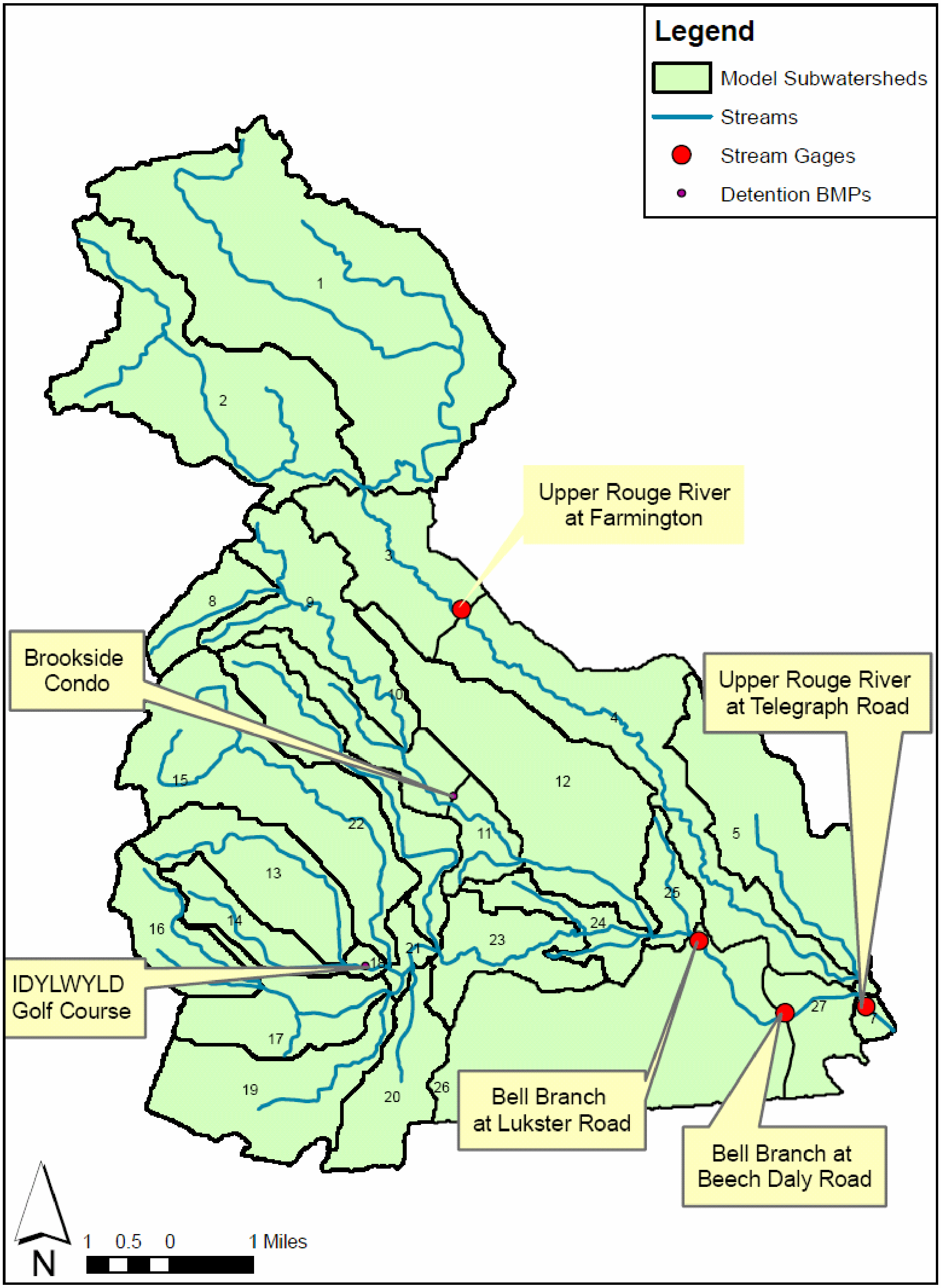


FIGURE 1B-2
Upper Rouge River Land Use

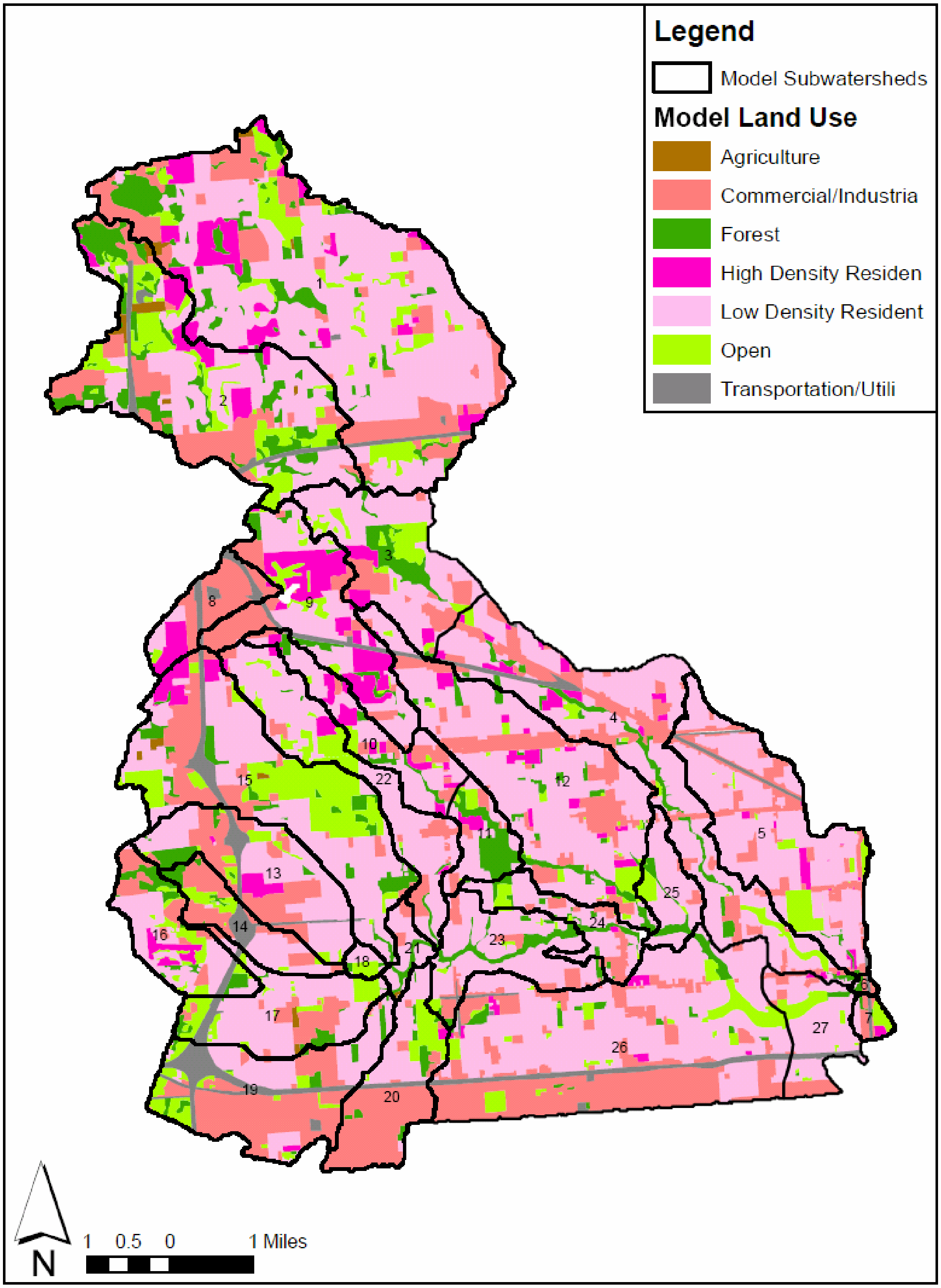


TABLE 1B-4
Hydrologic Calibration Results for 04166300 Upper Rouge River at Farmington

	Observed	Simulated	Error (%)
Total Runoff (inch)	185.9	183.4	-1.4
Total of Highest 10 percent Flows (inch)	72.5	69.8	-2.8
Total of Lowest 50 percent Flows (inch)	37.2	36.2	-3.8

FIGURE 1B-3
Calibration Hydrograph for Upper Rouge River at Farmington—04166300

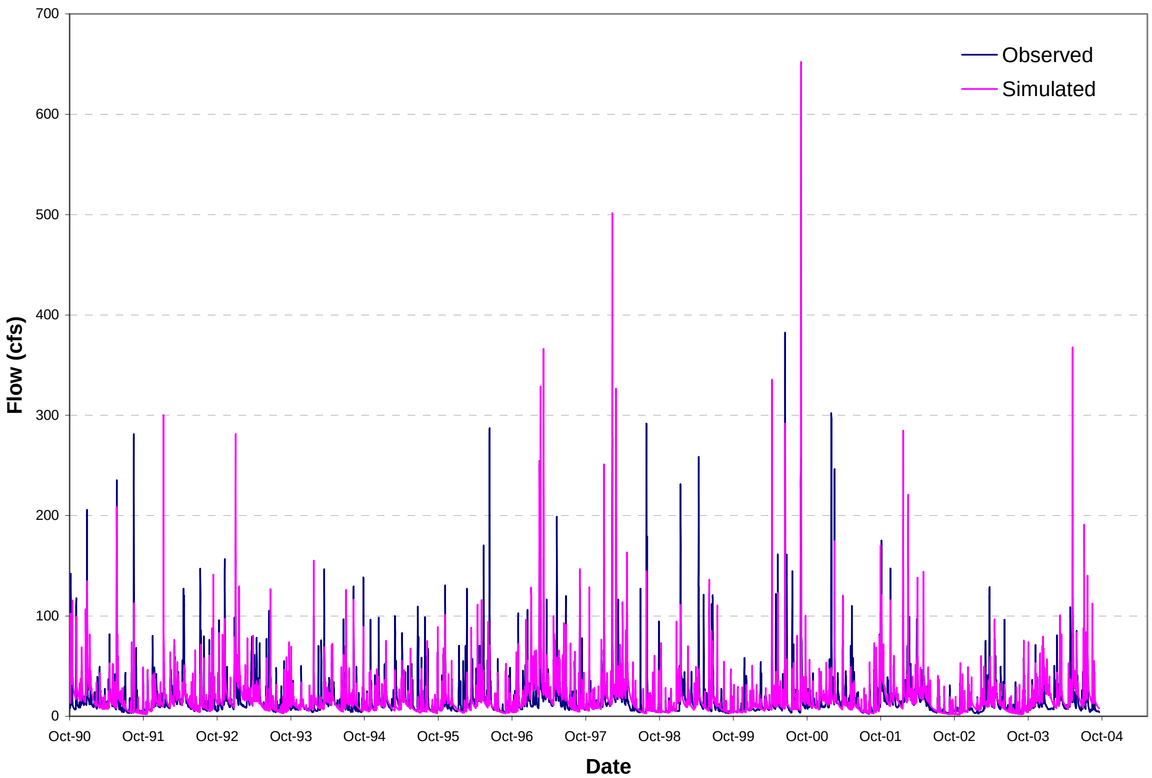


FIGURE 1B-4
Calibration Hydrograph for Upper Rouge River at Farmington—04166300

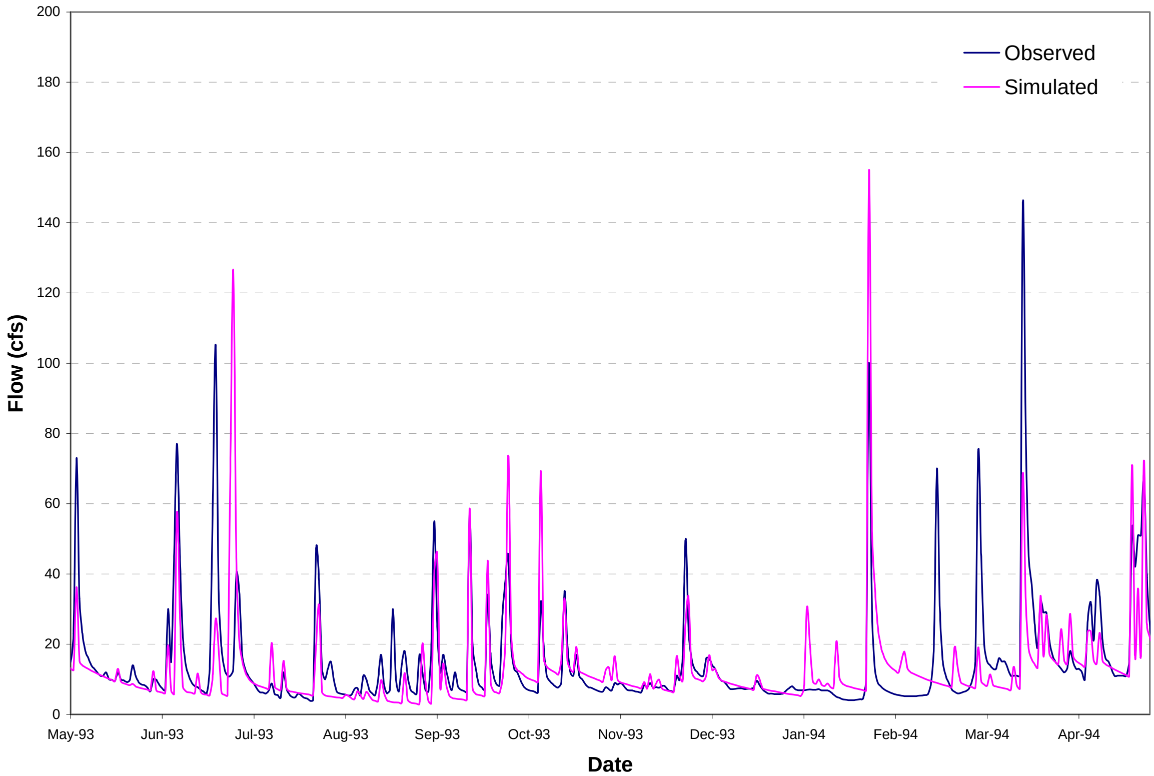
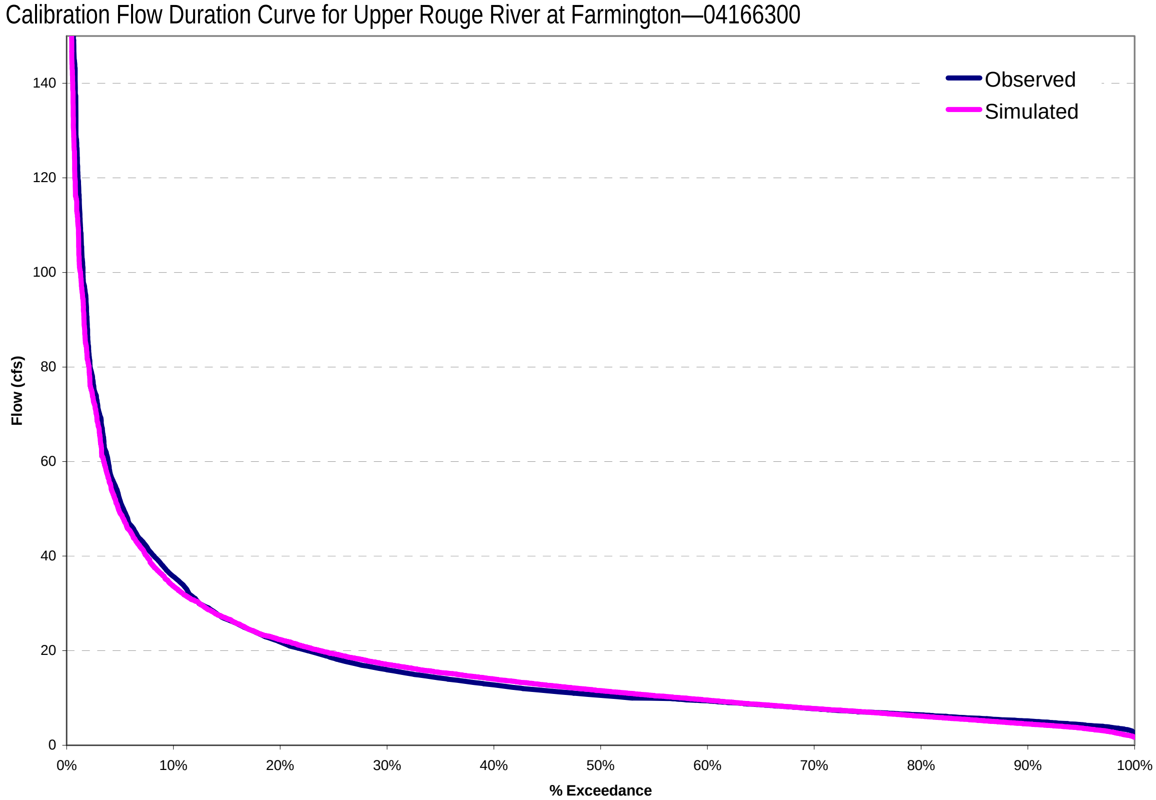


FIGURE 1B-5
Calibration Flow Duration Curve for Upper Rouge River at Farmington—04166300



The validation results for Telegraph Road are shown in Table 1B-5 and Figures 1B-6 through 1B-8. The results at this station show a fair agreement between simulated and observed values, though not as good as for the Farmington location. The total simulated runoff is 15 percent higher than observed, mostly due to overpredicted middle and low flows. Figures 1B-6 and 1B-7 show the hydrograph for the entire simulation period and for a single simulation year. The flow duration curve in Figure 1B-8 shows that the model reasonably predicts flow frequency for the large events, but overpredicts flow frequency through much of the middle and low flows. However, because the focus of the study was on storm flows at or above the 10 percent exceedence level, the validation was accepted and no further parameter adjustments were made.

TABLE 1B-5
Hydrologic Validation Results for 04166470 Upper Rouge River at Telegraph Rd

	Observed	Simulated	Error (%)
Total Runoff (inches)	75.2	86.4	15.0
Total of Highest 10 percent Flows (inches)	34.5	35.5	2.6
Total of Lowest 50 percent Flows (inches)	12.1	15.6	29.6

FIGURE 1B-6
Validation Hydrograph for Upper Rouge River at Telegraph Road—04166470

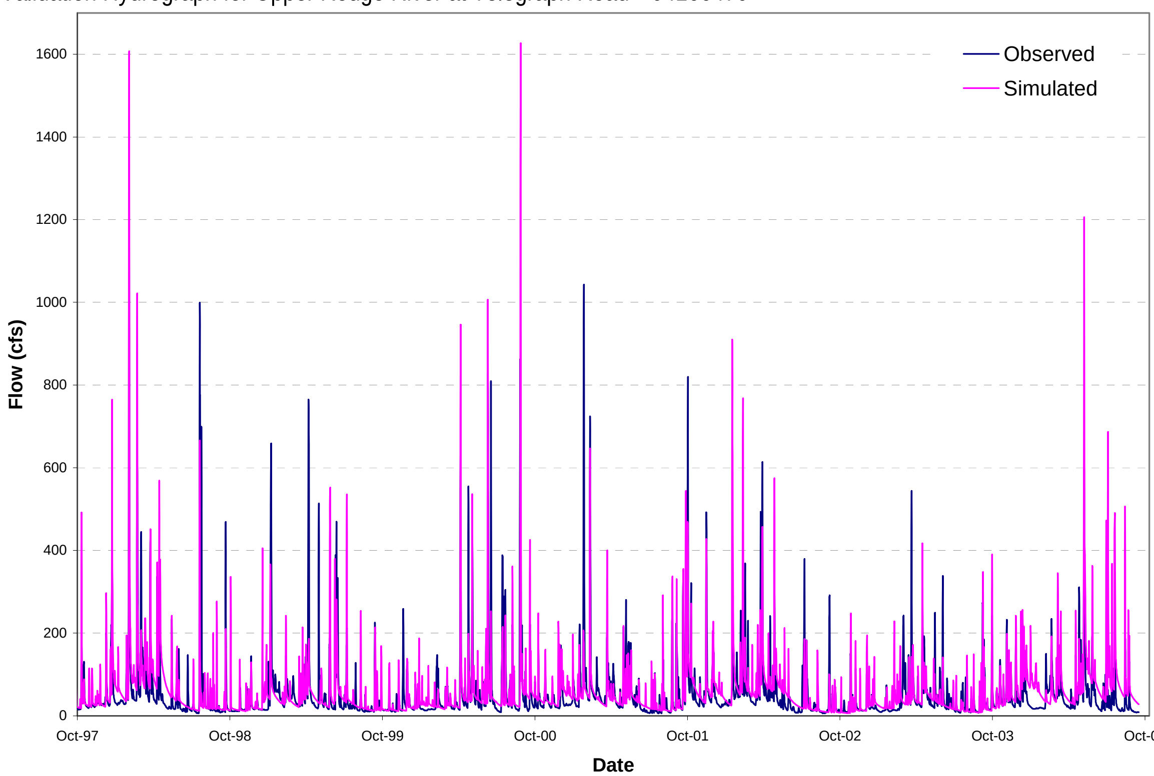


FIGURE 1B-7
Validation Hydrograph for Upper Rouge River at Telegraph Road—04166470

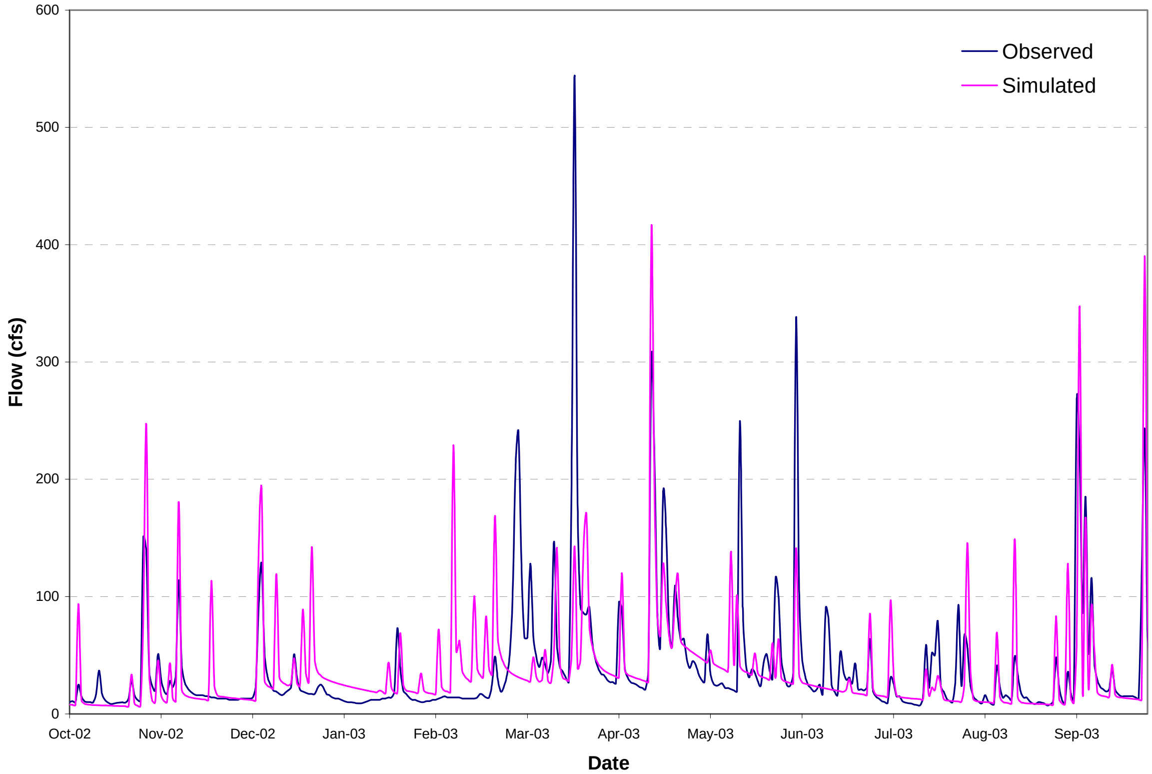
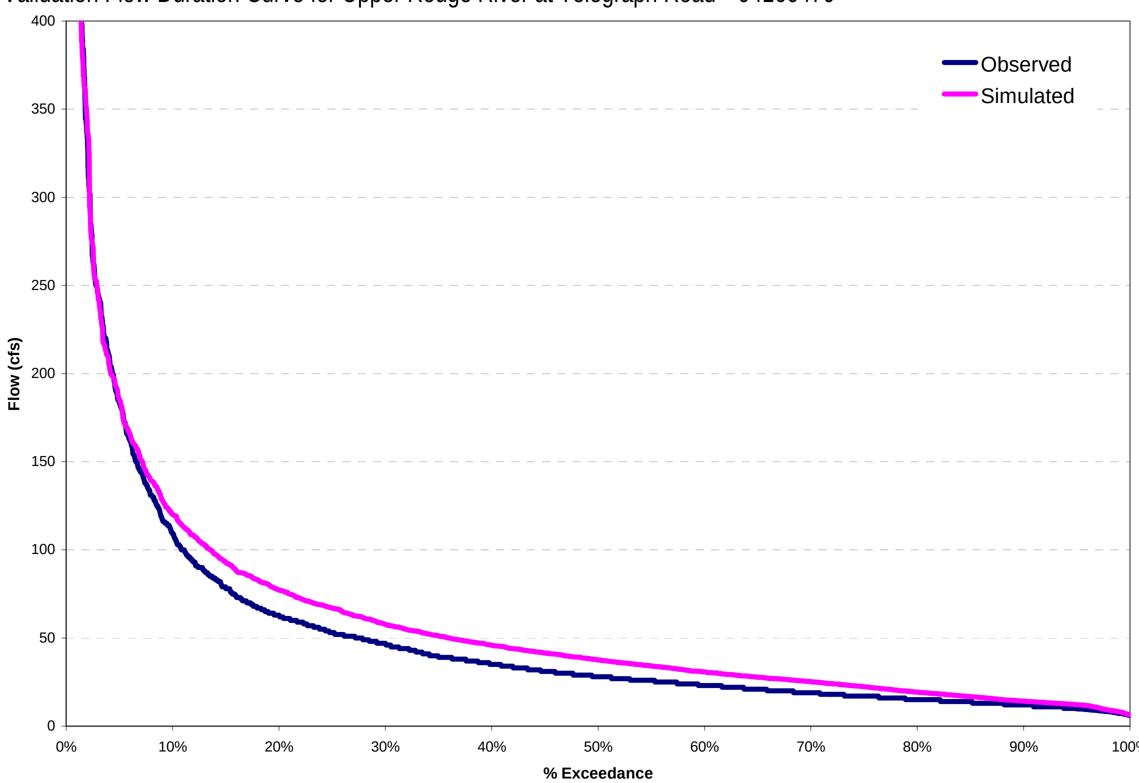


FIGURE 1B-8
Validation Flow Duration Curve for Upper Rouge River at Telegraph Road—04166470



Alternative Analysis

After the model was calibrated and validated, it was used to analyze a series of stormwater BMP scenarios to evaluate the types and levels of stormwater management necessary to meet target flows. Table 1B-6 summarizes the scenarios that were evaluated.

TABLE 1B-6
BMP Scenarios for Analysis

Scenario	Description
Base	Unmodified calibrated model for existing conditions.
Detention Basins 1.0 inch	Each subbasin has sufficient detention storage to hold 1.0 inch of runoff from all developed areas.
Detention Basins 0.5 inch	Each subbasin has sufficient detention storage to hold 0.5 inch of runoff from all developed areas.
Disconnect all imperviousness	Route flow from all impervious areas to adjacent pervious land to allow greater opportunity for infiltration.
Partially disconnect imperviousness	Route flow from 80 percent of commercial/industrial areas and 50 percent of residential areas to adjacent pervious land.
Rain gardens	Convert 10 percent of residential pervious area to new rain garden land use type, and route 50 percent of residential imperviousness to it.
Pervious pavement	Convert 50 percent of commercial/industrial impervious area to new pervious pavement.
Forested	Replace all land use with forest.
No imperviousness	Replace all impervious land with corresponding pervious (grassed) area. This scenario corresponds to the target flow condition.

The Forested scenario represents a return to presettlement conditions, which is presumed to give the most “natural” flow regime. The Forested scenario is therefore not a reasonable target for post-treatment flows since a return to presettlement conditions is unrealistic. This scenario represents an extreme change in the land use because much of the land has been developed prior to stormwater management considerations. While the goal is not to restore the land use to Forested conditions, the Forested scenario merely illustrates how different land uses influence watershed flows. Further, all of the data available for healthy fish populations and flow conditions are based on the current landscape, not that present several hundred years ago. It is not a goal or an achievable condition, but simply an additional benchmark for which to measure flow restoration using stormwater BMPs.

A second No Imperviousness target scenario was created for comparison to existing conditions. This scenario is more realistic as a target because it is, in principle, achievable through stormwater management. The No Imperviousness scenario simply replaced impervious areas with the corresponding underlying pervious areas, which, being grassed, would represent cleared land rather than the original forest. The No Imperviousness scenario represents a watershed that is not influenced by significant impervious area. Much of the fish population data that has been collected and correlated to flow was completed in watersheds with a small amount of impervious area. Consequently, the No Imperviousness scenario could be a potential flow target for implementing BMPs that offset impervious area affects.

Detention basins are the traditional method of stormwater management. Rather than attempting to model them individually, a single basin with a drawdown time of 72 hours was added to each modeled subbasin to represent the aggregate required storage.

The Disconnecting Impervious area scenarios is a straightforward approach, reflecting measures such as routing downspouts across lawns instead of down driveways and into the storm sewer system.

The translation of the Rain Garden and Pervious Pavement scenarios was based on work in the Milwaukee, Wisconsin, combined sewer area to reduce stormwater runoff through BMP implementation (Camp Dresser & McKee [CDM] 2004). The two scenarios were modeled by HSPF parameter adjustments to reflect the effect of infiltration BMPs on stream flow. These adjustments were applied to the calibrated pervious land parameters, where the BMPs were modeled by changing land use type parameters to reflect the BMP.

Result Comparison

The analysis of the effects of these scenarios focused on the change in the flow duration curve. The flow durations are compared against target yields, which were developed from prior research linking flow and healthy fish communities (Wiley et al. 1998). The flow yield units used in the research were cubic feet per second per square kilometer (cfs/km^2). The same units were kept is this study to maintain consistency.

June flow duration curves for the two simulated locations are shown in Figures 1B-9 through 1B-11. Figures 1B-9 and 1B-10 show the June flow duration curves for both Farmington Hills and Telegraph Road. Figure 1B-11 shows storms above the 30 percent exceedence level at Telegraph Road to better illustrate the effectiveness of individual BMPs.

For storm flows above the 10 percent exceedence level, all BMP implementations reduce the watershed yield below base conditions. Disconnection of imperviousness results in the greatest decrease in yield, followed by detention ponds. The implementation of detention ponds increases yields for storm events above the 10 percent exceedence level, resulting in a shift in the flow duration curve shape. This shift is caused by the extended drawdown time for ponds, which continue to release water for 72 hours following a storm event. For very small exceedence storm events (less than 1 percent), providing detention for 1 inch of runoff results in a greater yield reduction. However, for storm events with an exceedence level between 1 and 6 percent, providing 0.5 inch of detention produces a slightly greater yield reduction, again due to the extended release time for ponds. Beyond the 6 percent exceedence level, both storage capacities produce similar results.

Implementation of pervious pavement and rain gardens also produces a decrease in yield, with the modeled pervious-pavement scenario performing slightly better than the rain garden scenario. The flow duration curve for infiltration-based BMPs (disconnection, pervious pavement, and rain garden) is the closest to the no-imperviousness target curve.

The scenarios were also analyzed regarding how they affected flows for a set of design storms under typical June antecedent conditions. The chosen storm sizes were 0.5 inch,

FIGURE 1B-9
June Flow Duration Curves at Farmington

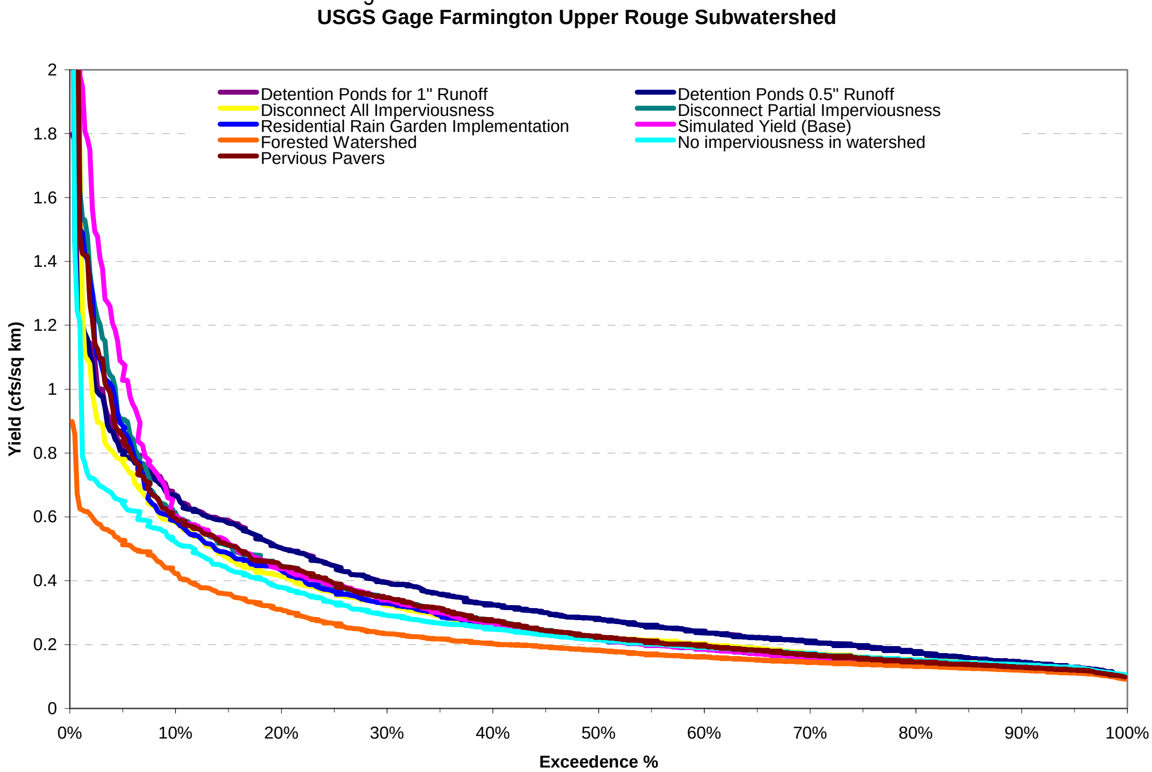


FIGURE 1B-10
June Flow Duration Curves at Telegraph Road

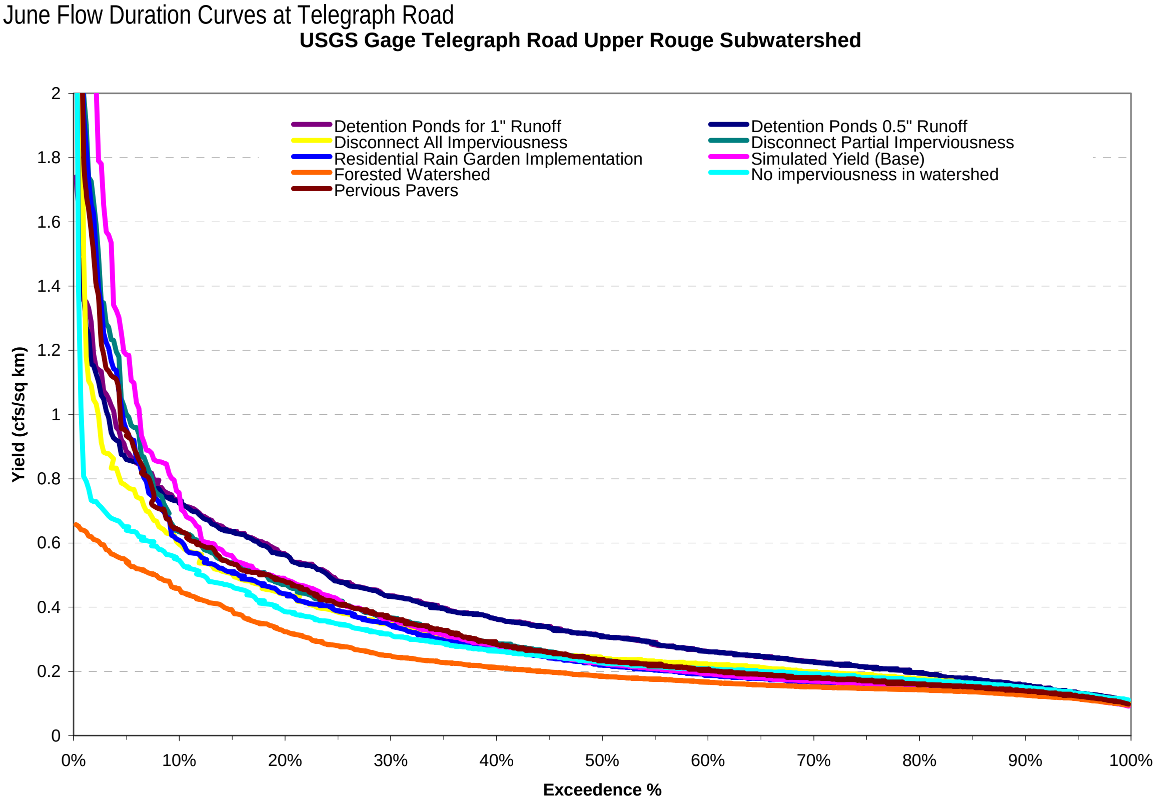
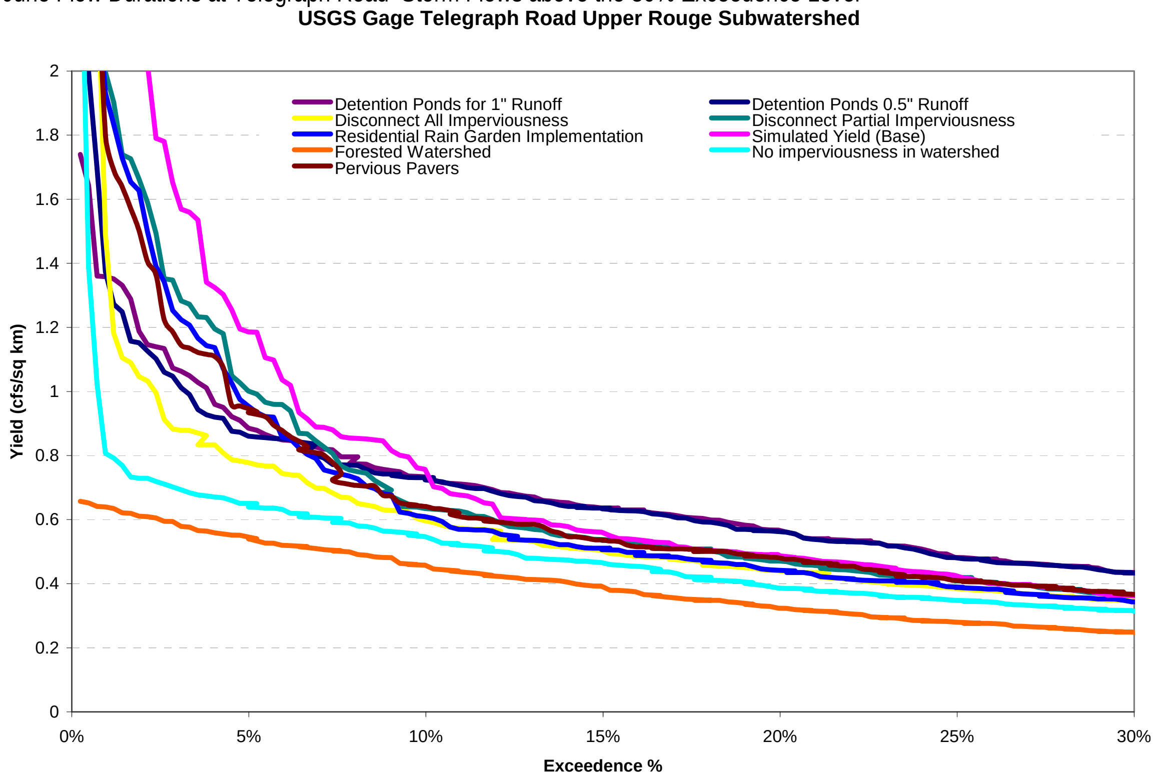


FIGURE 1B-11
June Flow Durations at Telegraph Road–Storm Flows above the 30% Exceedence Level



0.64 inch, 1.87 inch (1-year storm), and 2.26 inches (2-year storm). These storms were chosen because the effects of urbanization and the impacts upon the fish community are expected to be most noticeable for relatively frequent and smaller storms. This range of precipitation values spans the range of high flows believed to have a regular and frequent impact upon the fish community. These storm events were inserted into the historical rainfall record so that the rain event on June 15 of each year was replaced by the respective design storm. The daily precipitation total was distributed over the hourly input of the model according to the SCS Type II distribution. The average of the flows on those dates was computed to reflect the average effect of the scenario on that storm. These values are reported in Table 1B-7 for the modeled scenarios at both gage locations.

The results contained in Table 1B-7 could potentially be used to estimate the precipitation event associated with various flow frequencies. The precipitation exceedence curve for this watershed (Figure 1B-12) shows the frequency of precipitation events in June.

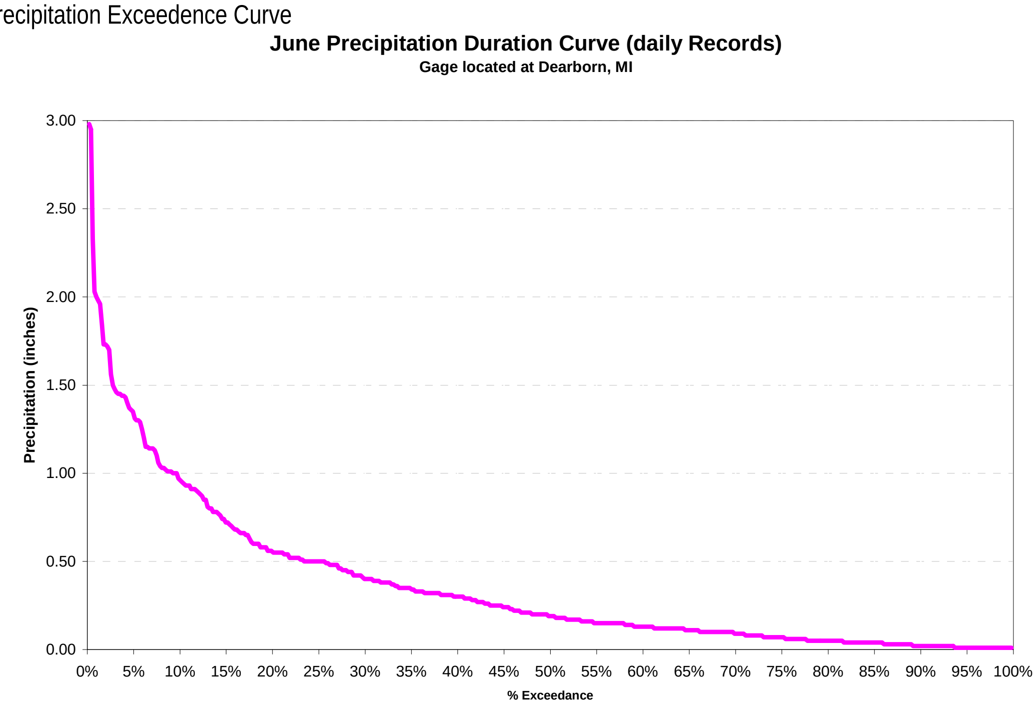
TABLE 1B-7
Normalized Daily Average Flows (cfs/km^2) for Various Design Storm Depths

Storm Depth (inch)	0.5	0.64	1.87	2.26
Farmington				
Base	0.484	0.635	2.369	3.053
Detention Basins 1.0 inch	0.428	0.443	0.647	0.750
Detention Basins 0.5 inch	0.423	0.438	0.742	0.989
Disconnect All Imperviousness	0.326	0.336	0.888	1.423

TABLE 1B-7
Normalized Daily Average Flows (cfs/km^2) for Various Design Storm Depths

Storm Depth (inch)	0.5	0.64	1.87	2.26
Partially Disconnect Imperviousness	0.439	0.549	1.900	2.489
Rain Gardens	0.421	0.529	1.810	2.342
Forested	0.235	0.237	0.346	0.457
Pervious Pavement	0.420	0.521	1.743	2.272
No Imperviousness	0.289	0.293	0.477	0.657
Telegraph				
Base	0.559	0.754	2.859	3.638
Detention Basins 1.0 inch	0.481	0.502	0.776	0.908
Detention Basins 0.5 inch	0.467	0.490	1.014	1.401
Disconnect All Imperviousness	0.353	0.370	1.021	1.552
Partially Disconnect Imperviousness	0.507	0.654	2.327	3.005
Rain Gardens	0.480	0.625	2.205	2.810
Forested	0.247	0.250	0.339	0.425
Pervious Pavement	0.477	0.608	2.065	2.646
No Imperviousness	0.306	0.311	0.466	0.617

FIGURE 1B-12
June Precipitation Exceedence Curve



Rouge River Conclusions

Of the BMPs analyzed, disconnecting all imperviousness achieved the best reduction in flows, although a close match was not obtained. The results indicated that application of bioretention on 50 percent of the residential areas has virtually the same effect as deployment of permeable pavement on 50 percent of commercial areas, although neither one of these approaches by itself is sufficient to match the target flow condition equivalent to zero percent imperviousness. While disconnecting all impervious area in the watershed does have a dramatic affect upon the flow duration curve, it does not fully restore the flow to the target condition. This indicates that while significant flow restoration is theoretically possible in an urbanized watershed, fully restoring a watershed to a condition with no imperviousness is very difficult.

Finally, the results indicate that a stormwater management approach based exclusively on ponds does decrease the high peak flows, but also produces the negative result of increasing the magnitude and frequency of lower-peak flows.

Menomonee River Watershed, Wisconsin

The following sections discuss the application of HSPF to the Menomonee River study area as well as data collection, watershed characterization, calibration, and scenario results.

Data Summary

An existing HSPF model developed for the Milwaukee Metropolitan Sewerage District (MMSD) by CDM (2000) was used in the Menomonee River study area. This model contained meteorological data from Mitchell Field Airport, Milwaukee, Wisconsin (NCDC 475479). Two hourly precipitation records were available within the study area, including Germantown (NCDC 473058), located in the Upper Menomonee River Basin, and Mt. Mary College (NCDC 475474), in the Lower Menomonee River Basin. A summary of the available data is provided in Table 1B-8.

Continuously measured flow data was obtained for use in validation of the existing model. Observed flow was available at five locations within the study area. The USGS maintains daily stream flow gages along the Upper Menomonee at Menomonee Falls and the Lower Menomonee at Wauwatosa. The USGS also maintains gages on three streams tributary to the Menomonee: Honey Creek at Wauwatosa, Little Menomonee River at Milwaukee, and Underwood Creek at Wauwatosa. Figure 1B-13 summarizes the locations of these subwatersheds.

Land use for the study area is shown in Figure 1B-14. The primary land use is low density residential (32 percent), agricultural (28 percent), commercial (17 percent), and other urban categories (10 percent). There are small portions of forest (8 percent) and open land (10 percent).

TABLE 1B-8
Summary of Available Data for Menomonee River Modeling

Data Description	Station ID	Location	Period
Air temperature	NCDC 475479	Mitchell Field, Milwaukee, WI	1928 Jul–2005 Oct
Precipitation	NCDC 475479	Mitchell Field, Milwaukee, WI	1928 Jul–2005 Oct
	NCDC 473058	Germantown, WI	1948 Jan–2005 Oct
	NCDC 475474	Mt. Mary College, Milwaukee, WI	1948 Jan–2005 Oct
Observed Flow	USGS 04087120	Menomonee River at Wauwatosa	1971 Oct–2004 Oct
	USGS 04087119	Honey Creek at Wauwatosa	1974 Dec–2004 Oct
	USGS 04087030	Menomonee River at Menomonee Falls	1974 Nov–2004 Oct
	USGS 04087070	Little Menomonee River at Milwaukee	1974 Nov–2004 Oct
	USGS 04087088	Underwood Creek at Wauwatosa	1974 Nov–2004 Oct

FIGURE 1B-13
Menomonee River Subwatersheds

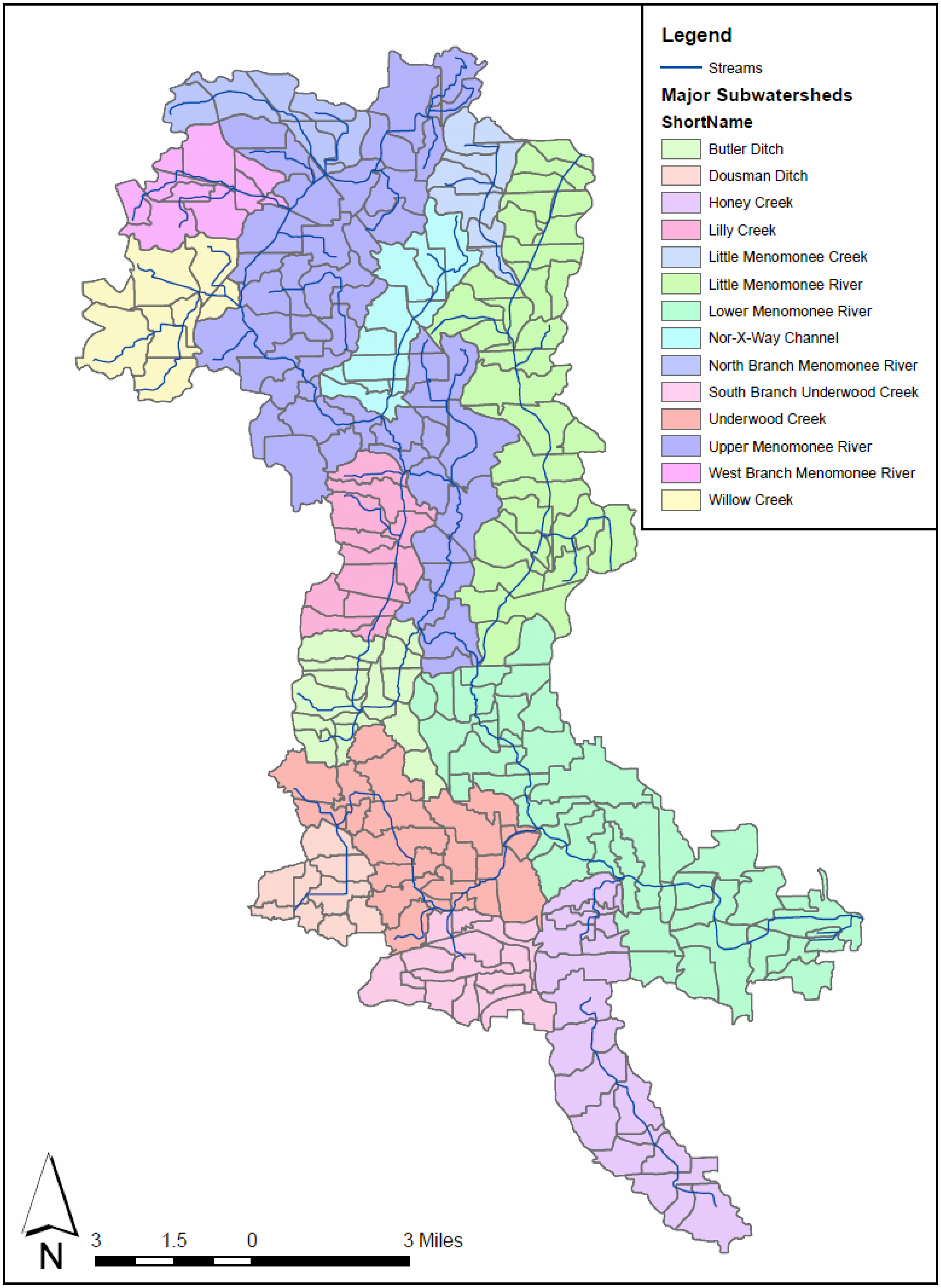
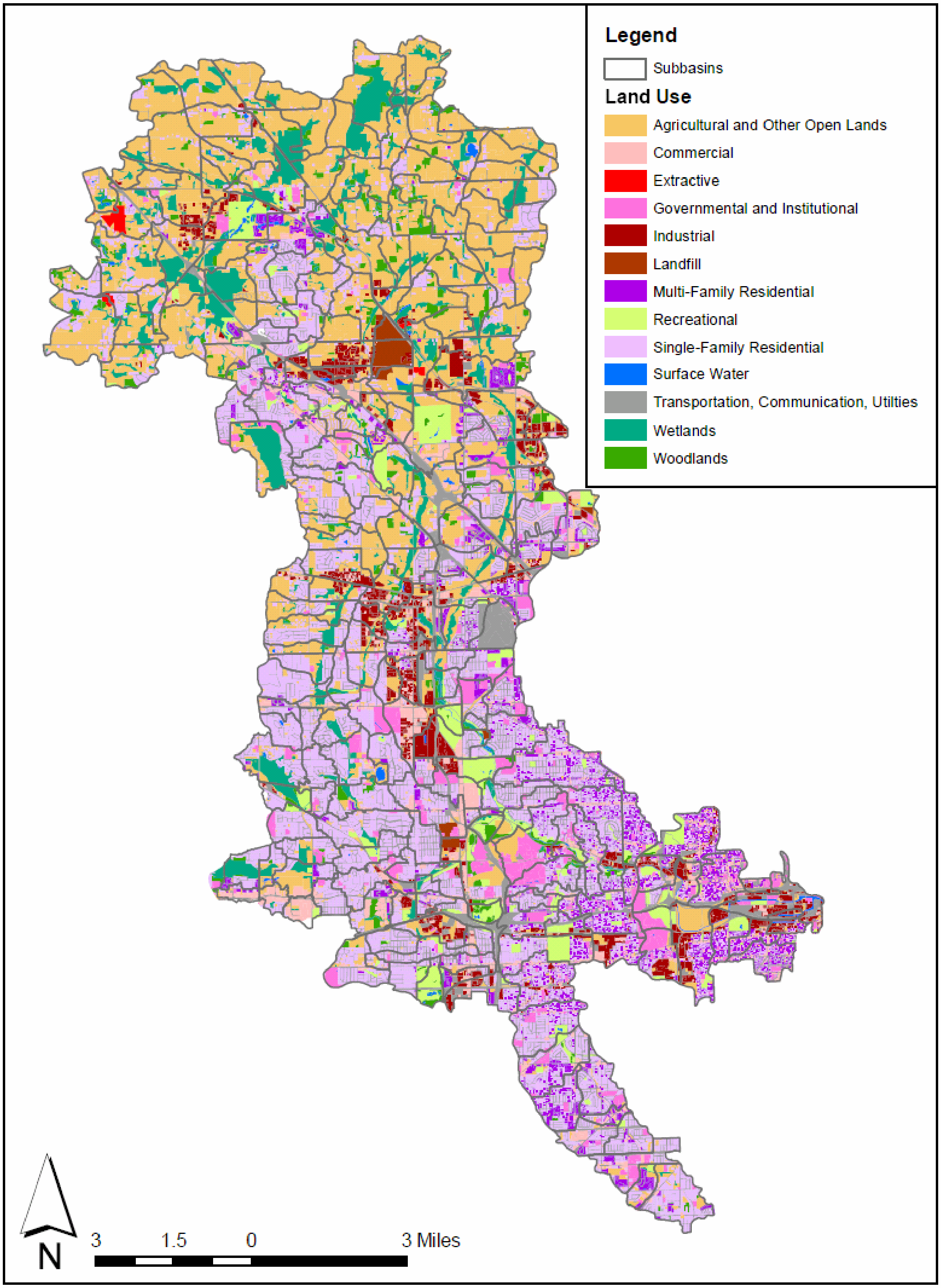


FIGURE 1B-14
Menomonee River Land Use



Calibration

The existing calibrated HSPF model was used for the study area. The USGS gage at Wauwatosa was used to validate the model for the current study purposes. The results at Wauwatosa are shown in Table 1B-9 and Figures 1B-15 through 1B-16. In all calibration and validation figures, the blue line represents the observed flows and the pink line represents the simulated flows. In general, there was good agreement between simulated and observed flows. The total runoff is within 11 percent of observed values, and both the sum of the highest (10 percent) and lowest runoff volumes (50 percent) are within 10 percent of the observed flows. Figures 1B-15 and 1B-16 show the hydrograph for the entire simulation period and a single simulation year. Because only one rainfall station was available for the entire calibration period and the measured station is assumed to be uniform over the entire study area, it is expected that individual storm peaks will not perfectly match between measured and modeled data. However, the range of overpredicted and underpredicted flows should be similar. The flow duration curve in Figure 1B-17 shows that the model accurately predicts flow frequency, but it slightly over predicts the very largest storms and underpredicted the lowest base flows. Overall, the calibration was acceptable for the purpose of the study.

TABLE 1B-9
Hydrologic Calibration Results for 04087120 Menomonee River at Wauwatosa

	Observed	**Simulated**	**Error (%)**
Total Runoff (inch)	108.6	117.2	8.4
Total of Highest 10 percent Flows (inch)	47.9	53.1	10.9
Total of Lowest 50 percent Flows (inch)	15.3	14.2	-7.2

FIGURE 1B-15
Validation Hydrograph for Menomonee River at Wauwatosa—04166300

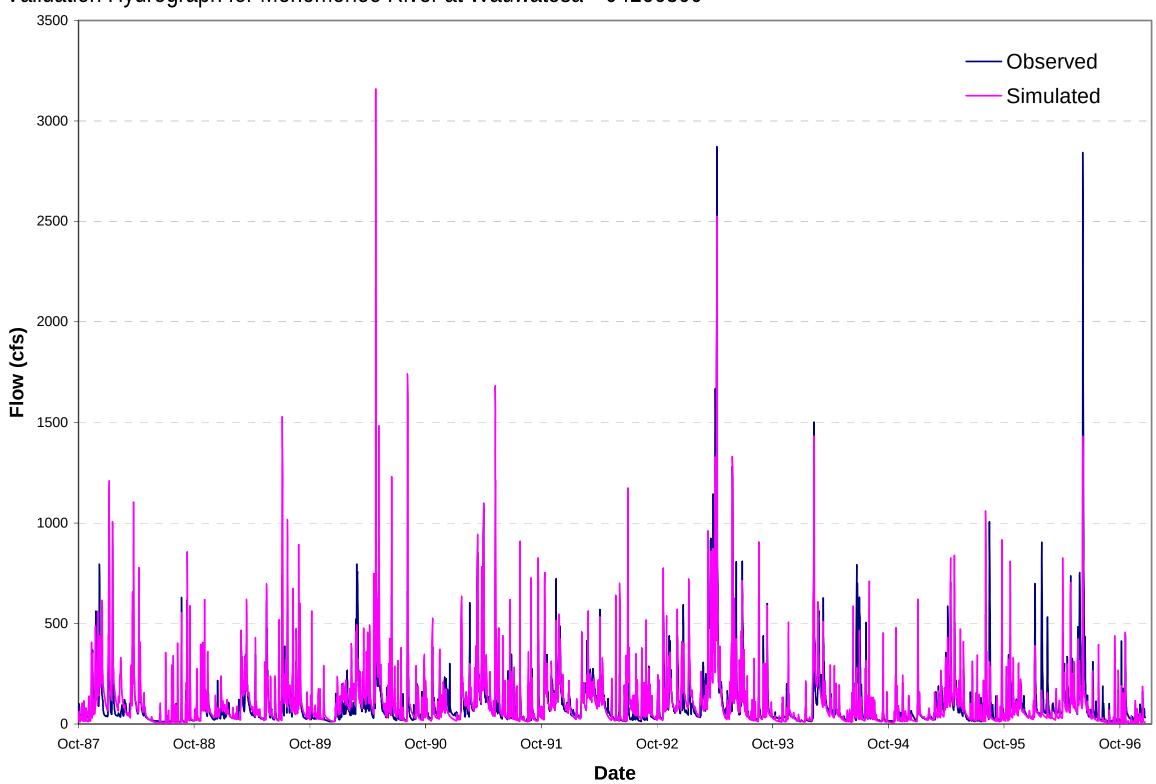


FIGURE 1B-16
Validation Hydrograph Menomonee River at Wauwatosa—04166300

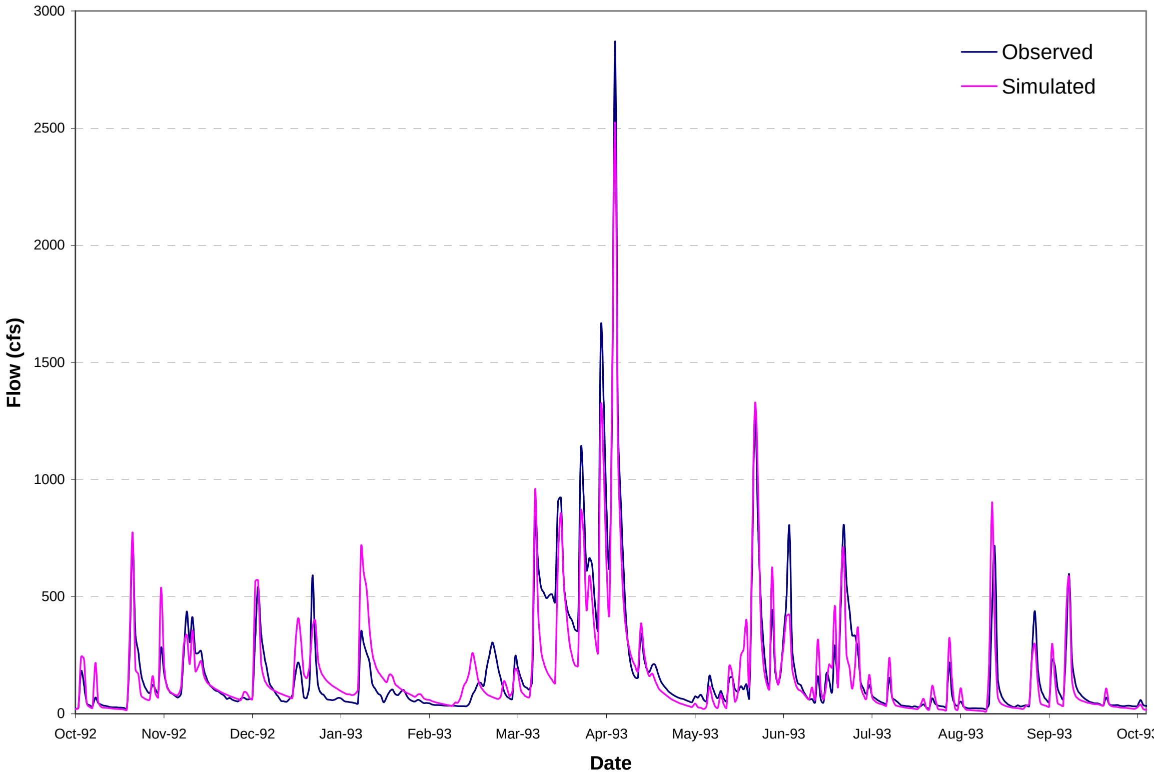
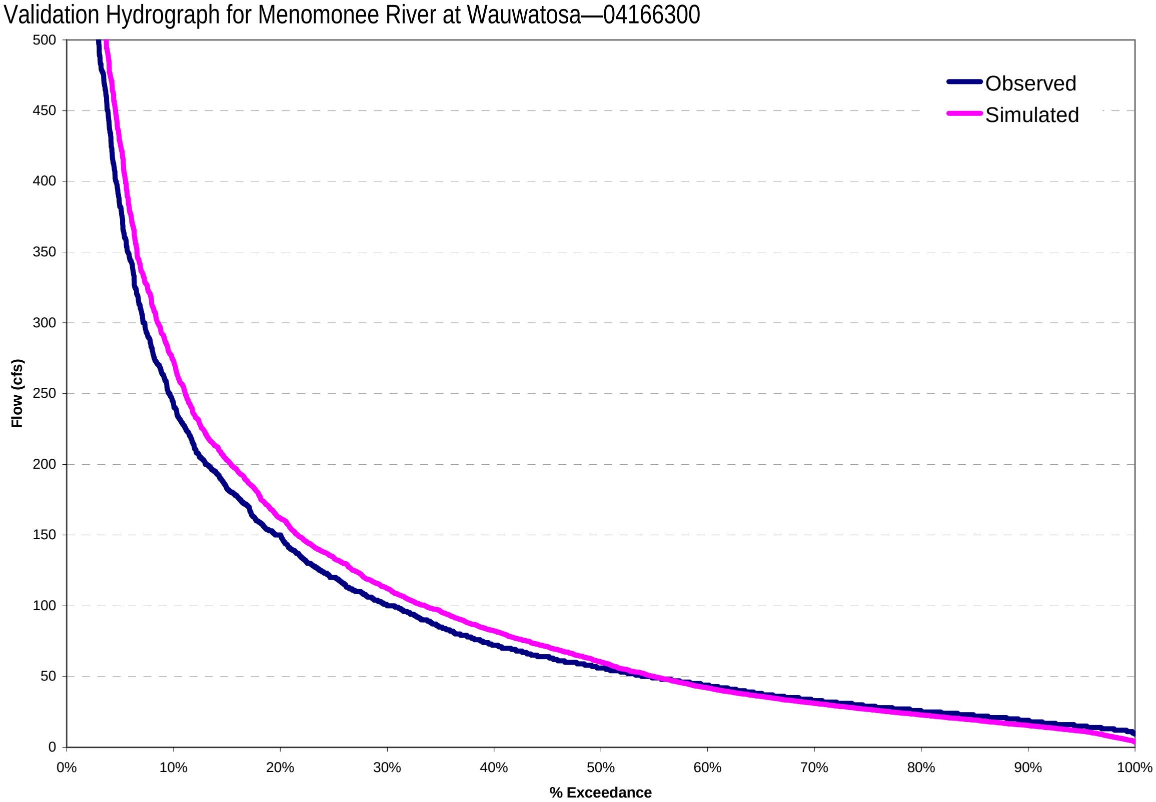


FIGURE 1B-17
Validation Hydrograph for Menomonee River at Wauwatosa—04166300



Alternative Analysis

After the model was calibrated, it was used to analyze a series of BMP scenarios to evaluate the types and levels of stormwater management necessary to meet target flows. Based upon the results of the Rouge River modeling, the scenarios were modified to better meet study goals. Several scenarios were removed and one scenario was modeled in addition to the Rouge River scenarios. The additional scenario predicts the combined effect of implementing both residential rain gardens and pervious pavement in commercial and industrial areas. Table 1B-10 lists the scenarios that were evaluated in the Menomonee River watershed.

TABLE 1B-10
BMP Scenarios for Analysis in the Menomonee River Watershed

Scenario	Description
Base	Unmodified calibrated model for existing conditions.
Detention basins 0.5 inch	Each subbasin has sufficient detention storage to hold 0.5 inch of runoff from all developed areas.
Disconnect all imperviousness	Route flow from all impervious areas to adjacent pervious land to allow greater opportunity for infiltration.
Partially disconnect imperviousness	Route flow from 80 percent of commercial/industrial areas and 50 percent of residential areas to adjacent pervious land.
Rain gardens	Convert 10 percent of residential pervious area to new rain garden land use type, and route 50 percent of residential imperviousness to it.
Pervious pavement	Convert 50 percent of commercial/industrial impervious area to pervious pavement.
Full rain garden and pervious pavement treatment	Convert 20 percent of residential pervious area to new rain garden land use type, and route 100 percent of residential imperviousness to it. Convert 100 percent of commercial/industrial impervious area to new pervious pavement.
No imperviousness	Replace all impervious land with corresponding pervious, grassed area. This scenario corresponds to the target flow condition.

Result Comparison

The analysis of the effects of these scenarios focused on the change in the flow duration curve. The flow durations are compared against target yields, which were developed from prior research linking flow and healthy fish communities (Wiley et al. 1998). The flow yield units used in the research were cfs/km^2. The same units were kept in this study to maintain consistency. June flow duration curves for the Menomonee River at Wauwatosa are shown in Figures 1B-18 and 1B-19.

FIGURE 1B-18
Effect of BMP implementation on June Flow Duration Curves for the Menomonee River at Wauwatosa, Wisconsin

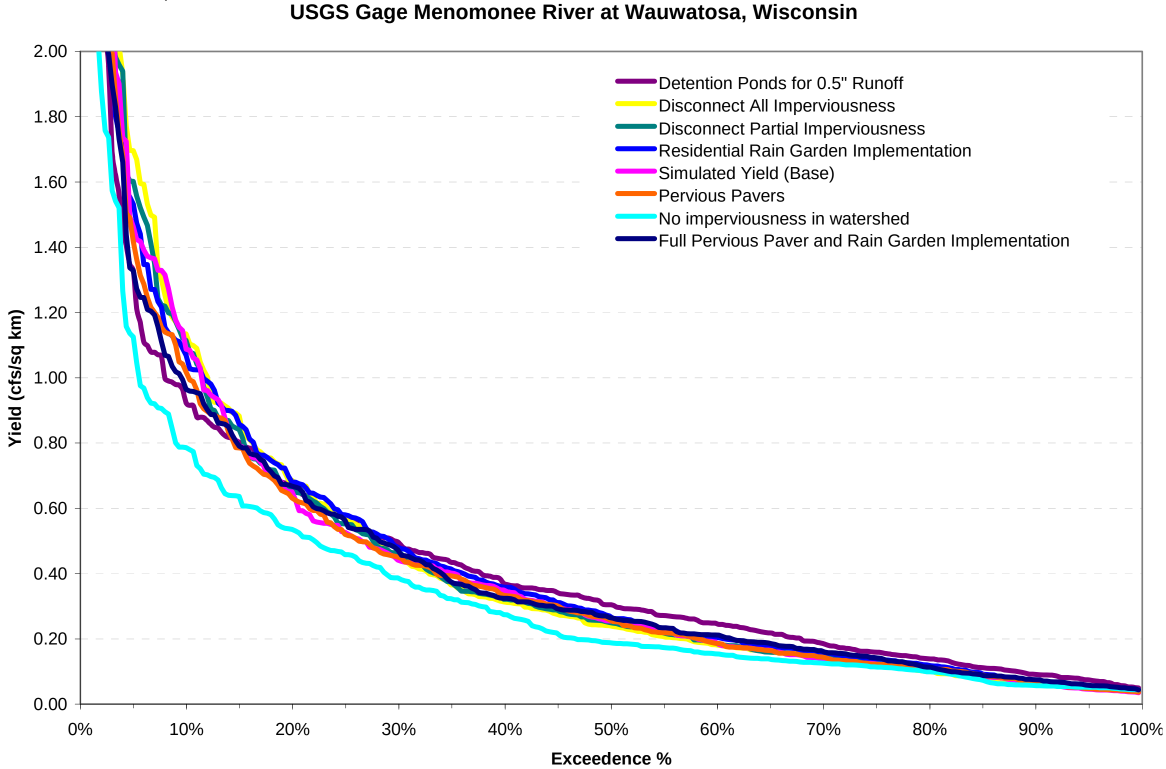
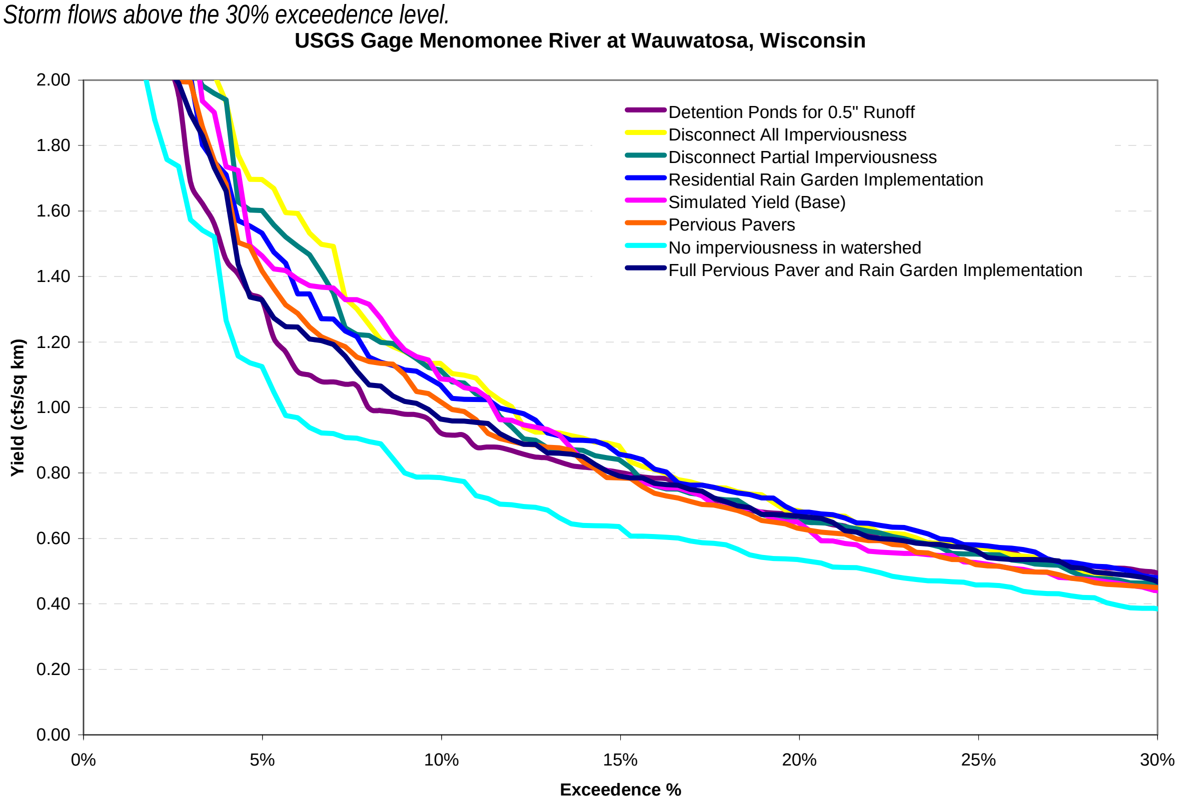


FIGURE 1B-19
Effect of BMP implementation on June Flow Duration Curves for the Menomonee River at Wauwatosa, Wisconsin
Storm flows above the 30% exceedence level.



Detention ponds were very effective in reducing yields for the storm flows with exceedence levels less than 15 percent; however, at higher exceedence levels, detention ponds cause a yield increase. Implementation of rain gardens and pervious pavement also resulted in decreases in yield. Disconnection of imperviousness did not have a dramatic effect as was seen in the Rouge River. This may be because soils in the Menomonee River basin have lower infiltration rates than those in the Rouge River basin.

To better understand the effect of location in the watershed on BMP effectiveness, a smaller subset of infiltration-based BMP scenarios were analyzed for two representative subwatersheds, including the Upper Menomonee River and Honey Creek. These results are shown in Figure 1B-20 and 1B-21. Land use in the Upper Menomonee River at Menomonee Falls is 58 percent agriculture with 10.6 percent imperviousness. The Honey Creek watershed is more urban with 36 percent imperviousness and no agriculture.

Current yields in the less urban Upper Menomonee River are relatively close to the watershed and simulated no imperviousness condition. As a result, decreases in yields associated with BMP implementation in this subwatershed are modest. Infiltration-based BMPs had a more dramatic effect in the urban Honey Creek subwatershed. Pervious pavement and rain garden implementation resulted in decreases in yield. The combined effect of the full implementation of pervious pavement and rain gardens resulted in a substantial reduction in simulated yields for the Honey Creek watershed, even though the target flow condition of no imperviousness in the watershed was not fully reached. Even if a natural flow cannot be fully reached through BMP implementation, beneficial effects such as a reduction in the frequency of peak flows would still occur. The results of BMP implementation will vary watershed to watershed with the control of frequent storms significantly influenced by the infiltration capacity of watershed soils.

The scenarios were also analyzed for their effectiveness for controlling flows for a set of design storms under typical June antecedent conditions. The chosen storm sizes were 0.5 inch, 0.75 inch, 1.00 inch, 2.13 inches (1-year), and 2.57 inches (2-year). These storms were chosen because the effects of urbanization and the impacts upon the fish community are expected to be most noticeable for relatively frequent and smaller storms. This range of precipitation values spans the range of high flows believed to have a regular and frequent impact upon the fish community. These storms events were inserted into the historical rainfall record so that the rain event on June 15 of each year was replaced by the respective design storm. The daily precipitation total was distributed over the hourly input of the model according to the SCS Type II distribution. The average of the flows on those dates was computed to reflect the average effect of the scenario on that storm. These values were modeled for the Base, No Imperviousness, and Full Rain Garden and Pervious Pavement Treatment scenarios. Table 1B-11 summarizes the results.

FIGURE 1B-20
Effect of BMP implementation on June Flow Durations for the Upper Menomonee River at Menomonee Falls, Wisconsin

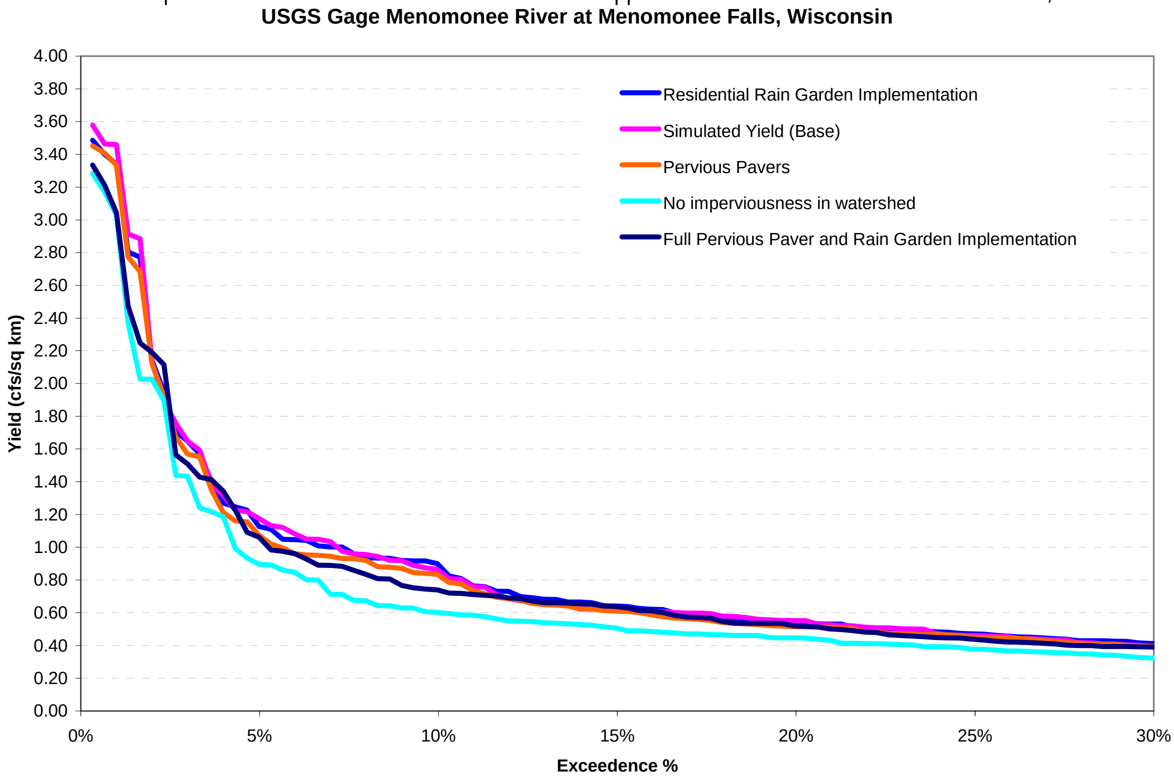


FIGURE 1B-21
Effect of BMP Implementation on June Flow Durations for Honey Creek at Wauwatosa, Wisconsin

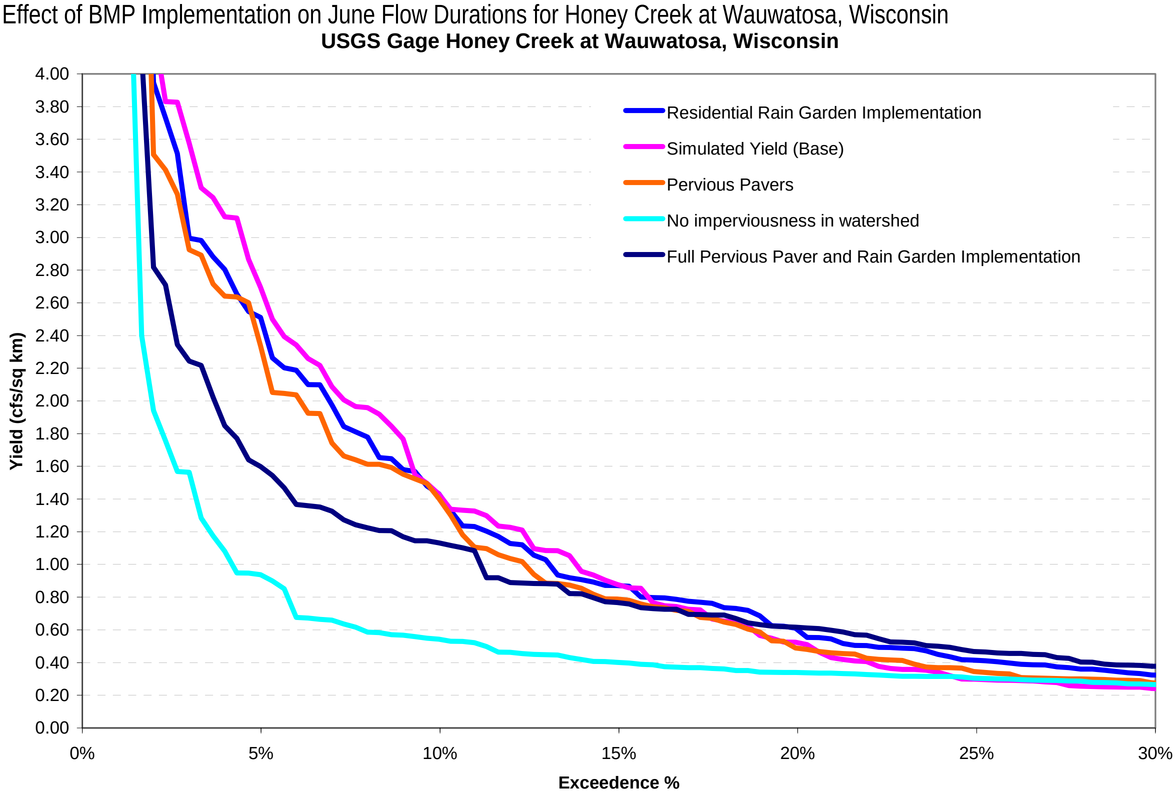


TABLE 1B-11
Normalized Daily Average Flows (cfs/sq-km) for Various Design Storm Depths

Storm Depth (inch)	0.5	0.75	1	2.13	2.57
Base	0.620	0.945	1.282	3.169	4.135
No Imperviousness	0.239	0.306	0.391	1.316	1.987
Full Rain Garden and Pervious Pavement Implementation	0.396	0.540	0.700	1.787	2.420

The results contained in Table 1B-11 could potentially be used to estimate the precipitation event associated with various flow frequencies.

Treating frequent storms should significantly counteract the peak flow effects associated with urbanization.

Menomonee Conclusions

The results show that for the highest flows, the best match to the target flow of no imperviousness is best achieved through detention pond BMPs, although a close match is not obtained. Implementing detention ponds in the Menomonee shows the same response as the Rouge in that, while ponds decrease peak flows, they also increase the magnitude and frequency of low flows.

The results also show that application of bioretention on 50 percent of the residential areas or permeable pavement implementation has a relatively small impact upon the watershed. The modeling results of disconnecting impervious area are not shown, but this practice did not restore the flow regime to the degree that was observed in the Rouge River. Overall, the results observed in the Menomonee River are different from what was observed in the Rouge River where infiltration-based BMPs appeared to have a much more significant impact.

Conclusion Comparison

An HSPF model was developed and calibrated for the Upper Rouge River watershed near Detroit, Michigan. A similar model was obtained and validated for the Menomonee River watershed near Milwaukee, Wisconsin. Using these models, the effect of BMP implementation on watershed yields was simulated and compared to the Base condition and a No Impervious area scenario, which represents a watershed target flow condition that is not influenced by significant impervious area.

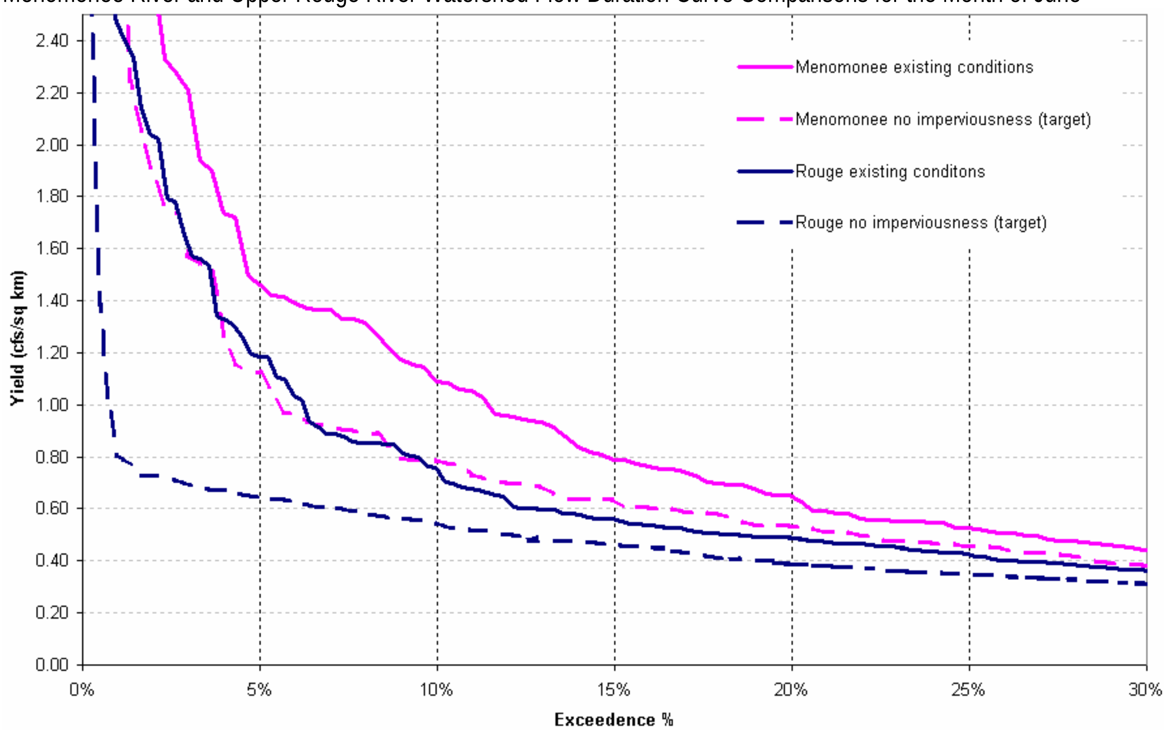
Implementing storage and infiltration-based BMPs in the Rouge and Menomonee River watersheds resulted in significant reductions in watershed yield for given flow exceedence frequencies. The simple approach of disconnecting imperviousness resulted in decreased yields in the Rouge River.

Several observations can be made between the characteristics of the two watersheds and the result of BMP implementation on flow regime restoration. The Upper Rouge River watershed flow regime responded more significantly to BMP implementation than the Menomonee River watershed. There could be several reasons for this. First, the infiltration potential of the Upper Rouge River watershed is higher than the Menomonee River watershed. As a result, simulation of infiltration based BMPs indicates a larger response in the Upper Rouge River watershed as compared to the Menomonee River watershed.

Second, the Upper Rouge River watershed is almost fully developed, while 28 percent of the Menomonee watershed land use is agricultural. As a result, the Menomonee has a significant portion of the watershed that offsets the urban impact upon the flow duration curve.

A comparison of observed flow conditions indicated that, for the higher end of the flow duration curve, flows are naturally higher in the Menomonee watershed, while for the lower end of the flow duration curve, flows are naturally lower in the Menomonee watershed. This indicates a higher runoff rate naturally occurs in the Menomonee. This finding is consistent with lower permeability soils in the Menomonee as compared to the Rouge. When examining the Menomonee watershed relative to the Rouge River watershed, the effect of implementing BMPs is not as dramatic. A comparison of the flows in the two watersheds is shown in Figure 1B-22.

FIGURE 1B-22
Menomonee River and Upper Rouge River Watershed Flow Duration Curve Comparisons for the Month of June



An important conclusion from these observations is that stormwater BMP retrofits in urbanized areas with high infiltration capacity soils will have a more dramatic restorative effect on the flow duration curve than BMP retrofits in watersheds with low permeability soils. Another observation is that it is more difficult to attain a target in a relatively impervious watershed, even though the natural soil conditions are closer to pavement, due to the limited capacity of the soils to absorb additional water that may run onto them from impervious surfaces.

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