tools across a range of differing environmental conditions. Third, a synthesis section summarizes and compares results from the four pilot watersheds and includes examples of how different types of impairments and restoration opportunities were identified and valued based on a suite of metrics and protocols developed during this project. Finally, a description of lessons learned and recommendations for further work are provided at the end of the report.

2. TOOLS TO ASSESS ANTHROPOGENIC CHANGES AND HYDROLOGIC ALTERATIONS

2.1 Basinwide Geospatial Screening Tools

Data Reconnaissance and Assessment

The goal of this task was to produce a GIS database that identifies all available and relevant GIS information for the entire Great Lakes Basin. Project team evaluated an extensive list of geospatial datasets developed by other efforts in the basin (e.g. GLEI project, The Nature Conservancy, USGS, GLC, U.S. EPA). Critical datasets were acquired and catalogued on the AES central server and datasets important to the entire project team were uploaded to the project ftp site. Over 300 geospatial data files in approximately 30 different categories (approximately 150 gigabytes) were acquired or derived for this project. Approximately one-third to one-half of these datasets became useful in achieving the aims of this project. A summary list of datasets gathered or created for this project is given in Appendix 1. Many of these datasets are available for download via links to original sites and are included in Appendix 1.

Development of the Screening Tool

The project team developed a consistent and systematic method to screen Great Lakes watersheds for potential hydrologic restoration opportunities using available geospatial data. The objective was to identify a candidate list of watersheds that are broadly representative of watershed types within the Great Lakes Basin and to thoroughly evaluate, compare, and validate hydrologic and GIS watershed assessment models and tools. The project team compiled basin-wide GIS datasets that are relevant to understanding potential causes of hydrologic alteration. Through correlation analysis and professional judgment the team developed six independent indicators of potential hydrologic impairment from these datasets:

- Imperviousness
- Dam Storage Capacity
- Canals/Ditches
- Minor Road Intersections
- Major Road Intersections
- Potential Restorable Wetlands (hydric soils without wetlands)

The project team incorporated these key parameters into a decision matrix and produced a list of 20 candidate watersheds that meet general criteria for potential hydrologic alteration and also meet the criteria for the experimental design as outlined in the proposal. Watersheds were evaluated at the 8-digit Hydrologic Unit Code (HUC) level. The potential impairment score was calculated by first summarizing the above metric data by watershed and normalizing by area. These normalized values for each metric were then sorted and aggregated into five classes using the “natural breaks” method in ArcGIS 9.1. Watersheds were assigned a score from 1 to 5 for each data category depending on the potential degree of impairment resulting from that particular data category (with 1 representing the least impairment and 5 the most). Since the team had determined the data categories to be independent of one another and representing different sources of hydrologic impairment, all scores were weighted equally with the exception of imperviousness which was determined to be a very high indicator of potential impairment and was given twice the weight of the other indicators. These scores were then summed for each watershed resulting in an overall surface hydrologic impairment score for the watersheds (Figure 2.1-1).

Identification of Four Demonstration Watersheds

Further criteria were used to choose pilot watersheds from the initial 20 candidate watersheds and include:

- Geographic location
- Hydrology
- Land use
- Type of water supply
- Data/coverage availability
- Ongoing or planned restoration activities

The project team worked with Advisory Group Members and other Growing Water project teams to identify additional completed, underway, or planned restoration opportunities in the basin and possible opportunities for collaboration. As a result, four pilot watersheds were selected for further analyses: the **Shiawassee watershed** in Michigan; the **St. Joseph watershed** in Michigan, Indiana, and Ohio; the **Milwaukee watershed** in Wisconsin; and the **Paw Paw watershed** in western Michigan. These watersheds represent regions with different hydrologic regimes, different landcover and land uses, and different water use/supply regimes.

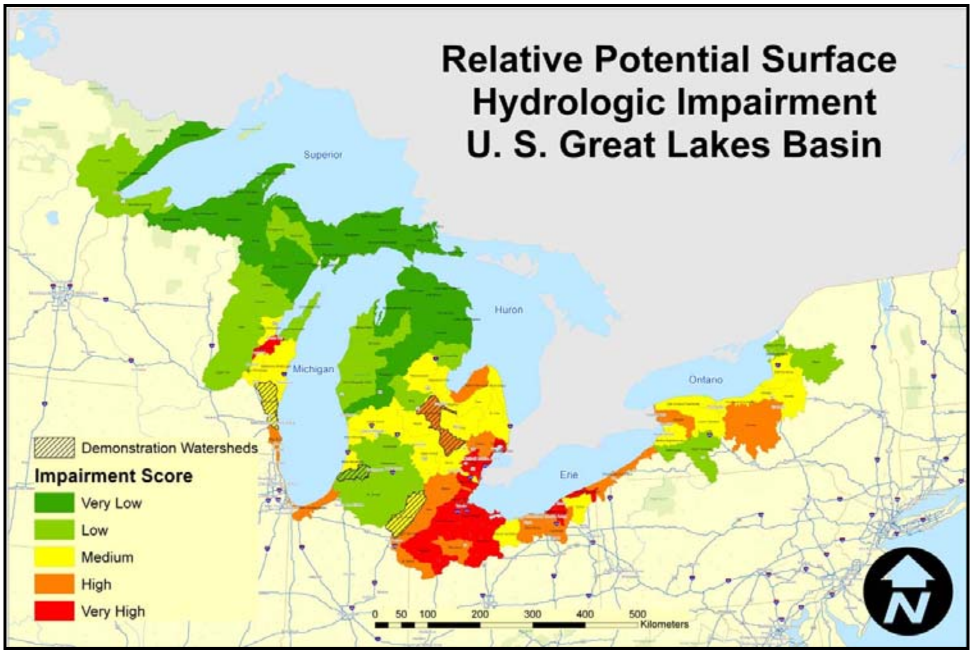

Figure 2.1-1 Summary map showing the relative potential hydrologic impairment of 8-digit HUC watersheds on the U.S. side of the Great Lakes basin.

2.2 Watershed assessment tools

Natural landscape features and processes support and provide critical hydrologic functions to a watershed. To evaluate impaired flows and associated environmental degradation, it is important to first identify hydrologic functions performed by specific landscape features and/or associated processes operating within a watershed. Changes to the natural processes and pathways that control how water flows across or through the landscape fundamentally alter natural hydrologic functions. Examples of hydrologic functions that are controlled by landscape features include the volume and timing of water: 1) collected and delivered by the land surface to tributary streams and rivers during precipitation events; 2) retained and/or stored on or within the watershed by wetlands, ponds, lakes, and dams; and 3) infiltrated into the ground to recharge both shallow and deep groundwater aquifers that may, or may not contribute to tributary streams and rivers.

These hydrologic functions are controlled, in part, by watershed features - local catchment area, soil type and vegetative cover, local elevation and slope, and the path that surface and ground waters take across or through the watershed before entering a tributary stream or river. Anthropogenic modifications to the watershed surface (land use/land cover) can significantly alter these functions and affect the ecological health of the Great Lakes basin. Following is a detailed description of watershed assessment tools and metrics that were developed and applied in the pilot watersheds to identify and quantify hydrologic impairments and potential restoration opportunities.

2.2.1 Stream Power Tool

A new method was developed that can be applied at multiple scales to assess the spatial distribution of energy (i.e. stream power) within a watershed. This tool's utility is furthered by its ability to assess changes in stream power over different time periods. The tool uses land cover snapshots (and precipitation, if known) from different periods of interest, often a base-case, or presettlement land cover, and current land cover. Also, a hypothetical worst-case, 100 percent impervious "paved paradise," scenario can be run to allow the tool user to assess to what degree current stream power has changed on the continuum from the presettlement scenario to the hypothetical worst-case scenario.

The stream power tool calculates a surrogate for total stream power using a flow accumulation approach that combines digital elevation models (slope); curve number (CN)[1]; and precipitation to calculate surface-water runoff for each grid cell, or pixel, within a watershed. Surface water runoff is then summed (accumulated) in a downstream direction to calculate the volume of water generated by a precipitation event (discharge). Discharge is then multiplied by slope and normalized by stream reach length to calculate energy in the system (stream power) (Figure 2.2.1-1).

This tool is based on the fundamental assumption that many of the observed impairments in Great Lakes tributaries and streams are due to changes in the duration, rate, frequency and magnitude of discharges from land cover change. The stream power tool generates a map of the watershed with individual stream segments color coded as a function of relative stream power.

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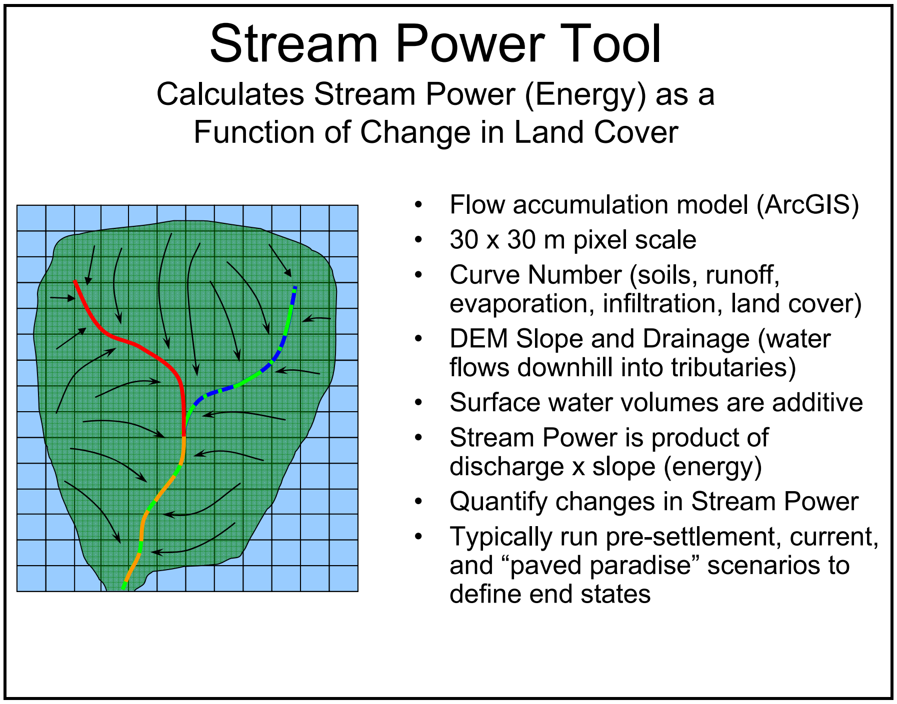
[1] Curve Number (CN) is a numerical characterization of runoff based on soil and land cover. (NRCS TR-55, 1986)



Stream Power Tool

Calculates Stream Power (Energy) as a
Function of Change in Land Cover

- Flow accumulation model (ArcGIS)
- 30 x 30 m pixel scale
- Curve Number (soils, runoff, evaporation, infiltration, land cover)
- DEM Slope and Drainage (water flows downhill into tributaries)
- Surface water volumes are additive
- Stream Power is product of discharge x slope (energy)
- Quantify changes in Stream Power
- Typically run pre-settlement, current, and "paved paradise" scenarios to define end states

Figure 2.2.1-1 Schematic diagram of how the flow accumulation model is used to calculate stream power for individual stream segments.

Differences in stream power are presented in two ways:

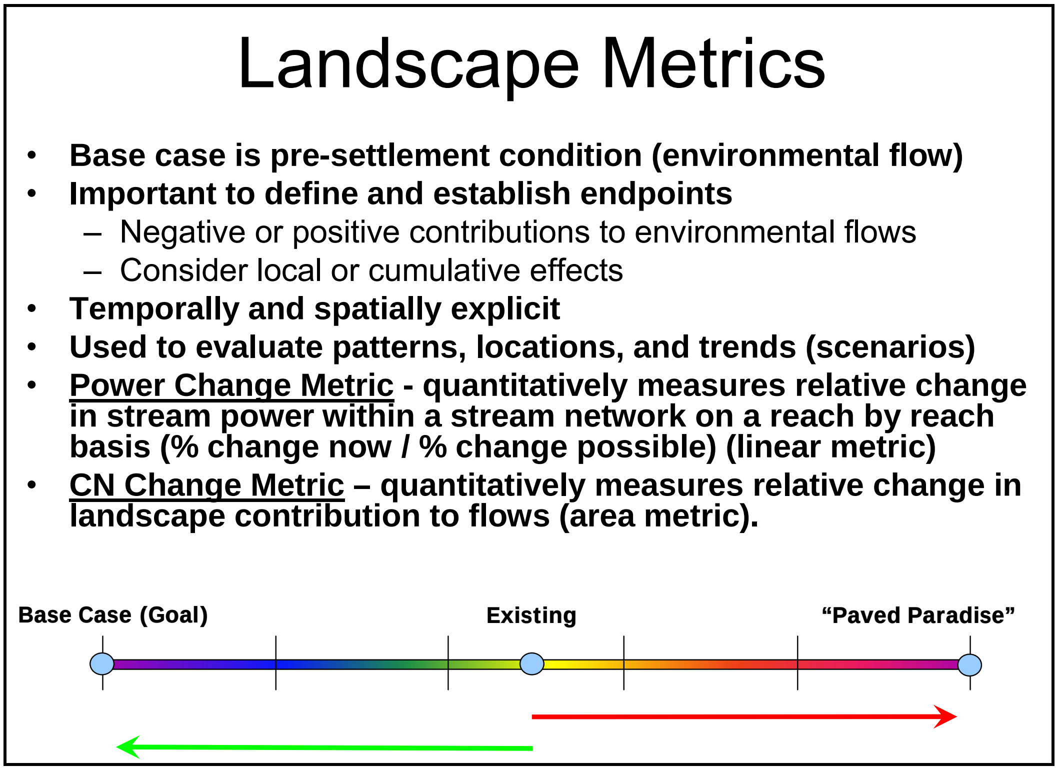
1) Using landcover from presettlement and recent time periods, absolute change in stream power can be calculated and compared using a percent power change calculation:

$$\textbf{Percent Power Change} = \frac{\textbf{Recent Stream Power} - \textbf{Presettlement Stream Power}}{\textbf{Presettlement Stream Power}}$$

This provides a measure of the deviation in stream power from presettlement conditions for every stream reach within the watershed. And,

2) Using a power change metric that provides a way to quantify and normalize potential hydrologic degradation (or improvement) in a watershed. The stream power tool uses land cover snapshots (and precipitation, if known) from, at least, presettlement, current, and the hypothetical worst-case, 100 percent impervious "paved paradise," scenarios. Each stream reach is then evaluated based on its power change and discussed in terms of where it lies on the continuum from presettlement (power change metric of 0) to paved paradise (power change metric of 100). When comparing actual change in stream power to the maximum power change possible an assessment of possible hydrologic alteration from land cover change can be made among stream reaches within a watershed that takes into account each reach's unique catchment characteristics (Figure 2.2.1-2).

$$\textbf{Power Change Metric} = \frac{\textbf{Recent Stream Power} - \textbf{PreSettlement Stream Power}}{\textbf{Paved Paradise Power} - \textbf{PreSettlement Power}}$$



Landscape Metrics

- **Base case is pre-settlement condition (environmental flow)**
- **Important to define and establish endpoints**
  - Negative or positive contributions to environmental flows
  - Consider local or cumulative effects
- **Temporally and spatially explicit**
- **Used to evaluate patterns, locations, and trends (scenarios)**
- **Power Change Metric - quantitatively measures relative change in stream power within a stream network on a reach by reach basis (% change now / % change possible) (linear metric)**
- **CN Change Metric – quantitatively measures relative change in landscape contribution to flows (area metric).**

Base Case (Goal) **Existing** **“Paved Paradise”**

Figure 2.2.1-2 A power change metric and CN change metric were developed to identify and specific areas on the landscape that influence hydrologic impairment. These metrics quantify the relative degree of hydrologic impairment due to changes in land cover/land use in a watershed.

In addition to the power change metric a CN change metric was developed to identify where on the landscape potential hydrologic alterations are greatest due to changes in land use/land cover over different time periods. Values of the CN change metric can be displayed for each 30 m pixel across the watershed creating a CN change surface. The CN change surface, when displayed with power change metric values for individual stream segments, is a powerful way to illustrate hydrologic alteration potential within a watershed and identify areas within the watershed where land cover change contributes most to hydrologic changes and changes in stream power (Figure 2.2.1-3).

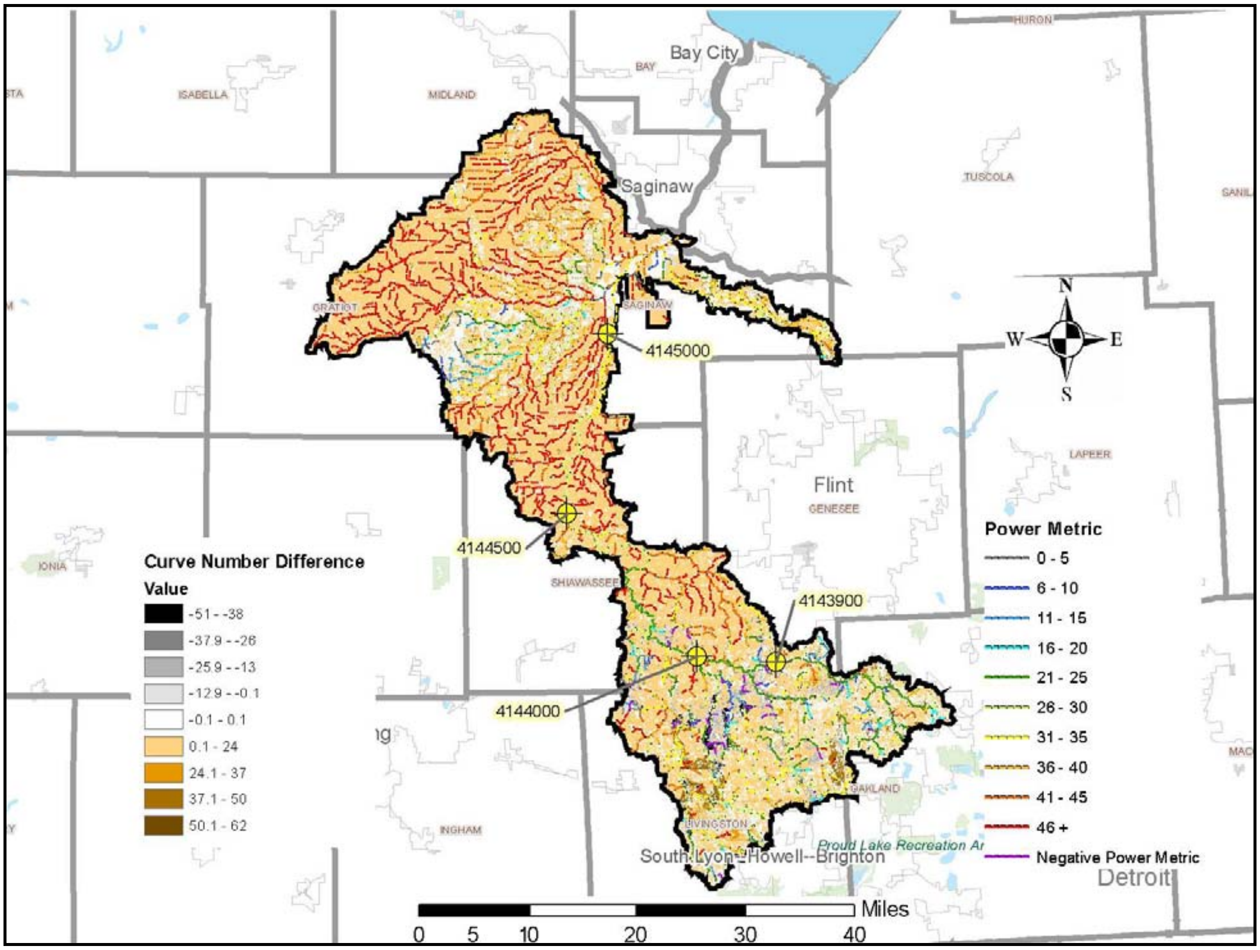


Figure 2.2.1-3 Map of Power Change Metric in the Shiawassee River Watershed with the CN Change Metric, or "Surface," Underlain Showing the Change in CNs from Presettlement to Now.

Moreover, this tool can be used to explore potential hydrologic improvements for different land cover restoration scenarios. The stream power and CN change tools were recently updated to run on ArcGIS 9.2 and have been distributed to project team members for evaluation and testing.

In addition to the power change and CN change tools, the project team developed methods to calculate the lineal length of hydrologic change or "improvements" downstream from a restoration site. These methods are used to provide a quantitative assessment of the lineal (or areal) benefits of downstream hydrologic improvements.

Stream power analyses were run for each of the four demonstration watersheds. In all four watersheds, comparison of the power change metric with present-day land use/land cover showed a strong correlation between higher power change metric values and agricultural or urban land uses. This is not surprising as agriculture and urban land uses are typically associated with highly efficient drainage systems designed to move water off the landscape as quickly as possible. Conversely, landscape features that retain and store water on the landscape (not necessarily lakes and ponds) will typically be associated with low power change metrics similar to natural presettlement conditions. A more detailed summary of the stream power results for each of the four pilot watersheds is included in the watershed summaries in Section 3.

2.2.2 Wetlands Water Retention/Storage Tool

The hydrologic benefits of wetlands are many. Therefore, this project undertook an assessment of presettlement, current and potentially restorable wetlands within each of the pilot watersheds. Current wetlands were determined from the National Wetlands Inventory (NWI) in the Shiawassee and Paw Paw watersheds and the Wisconsin Wetlands Inventory (WWI) in the Milwaukee. Data limitations in the St. Joseph watershed precluded a detailed wetland assessment there.

Presettlement wetlands were determined using the assumption that all hydric soils that are not now wetlands were wetlands before European settlement. Thus, presettlement wetlands were determined by adding non-wetland hydric soils to current wetlands. Percentages were calculated for each area of interest within the pilot watersheds[2].

Potentially restorable wetlands (PRWs) are all hydric soils that are not currently wetlands and occur on agricultural or rural lands. (PRWs are a smaller subset of presettlement wetlands described above. They do not include current wetlands nor do they include any non-wetland hydric soils that are on developed land. They are areas where wetlands likely were historically and hold potential restoration opportunities due to the current land use on which they occur.) PRWs represent a high chance for restoration since they are not located in developed areas.

The water retention/storage potential for wetlands has not been evaluated or mapped in the Great Lakes basin. This was surprising considering the hydrologic benefits that those wetlands provide and the historical loss of wetlands in the Great Lakes basin. Wetland losses not only impair habitat diversity, but also impair hydrologic function. Wetland restoration and protection efforts are often focused on maintaining and restoring habitat diversity (i.e. biodiversity), and may overlook the hydrologic benefits those wetlands provide to the watershed as a whole.

In response to this need, the project team developed a method that combines the flow accumulation approach developed for the stream power tool with existing wetlands, soils, and land cover mapping to identify and assess water retention/storage potential of the Basin's wetlands (Figure 2.2.2-1). The question was asked: How many inches of a storm event can a wetland retain, on average, before overflowing and contributing to channelized flow?

Average retention capacity is calculated by assigning water depth ranges for specific types of wetlands and/or vegetative communities as defined by the USFWS National Wetland Inventory protocols. These depths are then subtracted from the runoff grids calculated by the stream power tool, thus directly affecting the flows and stream power downstream from the wetland. The advantage of this approach is that:1) the relative importance of factors that control wetland water storage and retention in a catchment (number, type, size, and location of wetlands) can be evaluated, and 2) the effects of water storage and retention on overall watershed hydrology can be measured and quantified.

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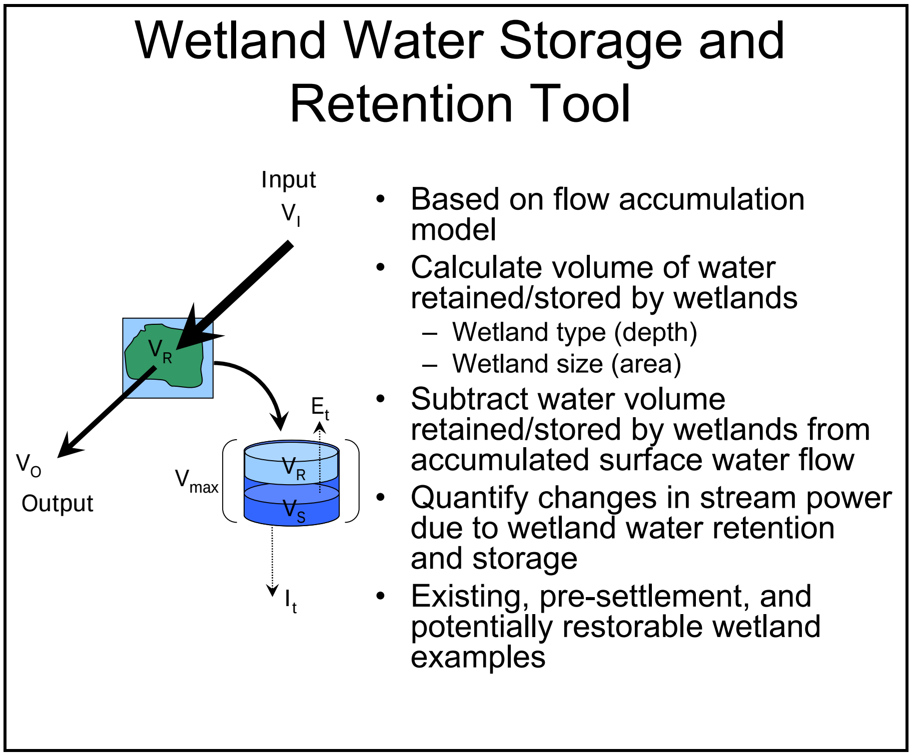
[2] Note: In urban areas soil surveys are often incomplete or not done as surveys were completed after extensive settlement. For example, there are large portions of the Milwaukee River watershed in metropolitan Milwaukee where soils data are unavailable and makes estimates of hydric soils difficult. This can lead to underestimation of presettlement wetlands in those areas.

The team next desired to understand what the effect would be on hydrology from restoring PRWs. At this scale it would be time consuming, if not impossible, to understand what type of wetland each PRW was presettlement. Thus, an area weighted average of the current retention depths was assigned to PRWs.



Wetland Water Storage and Retention Tool

- Based on flow accumulation model
- Calculate volume of water retained/stored by wetlands
  - Wetland type (depth)
  - Wetland size (area)
- Subtract water volume retained/stored by wetlands from accumulated surface water flow
- Quantify changes in stream power due to wetland water retention and storage
- Existing, pre-settlement, and potentially restorable wetland examples

Figure 2.2.2-1 The Wetland water storage and retention tool was developed to assess potential impacts of wetland loss (or gain) on overall watershed or catchment hydrology.

The stream power tool, when combined with the wetland water storage and retention tool, can identify the magnitude and location of improvements (or impacts) to hydrology resulting from changing the number, type, size, and location of wetlands in a watershed or catchment (Figure 2.2.2-2). These tools can be applied using existing wetland and presettlement wetland datasets, and can be used to predict potential hydrologic effects in response to anticipated changes in wetland distribution, for example, PRW restoration. The wetland water storage and retention tool was applied as a test case in the Milwaukee River watershed and results are discussed in section 3.4.

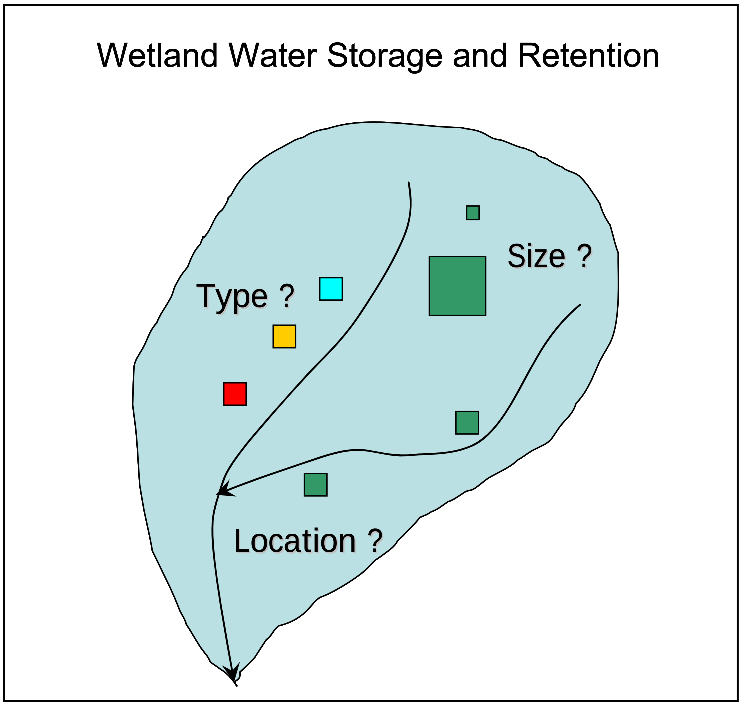


Figure 2.2.2-2 The wetland water storage and retention tool can be used to assess the factors that control wetland water storage and retention. Factors that can be evaluated include the number of wetlands and wetland type, size, and location.

2.2.3 Water use / pathway assessment

The project team considered the potential effects of flow path changes on hydrologic parameters as water moves across and through the watershed. These analyses considered such factors as withdrawal location, the type withdrawal, the amount of water diverted, consumed, and/or returned, and the type of receiving waters.

The project team was able to gather and synthesize existing data and information on factors contributing to hydrologic alteration due to flow path alterations within the four demonstration watersheds. Water use and water supply information were typically reported by political subdivision and/or community – not by watershed or subwatershed. This reporting framework makes it difficult to attribute water use at watershed or subwatershed scales. Where possible, staff from local Nature Conservancy chapters assisted the project team by identifying data sources and/or by providing the data on water use and water supplies where available for the pilot watersheds.

The project team compiled a list of public domain water allocation/flow path analysis packages that are currently being used in western states to model source-water supply, flow paths, and impact of water distribution systems on watershed hydrology (Appendix 2). Most of these packages are designed for surface water systems, but can be modified to include groundwater sources as well. For this project, the team tested the WEAP (Water Evaluation and Planning) tool developed by the Stockholm Environmental Institute to explore water use/pathway assessments in the pilot watersheds. The WEAP tool was not designed explicitly for this purpose, but has many features that can be used to assist in these types of analyses.

Hydrologic Impairments resulting from Flow Path Alterations – The project team developed a conceptual framework that identifies and describes critical flow path parameters and elements that must be considered when identifying linkages to potential hydrologic impairments (or improvements). For the purpose of this project, flow paths are considered to be the paths that connect source waters with receiving waters as water is diverted for anthropogenic use (e.g. public/private water supply, commercial/industrial, and irrigation). There are four critical flow path elements that need to be considered:

1. Source Waters - There are two primary sources of water where water is withdrawn for anthropogenic use – surface water and groundwater. Surface water withdrawals occur primarily from tributary rivers and streams, reservoirs, and the Great Lakes. Groundwater withdrawals occur from both shallow and deep aquifers. For the purpose of this project, shallow groundwater sources are defined by producing depths generally less than 60 feet with a reasonable expectation that local surface-groundwater interaction may occur. Deep groundwater sources are defined by producing depths greater than 60 feet with a reasonable expectation that local surface-groundwater interaction will not occur.

2. Diverted Flows - Waters that are withdrawn from a natural water source and re-directed for anthropogenic use. An example would be waters withdrawn from a river, treated in a public water treatment plant, and then distributed to a community as a public water supply. These waters may be consumed, lost due to evaporative processes, or returned to the hydrologic system.

3. Return Flows - Waters that are collected, treated in a wastewater treatment plant, and then returned to the hydrologic system (receiving waters).

4. Receiving Waters - The water bodies to which withdrawn waters are returned. The location where these waters are returned may be many miles from the withdrawal location and or may be in an entirely different watershed.

There are three attributes that influence how changes to flow paths will affect hydrology (see Table 2.2.3-1):

Table 2.2.3-1 Parameters associated with Flow Path Elements and Attributes

ATTRIBUTE	SOURCE WATERS	DIVERTED FLOWS	RETURN FLOWS	RECEIVING WATERS
Location	**Intake Location**	**Surface & Subsurface Flow Path Distance, Timing**	**Surface & Subsurface Flow Path Distance, Timing**	**Outfall Location**
Type	**SW River SW Reservoir SW Lake GW Shallow GW Deep**	**Flow Path Routing and Connections**	**Flow Path Routing and Connections**	**River, Reservoir, Wetland, Lake, GW Shallow, GW Deep**
Volume	**Low High**	**Surface & Subsurface Flow Rates**	**Surface & Subsurface Flow Rates**	**Low High**

SW – Surface Water, GW – Groundwater

Location – The distribution, pattern, and distance (and/or depth) between withdrawal and return points within a watershed. For surface waters, the location of withdrawal and return points will directly control where hydrologic alterations occur within a stream or river reach. For groundwater, the producing depth may determine whether or not there is potential for flow alteration. For example, shallow aquifers (depths less than 60 feet) may be locally connected to surface waters and/or near surface aquifers. Waters withdrawn from depths less than 60 feet and returned via septic systems may have a minimal impact on flows in shallow aquifers and/or adjacent surface waters. Deeper aquifers (depths greater than 60 feet) are not likely to be locally connected to shallow aquifers and/or surface waters. Waters withdrawn from depths greater than 60 feet and returned via septic systems may augment flows in shallow aquifers and/or adjacent surface waters and would therefore be considered a flow path alteration.

Type – The source waters (e.g., Surface water (SW) -River, SW-Reservoir, SW-Lake, Ground water (GW) – Shallow, GW-Deep) from which water is withdrawn and the receiving waters to which water is returned. There are significant differences in the processes that control how water moves across the landscape surface (surface water flows) vs. within the landscape (groundwater flows). These processes directly control the magnitude and timing of hydrologic alterations within a catchment. For example, groundwater withdrawn from depths greater than 60 feet and returned via wastewater treatment plants to surface waters would be considered to be a significant flow path alteration. Waters withdrawn from a river then returned to a shallow aquifer through private septic systems have an increased potential to alter the hydrology of both the water source (flow reductions in the river) and the receiving waters (flow augmentation in the shallow aquifer).

Volume – The amount of water withdrawn from source waters and/or returned to receiving waters.

Flow-path hydrologic alterations can be quantified by the proportion of water diverted for anthropogenic use and returned to a location that is substantially different from where the source water was withdrawn. Specifically, for each source water (surface or groundwater), diverted flow path water volumes (V_{DIVg} or V_{DIVs}) can be compared to the total volume of water withdrawn from groundwater sources (V_{GW}) or the total of volume of water withdrawn from surface water sources (V_{SW}), respectively. This **Diversion Ratio** (**D**) is a measure of the amount of water that is withdrawn and diverted along altered flow paths compared to the total amount of water withdrawn in a watershed. Water withdrawals with minimal flow path alterations will have Diversion Ratio values near zero (0). Withdrawals with significant flow path alterations will have Diversion Ratio values approaching one (1).

$$\mathbf{D_{GW} = V_{DIVg} / V_{GW}}$$

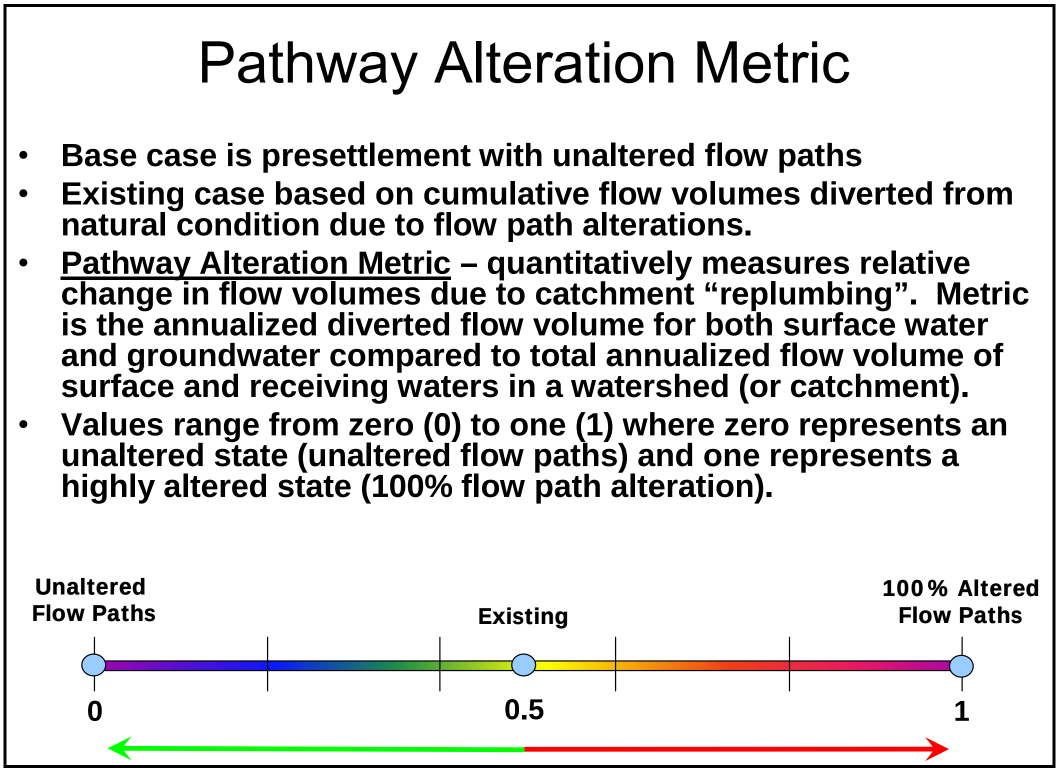
$$\mathbf{D_{SW} = V_{DIVs} / V_{SW}}$$

The impact of flow-path alterations on receiving waters will be dependent on the volume (and location) of return flows relative to the total volume of source waters and the receiving waters. The **Pathway Alteration Metric** (**PAM**) is the volume of diverted water that travels along altered flow paths relative to the total volume of source waters and/or the receiving waters (Figure 2.2.3-1.). Waters returned to nearby locations within the same hydrologic regime will have low altered flow path volumes and PAM values near zero (0). Waters returned to different locations and/or into a different hydrologic regime are considered to be altered flows and in watersheds where return flow volumes are large, may have PAM values that may be equal to, or greater than one (1).

$$\mathbf{PAM_S = (V_{DIVg} + V_{DIVs}) / V_{source\ waters}}$$

$$\mathbf{PAM_R = (V_{DIVg} + V_{DIVs}) / V_{receiving\ waters}}$$

Potential impacts to the hydrologic regime include flow augmentation and flow depletion. In general, observable flow path impacts typically occur at the surface and are associated with return flows and/or receiving waters. Flow augmentation (PAM_R – receiving water) values were calculated for three of the four pilot watersheds. Flow depletion (PAM_{S} - source water) values were not calculated for the pilot watersheds due to difficulties associated with estimating groundwater (or aquifer) source water volumes in these watersheds.



Pathway Alteration Metric

- **Base case is presettlement with unaltered flow paths**
- **Existing case based on cumulative flow volumes diverted from natural condition due to flow path alterations.**
- **<u>Pathway Alteration Metric</u> – quantitatively measures relative change in flow volumes due to catchment "replumbing". Metric is the annualized diverted flow volume for both surface water and groundwater compared to total annualized flow volume of surface and receiving waters in a watershed (or catchment).**
- **Values range from zero (0) to one (1) where zero represents an unaltered state (unaltered flow paths) and one represents a highly altered state (100% flow path alteration).**

Figure 2.2.3-1 A pathway alteration metric was developed to quantify the potential for hydrologic alteration due to altered flow paths. The PAM compares the cumulative volume of altered flows to the total volume of source and/or receiving waters within a watershed.

<u>Implementation and testing</u> - Even though data were not consistently available across all catchments, it was possible to assess regional flow patterns and to identify areas of potential flow alteration due to altered flow paths in the Shiawassee and Milwaukee watersheds, and to a lesser extent in the Paw Paw watershed in southwestern Michigan. The St. Joseph watershed is trisected by three States – Michigan, Indiana, and Ohio. Each of these states has different reporting requirements for water use; public, private, and industrial water supplies; wastewater discharges; and groundwater withdrawals (and well data). No pathway assessment was completed for the St. Joseph watershed due to a lack of consistent data across the watershed.

<u>2.2.4 Flow duration curve models</u>

Flow duration curves describe the relationship between the magnitude of discharge and how often it occurs over a specified interval. When developed from annual mean daily flow data they describe the overall range of flow conditions in the stream during an average year. We used existing multiple linear regression (MLR) models to produce a synthetic flow duration curve to characterize flow conditions in the pilot watersheds. We also applied landcover information from estimated presettlement and build out scenarios to these models where data were available. We then compared differences in potential exceedence flows for each of the landcover scenarios (recent, presettlement, potential future). The intent is to quantify the degree of hydrologic alteration in response to changes on the landscape and impacts of those changes on characteristic flows at the study sites.

Independent variables for MLR development were selected from summaries at USGS gage locations that included drainage area, mean annual precipitation, valley slope, surficial geology, and landcover using statewide datasets with rivers in Illinois, Michigan, and Wisconsin. These data were used as predictors of exceedence flows for recent twenty water year records (generally 1981-2000) from these gages. Models were developed using an addition ($p<0.05$)/removal ($p<0.10$) stepwise regression procedure with an initial focus on the median flow. After each addition (or removal) the predictive equation derived for the median flow model was re-parameterized with high flow (Q_{10}) and with low flow (Q_{90}) data. If this most recent change in the MLR model did not result in a major decrease in the fit (adjusted R^2 and/or standard error) of these models, the change was kept and development of the median flow model continued. When additional changes did not improve the fit of the models this combination of predictors was used to create a family of models for the additional exceedence flows (i.e., Q_5, Q_{10}, Q_{25}, Q_{75}, Q_{90}, Q_{95}). Overall these models had good fits with high flows consistently predicted more accurately than low flows. Models of this type have been described elsewhere (Allan et al. 2000, Seelbach et al. 2002) and used successfully in other projects (DePhilip et al. 2006, Holtrop et al. 2006).

2.2.5 Assessment of dams

The team used the best available information on the location of dams to estimate the potential impact of dams on stream flows in each of the four demonstration watersheds. In some watersheds, the dam datasets included some information about the size, storage capacity, purpose (e.g., hydroelectric, recreation, water supply), and operation (e.g., run of river, peaking) of each dam. The team calculated the number of dams and dam density for subcatchments within each of the four demonstration watersheds. The team also developed general hypotheses about the cumulative impacts of dams in each catchment; these hypotheses are listed in Section 2.4. Potential impacts of the operation of individual dams were not considered.

2.2.6 Assessment of channel modification

To estimate the degree channel modification within each watershed, the team identified stream reaches that were either coded as 'channelized' within the National Hydrologic Dataset (NHD) or appeared unnaturally straight on the digital raster graphic files (DRGs). The percent of total stream length that had been artificially straightened was calculated for several subcatchments within each of the four demonstration watersheds. The team also developed general hypotheses about the cumulative impacts of channel modification in each catchment; these hypotheses are listed in Section 2.4.

2.3. Hydrologic Assessment Tools and Metrics

The team applied a suite of relevant hydrologic evaluation tools within each of the four demonstration watersheds. These tools require a daily flow series as input. Methods for applying various hydrologic assessment tools within the four demonstration watersheds are described below.

2.3.1 Indicators of Hydrologic Alteration (IHA)

The Indicators of Hydrologic Alteration (IHA) software summarizes long periods of daily flow data into a manageable set of ecologically relevant hydrologic metrics. The IHA requires continuous daily stream flow data, either from streamflow gages or simulated using a watershed hydrologic model. In this study, all flow data for the demonstration watersheds came from USGS gages. The IHA software generates a total of 67 flow metrics, subdivided into 33 annual metrics and 34 metrics associated with Environmental Flow Components: extreme low flows, low flows, high flow pulses, flood events, and extreme flood events (TNC 2005). These IHA metrics allow the user to describe flow regimes in terms of magnitude, timing, frequency, duration and rate of change of flow events.

The IHA gives users the option of conducting either one- or two-period analyses. The one-period analysis is used to detect trends rather than to detect changes attributable to a specific event in time. The two-period analysis is useful when the period of record is sufficiently long to describe conditions before and after a discrete event (e.g., dam construction, change in dam operation) or to describe and compare historical and recent period ‘snapshots’. A sufficiently long period of record (20-30 years of continuous data are recommended) is needed to both detect trends and to compare two discrete time periods.

The project team completed one-period analyses for all stream gages within the four demonstration watersheds where >20 years of continuous data were available. For gages that had especially long periods of record, the team also conducted two-period analyses to compare flow conditions during historical and recent period ‘snapshots’. These two-period analyses were not intended to detect hydrologic alterations associated with discrete changes in the watershed; instead they were simply an alternative to the trend analyses used to describe changes over time. The team compared the results of the one- and two-period analyses to see if they were consistent.

Because the IHA requires daily stream flows as input, the tool can only be used to detect actual changes to flow metrics over time unless daily streamflows can be simulated under various land cover and water management scenarios using a hydrologic model. Many of the land cover and instream modifications within a watershed may predate the period of hydrologic record. In these cases, the IHA may not be able to detect the hydrologic impacts of these changes.

Given the number of potential variables that are calculated by the IHA, it was necessary to identify and focus on a set of parameters that could be tested in response to a specific set of quantifiable anthropogenic changes. The project team selected a subset of the IHA metrics to describe changes to seasonal and extreme flows. Median monthly flows were calculated for all sites. These flow magnitudes were summarized by season: Winter (November, December, January and February), Spring (March, April, May, and June) and Summer/Fall (July, August, September, and October). In all four demonstration watersheds, spring is the wet season and summer/fall is the dry season. The team also chose the annual 3-day maximum and the annual 7-day minimum to identify any changes to the magnitudes of high and low flow events, respectively.

2.3.2 Flow-Precipitation ratio

As has been noted in other GLPF-supported studies, there are regional climatic effects (i.e., increased precipitation, changes to intensity of precipitation, decreased snowfall) that may mask the effects of land cover change and/or instream channel modifications on flow regime. Where both flow and precipitation data were available for the same time period within the four demonstration watersheds, the project team evaluated whether changes in precipitation could explain changes in monthly flow magnitude. The team calculated a monthly Flow (Q) / Precipitation (P) ratio to normalize the effects of increased precipitation in order to more clearly isolate the impacts of anthropogenic changes on flow regimes. Changes in Q/P over time indicate that some factor (or combination of factors) besides precipitation volume is responsible for increases or decreases in watershed yield. Q/P is considered a measure of watershed 'efficiency'; if Q/P increases, the watershed is considered to be more 'efficiently' processing precipitation.

2.3.3 Richards-Baker flashiness index

The Richards-Baker flashiness index was also applied to the pilot watersheds (Baker et al 2004). The R-B Index is used to quantify the frequency and rapidity of short-term changes in streamflow. A variety of land and water management changes may lead to increased or decreased flashiness. This flashiness index is based on mean daily flows. The index is calculated by dividing the path length of flow oscillations for a time interval (i.e., the sum of the absolute values of day-to-day changes in mean daily flow) by total discharge during that time interval. This index has low interannual variability relative to most flow regime indicators and thus greater power to detect trends. The project team used stream gage data to calculate R-B Index values for each year during the period of record and then looked at trends in flashiness over time.

2.3.4 Base flow separation and baseflow index

Where available, base flow separation analyses were acquired from the USGS (Neff et al 2005) for each of the pilot watersheds. Neff et al. (2005) applied several different baseflow separation algorithms to a daily streamflow records to estimate a baseflow index (BFI). This baseflow index is an estimate of the groundwater component of streamflow. The team used the BFI calculated by Neff et al. (2005) to quantify trends and alterations to base flows for each of the four demonstration watersheds.

2.3.5 Relationships between the hydrologic alteration tools

Several of the flow metrics calculated for watersheds in this project describe similar flow characteristics. For example, both the IHA and the flow duration curve models include flow magnitude metrics. Table 2.3.5-1 shows the whether the flow metrics calculated using the different hydrologic assessment tools are expected to be positively (+) or negatively (-) correlated.

Table 2.3.5-1 Expected relationship between flow metrics calculated using the hydrologic and watershed assessment tools.

			Flow exceedance frequencies		Change in stream power
	Flow characteristic		Low flow magnitude	High flow magnitude	
		Flow metric(s)	Q95, Q90, Q75	Q25, Q10, Q5	Stream Power Metric
Indicators of Hydrologic Alteration	Summer/Fall – Magnitude	July, Aug, Sept, and Oct median flow	+		
	Spring – Magnitude	March, April, May, and June median flow		+	+
	Low flow (event) magnitude	7- day annual low flow	+		
	High flow (event) magnitude	3-Day annual high flow		+	+
Other Metrics calculated using gage data	Low Flow Magnitude	Base Flow Index	+		-
	Rate of Change	Flashiness Index			+
	Watershed Efficiency	Flow yield versus Precipitation Ratio (Q v. P)			+

2.4 Hypotheses about effects of watershed changes on flow metrics

The team developed generalized hypotheses about the hydrologic changes that may be expected as a result of anthropogenic modifications within the catchment, including dams, channel modifications, and land cover changes. Given the complexity and number of flow variables that are calculated by the hydrologic assessment tools applied in this project, the team focused on a few flow variables that were likely to respond to the land cover and instream modifications within the four watersheds.

The combination of land cover changes and instream modifications make it difficult to predict the hydrologic alterations associated with these anthropogenic changes and other changes that were not be quantified in this study (e.g., dam management, water use). Despite these complexities, it is useful to hypothesize about the expected hydrologic responses to changes in the watershed.

Land cover change*:* Loss of forest cover in a watershed may decrease evapotranspiration, surface roughness and infiltration and increase the volume and rate of water that flows through the watershed. Field observations from other studies provide evidence that loss of forest cover often results in increased annual, peak and, summer (low) flows. In general, loss of forest cover will increase stream power. Also, it is hypothesized that loss of wetlands will reduce water retention volumes and retention times within a watershed and, on average, lead to increases in stream power and increased high flows that can impair watershed hydrology. In general, the higher the degree of alteration from land cover change the greater the change in stream power.

Water use / pathways: The magnitude of hydrologic impairment will be a function of the location of the water withdrawal and return, the volume of water diverted relative to the total volume of source and receiving waters, and flow augmentation (or depletion) along return flow paths. Table 2.2.3-2 summarizes the potential for flow-path induced hydrologic alteration based on source water and receiving water type and typical volumes associated with those types. The row headings identify source water type. The column headings identify receiving water body type. The potential for flow-path hydrologic impairment is given in the cell where source water row intersects the receiving water body column. Flow-path hydrologic impairment is categorized from no measurable impact (0) to high impact (High) based on inferred differences in source and receiving water type.

Table 2.4-1 Potential for Flow Path Hydrologic Alteration based on Source and Receiving Waters

Source Waters	Return Flow	Receiving Waters					
		SW River	SW Reservoir	SW lake	SW Wetland	GW Shallow	GW Deep
SW River	→	O	Low	Low	High	High	n/a
SW Reservoir	→	Medium	O	Low	High	High	n/a
SW Lake	→	HIgh	High	O	High	High	n/a
SW Wetland	→	n/a	n/a	n/a	O	n/a	n/a
GW shallow	→	Medium	Medium	Low	Medium	O	n/a
GW deep	→	High	High	Low	High	Low	O

🟩 Minimal
🟨 Low
🟧 Medium
🟥 High
SW - Surface Water
GW - Groundwater

Consideration of these parameters allows us to infer the following hypotheses:

<u>Hypothesis I – Location</u>: Intakes and outfalls in close spatial (and temporal) proximity minimize potential for hydrologic impairment. Intakes and outfalls separated by large spatial (and temporal) distances increase the potential for hydrologic alteration.

<u>Hypothesis II – Type</u>: In-kind source and receiving waters minimize potential for hydrologic impairment. Different source and receiving waters (especially those that would not be naturally connected) increase the potential for hydrologic alteration.

<u>Hypothesis III - Volume</u>: Small withdrawal and/or return volumes minimize the potential for hydrologic alteration. Large withdrawal and/or return volumes increase the potential for hydrologic alteration.

Channel modification: The overall assumption is that channelization creates more efficient stream networks and more precipitation is delivered to the stream. This can have the effect of increasing high flow magnitude, increasing low flow magnitude, and increasing responsiveness (rate of change) within the stream network. Channelization may also be correlated with irrigation and/or flow augmentation, which changes the water balance by adding water (usually from groundwater) to the drainage network. Over the long term, if groundwater is used for irrigation, drawdown will likely occur and the groundwater component of streamflows may be diminished. Hypotheses about anticipated changes to specific flow metrics are listed in Table 2.4-2.

Table 2.4-2 Hypothesized effects of channel modification on flow metrics.

Flow characteristic	**Flow metric**	**Hypothesized effect of channel modification on flow metric**	**Assumption or explanation**
Summer/Fall – Magnitude	July, Aug, Sept, and Oct median flow	Increase (higher flows during dry season)	Channelization increases drainage efficiency. More precipitation is routed to the stream network, increasing dry-season flows.
Spring – Magnitude	March, April, May, and June median flow	Increase (higher flows during wet season)	Channelization increases drainage efficiency. More precipitation is routed to the stream network.
High Flow Duration	2+ Year flood duration	Decrease (shorter events)	Increased efficiency of stream network results in shorter high flow events.
High Flow Magnitude	3-Day annual high flow	Increase (higher flows)	Efficient drainage concentrates flow and magnifies peakflow.
Rate of Change	Flashiness Index	Increase	Channelized reaches increase responsiveness of the stream network.

Cumulative effects of dams in catchment – Table 2.4-2 includes draft of the potential cumulative effects of dams in a catchment on several flow characteristics. The overall assumption is that dams within the catchment increase water storage and may increase runoff when reservoirs are full or frozen. Recognize that individual dams, especially dams with controlled releases, could affect any of the flow metrics in any direction, the hypotheses relate to the cumulative effects of dams within a watershed.

Table 2.4-3 Hypothesized effects of dams within the catchment on flow metrics.

Flow characteristic	Flow metric	Hypothesized effect of dams in catchment on flow metric	Assumption or explanation
Summer/Fall – Magnitude	July, Aug, Sept, and Oct median flow	Decrease	Presence of reservoirs increase evaporation which leads to decreased stream flow. Increased reservoir storage also decreases streamflow.
Spring – Magnitude	March, April, May, and June median flow	Increase	Assuming reservoirs are frozen or full in spring, more precipitation is delivered to the stream network than if reservoirs / ponds were not present.
Low Flow Magnitude	7- day annual low flow	Decrease	Presence of reservoirs increase evaporation which leads to decreased stream flow. Increased reservoir storage also decreases streamflow.
High Flow Magnitude	3-Day annual high flow	Increase (higher flows)	Annual high flow usually occurs in spring, when reservoirs are frozen or full. This impervious surface concentrates flow and magnifies peakflow events.
Rate of Change	Flashiness Index	Increase	Presence of reservoirs increases flashiness in spring, but may decrease flashiness in summer. Overall, increases annual flashiness values.

These hypotheses are discussed for each of the four watersheds in Section 3 Watershed results.

3. WATERSHED RESULTS

3.1 Shiawassee River, Michigan

3.1 Watershed Results, Shiawassee River, Michigan

Location: The Shiawassee watershed is located south and west of Saginaw Bay in central Michigan and drains approximately 1160 square miles (742,400 Acres) via the Shiawassee River. The Shiawassee River flows northward into the Flint River and then joins the Tittabawassee and Cass Rivers to form the Saginaw River, which then flows into Saginaw Bay and Lake Huron. At least six subwatersheds drain the larger watershed and flow into the