Studies to Support an Implementation-Ready TMDL for Ruddiman Creek

Final Report

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List of Acronyms

ANOVA – analysis of variance
AOC – Area of Concern
AWRI – Annis Water Resources Institute
BMP – best management practice
BOD – biochemical oxygen demand
BOM – benthic organic matter
BUI – beneficial use impairment
CN – curve number
DCIA – directly connected impervious area
DO – dissolved oxygen
DPW – Department of Public Works
EPA/USEPA – United States Environmental Protection Agency
FDC – flow duration curve
FI – (Richards-Baker) Flashiness Index
FTC&H – Fishbeck, Thompson, Carr, & Huber, Inc.
GCM – general circulation model
GI – green infrastructure
GIS – geographic information system
GVSU – Grand Valley State University
IA – Integrated Assessment
LA – Load Allocation
LC – Loading Capacity
LID – low impact development
MAMSC – Muskegon Area Municipal Stormwater Committee
MB – main branch
MDEQ – Michigan Department of Environmental Quality
MOS – margin of safety
NB – north branch
NPDES – National Pollutant Discharge Elimination System
ORP – redox potential
P-51 – Procedure 51 (macroinvertebrate score)
PAH – polycyclic aromatic hydrocarbon
R-B – Richards-Baker (Flashiness Index)
RBP – Rapid Bioassessment Protocols
SD – standard deviation
SpC – specific conductance
SRP – soluble reactive phosphorus
SSC – suspended sediment concentration
SWAS – Surface Water Assessment Section
SWMM – Storm Water Management Model
TDS – total dissolved solids
TKN – total Kjeldahl nitrogen
TMDL – Total Maximum Daily Load

TP – total phosphorus
TSS – total suspended Solids
WARSSS – Watershed Assessment of River Stability and Sediment Supply
WB – west branch
WLA – Waste Load Allocation
WMSRDC – West Michigan Shoreline Regional Development Commission
WQS – Water Quality Standards

Executive Summary

Highly urbanized watersheds alter ecosystem structure and function, leading to many implications for the biotic integrity of streams. Ruddiman Creek, consisting of 3 tributaries (main, north, and west branches) that flow into Ruddiman Lagoon, is an urbanized and historically impaired water body in the Muskegon Lake Area of Concern in Muskegon County, MI. All 3 tributaries are on Michigan's 303(d) list due to biological community impairment as a result of excess sediment transport during storm flows (i.e., flashy hydrology), which is associated with the high degree of directly connected impervious area (DCIA) in this watershed. DCIA is defined as the subset of impervious surfaces that route stormwater directly to streams via stormwater conduits.

We used an Integrated Assessment (IA) approach to collect the information necessary for the Michigan Department of Environmental Quality (MDEQ) to develop an implementation-ready Total Maximum Daily Load (TMDL) for biota for the Ruddiman Creek watershed. Specifically, we 1) involved local stakeholders throughout the project to help inform the TMDL process and select appropriate stormwater best management practices (BMPs), 2) monitored hydrology and sediment transport during baseflow and storm conditions between 2011 and 2012, 3) developed field-calibrated hydrologic models to identify effective stormwater BMPs to reduce flashiness in Ruddiman Creek, 4) developed hydrologic targets for each tributary based on model outputs, and 5) modeled current and projected sediment transport before and after BMP implementation.

The first chapter addresses the integrated assessment process, including the development of a Stakeholder Steering Committee, which provided opportunities for stakeholders to use the

output from various forecasting models to understand the future effects of different BMP scenarios.

The second chapter focuses on baseflow and storm flow monitoring of the tributaries and storm sewer sites. Ruddiman Creek's hydrology is very responsive to rain events, and the high flows carry suspended and bedload sediment. Storm event suspended sediment load was 2-3 orders of magnitude greater than during baseflow. Bedload was also much greater during storm events than baseflow, but was quite variable among sites due to varying substrate and upstream transport barriers (e.g., stream crossings, increased gradient, wooded wetlands, etc.) at the 6 tributary monitoring locations.

The third chapter describes how the monitoring data were used to populate the U.S. Environmental Protection Agency's "Storm Water Management Model" (SWMM), which was employed to model hydrologic and hydraulic dynamics of the Ruddiman Creek watershed. The model was field-calibrated and validated, and modeled and observed results compared well. The SWMM model was integral to the process of TMDL target development, as it was used to characterize the flashiness of Ruddiman Creek, which is causing negative impacts to the biotic community. Using the calibrated SWMM model, the Richards-Baker Flashiness Index (FI) was calculated for Ruddiman Creek. Previously established Richards-Baker FI values for 35 Michigan streams were plotted against their respective MDEQ Procedure 51 (P-51) macroinvertebrate scores, revealing that as the flashiness index increases, the trend is for the macroinvertebrate community score to decrease; the branches in Ruddiman Creek have both high flashiness indices and poor macroinvertebrate scores. To attain "acceptable" P-51 scores, mitigation of the high flow storm events that carry sediment into the stream and scour the stream banks is needed.   Reducing the "flashiness" of the stream is done by reducing the directly connected impervious area (DCIA) within the watersheds through a suite of Low Impact Development (LID) and Green Infrastructure (GI) BMPs.

Chapter 4 describes the development of a BMP Scoping Tool, which was used to identify a BMP "benchmark scenario" that determined the amount of DCIA reduction needed to reduce Flashiness Index values to a level that would result in acceptable P-51 macroinvertebrate scores, which is the ultimate goal of the TMDL. The Scoping Tool is a spreadsheet application that approximates the output from the SWMM model, but is easier and quicker to manipulate than the SWMM model, allowing for the evaluation of a wide variety of different implementation scenarios. This tool allows the user to allocate BMPs within multiple sub-catchments in the Ruddiman Creek watershed to assess how the BMPs reduce flashiness (concomitant with the predicted increase in the P-51 macroinvertebrate scores). Five BMPs (rain gardens, rain barrels, green roof, porous pavement/ underground detention, natural infiltration) were chosen for modeling based on their acceptability by the stakeholders, as well as their proven success in reducing stormwater runoff. Output from the Scoping Tool was then input back into the SWMM model, which was run to determine the final reductions in DCIA needed for each branch. These reductions were then used to compute the TMDL targets, specified as a percent DCIA for each branch. A BMP opportunity map was developed to identify the areas where BMP implementation will most likely reduce flashiness and increase biotic health in Ruddiman Creek. The Scoping Tool can then be used by stakeholders in conjunction with the BMP map to evaluate possible BMP implementation scenarios and account for progress made.

Chapter 5 describes the selection and use of DCIA as a hydrologic surrogate for the Ruddiman Creek biota TMDL. The TMDL targets for each branch are expressed as a percent DCIA. Loading capacity for both waste load and load allocations is presented, including a margin of safety. Seasonal variation and critical conditions are also discussed. By reducing the DCIA from 21% to 12% (171 acres) in the main branch, from 7.5% to 2.9% (6.3 acres) in the north branch, and from 16% to 2.8% (22 acres) in the west branch (all include an explicit 20% margin of safety) through BMP implementation, Ruddiman Creek should attain a healthy macroinvertebrate population. Several key assumptions accompany this approach, which are discussed in the chapter.

Chapter 6 describes our use of the FLOWSED model to calculate total sediment loads and suspended sediment concentration (SSC) in Ruddiman Creek as a result of meeting TMDL DCIA targets. Sediment is listed as the pollutant causing biological community impairment in the Ruddiman Creek watershed (Goodwin et al. 2012); however, our field samples did not show significant impairment from sediment, at least based on the threshold for protection of fish communities suggested by Alabaster and Lloyd (1982). As a consequence, we focused primarily on hydrology, but also explored the relationship between hydrologic changes and sediment load. We identified BMPs that could be installed to reduce DCIA and stabilize hydrology (i.e., rain gardens, porous pavement/underground detention, green roofs, and natural infiltration); depending on their location and number, their implementation was projected to reduce the sediment load for each branch by approximately 15% to 50%.

Finally, Chapter 7 provides a synthesis of our field and modeling results, as well as a review of the key assumptions associated with our analyses. To raise macroinvertebrate scores to the minimally acceptable level, DCIA must be reduced from 21% to 12% (171 acres) in the main branch, from 7.5% to 2.9% (6.3 acres) in the north branch, and from 16% to 2.8% (22 acres) in the west branch. Modeling results reveal that these DCIA reductions also will result in reductions of suspended sediment load of 13% (29 tons/yr) in the main branch and 54% (29 tons/yr) in the west branch. Achieving these reductions in directly connected impervious area is not a trivial task, and may be difficult to implement in a heavily urbanized watershed. While BMP locations may be driven by practical measures such as cost and land availability, their effectiveness will depend heavily on their location within the watershed.

Introduction

Stream ecosystems and their biota are governed by numerous processes that operate and interact directly and indirectly at many spatial and temporal scales. For example, changes in land use, which alter landscapes and ecosystem structure and function, have many implications for the biotic integrity of streams (Allan 2004). With increasing development, landscapes shift from natural lands to surfaces with greater amounts of impervious cover (i.e., hardened surfaces such as roads, rooftops, parking lots; Dougherty et al. 2006), resulting in changes to the hydrologic regime of streams (Paul and Meyer 2001). Urbanization increases both impervious surfaces and stormwater conveyance, causing an increase in the magnitude and frequency of storm flows (i.e., “flashy hydrology”) compared to non-urbanized streams (Walsh et al. 2005). Flashy hydrology occurs because large areas of hardened surfaces and stormwater pipes quickly transport runoff to streams, much of which would otherwise permeate through the soils and recharge aquifers (Paul and Meyer 2001). Severe storms can result in heavy runoff; the effects from these episodic events are expected to increase as global climate change progresses (Masden and Figor 2007, Patz et al. 2008). Excess stormwater runoff has the following effects: increased nutrient, sediment, and pollutant transport; altered thermal regimes; eroded streambeds; and dislodged benthic organisms (Roy et al. 2005, Chadwick et al. 2006, Brown et al. 2009).

One of the key impacts associated with flashy stream flows is an increase in sediment flux, as both biotic habitat quality and quantity are negatively affected (Bledsoe and Watson 2001, Wagenhoff et al. 2012). Stormwater collects excess debris and surface sediment as it is transported along impervious surfaces and into conveyance systems. Additionally, the power and increased speed of the water entering the system can scour the streambed and erode stream banks. The resultant increase in suspended and bedload sediment transport can, in turn, alter stream morphology. For example, high peak flows can cause upstream scour leading to downstream sediment deposition, thereby increasing stream width and local elevation, resulting in bed aggradation and a loss of benthic habitat (Coats et al. 1985). As bedload and suspended sediment transport increase, prime biotic habitat becomes embedded with fine sediment, becoming more unstable. Reduced interstitial space in the streambed leads to decreases in specialized biota, thereby influencing the feeding, refugia, and reproduction of sensitive macroinvertebrates and fishes (Waters 1995, Newcombe and Jensen 1996, Sutherland et al. 2002). Poor biotic health caused by stormwater runoff often requires management intervention and ecosystem restoration.

Stormwater runoff and management are becoming increasingly important to municipalities because of their impacts on clean drinking water, flood prevention, drainage systems, and sanitation (Chocat et al. 2001). Though there is a concern for the quality of natural resources, there is rarely a consensus on how management should address those concerns. In addition, uncertainties related to stormwater mitigation and control, cost, operation and maintenance can delay implementation of stormwater best management practices (BMPs), including low impact development (LID), which is a category of stormwater management that seeks to retain/infiltrate stormwater at its source (Roy et al. 2008). Due to the many uncertainties surrounding the scientific and societal issues associated with stormwater management, approaches that are most likely to succeed involve local participation with multiple perspectives (Berkes et al. 2003, Gruber 2010).

The present study addresses the issues of stormwater runoff, sedimentation, and biotic health in the Ruddiman Creek watershed located in Muskegon County, Michigan. This heavily urbanized watershed is part of the Muskegon Lake Area of Concern (AOC). Muskegon Lake (including its contributing waterbodies) was listed as an AOC in 1985 due to historical discharges of nutrients, solids, and toxics, which resulted in severe ecological impairment (Steinman et al. 2008). To help delist Muskegon Lake as an AOC, a number of efforts have been completed to address and restore the lake's beneficial uses, though further efforts are still needed for Ruddiman Creek (MDEQ 2011). Due to the poor macroinvertebrate and fish communities in Ruddiman Creek, it is not meeting the other indigenous aquatic life and wildlife and warm water fishery designated uses.

Section 303(d) of the federal Clean Water Act and the United States Environmental Protection Agency's (USEPA's) Water Quality Planning and Management Regulations (Title 40 of the Code of Federal Regulations, Part 130) requires states to develop TMDLs for water bodies that are not meeting Water Quality Standards (WQS) for one or more contaminants. The TMDL process establishes the allowable loadings of a pollutant to a water body based on the relationship between pollutant sources and in-stream water quality conditions. TMDLs provide a basis for determining the pollutant reductions necessary from point and/or nonpoint sources to restore and/or maintain the quality of water resources. **Our overall project goal was to collect the technical information necessary to support the Michigan Department of Environmental Quality (MDEQ) in the development of a TMDL for biota.** Developing TMDL targets for directly connected impervious area (DCIA) to achieve reductions in flashiness and sediment loads, as well as identifying specific BMPs to meet TMDL targets, will help guide management decisions to improve macroinvertebrate and fish communities, with the goal of removing Ruddiman Creek from Michigan's 303(d) list of impaired waterbodies. This also will aid in removing the beneficial use impairment (BUI) for degraded benthos in the Muskegon Lake AOC.

We developed a flow chart to depict how the various elements fit together in this report (Fig. 1). Within an Integrated Assessment (IA) framework (Chapter 1), we monitored hydrology and sediment dynamics in Ruddiman Creek (Chapter 2) and used the data to model hydrology using a Stormwater Management Model (SWMM; Chapter 3) and sediment using a FLOWSED model (Chapter 6) for the watershed. The SWMM model was used to calculate existing Flashiness Index (FI) values (Chapter 3.3) and flow duration curves (FDCs; Chapter 3.1) for Ruddiman Creek. Previously established Flashiness Index values for 35 Michigan streams were plotted against their respective MDEQ Procedure 51 (P-51) macroinvertebrate scores; this relationship was used to set Flashiness Index goals to achieve "acceptable" P-51 macroinvertebrate scores in Ruddiman Creek (Chapter 3.3). A BMP Scoping Tool (Chapter 4) was developed, whose output approximates the results from the SWMM model, but is easier and quicker to manipulate than the SWMM model. This tool allowed us to evaluate a wide variety of implementation scenarios, and to identify a BMP "benchmark scenario", which would reduce directly connected impervious area (DCIA) to an amount that would result in the flashiness reductions necessary to achieve "acceptable" P-51 macroinvertebrate scores (Chapter 4.3). The output from the Scoping Tool was input back into the SWMM model (Chapter 4.3), which was used to develop the final reductions in DCIA (i.e., hydrologic targets) needed for each branch (Chapter 5). The FLOWSED sediment model was used to estimate the existing annual sediment yield in Ruddiman Creek, as well as future sediment yield based on meeting the TMDL DCIA targets and the resultant reduction in flashiness (Chapter 6). This, in turn, was used to estimate the projected sediment reduction following BMP implementation (Chapter 6.3). The chapters in the report describe our process of developing hydrologic targets and identifying the associated projected sediment reductions, which ultimately will be used by MDEQ to develop Ruddiman

Creek's TMDL for biota. In addition, appendices are included that provide supporting data, such as water quality and geomorphology, as well as BMP information and community feedback.

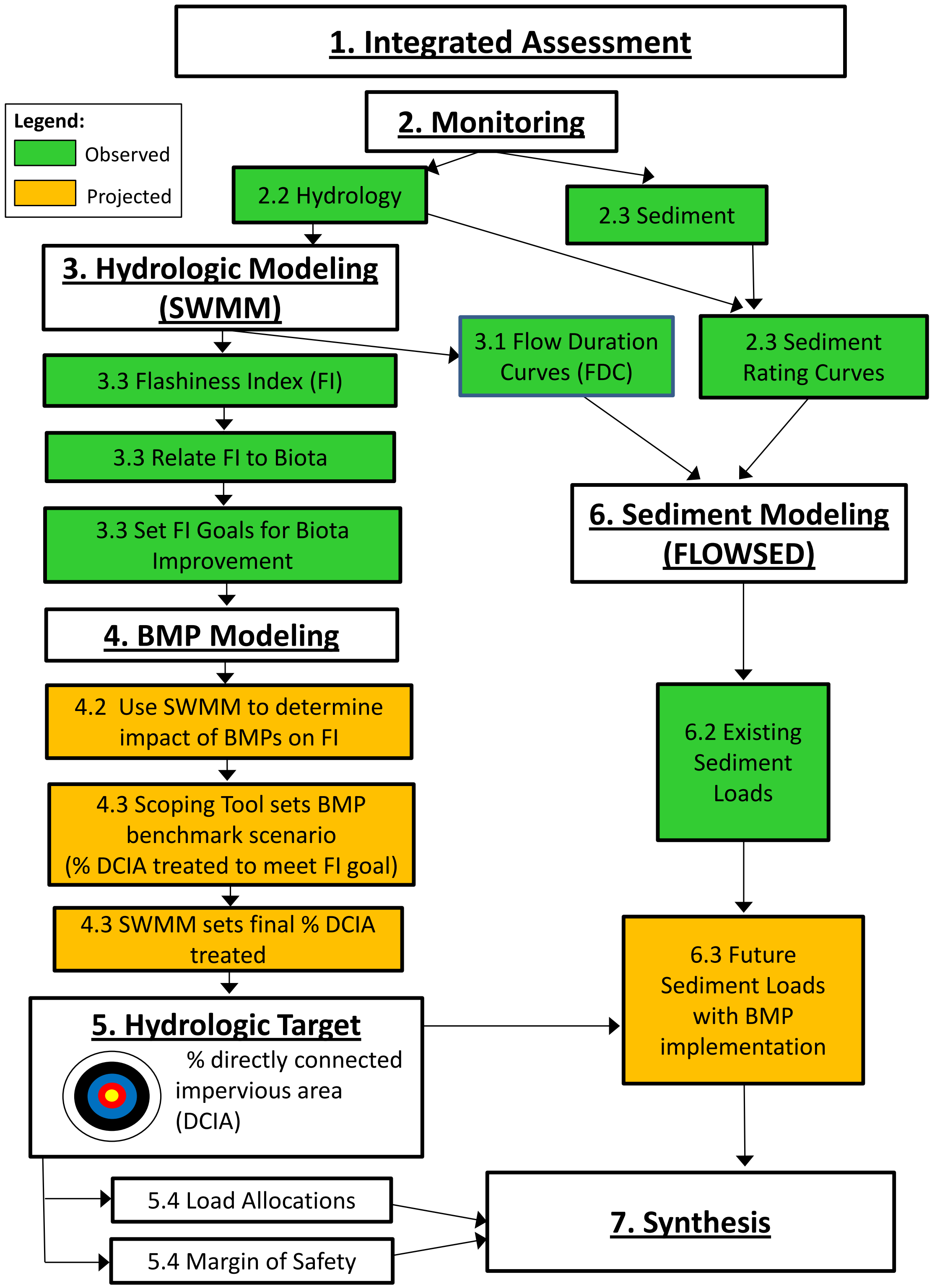


Fig. 1. Flow chart illustrating the process of hydrologic target development and sediment reduction projected with BMP implementation. Green shading identifies observed outcomes and orange shading identifies projected outcomes. Each step is labeled with its chapter or subchapter number.

Chapter 1: Integrated Assessment

Because of the complex ecological, political, and social processes related to stormwater management, the project team implemented an Integrated Assessment (IA) approach. Natural hydrology transcends jurisdictional boundaries and conventional solutions, and as a result, the IA approach is being utilized more often as a tool for solving environmental resource management questions and policy issues (Hisschemöller et al. 2001, Newham et al. 2007, Riahi et al. 2007). IA is a process that synthesizes existing natural and social scientific knowledge to solve a natural resource management problem or policy question (Parson 1995, Hillman et al. 2005). To increase our effectiveness at answering the policy question, our IA incorporated a broad range of participants - scientists (project team), decision-makers, stakeholders (project partners), and members of the general public (Rabalais et al. 2002).

We slightly modified the IA approach outlined in Scavia and Bricker (2006; Fig. 1.1).

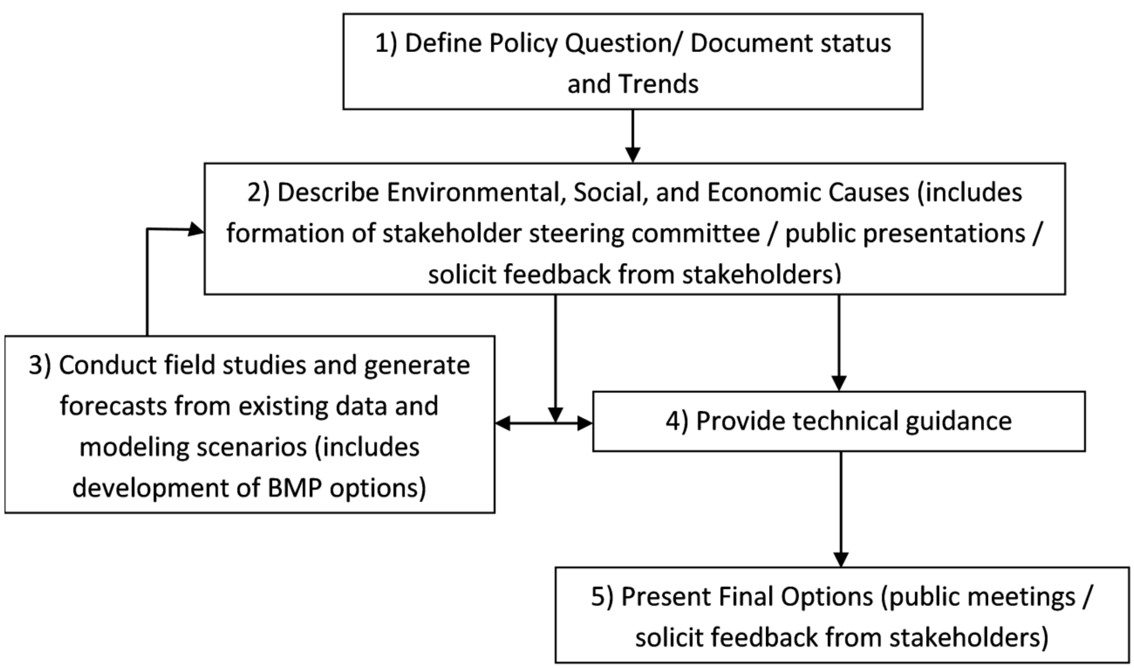


Fig. 1.1. Flow chart showing the methodology for our 5-step integrated assessment approach to address stressors in the Ruddiman Creek watershed.

1.1 Step 1 – Define Policy Question/Document Status and Trends

The key policy questions were what are the environmental impairments affecting the biota in Ruddiman Creek and how can they be removed or reduced in magnitude? Our main focus was to assess the environmental, social, political, and economic aspects of developing a TMDL for biota in Ruddiman Creek. Using existing stakeholder groups as a foundation, we developed a Stakeholder Steering Committee to help inform the IA process, identify data gaps and water quality management opportunities, and identify key stakeholders and other essential participants in the development and implementation of the Ruddiman Creek TMDL for biota following project completion. This, in combination with existing data sets (see Step 2), allowed us to document Ruddiman Creek's current status and trends.

The Stakeholder Steering Committee (Appendix A) included representatives from the City of Muskegon, the City of Norton Shores, the City of Roosevelt Park, and the City of Muskegon Heights, citizen boards, homeowners, developers and builders, commercial interests, local and regional conservation groups and agencies, recreational users, churches, teachers, MDEQ, Muskegon County, the Muskegon Lake Watershed Partnership, and the Muskegon River Watershed Assembly. Stakeholders were identified throughout the project to ensure a broad range of participation. The Stakeholder Steering Committee was led by the project team, which included representatives from MDEQ, GVSU-AWRI, the West Michigan Shoreline Regional Development Commission (WMSRDC), and Fishbeck, Thompson, Carr, and Huber, Inc. (FTC&H). Attendance by committee members was variable, with regular attendance by project team members, but intermittent attendance by other stakeholders. It appeared that attendance was influenced by the meeting agenda, and if the topics being covered were relevant to their constituency.

Stakeholder involvement in the IA process included representative service on the Stakeholder Steering Committee and the identification of venues for public education events regarding water quality issues, which gave the project team the opportunity to introduce the Ruddiman Creek IA to new audiences. Project team members presented project updates and outcomes to the Stakeholder Steering Committee (Table 1.1) and to local community groups throughout the project period. At the final Stakeholder Steering Committee meeting, attendees were given an opportunity to see monitoring updates, share BMP/LID experiences and goals, and use the model forecasts to help conceptualize the environmental effects of multiple BMP scenarios throughout the watershed. Stakeholder feedback in the form of comments and discussions at public meetings were used to develop a menu of alternative BMPs (Appendix B, Table B.1) to implement the Ruddiman Creek TMDL for biota.

Selected Stakeholder Steering Committee members were involved in the review of the completed project report. Additional public meetings were held at the conclusion of this project, summarizing outcomes, including BMP information, educational materials, alternatives and potential next steps. Roundtable discussion was encouraged to ensure that stakeholders understood and would be willing and able to implement the forthcoming TMDL, to highlight the strengths and weaknesses of each alternative, and to identify areas where additional data collection is needed. This feedback was used to refine our findings and overall assessment throughout the project.

Table 1.1. Ruddiman Creek Stakeholder Steering Committee meetings. All meetings included extensive outreach to specified audiences for feedback on certain discussion topics (presentations can be viewed at www.gvsu.edu/wri/director/ruddiman).

Meeting Date	Meeting Host	Participants	Target Audience	Discussion Topics
November 23, 2010	Glenside Neighborhood Association and Ruddiman Creek Task Force	42	General public	Kick-off meeting: Introduction to project/team/concepts; stakeholder outreach; local conditions of concern; applications of BMPs
February 8, 2011	Annis Water Resources Institute	17	Stakeholders/ General public	Introduction to project/team/concepts; IA approach and stakeholder involvement; meeting format and preferred communication
May 4, 2011	Mercy Health Partners	21	Stakeholders/ General public/ Institutional/ Commercial	Project overview/update; project flyer input; sampling overview and update; solicit stakeholder participation and future topics of discussion
August 9, 2011	CWC Textron	22	Stakeholders/ General public/ Municipal/ Industrial	Tour of CWC Textron's stormwater system; project overview; effects of stormwater runoff; current biotic health; current municipal stormwater management; future municipal BMPs (MAMSC* representative presentation); current habitat restoration update; future outreach ideas
November 8, 2011	McGraft Memorial Congregational Church	17	Stakeholders/ General public/ Residential	Project overview/update; public involvement; sampling results and updates; new watershed boundary; future modeling and BMP identification
June 26, 2012	Hooker De Jong, Architects and Engineers	24	Stakeholders/ General public/ Construction/ Architects/ Engineers	Project overview/update; sampling strategy; hydrologic modeling; LID and BMP presentation and feedback; funding opportunities/handout; next steps
October 2, 2012	Michigan Alternative and Renewable Energy Center and MLWP**	27	Stakeholders/ General public	Project overview/update; synthesis of data; BMP modeling with stakeholder feedback; BMP cost-benefit analysis; discussion of TMDL targets; next steps for TMDL development

*Muskegon Area Municipal Stormwater Committee
**Muskegon Lake Watershed Partnership

1.2 Step 2 – Identify and Examine Existing Data Sets and Other Information

The IA involved identifying and examining existing data sets and other information. A considerable number of studies have been conducted in the Ruddiman Creek watershed and Muskegon Lake AOC, much of which were already available to the project team. Existing information documented historical industrialization and urbanization which have severely degraded the Ruddiman Creek watershed.

Past studies have identified areas of sediment contamination with heavy metals and polycyclic aromatic hydrocarbon (PAH) compounds in the three branches of Ruddiman Creek (Earth Tech 2002), a waste drum disposal site on the main branch south of Barclay Avenue, and a site on the west branch near Sherman Boulevard where groundwater contaminated with petroleum products was venting into the stream (Rediske 2004). Remediation programs were initiated in 2003 to remove the waste drums (Hilgeman 2005) and in 2005 to remove contaminated sediments in the main branch (USEPA 2011). A total of 89,870 cubic yards of contaminated sediments were removed from the main branch and Ruddiman Lagoon, which contained 2,800 pounds of cadmium, 204,000 pounds of chromium, 126,000 pounds of lead, and 320 pounds of polychlorinated biphenyls (USEPA 2011). The remediation was divided into three areas: Ruddiman Pond, Glenside Boulevard, and Barclay Street (Appendix O). Specific sediment quality goals for the remediation were established, and verification sampling was conducted to document that the goals were met. The remediation of the main branch also utilized a sand/geotextile fabric/stone barrier over the remaining sediment to prevent recontamination. Hydrologic stabilization structures, including rock wing dams, braided stream channels, and a detention basin were constructed to minimize the effects of stormwater on downstream water quality. Based on our field surveys as part of this project, the braided stream channels installed in the Glenside and Barclay remediation areas (Appendix O) have been filled with sediment and are no longer functional. The rock wing dams and riffle areas that were installed west of Barclay Street (Appendix O) also were degraded by sedimentation and excessive stream flow. The wing dam near the outfall pipe and the detention basin that were constructed east of Barclay Street (Appendix O) are still present; however, their effectiveness appears to be overwhelmed when there is excessive hydrologic flow, which has resulted in downstream sedimentation and erosion.

Despite the remediation, Nederveld (2009) found that chronically degraded habitat conditions (e.g., sedimentation, poor woody debris retention, loss of riparian vegetation) and hydrologic impairments continued to negatively influence the macroinvertebrate community inhabiting Ruddiman Creek's main branch. Other investigations have shown that elevated flow rates can disrupt aquatic habitat (Scullion and Stinton 1983, Gurtz et al. 1988, Wood and Armitage 1997) and subsequently dislodge, damage, or kill aquatic invertebrates (Sagar 1983, Feminella and Resh 1990).

In 2008, a post-remediation study of the main branch and Ruddiman Lagoon was completed to determine the effectiveness of the contaminated sediment removal conducted in 2005/2006 (Battelle 2009). PAH compounds at levels in excess of 40 mg/kg were found in 12 out of 27 samples collected from Ruddiman Lagoon and in 13 out of 28 samples collected in the main branch; these levels are of concern because the consensus-based sediment quality guideline (Probable Effect Concentration) for PAH compounds is 22.6 mg/kg (MacDonald et al. 2000). With respect to the criteria established for the 2006 remediation, the following exceedances were noted:

- 7 of 27 samples in Ruddiman Lagoon and 7 of 28 samples in the main branch exceeded the cleanup criterion for PCBs (> 1 mg/kg)

- 3 of 27 samples in Ruddiman Lagoon and 8 of 28 samples in the main branch exceeded the cleanup criteria for metals (> 10 mg/kg Cd and 400 mg/kg Cr)

Sediment toxicity assays with *Chironomus dilutus* were conducted in 2008 at 5 locations in the Ruddiman Lagoon and the main branch, and percent survival ranged from 0-28% compared to 71% in the control (Battelle 2009). These results suggest that a new source of contamination may be present in Ruddiman Creek, and/or contaminants from non-remediated areas have been mobilized and have reached the creek and lagoon. More recently, MDEQ conducted a sediment survey in July 2011 (Knoll and Lipsey 2012) and reported elevated levels of various heavy metals and PAH compounds, which in addition to Battelle's 2008 sediment toxicity results, suggests that chemical contamination may be impacting fish and macroinvertebrate communities in Ruddiman Creek. Further post-remediation sampling by MDEQ took place in August 2012; as of January 2013, results were not yet available from MDEQ.

Recent Surface Water Assessment Section (SWAS) Procedure 51 (P-51) biological surveys by MDEQ (Lipsey 2009; Knoll and Lipsey 2012) have confirmed that Ruddiman Creek is not meeting the Other Indigenous Aquatic Life and Wildlife and Warm Water Fishery designated uses because of impaired fish and macroinvertebrate communities.

With the information gleaned in this step, we developed a presentation on the water quality issues facing Ruddiman Creek and the Muskegon Lake AOC, as well as the need for TMDL development and implementation. These presentations were given at meetings of the Stakeholder Steering Committee and the Muskegon Lake Watershed Partnership (Table 1.1).

1.3 Step 3 – Conduct Field Investigations and Generate Ecological Forecasts.

Field investigations complemented the existing data (Fig. 1.1). The investigations focused on generating critical information needed for developing modeling scenarios and setting TMDL targets, which are to be used by MDEQ to develop a biota TMDL for Ruddiman Creek following project completion. Details on the field investigations are given in Chapter 2.

Data generated during the field investigations were used to generate modeling scenarios and create ecological forecasts for Ruddiman Creek. The goal of the ecological forecasts was to determine if watershed modifications can be effective at reducing the system's flashiness, thus reducing negative impacts to the biotic community. Details on the ecological forecasts are given in Chapter 3 (Hydrologic Modeling), Chapter 4 (BMP Modeling), and Chapter 6 (Sediment Modeling).

1.4 Step 4 – Provide Technical Guidance

Based on the ecological forecasts generated in Step 3 of the IA, the project team identified appropriate targets for the Ruddiman Creek's TMDL for biota and developed specific recommendations on implementing the TMDL, including BMP identification and cost estimations. Further, the amount of sediment reduction expected with BMP implementation was projected. Details on the TMDL targets are in Chapter 5; BMP recommendations and cost estimations are in Appendices C and D; and sediment projections are in Chapter 6.

1.5 Step 5 – Community Feedback

One of the strengths of the Integrated Assessment approach is its potential effectiveness in outreach and education (Hisschemöller et al. 2001). The Ruddiman Creek IA involved the public from the start and used their feedback to refine our assessment, which was then presented to the Stakeholder Steering Committee, forming a continuous feedback process.

To select the most appropriate BMPs for the Ruddiman Creek watershed, stakeholders were presented with a suite of options developed from the literature, various modeling scenarios, and experiences provided by the project team and various stakeholders. These options were presented to the stakeholders, including municipalities and other landowners, within the watershed to generate feedback on which BMPs would be most appropriate for their communities. We explicitly solicited input from the municipalities located within the Ruddiman Creek watershed, which met monthly as the Muskegon Area Municipal Stormwater Committee (MAMSC). The MAMSC coordinates stormwater planning and management efforts under a voluntary watershed-based program, to meet their Phase II/MS4 stormwater permit requirements. Each of the municipalities and the MAMSC were invited to participate on the Ruddiman Creek Stakeholder Committee. The MAMSC appointed their consultant to provide their consolidated input to the project. Unfortunately, input was intermittent, given that this involvement was voluntary and uncompensated; in the future, provision of incentives (financial or otherwise) might ensure more consistent input and involvement from different sectors.

Details on the outcome of these efforts are given in Appendices B-D.

Chapter 2: Monitoring

The primary purpose of the Ruddiman Creek field investigations was to generate the data needed to set TMDL targets and inform BMP implementation. Thus, the main focus of the monitoring effort was characterization of hydrology and sediment dynamics. Additional information was gathered on water quality (Appendix G), geomorphology (Appendix H), and habitat parameters (Appendix H.4) that provide insight on the current status of Ruddiman Creek and can be used or reevaluated in future monitoring efforts for BMP effectiveness.

2.1 Site Description

Ruddiman Creek is in a heavily urbanized and historically degraded watershed (11 km^2, 4.24 mi^2) within the Muskegon Lake AOC. Municipalities within the watershed include portions of the Cities of Muskegon, Norton Shores, Roosevelt Park, and Muskegon Heights, Michigan (43º 14’ 04”; 86º 17’ 05”). The hydrography consists of three branches (main, west, and north), each of which feed into Ruddiman Lagoon (Fig. 2.1), which then connects to Muskegon Lake. The 2008 land use and cover (see Appendix E for land use and cover update methods) consists of residential (52.3%), commercial/services/institutional (20.1%), industrial (11.5%), deciduous forests (5.3%), urban/recreational grasses (5.4%), herbaceous open land/grasslands (3%), wetland (0.9%), transportation/communication/utilities (0.8%), and water (0.7%) (Fig. 2.2). The riparian corridor is mixed hardwood forest with a floodplain that slopes to mixed shrub/scrub and cattail marsh wetlands. Soils typically have high infiltration rates.

Sampling locations were chosen to represent spatial variation in water quality and hydrology in the three branches of Ruddiman Creek (tributary sites) and stormwater collection system (storm sewer sites) (Fig. 2.1). The project team identified contributing runoff areas for each site (Table 2.1; see Chapter 3 for additional information). Main branch stations, MB1 and MB2, were located downstream of the primary stormwater outlet and a major road stream crossing, respectively. West branch locations, WB1 and WB2, were located downstream of stormwater outfalls and major road stream crossings, respectively, while WB3 was located near the discharge point to Ruddiman Lagoon. The north branch station, NB, was located at a point of moderate stream gradient before it discharged into the wetlands of Ruddiman Lagoon. Three storm sewer sites (SS1, SS2, and SS3) were located in key service areas of the stormwater collection system, which serve as the headwaters of the main branch (Fig. 2.1).

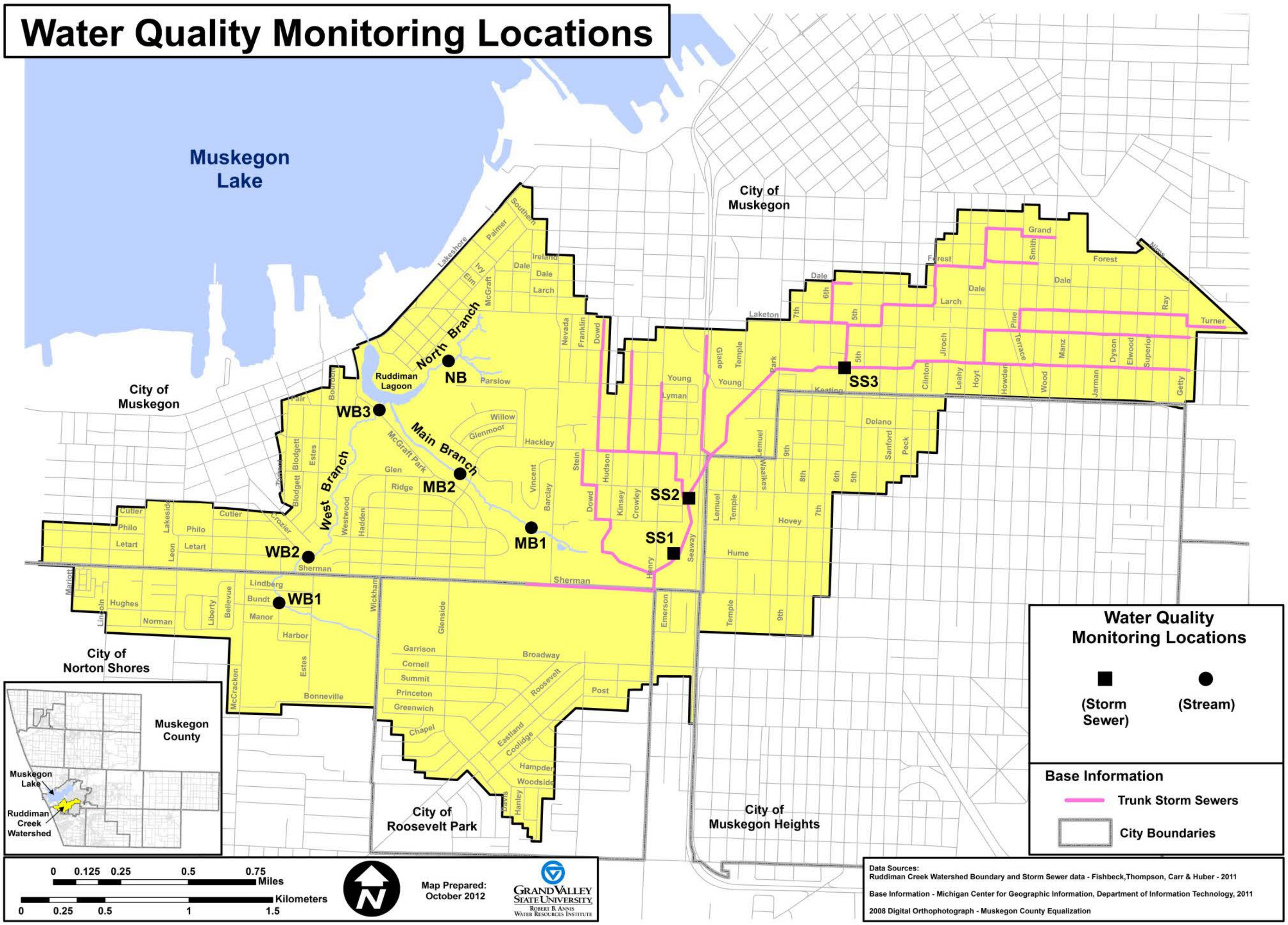


Fig. 2.1. Ruddiman Creek 2011-2012 monitoring locations

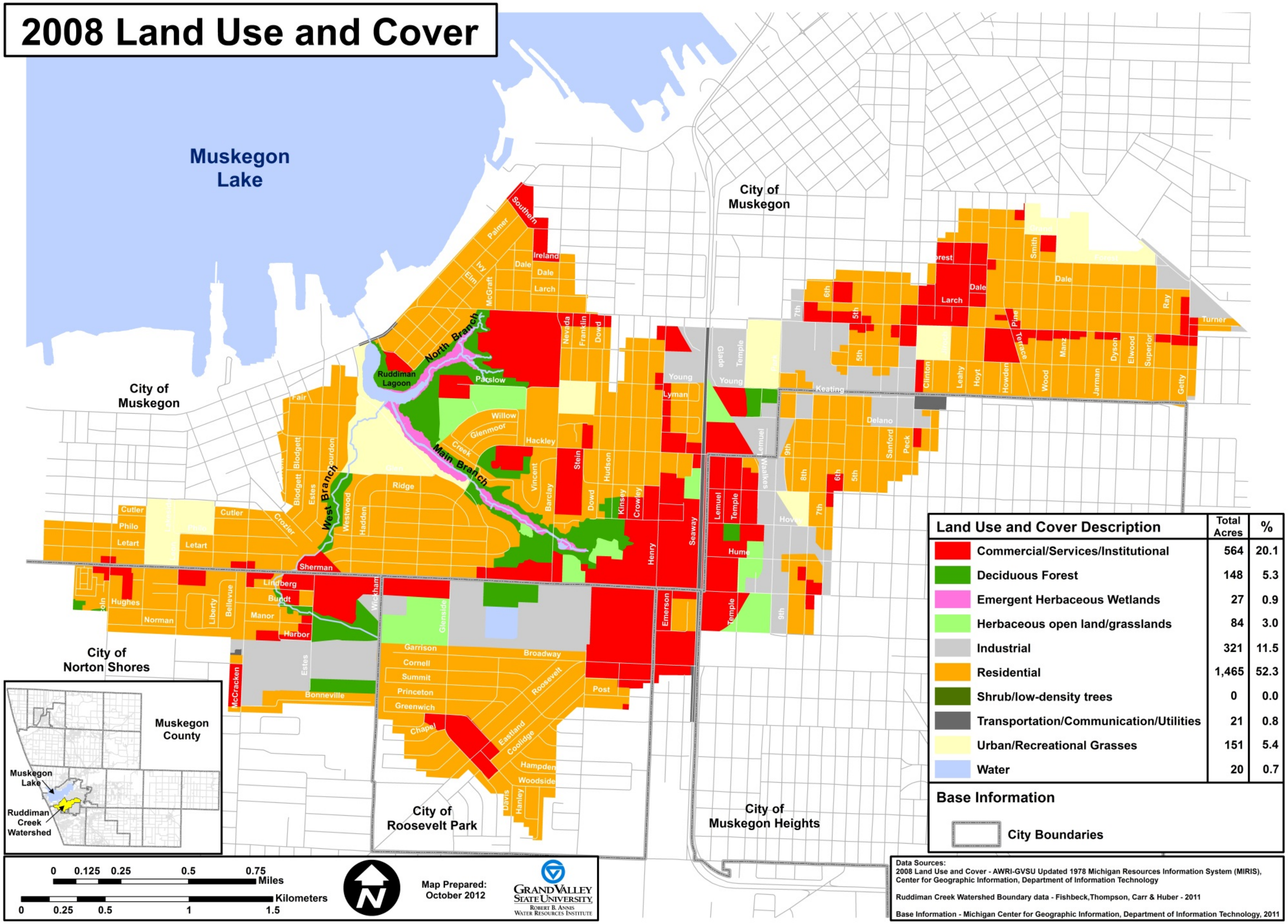


Fig. 2.2. Updated Ruddiman Creek 2008 land use and cover (see Appendix E for details).

Table 2.1 Upstream drainage area contributing to each monitoring location. Drainage areas include all sub-catchments upstream of each location.

Monitoring Location	Upstream Sub-catchment area, km^2 (mi^2)
SS3	2.05 (0.79)
SS2	4.01 (1.55)
SS1	4.66 (1.80)
MB1	5.76 (2.23)
MB2	6.23 (2.40)
NB	0.90 (0.35)
WB1	1.48 (0.57)
WB2	3.15 (1.22)
WB3	3.68 (1.42)

2.2 Hydrology

2.2.1 Methods

Submersible pressure and temperature recording systems (i.e., transducers; HOBO model U20) were installed within PVC stilling wells at each tributary site. Pressure was logged at 10-minute intervals throughout the study period and corrected for atmospheric pressure, using data collected by an additional transducer suspended at the top of the NB stilling well. Stream stage was measured manually during each visit using staff gauges attached directly to each stilling well. Measured stage values were regressed against atmospheric-corrected pressure readings; the resulting linear function was applied to the entire record of pressure readings to yield a high-frequency record of stream stage for the study period.

To develop a continuous hydrograph for tributary sites, manual flow measurements were taken at permanently-marked transects over a range of stages from base flow to storm flow, with a minimum of 12 measurements per location. Water depth and velocity were measured at twelve equally-spaced points along permanent transects using a Marsh-McBirney Flow Mate 2000 flow meter attached to a top-setting wading rod, according to USGS protocols (Rantz et al. 1982). The Windows-based hydrologic software, HYDROL-INF (Chu and Steinman 2009) was used to calculate stream discharge. Manual measurements were not taken at a regular time interval; rather, they were taken intensively during the first months of the project to develop discharge models, and as needed throughout the rest of the project to refine the models. Measured discharge was regressed against both measured stage values and atmospheric-corrected pressure recorded at the time of discharge measurement. The best-fit model was selected for each tributary site and the model function was applied to the high-frequency stage or pressure records, previously described. The stage-discharge model was used for 3 sites (MB1, MB2, WB2) and the pressure-discharge model was used for 3 sites (NB, WB1, WB3). The result was a hydrograph for each tributary site over the study period. The models were used to calculate discharge based on measured stage or pressure during monitoring events when manual measurements were not taken.

Discharge was determined at the storm sewer locations using ISCO 2150 Area Velocity Flow Modules and Sensors (Teledyne/ISCO 2009), which measure both velocity and water level. Using the geometric shape of the storm sewer pipe, a geometric relationship was established between depth and flow area and used to convert depth measurements into flow area. Flow rate was calculated by multiplying the flow area by average velocity. Measurements were taken in the three storm sewer locations every 5 minutes for a 13 month period beginning in January 2011 and ending in February 2012.

A suite of hydrologic variables considered important to benthic biota (Richter et al. 1996, Poff et al. 1997, Helms et al. 2009) was derived using the modeled discharge data for each site. These variables characterize the frequency and duration of spate flow (i.e., storm flow) over the course of a year. Magnitude (M) was determined by calculating median discharge from February 1, 2011-January 31, 2012. Spate flow frequency was determined by counting the number of occurrences when discharge was greater than 3 × M, 5 × M, and 7 × M. To avoid over-counting the number of events meeting a given magnitude criterion, discharge values exceeding the criterion that occurred within one hour of each other were considered to belong to the same event. Spate flow duration was determined by calculating the number of hours when discharge was greater than 3 × M, 5 × M, and 7 × M.

2.2.2 Results

Continuous discharge was modeled based on pressure (tributaries) and water level (sewers) data logged from January 24, 2011-February 22, 2012 at the sewer sites and from January 27, 2011-May 17, 2012 at the tributary sites (Table 2.2, Fig. 2.3, Appendix F). Data beyond the 13-month monitoring period were collected from the tributary sites to allow for additional storm event monitoring. Discharge was greatest in the main branch and lowest in the north branch (Fig. 2.3). Average baseflow discharge over the monitoring period ranged from 0.006-0.055 m^3/s in the storm sewers, 0.092-0.104 m^3/s in the main branch, 0.003 m^3/s in the north branch, and 0.023-0.049 m^3/s in the west branch (Table 2.3).

The six storm events that were monitored had rainfall totals ranging from 0.11-0.64 in, with intensities ranging from 0.09-0.79 in/hr (Table 2.3). In the main branch, including the storm sewers, the storm with the greatest intensity (9/3/11) produced the highest average discharge and the storm with the greatest rainfall total (6/9/11) resulted in the longest storm flow duration

(Table 2.3). In the north branch, the storm that produced the greatest discharge was the only winter storm event (12/14/11) and the storm that resulted in the longest duration of storm flow was the most intense storm (9/3/11; Table 2.3). In the west branch, the storm that had the longest duration of rainfall and the second-highest rainfall total (0.56 in; 3/30/12), resulted in both the greatest average discharge and longest duration of storm flow at WB1 and WB2 (Table 2.3).

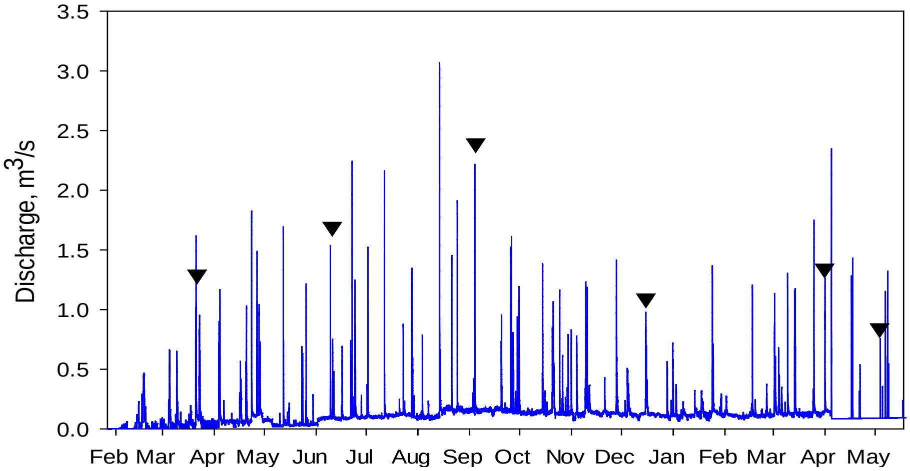
Although the magnitude of the hydrograph varied among storms, the shape and pattern among sites were similar; therefore, the 6/9/11 storm hydrograph is presented as an example (Fig. 2.4). Storm hydrographs were typical for a watershed with flashy hydrology, as discharge increased rapidly soon after peak rainfall, and decreased rapidly thereafter (Fig. 2.4). One exception to this pattern was WB3, where the storm hydrograph was more attenuated than at the other sites (Fig. 2.4). Peak discharge occurred very quickly after peak rainfall, particularly at SS1, SS3, WB1, and WB2, where 25 minutes or less lapsed between peak rainfall and peak discharge (Fig. 2.4). At SS2, MB1, MB2, and NB, peak discharge occurred 45-75 minutes after peak rainfall. Peak discharge was not reached until 2.5 hours after peak rainfall at WB3, most likely due to areas of stormwater retention between WB2 and WB3.

Median discharge, a measure of magnitude (M), ranged from 0.002 m^3/s at NB to 0.066 m^3/s at MB1 from February 1, 2011-January 31, 2012 (Table 2.4). It is expected that spate flow frequency and duration will increase with more impervious cover (Helms et al. 2009); these variables also should increase as one moves downstream because of accumulated flows. In Ruddiman Creek, both spate frequency and duration did increase in a downstream fashion in the main branch, but not in the storm sewers or the west branch. Indeed, SS3 had a higher spate flow frequency and duration than the other storm sewer sites, suggesting the most upstream region of this branch should be a priority target for BMPs. In the west branch, in-stream wetlands and detention areas between WB2 and WB3 likely attenuate flow, and result in the reduced spate flow frequency and duration values (Table 2.4).

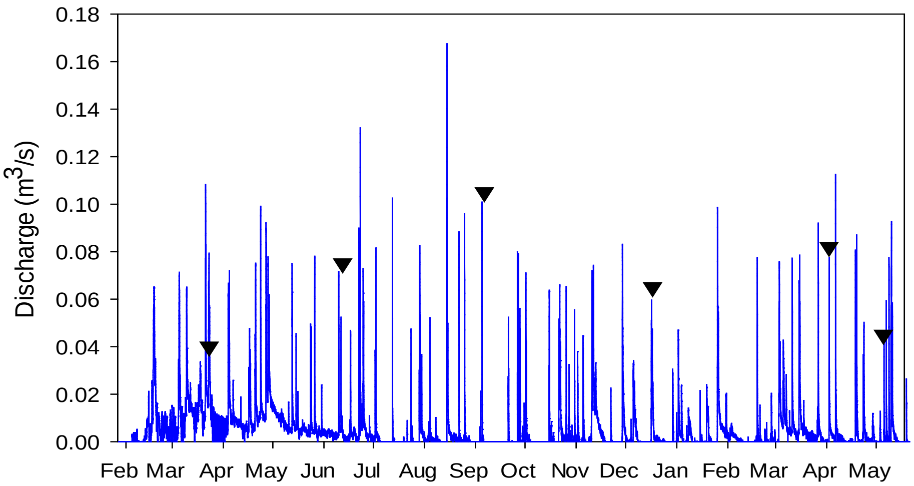
Table 2.2 Monitoring overview showing the amount of data that was collected for each monitoring location. Sites are shown from upstream to downstream within each branch.

Monitoring Location	Data collection period	Data collection interval	Approximate number of data points per site
SS3	1/24/2011 to 2/22/2012	5 minutes	113,500
SS2			
SS1			
MB1	1/27/2011 to 4/3/2012	10 minutes	62,200
MB2			
NB			
WB1			
WB2			
WB3			

A) Main branch station 1 (MB1), located downstream of Barclay Street.



B) North branch station (NB), located behind the U.S. Army Reserve.



C) West branch station 2 (WB2), located downstream of Sherman Boulevard.

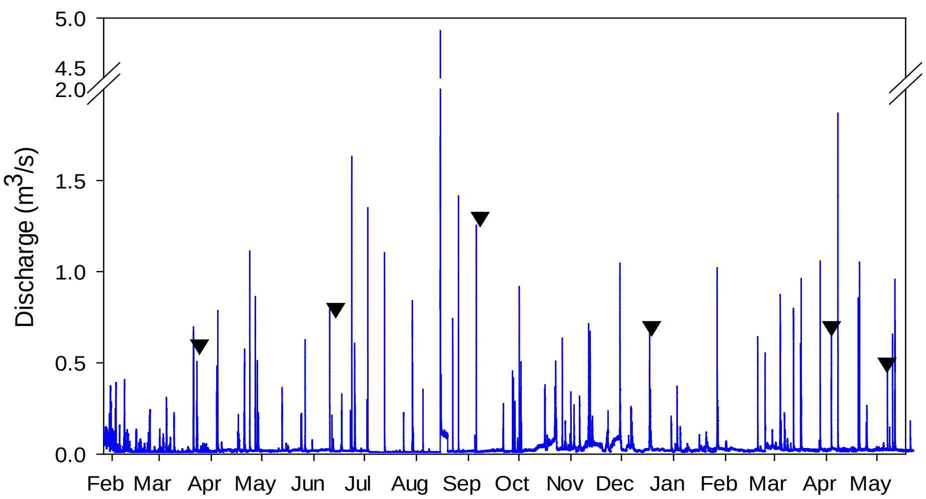
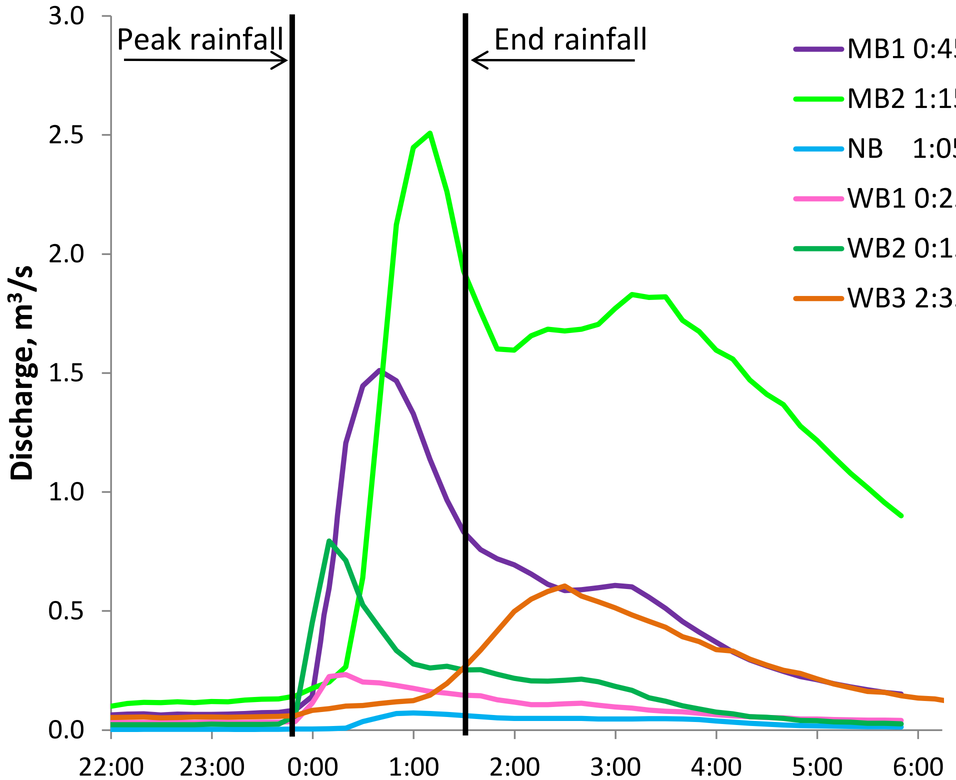


Figure 2.3. Example hydrographs for A) MB1, B) NB, and C) WB2 from January 27, 2011-May 17, 2012. Inverted triangles indicate storm sampling events. Note different y-axis scales for each panel. Hydrographs for all sites can be found in Appendix F.

Table 2.3. Hydrologic summary data, including storm event information. Rainfall amount, duration, and intensity are given for each storm sampling event. For each monitoring location, average discharge (Q) at baseflow, average Q during storm sampling events, and storm flow duration are summarized. Sites are presented in upstream to downstream order for each branch.

			Storm Event					
		Baseflow	**3/20/11**	**6/9/11**	**9/3/11**	**12/14/11**	**3/30/12**	**5/2/12**
	Rainfall (in)	--	0.36	0.64	0.29	0.21	0.56	0.11
	Duration (h)	--	3.13	3.42	0.37	2.33	5.00	0.18
	Intensity (in/h)	--	0.11	0.19	0.79	0.09	0.11	0.60
SS3	Avg Q (m^3/s)	0.006	0.175	0.063	0.044	0.236	--	--
	Duration (h)	--	2.58	4.75	3.83	1.42	--	--
SS2	Avg Q (m^3/s)	0.021	0.350	0.348	0.586	0.426	--	--
	Duration (h)	--	4.17	5.08	5.43	1.75		--
SS1	Avg Q (m^3/s)	0.055	0.605	0.611	0.923	0.444	--	--
	Duration (h)	--	3.58	4.58	4.08	2.17	--	--
MB1	Avg Q (m^3/s)	0.104	0.376	0.368	0.755	0.578	0.362	0.342
	Duration (h)	--	5.67	11.17	5.00	2.33	12.00	1.67
MB2	Avg Q (m^3/s)	0.092	0.466	0.784	3.487	0.262	0.186	0.120
	Duration (h)	--	4.33	16.50	10.50	4.50	9.00	5.00
NB	Avg Q (m^3/s)	0.003	0.044	0.026	0.017	0.045	0.015	0.014
	Duration (h)	--	5.50	10.17	12.17	2.17	3.50	6.33
WB1	Avg Q (m^3/s)	0.029	0.070	0.101	0.123	0.116	0.137	0.098
	Duration (h)	--	4.50	6.33	3.50	2.67	6.33	3.50
WB2	Avg Q (m^3/s)	0.023	0.194	0.210	0.187	0.349	0.238	0.149
	Duration (h)	--	4.33	6.00	6.33	2.67	7.83	3.50
WB3	Avg Q (m^3/s)	0.049	0.331	0.225	0.300	0.234	0.236	0.109
	Duration (h)	--	14.17	9.33	6.83	2.67	10.00	5.33

A)



B)

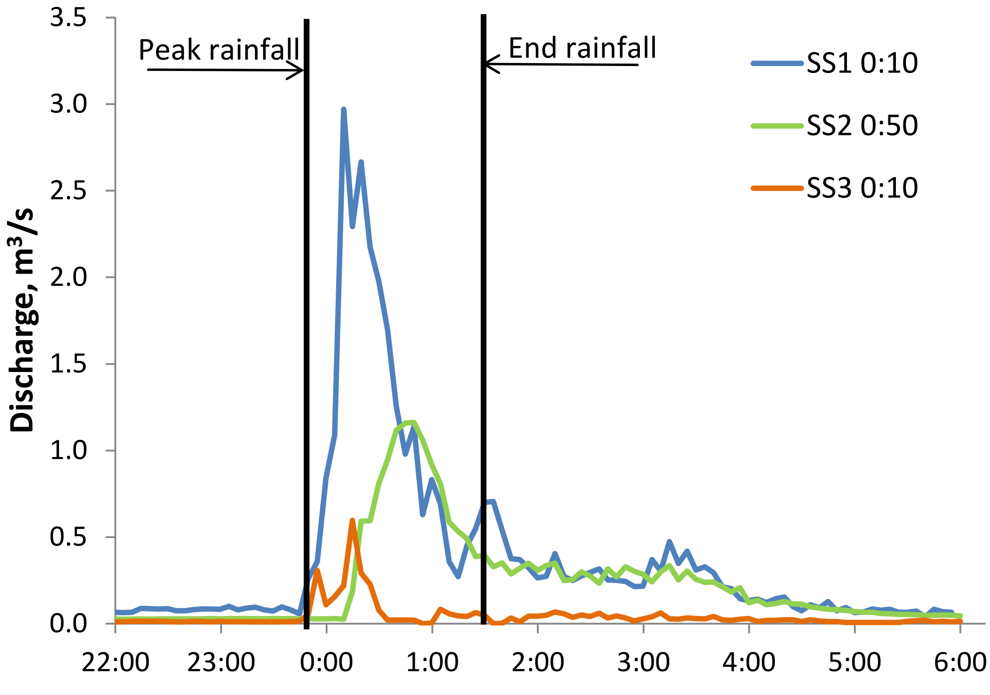


Fig. 2.4. Storm hydrographs from A) tributary sites and B) storm sewers during the 6/9/11 storm event. Time (hr:min) from peak rainfall to peak discharge is given in the legend.

Table 2.4. Hydrologic variables characterizing spate flow frequency and duration for 3 discharge magnitudes (M): 3 × M, 5 × M, and 7 × M, where M is median discharge (Q). All variables were calculated using continuous discharge values for one calendar year, from February 1, 2011-January 31, 2012. Sites are presented in order from upstream to downstream within each branch.

		3 x M		5 x M		7 x M	
Site	**Median Q, m^3/s**	**Frequency (#)**	**Duration (hrs)**	**Frequency (#)**	**Duration (hrs)**	**Frequency (#)**	**Duration (hrs)**
SS3	0.006	356	1026	191	579	151	406
SS2	0.021	105	400	90	247	72	195
SS1	0.057	166	417	93	228	80	161
MB1	0.066	98	513	82	294	73	186
MB2	0.051	90	2463	98	1753	116	1076
NB	0.002	179	2918	132	1953	117	1315
WB1	0.031	64	161	32	48	14	21
WB2	0.019	133	986	101	521	89	290
WB3	0.052	72	293	43	120	36	92

2.3 Suspended and Bedload Sediment

2.3.1 Methods

Dry weather (baseflow) sampling occurred monthly over a 13-month period (January 2011- February 2012) at the 6 tributary sites and 3 storm sewer sites previously described (Fig. 2.1). The 13-month sampling period allowed us to capture the range of annual temporal variability in chemical and physical parameters in Ruddiman Creek. Wet weather (storm event) sampling occurred during 6 storm events throughout the project period. Storm sewers were sampled during only 4 of the 6 storm events due to delays in the sampling schedule; tributary sites were sampled during all 6 storm events. Storm event sampling was in response to precipitation events of 0.1 in (0.254 cm) or greater, preceded by at least 72 hours of dry weather. Sampling was initiated when precipitation began and continued approximately every hour during the rise and fall of the hydrograph. When obtainable, four samples were selected from each site to capture the first flush, the middle of the initial rise, the peak, and the middle of the fall of the hydrograph. Rainfall data (amount and duration) for each storm were obtained from the National

Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (www.ncdc.noaa.gov) for the Muskegon County Airport weather station (3°10'N, 86°14'W), located approximately 3.2 km south of the Ruddiman Creek watershed.

Grab samples for suspended sediment concentration (SSC) were collected in 500-ml polyethylene bottles at all sites during baseflow and ~hourly during storm events. At tributary sites, samples were collected in the thalwag of the stream at mid-depth; a weighted sampler constructed of PVC was lowered into the storm sewers and used to fill sample bottles. All samples were stored at 4ºC until analysis in the laboratory; sample holding times were consistent with EPA recommendations (USEPA 1983; Appendix G, Table G.1). To determine SSC, the entire water sample in the 500 ml bottle was vacuum-filtered through pre-ashed glass fiber filters. Filters were dried at 105ºC for 8 hours and weighed to determine sediment mass. Suspended sediment load was calculated for each sample by multiplying SSC by discharge at the time of collection.

Baseflow bedload subsamples were collected (1-min duration) using a 3”×3” Helley-Smith sampler at 5 equally-spaced points across the stream at each site on the main and west branches (5-min total sampling time), and 3 equally-spaced points across the stream on the north branch (3-min total sampling time) because of its smaller width. During wet weather monitoring, 5 bedload subsamples (30-second duration) were collected on the main and west branch sites each time water samples were collected (2.5-min total sampling time), and 3 subsamples were collected on the north branch (1.5-min total sampling time). Grain size distribution of bedload was determined as described in Appendix H.5.

Instantaneous bedload transport rate (Q_b) in kg/min was calculated as:

$$Q_b = \frac{M_b}{T} \times \frac{1}{N} \times \frac{W}{0.076\ \mathrm{m}}$$

where M_b is the total dry mass of bedload sediment in kg; T, subsample duration in minutes; N, number of subsamples; W, wetted width of the channel in m; 0.076 m represents the width of a 3”×3” Helley-Smith sampler opening.

Sediment rating curves were established to characterize the relationship between sediment and discharge. A plot of SSC vs. discharge and bedload vs. discharge was created for each monitoring location and fit with a power function (Asselman 2000) using SigmaPlot 12.3. To facilitate sediment modeling efforts (see Chapter 6), discharge was plotted in cubic feet per second (cfs). Outliers were visually identified on scatterplots and eliminated when their inclusion prohibited the creation of a meaningful sediment rating curve. A total of 5 SSC points over 3 sites and two bedload points were excluded). Outliers that were excluded from sediment rating curves included two points at NB, one point at WB1 (SSC only), and two points at WB3 (SSC only). The excluded values represented 1% and 2% of the total bedload and SSC data points, respectively.

Total storm event bedload and suspended sediment load were estimated for each monitored storm event using the sediment rating curves. No attempt was made to determine if there was a relationship between storm sediment load and the antecedent dry period. Discharge for the duration of each storm was extracted from the continuous hydrograph from each site. Discharge from each recorded time interval (5 min for sewers, 10 min for tributaries) was used in the power equation derived from the sediment rating curve to create a continuous record of SSC (mg/L) and bedload (kg/d) for each storm. SSC was converted to suspended sediment load (kg/d) for each time interval by multiplying SSC by that time interval’s discharge value. Mass for each 5- or 10-minute time interval was determined by multiplying bedload or suspended sediment load by the length of the time interval. Mass values were summed for each storm to estimate total storm event bedload and suspended sediment load (kg/event).

Differences in average baseflow and storm event sediment load were determined using Kruskal-Wallis one-way analysis of variance (ANOVA) on ranks, due to lack of normality and/or unequal variance. Significant contrasts ($p<0.05$) were further analyzed with either Tukey (equal *n*) or Dunn's (unequal *n*) multiple comparison tests. All statistical analyses were performed using SigmaPlot 12.3.

2.3.2 Results

Mean suspended sediment concentration (SSC) during baseflow was < 10 mg/L at all monitoring locations (Table 2.5). Mean suspended sediment load during baseflow was <15 kg/d except at SS1 and MB2, where it was 36 and 47 kg/d, respectively (Table 2.5). Mean baseflow suspended sediment load was significantly lower at NB than at all other tributary sties, except for WB2 ($p<0.001$). MB2 had significantly higher mean baseflow suspended sediment load than the 2 most upstream storm sewers (SS2 and SS3); neither MB1 nor MB2 had mean baseflow suspended sediment load that significantly differed from SS1 (the most downstream storm sewer; $p<0.001$). Mean baseflow bedload was significantly lower at WB3 than at any other site, except for NB, which had significantly lower baseflow bedload than sites MB1 and WB1 ($p<0.001$; Table 2.5).

The range of SSC values measured during storm events was similar among sites and was between 1 and 2 orders of magnitude greater than baseflow SSC (Table 2.5). Suspended sediment load was variable among sites during storm events and was 2-3 orders of magnitude greater than during baseflow. The greatest mean loads measured were at MB2 and SS2, which were significantly higher than the mean loads at NB and WB1 ($p<0.001$; Table 2.5). SS1 and

MB1 also had higher mean storm suspended sediment loads than NB ($p<0.001$). Mean storm event suspended sediment loads at SS3, WB2, and WB3 were not significantly different from any other site. Bedload was also much greater during storm events than baseflow and was variable among sites; mean storm bedload was significantly lower at WB3 than at any other site except NB, where mean storm bedload was significantly lower than at MB2 ($p<0.001$; Table 2.5). Although mean storm bedload was substantially higher at MB2 than any other site, its high variability resulted in a significant difference only with NB (Table 2.5).

Sediment rating curves were fitted to sediment (SSC and bedload) and discharge data collected over the study period for each monitoring location (Figs. 2.5 and 2.6). The power function $S=aQ^b$ was used to model the relationship between sediment and discharge (Table 2.6), where S is sediment concentration (SSC) or load (bedload), Q is discharge, the a-coefficient represents an index of erosion severity, with high a-values indicating the presence of soils that can be easily eroded and transported, and the b-coefficient represents the erosive power of the stream (Peters-Kümmerly 1973; Morgan 1995). For SSC, the storm sewers and NB had the highest a-coefficients among sites, while WB1 and WB2 had the highest b-coefficients (Table 2.6). Regression coefficients were highly variable among sites for bedload. Bedload rating curves were particularly steep for the west branch sites, characterized by low a-values and high b-values, suggesting that increases in discharge resulted in large increases in bedload sediment (Fig. 2.6, Table 2.6). Correlation coefficients (R^2) ranged from 0.38-0.65 for SSC vs. discharge (Fig. 2.5). Bedload vs. discharge correlation coefficients were higher than for SSC at each site, ranging from 0.43-0.91 (Fig. 2.6).

Using the power functions from the sediment rating curves, total storm event sediment load was estimated for each storm. The mean total storm event suspended sediment loads at SS1, SS2, MB1, and MB2 were significantly greater than at NB ($p<0.001$; Fig. 2.7). Although MB2 had very high mean total storm event suspended sediment load, it was highly variable and thus not significantly different from any other site except NB ($p<0.001$; Fig. 2.7; see below).The second-highest mean total storm event suspended sediment load occurred at WB2, but due to high variability it was not significantly different than any other site (Fig. 2.7). Mean total storm event bedload was highest at MB2, and lowest at NB and WB3 ($p<0.001$; Fig. 2.7). Suspended sediment was generally the dominant form of storm sediment load, except at MB2 and WB1, where it was not significantly different from bedload ($p<0.001$; Fig. 2.7).

Mean total storm event suspended sediment load (kg/event) ranged from 20× higher than baseflow suspended sediment load (kg/d) at SS1 to 200× higher at WB2 (Fig. 2.7). Mean total storm event bedload (kg/event) was moderately higher than average baseflow bedload (kg/d), with 1-8× increases at all sites except at MB2, where the increase was 50× (Fig. 2.7).

At MB2, total storm event suspended sediment load was 1-3 orders of magnitude greater during the 9/3/11 storm (68,357 kg/event) than during other storms; it is not known whether this data point is an error or an acceptable estimate of sediment yield. Suspended sediment concentration was the highest-measured at MB2 during the 9/3/11 storm (339 mg/L), lending credibility to the total storm sediment load estimate. However, modeled stage and discharge did not align well with manual measurements taken during the storm (e.g., stage: 84 cm modeled vs. 34 cm measured; discharge: 20 m^3/s modeled vs. 4 m^3/s measured), which would result in an over-estimate of modeled storm event sediment load. Due to the uncertainty associated with the 9/3/11 data points at MB2, we performed statistical analyses with and without those data. Although the data exclusion resulted in a substantially lower mean suspended sediment yield, it was only moderately lower for bedload and did not change the outcome of comparative statistics among sites (Fig. 2.7).

Analysis of our sediment monitoring data revealed several key points about the sediment dynamics of the three branches of Ruddiman Creek. It is clear that a substantial amount of sediment is transported in Ruddiman Creek during storm events. The primary form of sediment transported by storm flows is suspended sediment, except at MB2 and WB1, where mean suspended sediment load and bedload were similar. Storm suspended sediment loads were greatest in the main branch, including the downstream-most storm sewers (SS1 and SS2). The lack of statistically significant differences between the storm suspended sediment load in the downstream-most storm sewers and the main branch sites suggests that the storm sewers are a primary contributor of suspended sediment to the main branch, but the high variance in the load data (especially at SS1) precludes us from making any definitive conclusions. Although the low storm suspended sediment load and bedload at the NB monitoring site suggests stream stability, our geomorphic surveys suggest that upstream reaches of the north branch are severely degraded and unstable (see Chapter 6.2 and Appendix H.2). It is likely that our one sampling location in the north branch was insufficient to adequately characterize the sediment dynamics in this branch, which accounts for this disparity in our results. Storm suspended sediment load was not statistically different among the three west branch sites, but bedload was lowest at WB3, reflecting the bed stability created by riprap placed at the culvert outlet located immediately upstream. This suggests that upstream reaches offer an excellent opportunity for sediment mitigation in the west branch.

		Baseflow						Storm Events					
		SSC, mg/L		SS Load, kg/d		Bedload, kg/d		SSC, mg/L		SS Load, kg/d		Bedload, kg/d	
SS3	Mean	7 ± 16	NS	6 ± 17	a,b	-- --	--	184 ± 163	NS	1,798 ± 1,506	c,b	-- --	--
	Range	0 – 0		0 – 0		-- --	--	31 – 493		173 – 4,896		-- --	--
SS2	Mean	6 ± 11	NS	7 ± 11	a,b,c	-- --	--	141 ± 87	NS	10,703 ± 13,600	c	-- --	--
	Range	0 – 0		0 – 0		-- --	--	32 – 309		196 – 46,545		-- --	--
SS1	Mean	5 ± 12	NS	36 ± 95	NS	-- --	--	86 ± 72	NS	9,977 ± 13,383	NS	-- --	--
	Range	0 – 0		0 – 0		-- --	--	1 – 236		29 – 45,121		-- --	--
MB1	Mean	2 ± 1	NS	14 ± 13	b,c,d	139 ± 248	c	89 ± 73	NS	5,610 ± 7,974	c,b	963 ± 888	c,b
	Range	0 – 4		0 – 41		1 – 897		9 – 288		123 – 31,137		58 – 2,609	
MB2	Mean	5 ± 3	NS	47 ± 64	d	77 ± 153	c,b	114 ± 113	NS	16,422 ± 26,599	c	11,617 ± 13,008	c
	Range	1 – 12		4 – 228		0 – 530		22 – 372		799 – 84,714		5 – 36,795	
NB	Mean	9 ± 12	NS	1 ± 1	a	3 ± 4	a,b	74 ± 93	NS	268 ± 253	a	51 ± 57	a,b
	Range	0 – 47		0 – 4		0 – 12		19 – 338		49 – 935		6 – 162	
WB1	Mean	4 ± 6	NS	11 ± 14	b,c,d	53 ± 61	c	102 ± 149	NS	1,098 ± 1,529	a,b	1,716 ± 3,246	c,b
	Range	1 – 22		2 – 53		0 – 221		12 – 571		36 – 6,064		5 – 12,089	
WB2	Mean	4 ± 5	NS	7 ± 9	NS	25 ± 32	c,b	81 ± 84	NS	3,018 ± 6,618	NS	1,812 ± 3,305	c,b
	Range	1 – 15		1 – 32		1 – 105		0 – 286		0 – 26,521		24 – 13,181	
WB3	Mean	3 ± 2	NS	12 ± 9	c,d	1 ± 2	a	76 ± 79	NS	1,860 ± 1,943	NS	54 ± 80	a
	Range	1 – 9		3 – 30		0 – 6		8 – 308		49 – 6,635		1 – 300	

Table 2.5. Mean (± standard deviation) and range of suspended sediment concentration (SSC), suspended sediment (SS) load, and bedload values measured during baseflow and storm event monitoring. Sites are presented in upstream to downstream order within each branch. Statistically-significant contrasts are indicated by different letters within columns. NS = no significant contrasts.

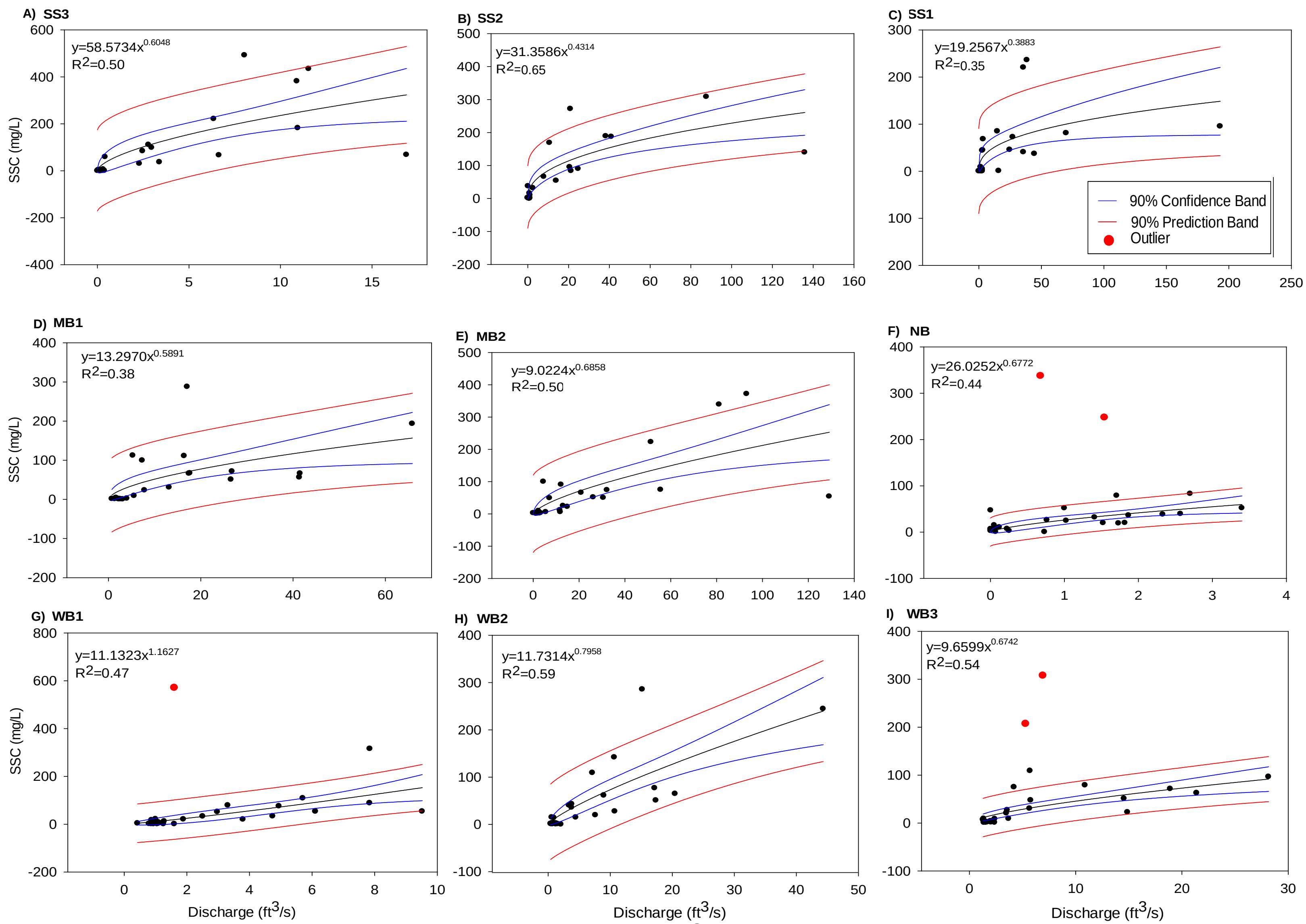


Fig. 2.5. Suspended sediment rating curves. Discharge plotted in ft^3/s to facilitate sediment modeling (see Chapter 6). SSC= suspended sediment concentration. See upper right panel for symbol legend.

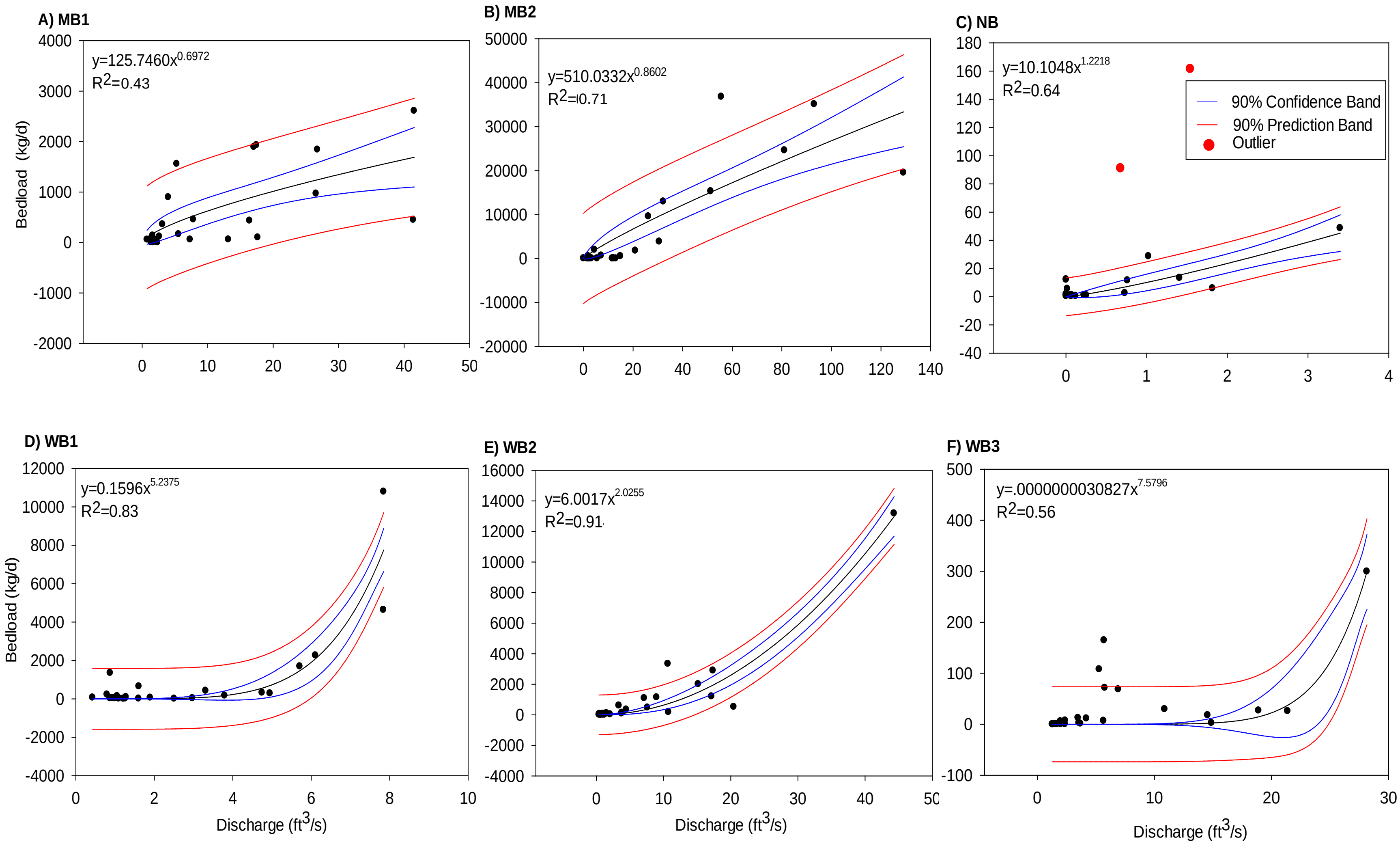
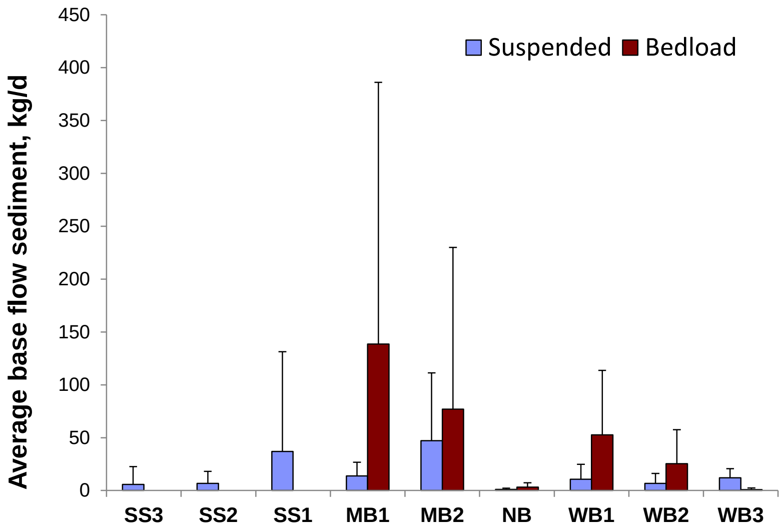


Fig. 2.6. Bedload sediment rating curves. Discharge plotted in ft^3/s to facilitate sediment modeling (see Chapter 6). See upper right panel for symbol legend.

Table 2.6. Power functions and associated correlation coefficients (R^2) for suspended and bedload sediment. Suspended (mg/L) or bedload (kg/day) sediment = a(Discharge (ft^3/s))^b

Site	Type	Equation	R^2
MB1	Suspended	$13.2970x^{0.5891}$	0.381
MB2	Suspended	$9.0224x^{0.6858}$	0.504
NB	Suspended	$26.0252x^{0.6772}$	0.438
WB1	Suspended	$11.1323x^{1.1627}$	0.474
WB2	Suspended	$11.7314x^{0.7958}$	0.595
WB3	Suspended	$9.6599x^{0.6742}$	0.541
SS1	Suspended	$19.2567x^{0.3883}$	0.349
SS2	Suspended	$31.3586x^{0.4314}$	0.648
SS3	Suspended	$58.5734x^{0.6048}$	0.505
MB1	Bedload	$125.746x^{0.6972}$	0.428
MB2	Bedload	$510.0332x^{0.8602}$	0.707
NB	Bedload	$10.1048x^{1.2218}$	0.643
WB1	Bedload	$0.1596x^{5.2375}$	0.832
WB2	Bedload	$6.0017x^{2.0255}$	0.914
WB3	Bedload	$0.0000000030827x^{7.5796}$	0.564

A) Baseflow sediment load



B) Total storm event sediment load

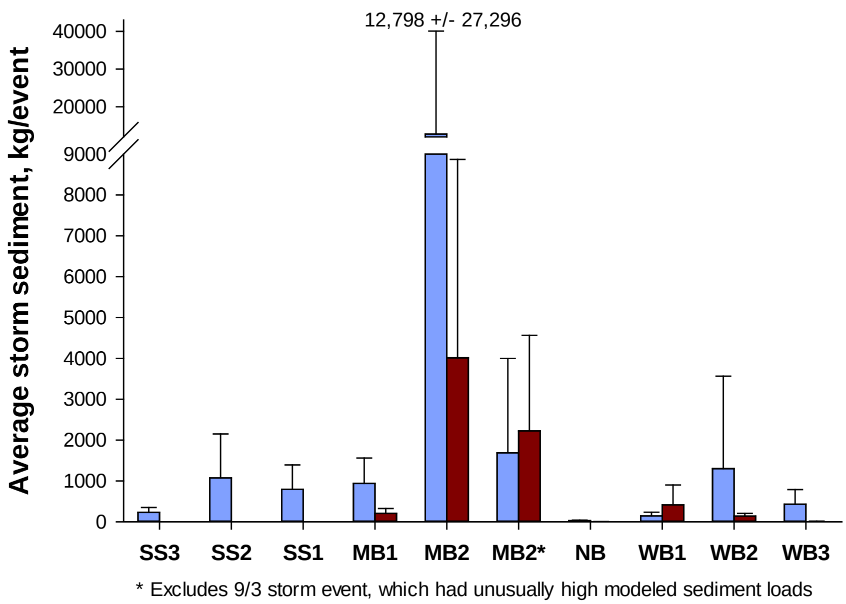


Fig. 2.7. Mean (+ standard deviation) sediment load during A) baseflow and B) storm events. Total storm event means are the mean sediment load (kg/event) of all storms sampled (n=6 for tributaries, n=4 for sewers). MB2 is presented with and without the 9/3/11 storm event, which had unusually high modeled suspended sediment loads (mean value above bar). Note the broken y-axis on panel B and the different units and y-axis scales in both panels.

Chapter 3: Hydrologic Modeling

3.1 Model Development

3.1.1 Methods

The U.S. Environmental Protection Agency computer program “Storm Water Management Model” (SWMM) was used to model hydrologic and hydraulic dynamics of the Ruddiman Creek watershed. SWMM was used to generate hydrologic forecasts for Ruddiman Creek to determine the effectiveness of watershed modifications in reducing the system’s flashiness (see Chapter 3.3), thus reducing negative impacts to the biotic community.

Discharge records from the nine monitoring locations required several pre-processing steps prior to hydrologic model calibration and stream flashiness evaluation. The following steps were performed:

- Data were selected for the period from February 1, 2011 to January 31, 2012 at all locations.
- Missing data values were identified and assigned a zero value. Model calibration (Chapter 3.2) used an approach that was insensitive to existence of missing data.
- Discharge measurements (collected on either 5- or 10-min intervals) were used to compute average values over hourly and daily time intervals (see Chapter 2.2.2). The hourly values were used in conjunction with the hydrologic model because SWMM uses hourly precipitation values as input. The daily values were used to evaluate the stream’s flashiness using the R-B Flashiness Index (see Chapter 3.3), which is defined based on daily flow variations.

- Dry weather flows in the storm sewers (and subsequently much of the stream baseflow) were assumed to primarily consist of industrial discharges and/or groundwater discharges (i.e., sump pumps or infiltration), although other sources of dry weather flow (i.e., washing of cars, watering of lawns) may also contribute to a lesser extent and in varying amounts.

  Since SWMM cannot model the industrial discharges and/or groundwater seepage, hydrologic model calibration needed to be performed without a baseflow component. Baseflow was computed and extracted from the hourly data record in preparation for model calibration. Since there was no way to easily quantify the industrial discharges, the baseflow was modeled using a 10 percentile hourly value over a 3-day moving block of discharge values (R. Hoeksema, personal communication). Considering the amount of discharge data available it was not practical to calculate base flow using hydrograph separation techniques. Since the base flow varied with both groundwater inputs and industrial contributions, it was not possible to separate it using hydrologic modeling. A practical method appropriate for this project is to determine the base flow as a low percentile flow calculated over a time frame longer than the typical flood response time of the watershed. Visual inspection showed that a 10 percentile flow based on hourly data computed over a 3 day period would be appropriate for all monitoring locations. Average baseflow values were computed for later inclusion in the hydrologic model. With baseflow removed, total runoff volume for the 1 year of record was computed.

To develop the SWMM model for Ruddiman Creek, we:

- Identified watershed sub-catchments. First, the entire Ruddiman Creek watershed boundary was delineated based on field surveys and analysis of the storm sewer network and topography. Then, the watershed was split into smaller contributing areas (sub-catchments).
- Determined initial values for the sub-catchment parameters, including area, width, slope, percent imperviousness, surface roughness for both pervious and impervious areas, depth of surface storage for both pervious and impervious areas, Natural Resources Conservation Service (NRCS) Curve Number (CN) (U.S. Department of Agriculture 1986) for computing the amount of infiltration from the pervious portion only, and soil drying time.
- Identified the main elements of the stormwater conveyance system. These included all stream and storm sewer reaches (referred to as conduits in SWMM) required to transport runoff from the sub-catchments to the confluence into Muskegon Lake.
- Determined the physical parameters of the stormwater conveyance system conduits (i.e., pipe diameter, channel cross section, roughness, and slope).
- Connected the various model elements together. SWMM uses a node-link modeling structure. Nodes are the location where surface runoff enters the conveyance system. The nodes are also locations where conduits (sections of stream or storm sewer) are connected to each other allowing stormwater to flow from the upper reaches of the watershed to the outlet.
- Obtained precipitation data for the simulation period (February 1, 2011 to January 31, 2012) as well as a 12-year period (January 1, 2000 to January 31, 2012) from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data

Center (www.ncdc.noaa.gov; Muskegon County Airport weather station [3°10'N, 86°14'W]) and linked them to the model.

- Ran the simulation.

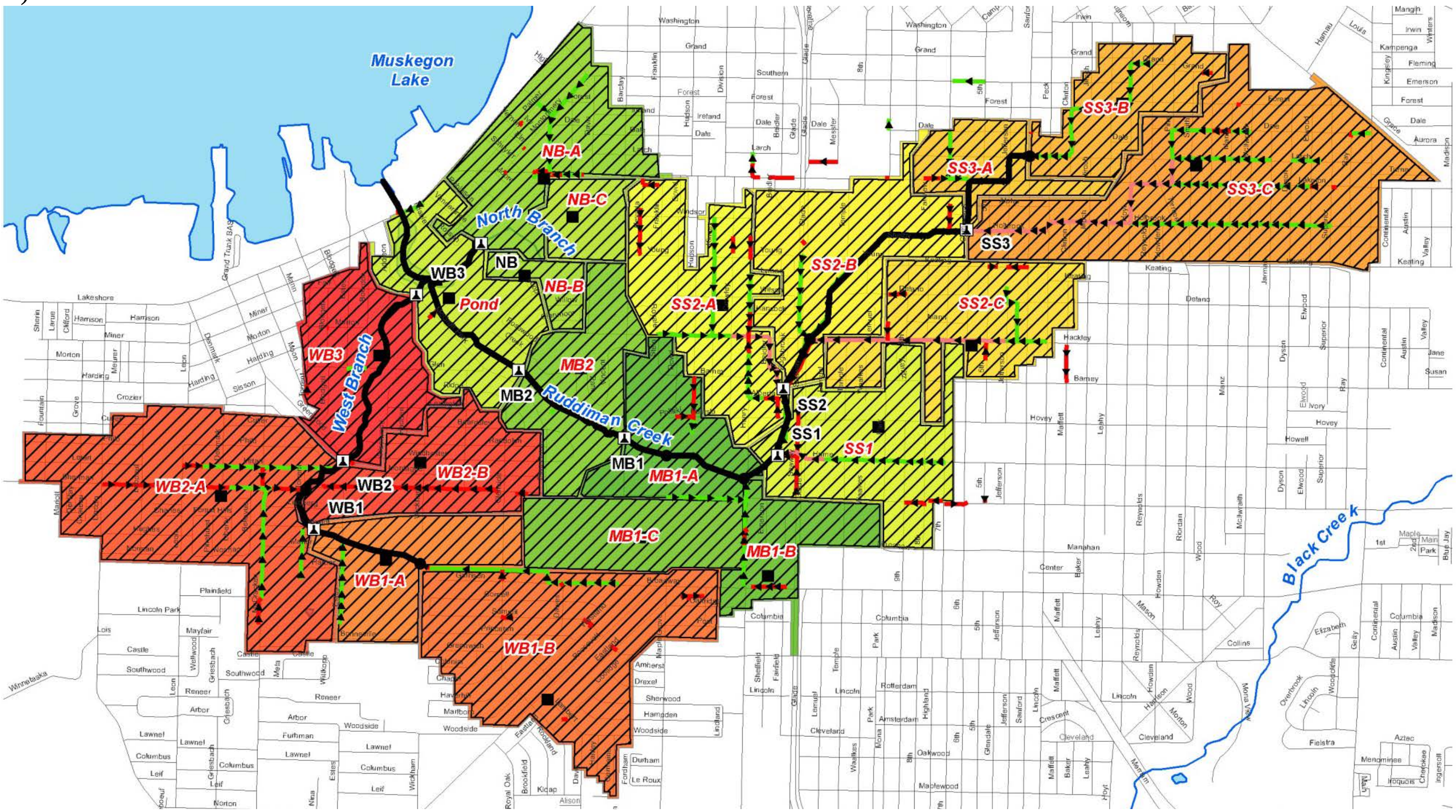
Two SWMM models were developed for the watershed: a "full" model and a "combined" model. The full model (Fig. 3.1A) had 20 sub-catchments defined by monitoring locations and general land use characteristics. This model was used to predict the impact of proposed watershed changes. A simpler combined model (Fig. 3.1B) was developed for calibration. In the combined model, all of the sub-catchments that contribute stormwater between any pair of successive monitoring locations along the same branch were combined. For example, in the full model, three sub-catchments contributed stormwater between monitoring locations SS2 and SS3. They were labeled SS2-A, SS2-B, and SS2-C (Fig. 3.1A). Those were combined to create sub-catchment SS2 in the combined model (Fig. 3.1B). The combined model reduces the number of parameters to be determined during the calibration process. Furthermore, as the calibration progressed from upstream to downstream, monitoring information from the next downstream location was added for each new sub-catchment to be calibrated. The only difference between the conveyance systems in the two models is the upstream extent.

While using two models is somewhat more complicated, the advantage is that calibration can be done with a simple model while the watershed response to proposed stormwater management changes can be predicted with a more detailed model. The key elements of the two models are given in Table 3.1. The differences in the numbers of nodes and conduits can be seen in Fig. 3.1.

Table 3.1. Key elements of the full and combined SWMM models for Ruddiman Creek.

Feature	Full Model	Combined Model
Sub-catchments	20	10
Conveyance network nodes	15	12
Outfalls (pour points)	1 (Muskegon Lake)	1 (Muskegon Lake)
Pond	1(Ruddiman Lagoon)	1 (Ruddiman Lagoon)
Conduits (both stream and storm sewer reaches)	10 stream reaches 6 storm sewer reaches	8 stream reaches 5 storm sewer reaches

A) Full SWMM model schematic



B) Combined SWMM model schematic

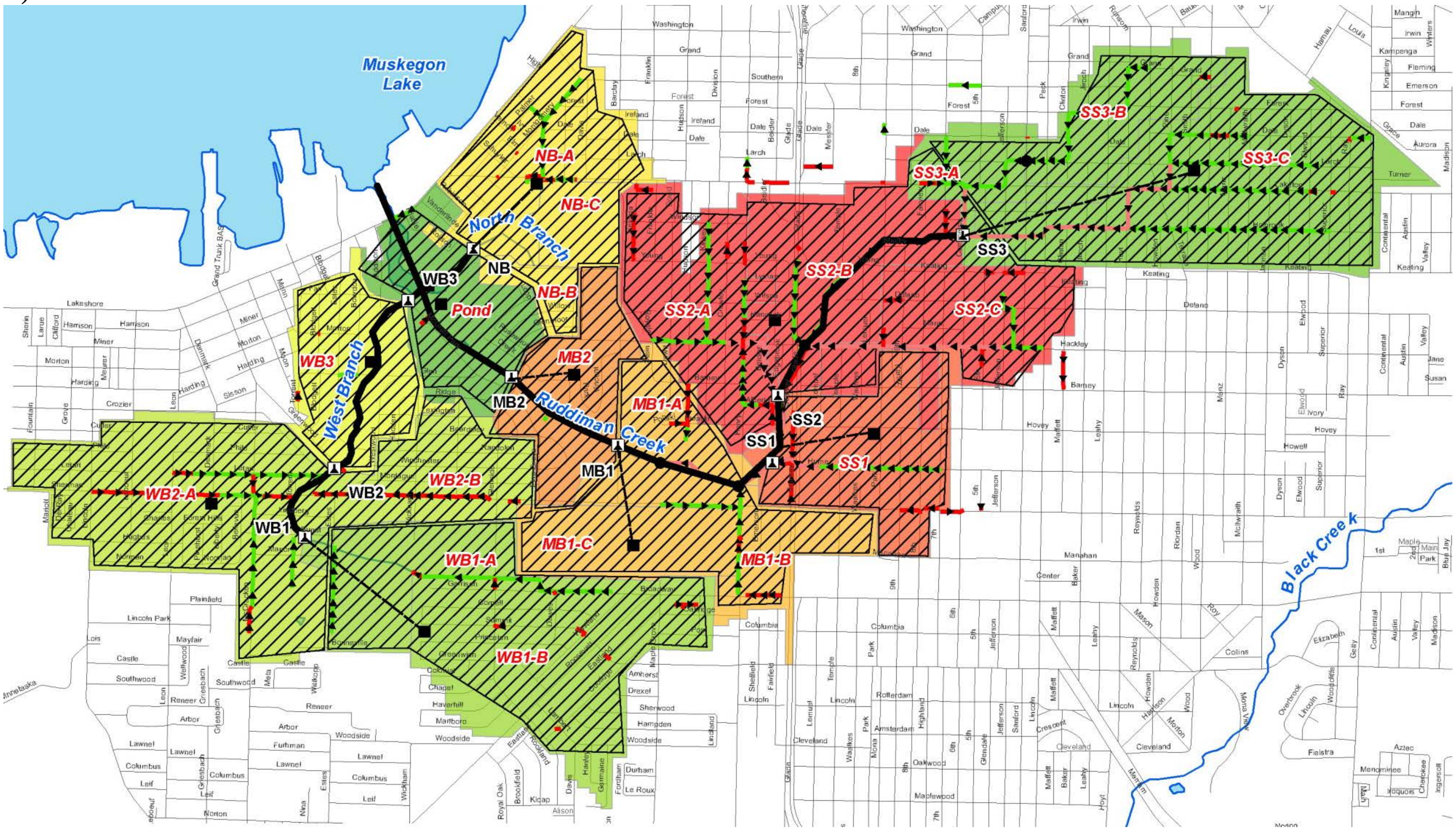


Fig. 3.1 SWMM model schematic. Black dots indicate the central point of each sub-catchment, shading colors differentiate one sub-catchment from another. Green lines with black arrows indicate storm sewers <24 inches in diameter, while red lines with black arrows indicate storm sewers >24 inches in diameter.

3.1.2 Results

Some minor inconsistencies exist for baseflow discharge (Table 3.2); mean discharge at SS1 was higher than at MB1, and WB1 was higher than at WB2, although the overall differences were modest and likely within statistical error. As expected, areas that are more residential in nature (SS3, SS2, NB, WB1, and WB3) had lower annual runoff values (193-316 $m^3/day/km^2$; Table 3.3) than commercially dominated areas (SS1, MB1, and WB2), with annual runoff values ranging from 335-411 $m^3/day/km^2$ (Table 3.2). Location MB2 was subject to stream flow backing up from Ruddiman Lagoon, thereby precluding the development of a meaningful relationship between stream depth and discharge at this site. As a result, discharge measurements above 0.16 m^3/s (0.56 ft^3/s) were considered unreliable.

Table 3.2 Calculated baseflow discharge and annual runoff volumes for monitoring locations in Ruddiman Creek. Shaded values represent totals for each branch. Sites are presented from upstream to downstream within each branch. N/A = Not Available

Location	Sub-catchment area, km^2 (mi^2)	Baseflow, m^3/s (ft^3/s)	Runoff volume, 10^6 m^3/yr (10^6 ft^3/yr)	Runoff volume per day per unit area, $m^3/day/km^2$ ($ft^3/day/mi^2$)
SS3	2.05 (0.79)	0.007 (0.24)	0.206 (7.28)	276 (25,227)
SS2	4.01 (1.55)	0.019 (0.68)	0.377 (13.32)	257 (23,544)
SS1	4.66 (1.80)	0.059 (2.08)	0.698 (24.65)	411 (37,552)
MB1	5.76 (2.23)	0.052 (1.83)	0.839 (29.63)	399 (36,485)
MB2	6.23 (2.40)	0.075 (2.66)	N/A	N/A
NB	0.90 (0.35)	0.002 (0.08)	0.063 (2.23)	193 (17,613)
WB1	1.48 (0.57)	0.030 (1.05)	0.140 (4.93)	259 (23,683)
WB2	3.15 (1.22)	0.020 (0.70)	0.385 (13.58)	335 (30,606)
WB3	3.68 (1.42)	0.047 (1.66)	0.425 (15.00)	316 (28,934)

Hourly discharge data (storm conditions only) were used to create flow duration curves (FDC) at each monitoring location. A flow duration curve is a plot of discharge as a function of exceedance probability. The FDC for MB1 is shown in Fig. 3.2. With baseflow conditions removed, the exceedance probability for a flow of zero is 0.09 (i.e., storm flows occur 9% of the time).

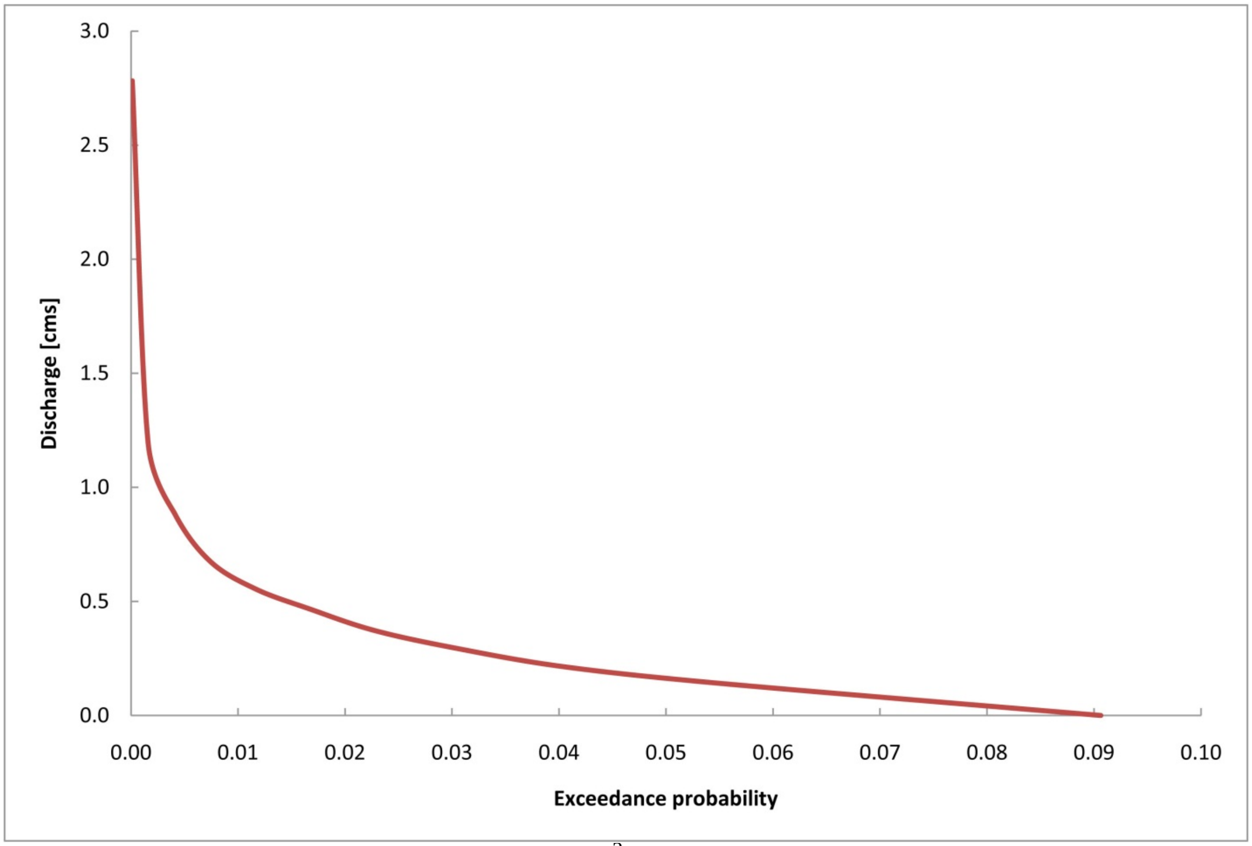


Fig. 3.2 Flow Duration Curve for MB1; cms=m^3/s.

3.2 Model Calibration and Validation

3.2.1 Methods

Model calibration was performed to determine the set of model parameters that best reproduced the watershed's hydrologic response. Calibration involved adjusting model parameters until model results reasonably matched monitored results. Calibration was performed using the combined model (without baseflow). The initial values of the parameters to be adjusted were calculated from available Geographic Information System (GIS) data sets (Michigan Geographic Data Library, http://www.mcgi.state.mi.us/mgdl/): land cover (from 1992 IFMAP satellite imagery), soil type, digital elevation model (DEM), and sub-catchment shape (length and width). Calibration proceeded from upstream to downstream monitoring locations along each branch. Each monitoring location provided calibration data that had one un-calibrated upstream sub-catchment requiring parameter adjustments.

The parameters that were adjusted in the calibration process were sub-catchment width, percent slope, percent impervious area, Manning's roughness coefficient (a measure of the average surface roughness) for both the pervious and impervious areas, depth of surface storage for both pervious and impervious areas, pervious area Curve Number (CN), and drying time. Since the sub-catchment area was accurately measured from the GIS information, it was not adjusted in the calibration process. Pervious areas were mostly sandy soils, thus the related parameters (Manning's roughness, depth of surface storage, CN, and drying time) had a small influence on the calibration.

Calibration was performed manually. Parameters were adjusted one sub-catchment at a time within a physically reasonable range of values (i.e., values for the physical characteristics of the subcatchment listed above were not considered as a calibration value if they did not make good sense). Parameters with the greatest influence were adjusted first. After each adjustment, performance measures were computed for the nearest downstream monitoring location. As many as 30 iterations were required to calibrate each sub-catchment.

The final model calibration step involved applying the calibrated parameters from the combined model to the full model. The calibrated model parameters for sub-catchment SS3, for example, needed to be recalculated for the full model sub-catchments SS3-A, SS3-B, and SS3-C. Most of the calibrated parameters remained unchanged between the combined model and the full model sub-catchments. The exceptions were the sub-catchment area (calculated, not calibrated), width, and percent impervious. The full model sub-catchment width was computed to maintain the calibrated length to width ratio from the associated combined model sub-catchment. The full model percent impervious values were recomputed to provide the total directly connected impervious area (DCIA) from the associated combined model sub-catchment and to capture variations in imperviousness as observed in 2001 IFMAP satellite imagery (see Appendix M for resulting DCIA values). For example, the combined-model-calibrated impervious area for sub-catchment SS3 must equal the total impervious area from the full model in sub-catchments SS3-A, SS3-B, and SS3-C (see Fig. 3.1). But SS3-A, SS3-B, and SS3-C cannot have the same percent imperviousness because of the different land uses within these smaller sub-catchments. Calculated baseflow was inserted into the appropriate model junctions to create the final full model.

Validation is an independent check on the calibrated parameters to verify that they are appropriate. The calibration process used one period of record to compute the model parameters. Validation assessed how close the performance measures were during the validation period. Since there was only one year of monitoring data, the calibration and validation period needed to be part of the same year. To avoid seasonal influences, the calibration period was based on even numbered months (February, April, etc.) and the validation period was based on odd numbered months (January, March, etc.).

The primary performance measure used to direct the Ruddiman Creek model calibration was based on the Flow Duration Curve (FDC) fit. The advantage of using the FDC as a primary calibration instrument was that it is unaffected by missing monitoring data and errors in timing of hydrograph peaks. The FDC at monitoring location MB1 is shown in Fig. 3.2. The FDC can be computed from both monitored and modeled results by counting the number of (hourly) discharge values that equal or exceed a given value. Points along the FDC were calculated at the interface between ten segments representing equal monitored flow volumes. The performance measure used was the root mean squared error (RMSE) between the monitored and measured exceedance probabilities at the interior nine points separating the ten segments of the curve (Westerberg et al. 2011). This measure is defined as:

$$RMSE_p = \sqrt{\frac{\sum_{i=1}^{9}(p_o - p_m)_i^2}{9}}$$

where p_o and p_m are the observed and modeled exceedance probability values, respectively. This shows the measure of the horizontal separation between the modeled data and the monitored data (Fig. 3.3). The goal was to adjust the model parameters to minimize this measure.

The ratio of the modeled and the monitored runoff volume was an additional statistic used to measure the performance of the model. When calibrated properly, the value of this statistic should be close to 1. Unfortunately, some monitoring sites (e.g., SS1 and SS2) had long periods of missing data due to equipment malfunction, which resulted in some values >1 since more volume was modeled than monitored. If this performance measure was computed for even and odd months separately, then the missing data issue can lead to larger differences between the calibration and validation statistics. This statistic is simple to calculate, but it does not capture the temporal variation in discharges needed for a useful model. An additional check on the calibration was performed by computing the Nash-Sutcliffe efficiency coefficient (E; Nash and Sutcliffe 1970) for daily flows:

$$E = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T}(Q_o^t - \overline{Q_o})^2}$$

where Q_o^t is the observed discharge at time t, Q_m^t is the modeled discharge at time t, and $\overline{Q_o}$ is the average observed discharge value over the period of simulation.

3.2.2 Results

Odd-numbered months validated even-numbered months well. The largest absolute difference occurred at location SS3. The largest (even-numbered month) $RMSE_p$ value (excluding MB2; see below) was 0.0062 at NB (Table 3.3). This is a reasonable value given the range of values in the FDC. Runoff volume ratios remained close to 1, further validating the results (Table 3.3).

A Nash-Sutcliffe efficiency coefficient value of 1 indicates a perfect model fit, and a value of 0 indicates that the mean discharge is as good a predictor as the hydrologic model. While it would be best to have all values of this statistic as close to 1 as possible, there are several factors that keep this from happening; 1) unmodeled variability in flow, including industrial discharges, 2) a very short hydrologic response time, and 3) a lack of rain gages in the watershed, resulting in uncertainty in the difference between actual and estimated precipitation (from the rain gage at the airport). Furthermore, calibration was centered on the FDC while the Nash-Sutcliffe statistic was used for validation. The hydrologic model's validity is strengthened with all values being greater than zero (0.25—0.71; Table 3.3).

Figure 3.4 shows the hydrograph of the calibrated model for site MB1 over the time period October 11 to November 11, 2011. The timing of the peaks and general shape of the hydrographs show good agreement, with no obvious pattern of peak flows being over- or under-estimated by the modeled results. Fig. 3.5 is a close up view of the 3-day period from November 8 through November 11, 2011.

Table 3.4 provides a summary of the calibrated model parameters for the full model.

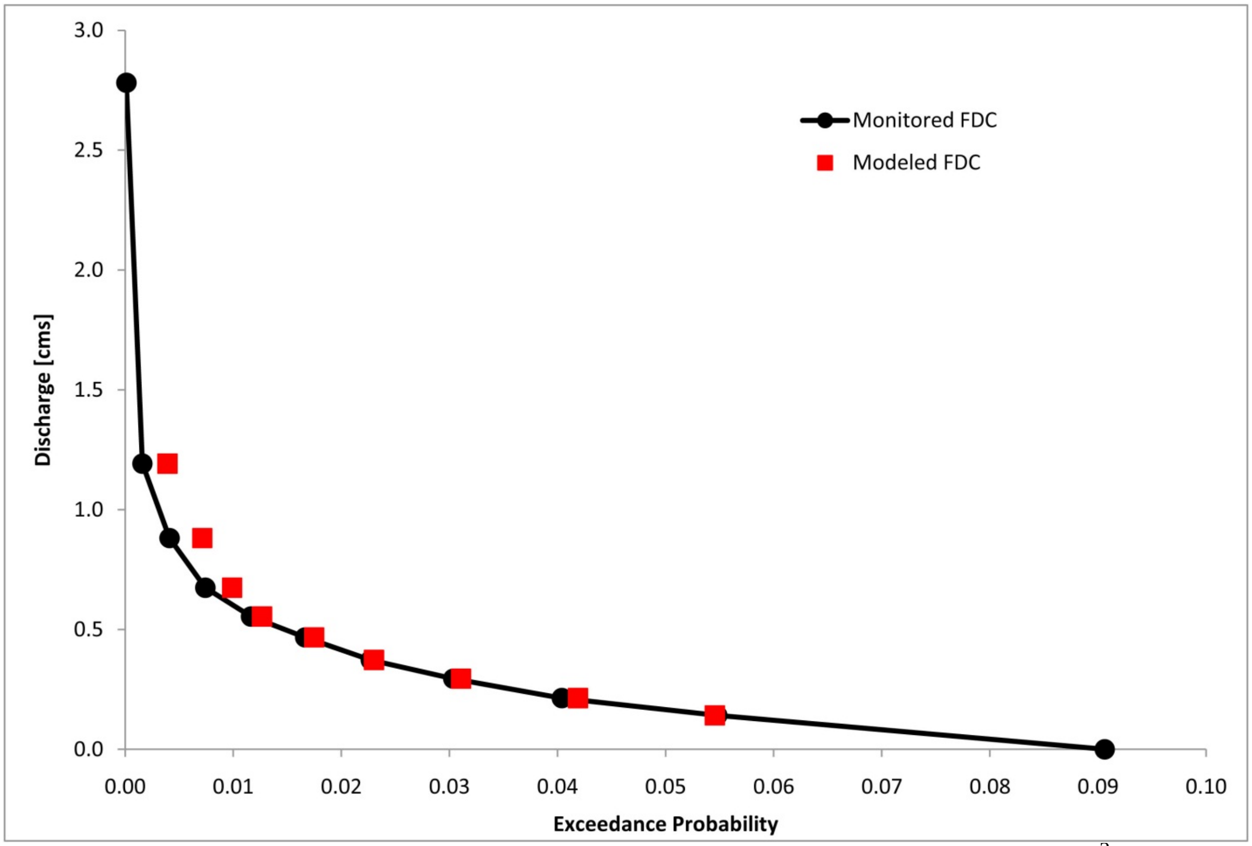


Fig. 3.3. Flow Duration Curves for MB1 using monitored and modeled data; cms = m^3/s.

Table 3.3 Calibration and validation results. N/A = data not available.

Monitoring Location	*$RMSE_p$*		Runoff volume ratio (all months)	Nash-Sutcliffe efficiency coefficient (daily discharges)
	Even months	Odd months		
SS3	0.0041	0.0057	1.13	0.48
SS2	0.0053	0.0049	1.07	0.67
SS1	0.0011	0.0014	1.04	0.55
MB1	0.0017	0.0021	1.28	0.25
MB2*	0.0087	0.0094	N/A	N/A
NB	0.0062	0.0072	1.15	0.27
WB1	0.0012	0.0018	1.03	0.47
WB2	0.0017	0.0015	1.18	0.63
WB3	0.0027	0.0033	1.06	0.71

* Location MB2 was difficult to calibrate since any monitored discharge above 0.16 m^3/s (0.56 ft^3/s) was inaccurate. Despite this, it was still possible to create a truncated FDC for calibration.

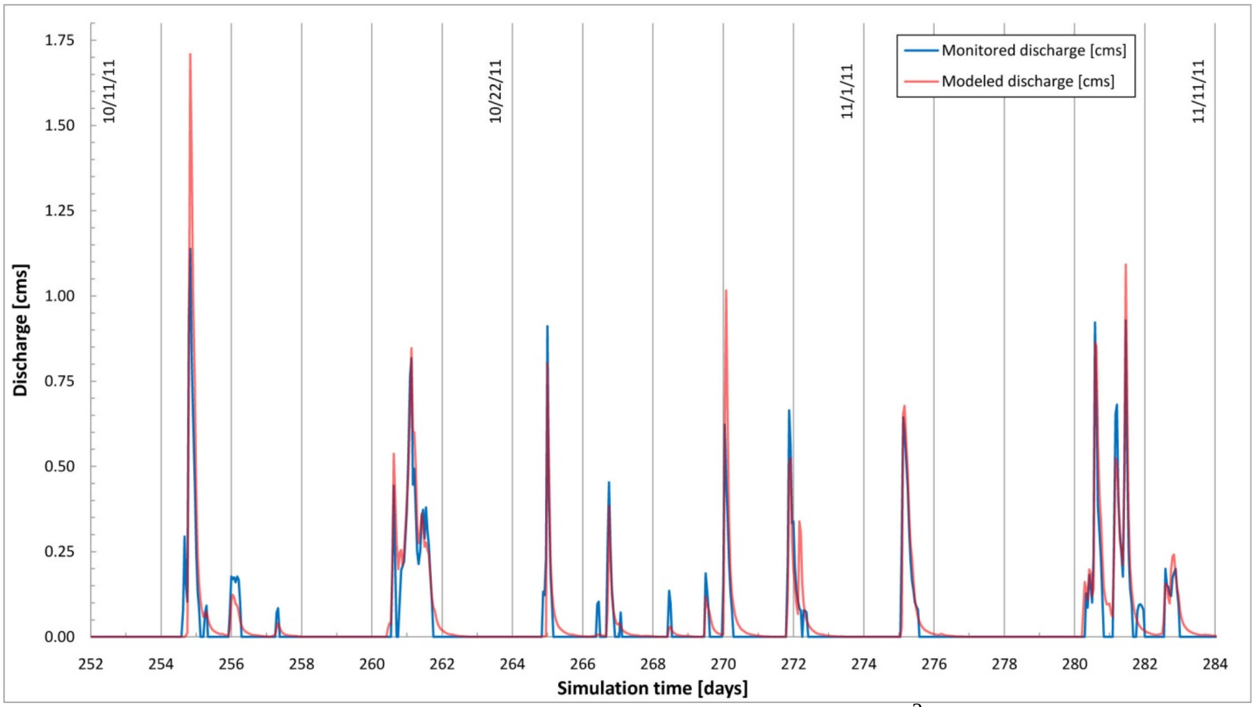


Fig. 3.4 MB1 Hydrograph October 11 to November 11, 2011; cms = m^3/s.

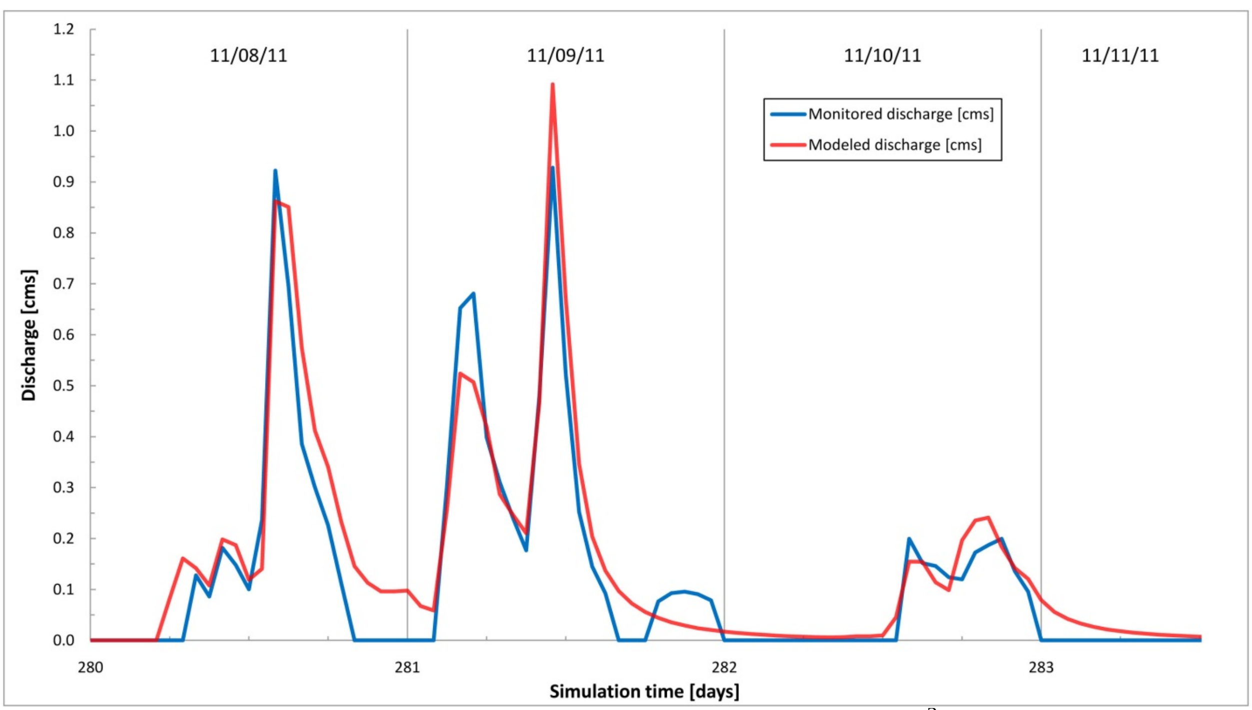


Fig. 3.5 MB1 Hydrograph November 8 to November 11, 2011; cms = m^3/s.

Table 3.4. Summary of the calibrated parameters for the full SWMM model.

Sub-catchment	Area, ha (ac)	Calibrated parameter values								
		Width, m (ft)	% Slope	% Directly connected impervious	Manning's n		Depth of surface storage, cm (in)		Pervious Curve Number	Drying time, days
					Impervious area	Pervious area	Impervious area	Pervious area		
SS3-A	26 (65)	109 (359)	0.1	18.0	0.010	0.41	0.00 (0.00)	5.20 (2.05)	49	5
SS3-B	40 (100)	135 (444)	0.1	24.6	0.010	0.41	0.00 (0.00)	5.34 (2.10)	49	5
SS3-C	138 (341)	250 (821)	0.1	6.4	0.010	0.41	0.00 (0.00)	5.32 (2.09)	49	5
SS2-A	67 (166)	1176 (3859)	0.1	9.6	0.010	0.41	0.25 (0.10)	2.61 (1.03)	66	5
SS2-B	70 (174)	1204 (3952)	0.1	10.1	0.010	0.41	0.25 (0.10)	5.46 (2.15)	48	5
SS2-C	59 (146)	1101 (3613)	0.1	8.7	0.010	0.41	0.25 (0.10)	5.26 (2.07)	49	5
SS1	65 (160)	914 (3000)	1.8	51.0	0.013	0.41	0.10 (0.04)	5.50 (2.16)	48	5
MB1-A	42 (104)	94 (308)	0.1	28.9	0.010	0.41	0.25 (0.10)	3.68 (1.45)	58	5
MB1-B	29 (72)	78 (257)	0.1	49.8	0.010	0.41	0.25 (0.10)	5.33 (2.10)	49	5
MB1-C	39 (97)	91 (298)	0.1	44.3	0.010	0.41	0.25 (0.10)	5.47 (2.15)	48	5
MB2	46 (115)	91 (300)	0.5	15.0	0.010	0.41	0.25 (0.10)	3.71 (1.46)	58	5
NB-A	61 (151)	578 (1896)	2.0	3.2	0.010	0.41	0.00 (0.00)	3.12 (1.23)	62	5
NB-B	11 (27)	244 (800)	2.0	17.7	0.010	0.41	0.00 (0.00)	5.48 (2.16)	48	5
NB-C	18 (44)	313 (1028)	2.0	16.1	0.010	0.41	0.00 (0.00)	2.89 (1.14)	64	5
WB1-A	43 (107)	73 (241)	0.1	18.6	0.013	0.41	0.10 (0.04)	5.63 (2.22)	47	5
WB1-B	104 (258)	114 (373)	0.1	7.8	0.013	0.41	0.10 (0.04)	5.37 (2.11)	49	5
WB2-A	119 (294)	514 (1687)	0.1	8.4	0.013	0.41	0.10 (0.04)	5.44 (2.14)	48	5
WB2-B	48 (119)	328 (1075)	0.1	48.5	0.013	0.41	0.10 (0.04)	5.30 (2.09)	49	5
WB3	53 (131)	152 (500)	0.1	5.0	0.013	0.41	0.51 (0.20)	4.76 (1.87)	52	5
Pond (Ruddiman Lagoon)	54 (132)	1463 (4800)	2.0	7.5	0.013	0.41	0.00 (0.00)	5.15 (2.03)	50	5

3.3 Flashiness and Biota

3.3.1 Methods

A primary use of the Ruddiman Creek hydrologic model (SWMM) was to determine the impact of stormwater management changes on the flow regime of the stream. In particular, how will watershed changes impact the flashiness (i.e., the rapid response to precipitation) of Ruddiman Creek and, in turn, how might sediment and biota respond? A flashy stream will have a longer hydrograph path length (i.e., higher peaks) than a stream with more stable flows (i.e., lower, more gradual peaks). In concept, flashiness compares the path length of a flashy stream to the path length of the same stream with no discharge variation at all. A conceptually-sound statistic that measures this path length and uses consistent units is the Richards-Baker (R-B) Flashiness Index (Baker et al. 2004):

$$FI = \frac{\sum_{i=1}^{n} |q_i - q_{i-1}|}{\sum_{i=1}^{n} q_i}$$

where q_i is the discharge at time period *i* out of *n* time periods. The R-B Flashiness Index is normally computed using daily discharges over a period of one year. It should be recognized that discharges computed at a daily scale will likely filter out some of the hydrologic variability seen in Ruddiman Creek because flashiness responds at a shorter time scale in this system; however, for comparison with other watersheds it is necessary to use a consistent discharge time scale (i.e., daily discharge). The R-B Flashiness Index is dimensionless and can be computed using discharge rates or volumes. A stream with no change in discharge over an entire year period would score a value of zero. The theoretical maximum value of this index is 2.

R-B Flashiness Index values for current conditions in Ruddiman Creek were computed from both monitored and modeled (SWMM model with baseflow) discharge data over the one-year monitoring period. This was done to check the ability of the model to predict the flashiness over the monitoring period. The SWMM model also was run using the 12-year precipitation data (January 1, 2000 to January 31, 2012) and R-B Flashiness values were computed from this 12-year period of modeled discharge values. This was done to see if there was any difference between flashiness modeled over short (1 year) or long (12 year) time intervals.

An analysis of the impact of climate change on flashiness index values also was performed. Details are given in Appendix I.

A study of R-B Flashiness Index values for gaged Michigan rivers and streams was performed previously by the Michigan Department of Environmental Quality (Fongers et al. 2007). From this dataset, we extracted R-B Flashiness Index values for 41 small watersheds (≤78 km^2 [30 mi^2]) for comparison with Flashiness Index values calculated for Ruddiman Creek. Macroinvertebrate community scores (P-51) calculated by the MDEQ (see Appendix K for P-51 overview) were acquired (T. Lipsey 2012; personal communication) for 35 of the 41 sites extracted from Fongers et al. (2007) (see Appendix N). These scores were from the most recent survey date at stations sampled within 1 mile of the USGS gage that was used to calculate Flashiness Index values. We attempted to include surveys only when survey dates fell within the dates used to calculate the Flashiness Index. P-51 macroinvertebrate scores were regressed against the R-B Flashiness Index scores for the 35 small Michigan watersheds using linear regression (Microsoft Excel®). Ruddiman Creek sites with P-51 macroinvertebrate scores were then added to the dataset and a second linear regression was performed. Confidence bounds (95%) were determined for the new Ruddiman Creek data points added to the set (Fig. 3.6).

3.3.2 Results

Table 3.5 provides a statistical summary of the R-B Flashiness Index values provided by the MDEQ and reported by Fongers et al. (2007) for the 41 Michigan streams with drainage areas of 78 km^2 (30 mi^2) or less. Table 3.6 provides a summary of the Ruddiman Creek R-B Flashiness Index values from both (SWMM) modeled and monitored flow data. The Ruddiman Creek values were greater than the mean and median, but lower than the maximum, of the MDEQ values. In a study of 22 Midwestern streams, Baker et al. (2004) identified a trend between flashiness and watershed size, with small watersheds having higher average R-B Flashiness Index values and a larger range of values than relatively larger watersheds. Given that the Fongers et al. (2007) data include watersheds up to 78 km^2 and the largest Ruddiman Creek sub-catchment is only 6 km^2, it is not surprising that the Ruddiman Creek's R-B Flashiness Index values are at the upper end of the range reported by Fongers et al.

An excellent match exists between the flashiness index values from monitored and modeled (SWMM) data (Table 3.6), further validating the SWMM model results. Furthermore, an excellent match exists between R-B Flashiness values computed using the 1- and 12-year SWMM model runs. This suggests that the 1-year modeling period is representative of the longer 12-year period.

Flashiness Index values were highest at MB1, NB, and WB2 (Table 3.6). These sites were therefore considered "key monitoring locations" and were the focus of BMP modeling (Chapter 4) and TMDL target identification (Chapter 5).

Table 3.5. R-B Flashiness Index statistics for small (< 78 km^2 [30 mi^2]) watersheds in Michigan (n=41; Fongers et al. 2007). The Flashiness Index value for one watershed smaller than 10 km^2 is also reported, to facilitate a more direct comparison with the Ruddiman Creek watershed (11 km^2). Note: only one watershed in the Fongers et al. dataset was under 10 km^2.

Statistic	R-B Flashiness Index
Mean	0.365
Minimum	0.006
25%	0.156
50% (Median)	0.314
75%	0.497
Maximum	0.848
Value for watershed smaller than 10 km^2 (3.8 mi^2)	0.627

Table 3.6. Richards-Baker (R-B) Flashiness Index values calculated for 1 year of monitored discharge, and for 1- and 12-yrs of SWMM-modeled discharge. Macroinvertebrates were sampled at the monitoring locations indicated below by MDEQ on July 15, 2011 (see Knoll and Lipsey 2012 and Appendix K for more details). The monitoring locations with the highest Flashiness Index values (i.e., key monitoring locations) are shown in bold.

Monitoring Location	Sub-catchment area, km^2 (mi^2)	R-B Flashiness Index values			P-51 Macroinvertebrate Score
		Monitored	SWMM, 1yr	SWMM, 12 yr	
SS3	2.05 (0.79)	0.764	0.751	0.764	---
SS2	4.01 (1.55)	0.630	0.586	0.582	---
SS1	4.66 (1.80)	0.464	0.453	0.445	---
MB1	**5.76 (2.23)**	**0.512**	**0.569**	**0.564**	**-5**
MB2	6.23 (2.40)	---	0.457	0.452	-4
NB	**0.90 (0.35)**	**0.721**	**0.724**	**0.742**	**-6**
WB1	1.48 (0.57)	0.206	0.265	0.255	---
WB2	**3.15 (1.22)**	**0.578**	**0.598**	**0.598**	**-6**
WB3	3.68 (1.42)	0.372	0.350	0.338	-6

The R-B Flashiness Index (FI) scores explained approximately 30% of the variation in the P-51 macroinvertebrate scores for the 35 small Michigan watersheds with a regression equation:

$$P51=2.706 - 7.111(FI))$$

where *P51* = P-51 macroinvertebrate score, and *FI* = R-B Flashiness Index. The R^2 value is 0.304. The regression relationship is statistically significant with a p-value of 0.0006.

These data show that the lowest quartile R-B Flashiness Index values tend to correspond with sites that have “acceptable” or “excellent” P-51 ratings. The highest quartile R-B Flashiness Index values tend to be associated with “poor” to “acceptable” P-51 ratings. The middle two quartile R-B Flashiness Index values are generally associated with “acceptable” P-51 ratings. The overall relationship between FI values and P-51 ratings suggests that reducing the flashiness of a stream by reducing imperviousness through the implementation of stormwater BMPs that infiltrate or detain runoff, may improve the macroinvertebrate community score.

The regression equation for P-51macroinvertebrate scores as a function of the R-B Flashiness Index was updated to include the Ruddiman Creek data (Fig. 3.6). There was no P-51 score available for the WB1 monitoring location; therefore, it was not included in the analysis. Since the R-B Flashiness Index at monitoring location MB2 could by computed only from modeled data, only 4 Ruddiman Creek data points were used to produce an updated regression equation:

$$P51 = 2.722 - 8.288\, FI$$

where *P51* = P-51 macroinvertebrate score, and *FI* = R-B Flashiness Index. The revised R^2 value is 0.314. The regression relationship is statistically significant with a p-value of 0.0002.

The relationship between R-B Flashiness Index values and P-51 scores from Ruddiman Creek (n=4) and other small watersheds in Michigan (n=35, Fongers et al. 2007) was used as the basis for target setting to achieve improvement in the benthic community of Ruddiman Creek (see Chapter 5). Attempting to quantify this relationship was a critical step in the target-setting process because an appropriate reference watershed could not be identified for Ruddiman Creek, and we needed to identify a relationship between biotic health and a pertinent hydrologic measure. The targets were set (see Chapter 5) to reduce the flashiness at the three key monitoring locations with the highest R-B Flashiness Index along each of the three branches: MB1, WB2, and NB.

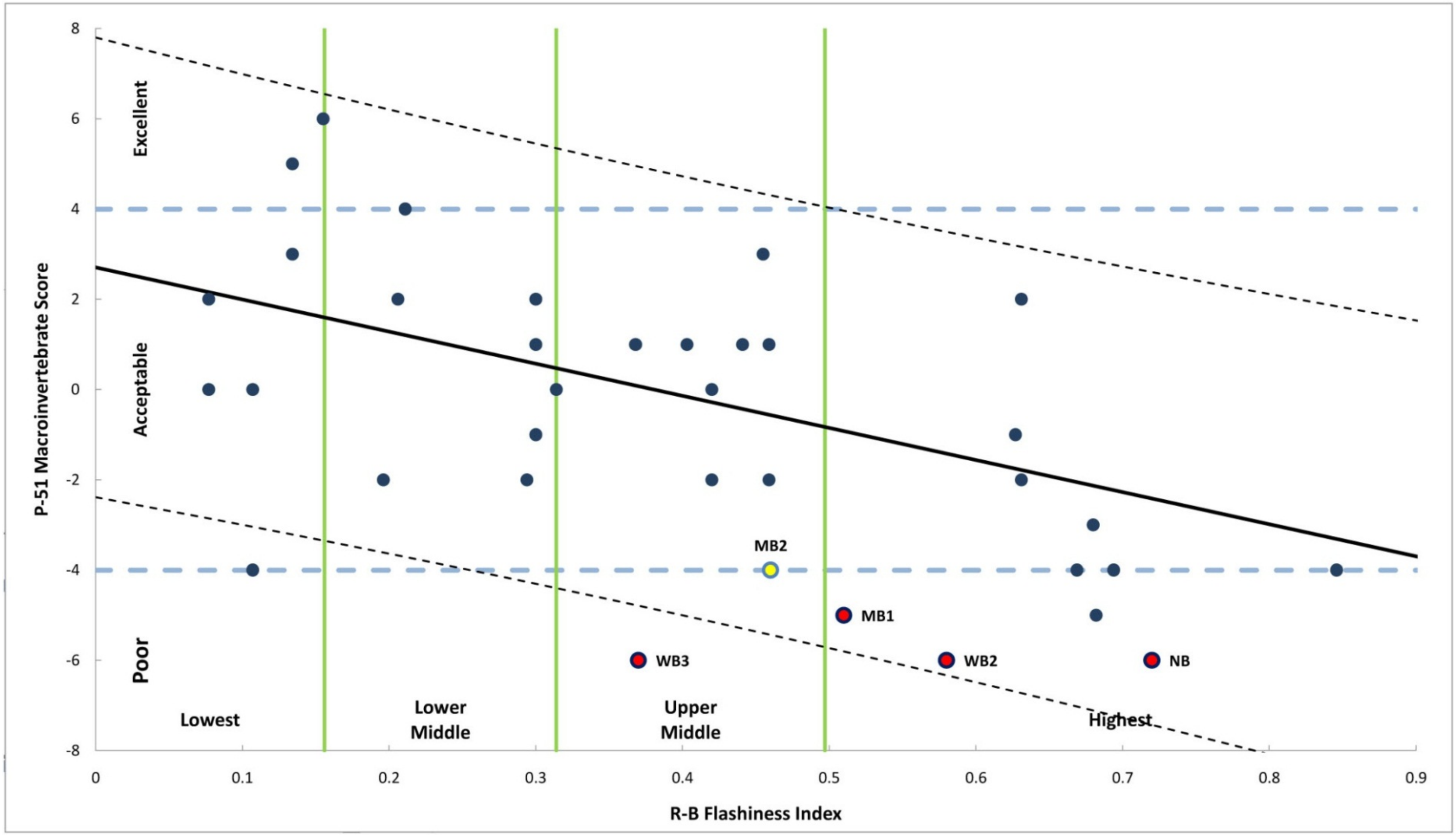


Fig. 3.6. P-51 Macroinvertebrate scores (T. Lipsey 2012; personal communications) versus R-B Flashiness Index values (Fongers et al. 2007) for 35 Michigan watersheds with an area of < 78 km^2 (30 mi^2) with the linear regression (solid line) and the 95% confidence bounds (black dashed lines). Four quartile (vertical) ranges of R-B Flashiness Index (lowest, lower middle, upper middle, and highest) and the P-51 macroinvertebrate community ratings (horizontal; poor, acceptable, and excellent). Ruddiman Creek data (excluding WB1, since no P-51 score was available) are shown in yellow and red. Data points in red are based on monitored discharge data and the yellow data point is based on modeled discharge data (not included in regression line). R^2 = 0.304 for 35 data points consisting of the Michigan watersheds extracted from Fongers et al. (2007). R^2 = 0.314 for 35 Fongers et al. sites plus the 4 Ruddiman Creek sites (red dots; n=39).

Based on the relationship of R-B Flashiness Index values and P-51 macroinvertebrate scores (Fig. 3.6), the R-B Flashiness Index would have to be reduced (i.e., stream made less flashy) to reach a minimally acceptable P-51 macroinvertebrate score of -4 (see Chapter 5 for Hydrologic Targets). For example, for location MB1 to reach an “acceptable” macroinvertebrate rating, its P-51 score must increase by 1 unit (i.e., from -5 to -4; see Fig. 3.6). Since the revised regression line has a slope of -8.288, this would require an R-B Flashiness Index reduction of 1÷8.288, or 0.12 units (Table 3.7). The P-51 scores at locations NB and WB2 each need to increase by 2 units (i.e., from -6 to -4); therefore, their R-B Flashiness Index values should decline by 0.24 units (Table 3.7). Confidence bounds can be constructed for the flashiness reduction based on the 95% confidence interval for the regression line slope (Table 3.7). The regression slope has a standard error of 2.10. As a result, the 95% confidence interval on the regression line slope is -4.21 to -12.36.

Achieving these reductions requires the implementation of BMPs—the number and type will influence the degree of reduced flashiness, which in turn, will improve the P-51 macroinvertebrate score. The following section describes the process by which we modeled the effects of implementing different BMPs throughout the Ruddiman Creek watershed.

Table 3.7. R-B Flashiness Index (FI) goals for reaching minimally acceptable P-51 macroinvertebrate scores. FI reduction goals were generated using the slope of the P-51 vs. FI regression. Lower and upper bounds are based on the 95% confidence interval for the regression line slope. Current FI and FI goals are based on modeled FI values.

Location	Current FI	FI Reduction Needed			FI Goal		
		Lower Bound	Goal	Upper Bound	Lower Bound	Goal	Upper Bound
MB1	0.569	0.08	0.12	0.24	0.489	0.449	0.329
NB	0.724	0.16	0.24	0.48	0.564	0.484	0.244
WB2	0.598	0.16	0.24	0.48	0.438	0.358	0.118

Chapter 4: BMP Modeling

4.1 Design Parameters

The SWMM program was used to model the impact of BMPs in reducing the flashiness in the Ruddiman Creek watershed, with the goal of achieving the Flashiness Index reductions identified in Table 3.7 to support healthier macroinvertebrate communities. The goal of this modeling effort was to identify the amount of reduction in directly connected impervious area (DCIA) needed to meet the Flashiness Index reductions necessary to achieve acceptable P-51 macroinvertebrate scores (Table 3.7). DCIA is not strictly a surrogate for the Flashiness Index, but can be thought of as a driver that strongly influences the FI value.

Structural BMPs options were initially chosen from the Low Impact Development Manual for Michigan (SEMCOG 2008), the International Stormwater BMP database developed by the American Society of Civil Engineers and the Water Environment Federation (www.bmpdatabase.org), and as a result of the feedback from community members during outreach meetings. The final LID BMP options selected for the Ruddiman Creek hydrologic model were 1) rain barrels, 2) porous pavement/underground detention, 3) rain gardens (modeled as a bioretention cell), 4) green roofs (also modeled as a bioretention cell), and 5) natural infiltration; these five BMPs represent the most common types of stormwater treatment practices that effectively treat DCIA and thus reduce stream flashiness.

Porous pavement/underground detention, green roofs, and rain gardens were modeled using built-in SWMM LID modules. These modules required up to 18 design parameters to fully define the BMP's performance (Table 4.1). The first step involved selecting a set of typical values for these design parameters and testing their responsiveness to changes in flashiness. The parameters that were most responsive were further investigated and refined based on professional judgment and experience. The final values selected for the SWMM LID module design parameters are given in Table 4.1.

Since much of the Ruddiman Creek watershed contains brownfield sites, the built-in SWMM BMPs were modeled with underdrain systems that reduce infiltration of stormwater through potentially contaminated soils. The longer stormwater remains in the storage layer beneath the designated BMP, the greater the impact on reducing stream flashiness. However, excessively long underdrain times will cause problems with successive storm events. If the BMP storage layer is not fully drained when the next storm occurs, the BMP will have less storage capacity, and therefore be less effective for the second storm. The underdrain parameters were selected to drain the BMP storage layer within a 72 hour time period. This storage time is commonly used in LID manuals and BMP design criteria (SEMCOG 2008).

Rain barrels were selected as one of the BMP types to be modeled in SWMM. However, they were modeled differently than the rain barrel routine included the built-in SWMM LID modules. The built-in SWMM rain barrel module captures roof runoff and discharges it as either delayed irrigation or overflow. These discharges can be sent to pervious or impervious areas but not both. Because the soils in the Ruddiman Creek watershed are generally sandy (i.e., low runoff potential and high infiltration rates), most of the runoff reaching the stream comes from the directly connected impervious areas, not the pervious areas. The most effective rain barrel is one that captures roof runoff from a downspout that normally discharges to a storm sewer and uses the stored water to irrigate pervious areas. This rain barrel will still likely overflow to the storm sewer. Hence, the built-in SWMM module will not work because overflow and irrigation discharges are sent to both impervious and pervious areas.

Instead of using the built-in SWMM rain barrel module, each rain barrel was modeled by replacing a portion of the impervious roof area with pervious. The calculations assumed that a home with a 130 m^2 (1400 ft^2) footprint has two rain barrels to capture runoff from each half of the roof. A 189 liter (50 gallon) rain barrel can hold the equivalent of 0.291 cm (0.114 in) of runoff from a 65 m^2 (700 ft^2) roof section; any larger storm would overflow the rain barrel. The SWMM rain barrel model showed that the stormwater capture efficiency is approximately 16%; therefore, each rain barrel in the model converts 10.4 m^2 (112 ft^2) of impervious roof surface to pervious.

Infiltration practices also were not modeled with the built-in SWMM LID modules. Instead, the directly connected impervious areas treated by infiltration were replaced by pervious areas in the SWMM model. The final set of BMP design parameters are listed in Table 4.1.

Table 4.1. BMP parameter values for BMPs modeled with built-in SWMM modules.

Layer	Design Parameter	Description	LID Type		
			Bio-Retention		Porous Pavement
			Rain Garden	Green Roof (Extensive)	
Surface	Storage depth, cm (in)	The maximum depth to which water can pond before overflow occurs.	30 (12)	2.5 (1)	5.1 (2)
	Vegetation, (volume fraction)	The fraction of the volume within the storage depth filled with vegetation.	0	0	0
	Surface Roughness, (n)	Manning's n for overland flow over the surface.	0	0	0.1
	Surface Slope, (%)	Slope of porous pavement surface	0	0	0
Soil	Thickness, cm (in)	The thickness of the soil layer.	91 (36)	15 (6)	
	Porosity, (volume fraction)	The volume of pore space divided by total volume of soil.	0.47	0.64	
	Field capacity, (volume fraction)	Volume of pore water divided by total volume after the soil has been allowed to drain fully.	0.31	0.50	
	Wilting point, (volume fraction)	Volume of pore water divided by total volume for a well dried soil.	0.06	0.05	
	Conductivity, cm/hr (in/hr)	Hydraulic conductivity for the fully saturated soil.	5.3 (2.1)	6.3 (2.5)	
	Conductivity slope	Slope of the curve of log(conductivity) versus soil moisture content.	10	10	
	Suction Head, cm (in)	The average value of soil capillary suction along the wetting front.	8.9 (3.5)	8.9 (3.5)	
Pavement	Thickness, cm (in)	The thickness of the pavement layer.			6.3 (2.5)
	Void Ratio	The volume of void space divided by the volume of solids in the pavement.			0.15
	Permeability, cm/hr (in/hr)	Permeability of the concrete or asphalt			254 (100)
	Clogging factor	Number of pavement layer void volumes treated to completely clog the pavement.			0

Table 4.1. (continued)

Layer	Design Parameter	Description	LID Type		
			Bio-Retention		Porous Pavement
			Rain Garden	Green Roof (Extensive)	
Storage	Height, cm (in)	Thickness of storage layer.	23 (9)	5.1 (2)	61 (24)
	Void Ratio	The volume of void space divided by the volume of solids in the layer.	0.67	0.67	0.67
	Conductivity, cm/hr (in/hr)	The rate at which water infiltrates into the native soil below the layer.	0	0	0
	Clogging Factor	Total volume of treated runoff to completely clog the bottom of the layer.	0	0	0
Underdrain	Drain Coefficient, cm^.5/hr (in^.5/hr)	Coefficient *C* and exponent *n* that determines the rate of flow through the underdrain as a function of height of stored water above the drain height. $q = C(h-Hd)^n$ where q is outflow per unit area Lid [in/hr], h height of stored water (in), and Hd is the drain height. If the layer does not have an underdrain then set C to *0*.	0.0531 (0.0333)	0.0250 (0.0157)	0.0325 (0.0204)
	Drain exponent		0.5	0.5	0.5
	Drain offset height, cm (in)	Height of underdrain piping above the bottom of a storage layer or rain barrel.	0	0	0

4.2 R-B Flashiness Index Sensitivity

With BMPs included in the SWMM model, we next calculated the impact that the BMPs have on decreasing the R-B Flashiness Index through reductions in DCIA. This was done by calculating the R-B Flashiness Index sensitivity, defined as the change in R-B Flashiness Index divided by the amount of DCIA treated. (Appendix J). This was done by treating 10% of the DCIA using each of the 5 BMPs in each sub-catchment, one BMP and one sub-catchment at a time, to compare the effectiveness among the 5 BMPs in reducing flashiness. The calculated R-B Flashiness Index change at all downstream stream monitoring locations was then determined from the model. This process required 95 model runs (5 BMPs applied to 19 sub-catchments).

The R-B Flashiness Index sensitivity was computed at every stream monitoring location due to implementation of BMPs in each sub-catchment. The full table of sensitivity values is provided in Appendix J. These values vary somewhat among the sub-catchments upstream of a given monitoring location. Table 4.2 gives values of these sensitivity parameters averaged over all upstream sub-catchments for the three key monitoring locations with the highest R-B Flashiness Index (MB1, NB, and WB2; see Chapter 3.3) along the particular branch.

4.3 BMP Benchmark Scenario and Scoping Tool

Microsoft Excel® spreadsheet software was used to develop a BMP Scoping Tool to simplify the process of calculating the new R-B Flashiness Index values that will be generated under the different BMP scenarios. The Scoping Tool was developed using the R-B Flashiness Index sensitivity values described above, and assumes that R-B Flashiness Index change is a linear function of the amount of DCIA treated by various BMPs (see below). The Scoping Tool input is the amount of DCIA treated in each sub-catchment.

The Scoping Tool was used to identify a BMP "benchmark scenario" that would reduce the R-B Flashiness Index at the key monitoring locations by the amounts given in Table 3.7 (0.12 units at MB1, and 0.24 units at NB and WB2). This is the reduction in flashiness needed to achieve a minimally acceptable P-51 macroinvertebrate score ("-4") and is shown graphically in Figure 4.1. It also was used to create a SWMM input file for further analysis using the calibrated hydrologic model. More details on the Scoping Tool are included in Appendix L.

There are numerous possible combinations of BMPs in different sub-catchments that could yield the desired results (i.e., acceptable P-51 scores) and also result in different levels of treatment. Identification of a reasonable benchmark scenario required some preliminary assumptions regarding which BMPs to use.

Rain barrels tend to be an order of magnitude less effective than other BMPs (Table 4.2) because of the modeling assumption that rain barrels would overflow (due to limited capacity) and direct the excess stormwater to the storm sewer system. For the benchmark scenario, the minimal contribution of rain barrels was not counted toward meeting the flashiness reduction goal. In other words, the rain barrels' contribution in reducing runoff that otherwise would discharge water back into the storm system was considered to be a "bonus" and not included in the calculations. The Scoping Tool also estimated the impact of regional detention or retention practice because the SWMM hydrologic model did not include any regional storage facilities. The flashiness impact was assumed to be similar to that of infiltration, and the infiltration sensitivity parameters were used.

The modeled BMP benchmark scenario assumed a uniform distribution of five typical BMPs (rain garden, porous pavement, underground detention, green roof, rain barrel, and infiltration) applied in all sub-catchments that resulted in meeting flashiness reduction targets. The Scoping Tool output indicates that the degree of treatment (i.e., percent reduction in DCIA) should be 36% in the main branch, 59% in the north branch, and 77% in the west branch. (See Appendix L for Scoping Tool inputs/outputs).

The key assumption behind the Scoping Tool is that there is a linear relationship between the R-B Flashiness Index change and the amount of directly connected impervious area treated by the BMPs. Several comparison runs were made to check this assumption. The errors in using the Scoping Tool versus the SWMM model do not exceed 13% for all branches (Table 4.3). The Scoping Tool produced conservative results for the BMP benchmark scenario relative to SWMM model output (Table 4.3). Therefore, the Scoping Tool can be used with confidence by watershed managers to explore numerous BMP scenarios and track BMP implementation. Data from a given case study using the Scoping Tool can then be imported back into the calibrated SWMM model to produce the final prediction of flashiness reduction, which in turn can be used to calculate the improvement in the associated P-51 score.

Since the Scoping Tool produced conservative results, the SWMM model was used to further refine the benchmark scenario. Several runs were made using SWMM (instead of the Scoping Tool) resulting in the following revised values of the required degree of treatment (i.e., percent reduction in DCIA): 35% in the main branch, 52% in the north branch, and 68% in the west branch. These reductions were used as the basis for calculating the loading capacity for the TMDL DCIA target (Chapter 5.4.3).

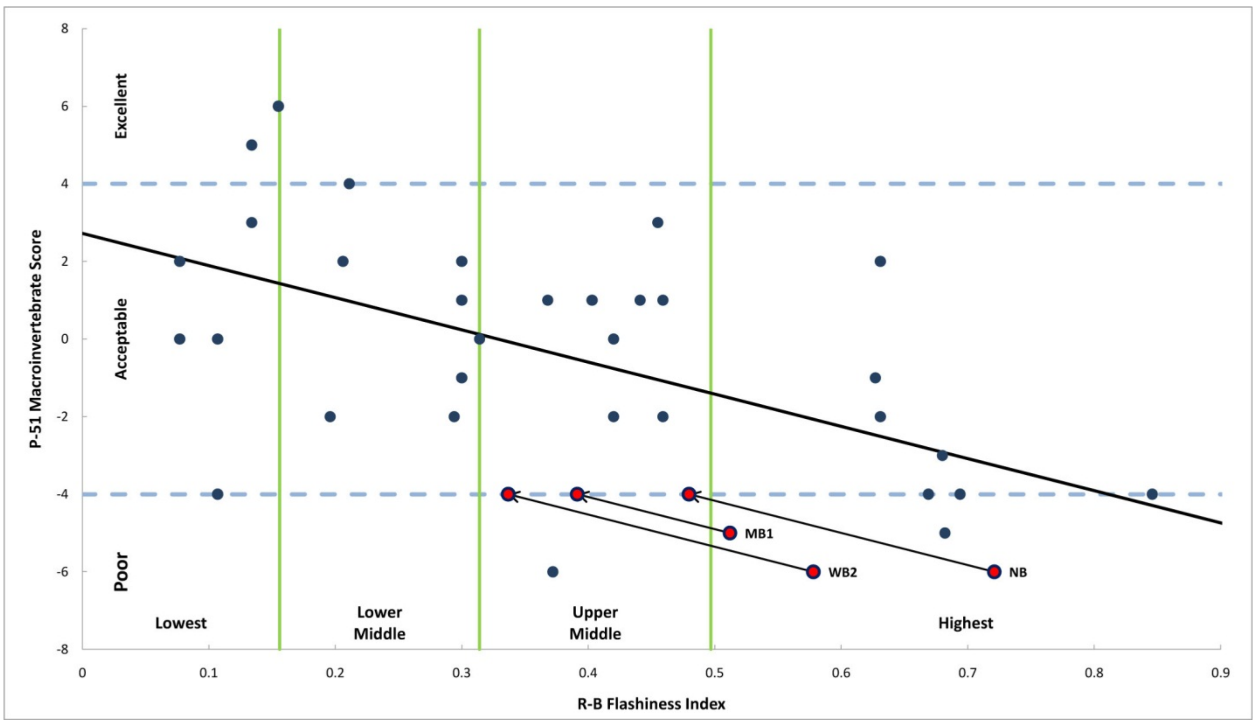


Fig. 4.1. Scoping Tool graph showing the reduction in R-B Flashiness Index values that would increase Ruddiman Creek P-51 macroinvertebrate scores (red dots) to acceptable scores (-4) at the key monitoring locations (MB1, NB and WB2), following the trend line (R^2 =0.314) that includes 35 other small Michigan watersheds (<78km^2 [30 mi^2]; blue dots).

Table 4.2 Flashiness Index sensitivity for the 3 key monitoring locations (see Chapter 3.3). DCIA refers to directly connected impervious area.

Monitoring Location	Branch	Upstream sub-catchment area, ha (ac)	Total upstream DCIA, ha (ac)	Change in R-B Flashiness Index per hectare (acre) of DCIA treated,1/ha (1/ac)				
				Green Roof	Rain Garden	Porous Pavement or Underground Detention	Rain Barrel	Infiltration
MB1	Main	576 (1424)	119 (295)	0.00291 (0.00118)	0.00399 (0.00161)	0.00221 (0.00090)	0.00043 (0.00017)	0.00270 (0.00109)
NB	North	89.8 (222)	6.76 (16.7)	0.0631 (0.0255)	0.0621 (0.0251)	0.0560 (0.0227)	0.0091 (0.0037)	0.0567 (0.0230)
WB2	West	315 (778)	49.4 (122)	0.00638 (0.00258)	0.00940 (0.00380)	0.00460 (0.00186)	0.00096 (0.00039)	0.00598 (0.00242)
Total		**907 (2242)**	**176 (434)**					

Table 4.3. R-B Flashiness Index Reduction Targets

Benchmark Scenario Case	Calculated Reduction in R-B Flashiness Index needed to attain minimally acceptable P-51 scores		
	MB1	WB2	NB
Scoping Tool Estimate	0.12	0.24	0.24
Refined Estimate from SWMM Model	0.124	0.269	0.271
Scoping Tool Error	3.3%	12%	13%

Chapter 5: TMDL Target

5.1 Surrogate Measure: DCIA

Ruddiman Creek requires a Total Maximum Daily Load (TMDL) for biota because the water body is not meeting its designated uses for other indigenous aquatic life and wildlife and warm water fishery. Impaired biota in Ruddiman Creek are a result of numerous and interrelated stressors (Knoll and Lipsey 2012). Much of this stress is associated with the very large amount of urbanized land use in this watershed; with urbanization comes large areas of impervious surface, such as parking lots, roofs, and roads that prevent the infiltration of water into the ground. Accumulated contaminants, including sediment, nutrients, heavy metals, pesticides, and toxic organic compounds, can wash off of these surfaces and into streams during storms (Taulbee et al. 2009, Johnson et al. 2011). These compounds can serve as chemical stressors to the stream ecosystem, impacting both water quality and stream ecosystem structure and function (Taylor et al. 2004, Walsh et al. 2005), and resulting in a set of consistently observed effects termed the "urban stream syndrome" (Walsh et al. 2005). These cumulative symptoms include changes to water chemistry, stream channel morphology, hydrology, and biotic richness (Paul and Meyer 2001, Walsh et al. 2005); because these stressors interact with each other, and can have either additive or synergistic effects, it is difficult to disentangle the impact of one stressor from another (Johnson et al. 2011). In addition to current stormwater inputs, the industrial activities in the Ruddiman Creek watershed led to contaminated sediment and a subsequent sediment remediation project.

Nederveld (2009) evaluated the success of the 2005-2006 sediment remediation project in the Ruddiman Creek watershed in terms of its impact on the macroinvertebrate community. After approximately 1.5 years of recovery, Nederveld (2009) found that stream quality had not reached acceptable conditions based on macroinvertebrate scores using the Family Biotic Index (Hilsenhoff 1988). However, significant improvement in stream quality did occur as indicated by a greater abundance of sensitive taxa (%) and a richer macroinvertebrate community. Further improvements in stream condition appeared to be limited by chronically degraded habitat (e.g., sedimentation, poor woody debris retention, loss of riparian vegetation) and hydrologic instability. It was recommended that future restoration strategies consider and address the interrelated and complex factors associated with sediment contamination, degraded habitat and water quality, and altered hydrology.

MDEQ performed qualitative macroinvertebrate sampling 3 years after remediation in June 2009 (MB1 and MB2), and 5 years after remediation in July 2011 (NB, WB2, WB3) with only one acceptable score at MB2 (see Ruddiman data points in Figure 3.6).

The storm events observed during our study period resulted in a rapid response in the hydrograph of the main branch. Nederveld (2009) found that hydrologic alterations had the potential not only to alter the hydrologic regime, but to significantly impact macroinvertebrate communities. Other investigations have shown that elevated flow rates can disrupt aquatic habitat (Scullion and Stinton 1983, Gurtz et al. 1988, Wood and Armitage 1997) and subsequently dislodge, damage, or kill aquatic invertebrates (Sagar 1983, Feminella and Resh 1990).

Based on the conclusions of these previous studies, altered hydrology was the primary focus of this study. The hydrologic analysis conducted during this study was used as the basis for a surrogate measure to express the Ruddiman Creek TMDL for biota. A number of hydrologic measures calculated during the study process were considered for selection as the TMDL surrogate, the most notable being the R-B Flashiness Index. However, the R-B Flashiness Index was not selected as the final TMDL metric because it is a difficult concept for most watershed stakeholders and regulators to grasp and is not as easily measured as other metrics. A reduction in peak discharge rate or volume for a given frequency of occurrence, which has been used in other TMDLs, was found inadequate for the Ruddiman Creek watershed for the following reasons. First, flashiness reduction can be achieved without a reduction in volume, making a volume target less meaningful. Second, while the frequency and duration of discharges of a given magnitude (i.e., hydrologic variables important for biota; see Chapter 2.2) can be calculated for Ruddiman Creek, it is a less direct approach than using the R-B Flashiness Index, which itself is a measure of the frequency and magnitude of discharges.

Directly Connected Impervious Area (DCIA) is a conventional measure that has been used in other TMDLs (Eagleville Brook CT, Barberry Creek ME) and is relatively easy to measure. BMP modeling showed a very close relationship between flashiness and DCIA. (See Chapter 4.2 discussion on R-B Flashiness Index sensitivity). Therefore, percent DCIA was selected as the TMDL surrogate for Ruddiman Creek.

The linkage analysis used to relate the surrogate measure (DCIA) to biota is presented in Fig. 1. Because a reference watershed approach was not possible given the unique characteristics of Ruddiman Creek, the analysis relied exclusively on monitoring both flow and sediment over a period of approximately one year (Chapter 2), and hydrologic modeling using a continuous simulation model (EPA-SWMM; Chapters 3 and 4). In addition to the focus on hydrology (left side of flow chart; Fig. 1), a study of sediment supply and stream stability (right side of flow chart; Fig. 1) was conducted in tandem with the hydrologic analyses (Chapter 6). The purpose of the sediment analysis was to 1) quantify the current amount of suspended sediment in the system, 2) relate it to the current hydrology of the system, and 3) calculate the anticipated reductions in suspended sediment that would result from the flashiness reductions identified in the BMP benchmark scenario (Chapter 4.3). Stream channel morphology was studied to assess if the stream is in balance with the current amount of sediment transport.

5.2 Strengths and Weaknesses of TMDL Target Approach

5.2.1 Strengths

Peer-reviewed research has documented the impact of altered stream hydrology on biotic communities, focusing on some measure of stormwater runoff (Pratt et al. 1981, Gray 2004, Helms et al. 2009). Retention of runoff helps return a stream with altered hydrology to a more natural flow regime, which in turn creates a physical condition that is more conducive to native biota (Poff et al. 1997). One of the most effective ways to retain stormwater is to reduce the amount of directly connected impervious area (Meierdiercks et al. 2010) as this connection provides a direct conduit for runoff into streams. Therefore, an approach that seeks to reduce the effect of stormwater runoff on stream biota via a reduction in DCIA has great potential for success. Hence, our conceptual approach is based on sound, peer-reviewed scientific principles—the reduction of the flashiness and high flows should allow the stream to reach attainment (based on P-51 scores).

The hydrologic analysis makes use of the flow duration curve (FDC), which is a well-established statistical approach to account for variations in wet and dry weather flows over time. Replication of the FDC was the primary calibration target for the hydrologic model. The advantage of using the FDC as a primary calibration instrument was that it is unaffected by missing monitoring data and errors in timing of hydrograph peaks. Using the FDC for model calibration made the best use of available monitoring data and provided good replication of modeled and monitored stream flashiness scores (Chapter 3).

The validity of the numeric water quality targets was checked using the Work Index as a measure of physical stresses on the stream channel. Stream power indicates the potential for accelerated streambank and bed erosion, and accelerated erosion can negatively impact biotic habitat (Gammon 1970, Waters 1995, Wood and Armitage 1997). The primary water quality target was computed as a reduction in DCIA by means of stormwater management. This target was initially computed based on a target reduction in stream flashiness (as measured by the R-B Flashiness Index and correlated with P-51 macroinvertebrate ratings). The resulting stream power over time (i.e., the work done on the stream channel by the volume, rate, and duration of flow) was calculated in a Work Index (Appendix H.3). Water quality targets were shown to reduce the amount of erosive power exerted on the stream channel to between 30 and 70% of the existing condition value (see Appendix H.3). The results of the Work Index calculation (Appendix H.3) validate the assumption that the reduction in flashiness does in fact reduce the amount of critical stream power exerted on the channel over time. This is important because without a significant reduction in volume, stream power at and near the critical bankfull condition might have increased, indicating that our flashiness metric would not be effective at reducing stresses on the stream channel.

5.2.2 Weaknesses

The primary weakness in the linkage analysis is the large amount of unexplained variance in the correlation between the P-51 macroinvertebrate scores and the R-B Flashiness Index. Linear regression revealed a relatively low correlation coefficient (R^2 = 0.304 [and 0.314 when the four Ruddiman Creek data points were added]) between the two variables. One explanation for the weak correlation is that other factors besides flashiness affect biotic community health (e.g., contaminants, food web interactions). A clear relationship exists between increasing flashiness and decrease in biota health, and has been used as the basis for stormwater management guidelines (Schueler1995, Schueler and Galli 1992); thus, based on established and peer-reviewed scientific knowledge of the relationship between biotic health and flashiness, we focused on altered hydrology. We also recognize that other stressors exist in this urban watershed; if the reduction in flashiness does not result in improved biotic health over time, then we recommend that the role of these additional stressors be examined and addressed, as appropriate.

Further, it is assumed that the relationship between the R-B Flashiness Index and the P-51 score would be linear and the slope would be the same as that established for the 35 Michigan watersheds (Fig. 4.1). However, it is unlikely that the slope for Ruddiman would be the exact same as for the other watersheds. Hence, it is possible that the FI goals reported in Table 3.7 may result in P-51 scores that are somewhat better or worse than those reported, given the potential uncertainty in the relationship.

Finally, our analysis is based on one year of hydrologic data. 2011 calendar year was a wet year (9.01 in. above the long-term mean of 33.49 in.), although we did not analyze if the distribution of precipitation was representative of the long-term record. The year also was slightly warmer than average (49.6°F vs. long-term mean of 48.6°F), which may have allowed more soil infiltration and resulted in more evapotranspiration, thereby somewhat counterbalancing the effect of greater precipitation.

5.3 Numeric Water Quality Target

The numeric water quality target is the percentage of directly connected impervious area (DCIA) for each branch of Ruddiman Creek above which it is unlikely that acceptable P-51 macroinvertebrate scores will be achieved. Impervious cover targets are summarized in Table 5.1. The percent DCIA treated is also shown in relation to the percent of DCIA for each branch.

Table 5.1 Target directly connected impervious area (DCIA) for the 3 key monitoring locations (see Chapter 3.3).Target DCIA values are those needed to achieve the Flashiness Index goals shown in Table 3.7, including a 20% margin of safety.

Branch	Monitoring location	Upstream drainage area, ha (ac)	Estimated Current DCIA, ha (ac)	Estimated Current Percent DCIA	Percent DCIA treatment needed*	Target Percent DCIA	Target DCIA ha (ac)
Main	MB1	576 (1424)	119 (295)	21%	42%	**12.0%**	69 (171)
North	NB	90 (222)	6.8 (16.7)	7.5%	62%	**2.9%**	2.6 (6.3)
West	WB2	315 (778)	49.4 (122)	16%	82%	**2.8%**	8.9 (22)

* Includes 20% MOS

The ultimate TMDL target is the reestablishment of healthy and diverse macroinvertebrate communities that, when monitored using Procedure 51 methodology (MDEQ 2008), result in a consistent 'acceptable' or 'excellent' rating. Achievement of the biological target will override the numeric hydrology target. However, if the numeric target is met but the biological target is not achieved, then other factors (e.g., water and soil chemistry, substrate/habitat), as well as whether the %DCIA reduction targets were insufficient, will need to be further evaluated.

5.4 Loading Capacity

Loading Capacity (LC) is the greatest amount of directly connected impervious area the Ruddiman Creek watershed can support without violating the stream's aquatic life criteria. The LC is the sum of individual Waste Load Allocations (WLAs) for point sources and Load Allocations (LAs) for nonpoint sources and natural background levels. In addition, the LC must include a Margin of Safety (MOS), either implicitly or explicitly, within the WLA or LA that accounts for uncertainty in the relationship between pollutant loads and the quality of the receiving water. Conceptually, this definition is expressed by the equation:

$$LC = \sum LA + \sum WLA + MOS$$

5.4.1 Allocations

In addition to the overall numeric target and LC, the TMDL must also allocate the LC between point sources (WLA) and nonpoint sources (LA). U.S. EPA guidance allows for a gross allocation between WLA and LA, rather than accounting for every discrete stormwater conveyance and the areas draining into them (USEPA 2002).

All sub-catchments of the Ruddiman Creek watershed are entirely located within municipalities (City of Muskegon, Muskegon Heights, Norton Shores and Roosevelt Park) with municipal separate storm sewer systems (MS4s) that are federally regulated under the National Pollutant Discharge Elimination System (NPDES) program. Under this program, storm sewer discharges are considered point sources and would be counted as a WLA.

The entire Ruddiman Creek watershed is within the defined MS4 urbanized areas. It is not feasible to distinguish between storm water reaching Ruddiman Creek through MS4 outfalls (WLA) and non-point sources of stormwater runoff from overland flow and private drainage systems (LA). Therefore, the percent DCIA targets apply to all stormwater drainage areas in the watershed (i.e., both WLA and LA areas; Table 5.3). Refer to the following sections for derivation of the WLA and LA percentages.

5.4.2 Margin of Safety (MOS)

TMDL analyses are required to include a margin of safety (MOS) to account for uncertainties in the relationship between load and waste load allocations and water quality. The MOS may be either explicit or implicit in the analysis.

An implicit approach would have incorporated the uncertainty in the slope of the P-51 macroinvertebrate score versus RB Flashiness Index plot. This uncertainty, based on a 95% confidence interval in the regression line slope, yields a range of RB Flashiness Index reduction values instead of a single target reduction value (see Table 3.7). Calculations using the Scoping Tool show that target RB Flashiness Index reductions of 0.48 at locations NB and WB2 are not physically achievable even with treatment of 100% of the directly connected impervious area (results not shown). As a consequence, an explicit MOS of 20% was selected (as described below).

The benchmark scenario (Chapter 4.3) identified the reductions in DCIA necessary to achieve the reductions in R-B Flashiness Index values that would result in improved macroinvertebrate communities. Although the benchmark scenario assumed a uniform distribution of equal amounts of BMP types, actual BMP implementation, effectiveness, and types of practices may vary widely. Thus, an explicit margin of safety was included in the analysis. A uniform factor for the margin of safety was desired, and we used a conservative estimate (see below). Comparison of the benchmark scenario to a "worst case" scenario was used to calculate the margin of safety (Table 5.2). The worst case scenario assumes that DCIA is treated with the least effective of the five BMPs used in the benchmark scenario (i.e., porous pavement). It is not anticipated that the actual treatment will follow the worst case scenario. Therefore, a split of the difference between the benchmark and worst case scenarios was selected to determine a reasonable margin of safety. This difference is approximately equal to a 20% margin of safety.

An explicit MOS of 20% was applied uniformly to the DCIA reduction targets identified by the benchmark scenario to arrive at the TMDL impervious cover target. The MOS accounts for the uncertainties in the types of BMPs implemented, the distribution of those BMPs, and the effectiveness of the BMPs. While the MOS was not applied directly to the relatively weak correlation between P-51 scores and R-B Flashiness Index values described in the Chapter 5.2.2 (Weaknesses), it is a conservative number that can account for a variety of unknowns.

Table 5.2. Results of benchmark and worst case scenarios. Note that the worst case scenario is based on implementation of the least efficient BMPs, thereby requiring a higher %DCIA to achieve the TMDL targets.

Branch	Directly Connected Impervious Area (DCIA) Treated					
	Benchmark Scenario		Worst Case Scenario		Benchmark Scenario with 20% MOS	
	%	ha (ac)	%	ha (ac)	%	ha (ac)
Main	35%	42 (103)	50%	59 (147)	42%	50 (124)
North	52%	3.5 (8.7)	72%	4.9 (12)	62%	4.2 (10.4)
West	68%	34 (83)	100%	50 (122)	82%	41 (100)

5.4.3 Resultant Loading Capacity (LC)

The LC for Ruddiman Creek expressed in terms of the TMDL directly connected impervious area target is summarized in Table 5.3, and is based on the equations:

WLA + LA = % DCIA (1- fraction DCIA reduced)

MOS = 1.2

LC = %DCIA [(1-fraction DCIA reduced (MOS)]

The associated reductions in sediment loads projected for Ruddiman Creek are summarized in Chapter 6.3.

Table 5.3 Loading capacities for each branch of Ruddiman Creek. Description of how WLA and LA were addressed can be found in Section 5.4.1 (Allocations).

Branch	Current Percent DCIA	Fraction DCIA Reduced	WLA + LA	MOS	LC
Main	21%	0.35	13.5%	1.2	12%
North	7.5%	0.52	3.6%	1.2	2.9%
West	16%	0.68	5.0%	1.2	2.8%

DCIA= Directly Connected Impervious Area; WLA= Waste Load Allocation; LA= Load Allocation; MOS= Margin of Safety; LC= Loading Capacity

Notes:

Storm sewer discharges are considered point sources (MS4 outfalls) and would be counted as a WLA.

Non-point sources of stormwater runoff from overland flow and private drainage systems would be counted as LA.

The percent DCIA targets apply to all stormwater drainage areas in the watershed (i.e., both WLA and LA areas).

5.5 Seasonal Variation

Surface water discharges and sediment loads vary by season in response to rainfall and snow melt events. Seasonality is addressed in the TMDL targets by using flow duration curves (FDCs), which incorporate seasonal variation in discharge. The FDCs used for the hydrologic analysis were based on a full year of flow monitoring data (February 2011 through January 2012), which encompasses all four seasons.

5.6 Critical Conditions

The “critical condition” is the set of environmental conditions (e.g., flow) used in developing the TMDL that result in attaining water quality standards at an acceptably low frequency of occurrence (e.g., a large stormwater runoff event). If the critical condition is protective for the larger, but less frequent occurrence, it should also be protective of other smaller, more frequent occurrences.

The biological communities in Ruddiman Creek classified as “poor” are linked to the excessive flows attributed to wet weather discharges (i.e., runoff). Suspended sediment monitoring data show that elevated concentrations are also associated with wet weather flows.

As a result, the critical condition for biota and suspended sediment is wet weather/high flows, particularly those that are large enough to produce bankfull flow. Since the FDCs used in the linkage analysis include wet weather discharges of varying frequencies, the critical condition is accounted for within the full range of discharges represented by the FDCs.

Baseflow is also a critical condition for biota, since without an adequate baseflow some aquatic invertebrates cannot survive. A reduction in baseflow will also result in an increase in the R-B Flashiness Index. Increased infiltration through BMPs in favorable areas of the watershed will help stabilize and increase baseflow, which should improve conditions for biota. Reducing industrial NPDES discharges (which contribute to baseflow through storm sewer discharges) must also be carefully considered; reducing NPDES discharges too drastically could reduce baseflow in certain locations of the watershed. Diverting NPDES discharges to BMPs (i.e., retention basin, or infiltration) could impact biota if these discharges are an important component of baseflow, so diversions should be monitored carefully.

5.7 Implementation

Impervious cover is used as a surrogate for the impacts that stormwater has on aquatic life in Ruddiman Creek. Designated use attainment will be assessed by directly measuring the aquatic life. Tracking the reduction in or disconnection of impervious area will be used as an interim measure to assess progress over time. Note that disconnection does not mean just the removal of impervious cover (see below). A flow and sediment monitoring program is recommended after DCIA reductions have been implemented to measure reduction in stream flashiness and sediment load of each branch, and provide further confirmation of the relationship between percent DCIA reduction and biotic health.

Stormwater design criteria for impervious cover reduction are necessary for successful implementation of the Ruddiman Creek TMDL. The stormwater design criteria must be written with sufficient detail for design and review engineers to follow. It must be adopted by the local municipalities and the Muskegon County Drain Commissioner for all new and re-development within the Ruddiman Creek watershed. To guide this process, criteria were defined to determine what constitutes a "reduction" in DCIA. The hydrologic modeling that we performed (Chapter 3) considered DCIA effectively "reduced" when:

1. Impervious surfaces are physically removed and replaced with pervious surfaces.
2. Impervious surfaces are disconnected from the storm sewer system by routing runoff to a pervious area meeting minimum size, length, and slope requirements (e.g., a rain barrel with an overflow directed to yard, away from the storm sewer).
3. Impervious surfaces are disconnected from the storm sewer system by routing runoff to an infiltration BMP sized for stream protection volume.
4. An underdrained LID BMP (rain garden, porous pavement, green roof) is engineered and implemented for stream protection and volume reduction with a *hold time no less than 72 hours*.

Future development in the watershed that has the potential to increase impervious cover must be required to treat all new DCIA, or coordinate a trading agreement if such a program is set up by the drainage district or municipality.

Because BMPs are designed for a single event, a 2-year storm was selected to provide effective treatment for up to 95% of all probable storms in a given year (SEMCOG 2008). The 2-year storm event represents rainfall frequencies that have the greatest impact on stream channel formation, and is therefore used in Michigan for stream protection.

An underdrained BMP provides treatment through “extended detention” of runoff, thereby reducing and extending peak flows. This type of BMP provides some volume reduction due to the ability of the filter media to adsorb and/or uptake water (Carpenter and Hallam 2007). A standardized amount of volume reduction provided by a given type of underdrained BMP has not been quantified for general application, and was not accounted for in the modeling. Therefore, the assumptions regarding BMP effectiveness (Table 4.1) used in the modeling are conservative.

Future reductions in DCIA achieved through BMP implementation will be tracked within each branch individually using the Scoping Tool developed during this study. The Scoping Tool provides an accounting by sub-catchment of the number of directly connected impervious acres treated with a variety of available BMP types. Following BMP implementation, continuous flow monitoring of Ruddiman Creek at the three key monitoring locations (MB1, NB, and WB2; see Chapter 3.3) over the course of a year would need to be conducted to determine the actual change in flow duration curve and R-B Flashiness Index.

Chapter 6: Sediment Modeling

Sediment modeling was performed to quantify the relationship between hydrology (flow) and sediment load in Ruddiman Creek, and link a measurable in-stream pollutant to the hydrology and hydrologic changes in the watershed. As stated previously, one of the key impacts associated with flashy stream flows is an increase in sediment flux (Bledsoe and Watson 2001, Wagenhoff et al. 2012) because the power and increased speed of the storm flow entering the system can scour the streambed and erode stream banks. The resultant increase in suspended and bedload sediment transport can, in turn, alter stream morphology and result in a loss of benthic habitat (Coats et al. 1985). While not the primary target for the Ruddiman Creek biota TMDL, annual sediment load and average suspended sediment concentrations (SSC) were used to further validate the hydrologic target (DCIA) in terms of fisheries conditions (long-term average SSC concentrations for moderate to optimum fish communities; Alabaster and Lloyd 1982) and geomorphic goals ("good/fair" condition for stream stability; Rosgen 2006).

6.1 FLOWSED Model

The FLOWSED sediment supply model was developed as part of the Watershed Assessment of River Stability and Sediment Supply (WARSSS; Rosgen 2006). FLOWSED provides insight on the overall stability of a stream, including the potential for aggradation or degradation. FLOWSED was used to: 1) calculate the current annual sediment load at each sampling location to provide a baseline against which to evaluate the effectiveness of proposed efforts to stabilize hydrology within the watershed, 2) to compare sediment transport rates among monitoring locations, and 3) to estimate future conditions assuming a more stabilized hydrology resulting from the installation of upland BMPs; future conditions were based on the BMP benchmark scenario (see Chapter 4.3), which served as the basis for calculating TMDL targets. For existing conditions, the FDC and sediment rating curve equations for bedload and SSC that were developed based on field data (see Chapter 2.3) were used as the baseline input into FLOWSED. For future conditions, the same sediment rating curve equations were utilized as described above; however, the *existing* FDC was replaced with the *projected* FDC based on meeting the DCIA reductions identified in the BMP benchmark scenario. Existing and projected FDCs (including baseflow) for each of the three key monitoring locations are included in Appendix P. The benchmark scenario assumes the uniform application of the five BMP types (rain gardens, porous pavement/underground detention, green roofs, rain barrels and infiltration) throughout the watershed to achieve the R-B Flashiness Index reductions needed to improve P-51 macroinvertebrate scores (see Table 3.7 and Chapter 4.3).

6.2 Existing Sediment Loads

Existing annual sediment loads were calculated for each of the six tributary monitoring locations and the storm sewer outlet (SS1) to the main branch of Ruddiman Creek (Table 6.1). Sediment loadings from the main branch of Ruddiman Creek correlate well with the geomorphic assessment and scour chain monitoring data (Appendix H), as described below.

The suspended sediment load supplied by the upstream storm sewer (SS1) is approximately 41 tons per year less than the annual suspended load being transported by the stream channel at MB1 (Table 6.1). Because there are no other direct sediment inputs to MB1, the source of additional sediment being transported is most likely from erosion within the stream channel or re-suspension of material already deposited; therefore, the sediment data confirm the conclusion drawn for the geomorphic assessment that MB1 is unstable and degrading.

The suspended sediment load currently being transported at MB2 is approximately 16 tons per year less than the sediment load supplied by MB1 (Table 6.1); therefore, the data indicate that MB2 does not have the ability to transport the supplied upstream sediment load and has the potential to aggrade. This confirms the conclusion drawn from the geomorphic assessment and scour chain data (see Appendix H). However, the bedload data appear to contradict this conclusion, with MB2 transporting over five times the amount of bedload as MB1 (Table 6.1). The very high bedload rate measured at MB2 would suggest that the stream bottom is degrading; however, this is not borne out by the geomorphic assessment or scour chain data.

However, due to the lack of reliable high flow data at MB2 (because of flow being affected by Ruddiman Lagoon), the contradictory sediment transport characteristics of this site warrant further investigation.

The NB monitoring location has the lowest annual discharge and sediment loading (Table 6.1). The reach transported only 4 tons of sediment annually. Based on the noted degrading section of stream channel along the upper reach of the north branch, it is likely that the annual sediment load being supplied above the north branch sampling location is actually higher than 4 tons per year. Due to a slight gradient increase at the mid-reach of the north branch, much of the excess sediment drops out of the channel prior to reaching the monitoring location, resulting in stable conditions at the NB monitoring location.

Sediment analysis in the west branch confirms the geomorphic assessment and scour chain data results, which suggest the stream is fairly stable. In general, each reach is capable of transporting the upstream sediment supply. Increases in sediment transport capacities between reaches (Table 6.1) are more likely the result of increased point source sediment inputs (i.e., storm sewers and roadway ditches) than excessive in-stream erosion based on the geomorphic assessment completed during this study (Appendix H2). The lack of bedload transport at WB3 (Table 6.1) is most likely due to storm flow dissipation through the wooded floodplain areas between WB2 and WB3 (i.e., McGraft Park), as well as fixed artificial rock bottom (i.e., riprap) at the monitoring location.

Table 6.1 Annual sediment loads – existing conditions

Ruddiman Creek	Sub-catchment	Existing Conditions		
		Suspended Sediment (ton/yr)	Bedload (ton/yr)	Total Sediment (ton/yr)
Main Branch	SS-1	91	<1	91
	MB-1	132	99	231
	MB-2	116	503	619
North Branch	NB	3	1	4
West Branch	WB-1	13	6	19
	WB-2	40	14	54
	WB-3	43	<1	43

6.3 Projected Sediment Reductions

6.3.1 Future Suspended Sediment Concentrations

The projected sediment reductions associated with the BMP benchmark scenario, from which the TMDL DCIA targets were derived, are intended to link a measurable in-stream pollutant to the hydrologic changes in the watershed. Measured mean annual suspended sediment concentration (SSC) was used to draw comparisons with published values for the protection of aquatic life (i.e., the goals for protection of fish communities presented below). Mean annual SSC and 90% confidence intervals were calculated using FLOWSED (Chapter 6.1). The SSC confidence intervals were based on the sediment rating curve confidence intervals presented in Fig. 2.5.

A numeric value of 80 mg/L total suspended solids (TSS) for wet-weather flows has been used by in past TMDLs as a general water quality target, based on prior studies of the effects of suspended sediment on aquatic life (cf. Alabaster and Lloyd 1982). 80 mg/L is the maximum long-term average water quality goal for TSS to provide for the protection of moderate to good fish communities (Table 6.2).

Vohs et al. (1993) suggested that a chemically inert long-term average TSS concentration of 100 mg/L appears to separate those streams with a fish population from those without. Gammon (1970) demonstrated decreases in the standing crop of both fishes and macroinvertebrates in river reaches continuously receiving SSC concentrations above 40 mg/L.

All branches of Ruddiman Creek meet the “Good to Moderate” threshold suggested by Alabaster and Lloyd (1982) for protection of fish communities, and the north branch meets the long-term threshold of 25 mg/L for optimum conditions for fish communities (Table 6.3). These data suggest that existing SSC, at least based on annual mean values, may not be a substantial cause of biota impairment. Of course, short-term increases in SSC during storm events (see Table 2.5) may cause impacts. Improvements in watershed hydrology resulting from the BMP benchmark scenario (uniform application of rain gardens, porous pavement/underground detention, green roofs, rain barrels, and infiltration throughout the watershed to reduce flashiness and increase macroinvertebrate health; see Chapter 4.3) are projected to reduce SSC by 25-50% in the three branches of Ruddiman Creek (Table 6.3), which keeps the main branch in the good to moderate ranking and the north branch in the optimum ranking, but moves the west branch from good-moderate to optimum (Table 6.3).

Table 6.2 Total suspended solids (TSS) long-term average water quality goals for the protection of fish communities suggested by Alabaster and Lloyd (1982).

Ranking	TSS Range
Optimum	≤ 25 mg/L
Good to Moderate	> 25 to 80 mg/L
Less than Moderate	>80 to 400 mg/L
Poor	> 400 mg/L

Table 6.3 Annual mean suspended sediment concentrations (SSC) predicted using sediment rating curves and flow duration curves (including baseflow) in FLOWSED for the existing conditions in Ruddiman Creek and the BMP benchmark scenario.

Location	Existing Conditions		BMP Benchmark Scenario		
	SSC, mg/L	90% Confidence Interval	SSC, mg/L	90% Confidence Interval	% SSC Reduction from Existing
Main Branch	44	22-67	33	14-52	25%
North Branch	19	13-32	12	6-18	37%
West Branch	34	20-48	17	6-28	50%

6.3.2 Future Sediment Loads

Predicted future sediment loads resulting from the BMP benchmark scenario were calculated using FLOWSED at the three key monitoring sites (MB1, NB, and WB2)

The scenario does not assume any stabilization improvements to the stream channel; therefore, existing bedload and suspended sediment rating curves were used. The existing flow duration curve was replaced with the projected flow duration curve based on the BMP benchmark scenario. It is projected that BMP benchmark scenario implementation will reduce the total sediment load at MB1, NB, and WB2 by 13%, 50%, and 54%, respectively (Table 6.4).

It is interesting to note that negligible bedload reduction is predicted at MB1 (Table 6.4). This is as a result of the specific change in FDC at this location. In the FDC resulting from the BMP benchmark scenario, lower flows are increased and higher flows are decreased (Appendix P). While this is true for all monitoring locations, the higher flows at MB1 are not decreased enough over a broad enough range to offset the increase in low flows and associated bedload. The net effect is a negligible decrease in bedload.

Printouts of FLOWSED worksheets for existing conditions and the BMP benchmark scenario at each of the three key monitoring locations (MB1, NB, and WB2) are included in Appendix Q.

6.3.3. Rosgen Stable Stream Condition

The stability of a stream is dependent upon its ability to transport not only water but also sediment produced by its watershed *in such a manner that the stream maintains its dimension, pattern, and profile without either aggrading or degrading* (Rosgen 1996). The ability of a stream to move the supplied sediment load is critical to preserving its physical and biological functions. Excessive sediment input can lead to aggradation (deposition of sediment along the channel bottom), while increases in flow regime may accelerate erosion of the channel bed and banks (degradation).

Rosgen (2006) has developed dimensionless sediment rating curves for bedload and suspended sediment for "good/fair" condition in different stream types in terms of stability (i.e., Rosgen Stable Stream Condition). These power function equations utilize field-measured bedload, suspended sediment, and discharge data collected at the bankfull stage to convert Rosgen's dimensionless sediment rating curves into dimensional sediment rating curves for use in estimating annual sediment load. The "good/fair" sediment rating curves developed by Rosgen served as a comparison for existing conditions. Annual sediment loads under future conditions remain higher than the Rosgen Stable Stream Condition. This indicates that further in-stream BMPs would be needed to achieve a balance in sediment delivery and transport, and flow.

Table 6.4. Annual sediment loads (ton/yr) at monitoring locations under existing conditions, future conditions projected for the BMP benchmark scenario, and the Rosgen stable stream condition. Percent reduction in annual sediment load from existing conditions is shown in parentheses for the BMP and Rosgen scenarios. FLOWSED worksheets used to calculate annual sediment loads are in Appendix Q.

Branch	Monitoring Location	Annual Sediment Load, ton/yr (% reduction from existing)								
		Existing Conditions			Future Conditions (BMP Benchmark [Target] Scenario)			Rosgen Stable Stream Condition		
		Suspended	Bedload	Total	Suspended	Bedload	Total	Suspended	Bedload	Total
Main	MB1	132	99	231	103 (22%)	99 (0%)	202 (13%)	47 (64%)	6 (94%)	53 (77%)
North	NB	3	1	4	2 (33%)	<1 (50%)	2 (50%)	1 (67%)	<1 (50%)	1 (75%)
West	WB2	40	14	54	20 (50%)	5 (64%)	25 (54%)	16 (60%)	1 (93%)	17 (69%)

Chapter 7: Synthesis

The Ruddiman Creek watershed is highly urbanized; impervious cover from developed land is over 50%, far exceeding the 10-15% threshold that has been suggested to cause biotic impairment in streams (Wang et al. 2001). As a consequence, the tributaries in the Ruddiman Creek watershed are subject to altered hydrology, characterized by high flashiness. The unnatural flow regime can physically dislodge benthic organisms; mobilize sediment, causing habitat impairment; and transport previously buried or sequestered contaminants, rendering them bioavailable to organisms (cf. Cooper et al. 2009; Johnson et al. 2011). Collectively, these problems fall within the 'urban stream syndrome' (Walsh et al. 2005), a term used to describe a collection of consistent ecological stressors associated with urbanized lotic ecosystems.

Given the hydrologic problems facing Ruddiman Creek, it is perhaps not surprising that the macroinvertebrate and fish communities have been classified as poor or unacceptable, and a TMDL is required to address its failure to meet the associated designated uses. The purpose of this study was to collect the appropriate data to characterize the watershed's hydrology, develop hydrologic targets to restore a more natural hydrology to the system with the assumption that this will also reduce sediment loads and restore the biota to more acceptable levels, and identify appropriate BMPs that will lead to the more natural hydrology.

Prior studies conducted to support TMDLs for urban watersheds used surrogates, such as percent impervious cover (Eagleville Brook, CT) in place of altered hydrology, or used a reference stream approach to identify appropriate hydrologic characteristics for the impaired stream (Potash Brook, VT). We could not identify an appropriate reference stream for Ruddiman Creek, so our approach focused on first establishing a relationship between stream flashiness and macroinvertebrate condition. Second, we developed a relationship between directly connected impervious area (DCIA) and stream flashiness using the Scoping Tool. DCIA, defined as the subset of impervious surfaces that route stormwater directly to streams via stormwater conduits, is considered to be a better predictor of stream impairment than total impervious area (Roy and Shuster 2009). By applying different BMPs to the watershed using the Scoping Tool, we could model the reductions in flashiness resulting from DCIA reductions, which in turn could be translated to improvement in macroinvertebrate scores. The amounts and types of BMPs could be manipulated until we 'drove' the macroinvertebrate scores from unacceptable to a minimally acceptable range, due to changes in hydrology and reductions in flashiness.

Using the above approach, we determined that the amount of DCIA that needed to be reduced for the main, north, and west branches (including a margin of safety) was 42%, 62%, and 82%, respectively. This translates to a target DCIA of 12%, 2.9%, and 2.8% for the main, north, and west branches, respectively (Table 5.3). Implementation of BMPs will result in total sediment load reductions of 13% (29 tons/yr), 50% (2 tons/yr), and 54% (29 tons/yr) in the main, north, and west branches, respectively (see Table 6.4). These percent reductions should be placed in context, given the assumptions we needed to make as part of our overall analyses:

The relationship between the flashiness index and macroinvertebrate scores (P-51) contained a significant amount of unexplained variance ($r^2 = 0.30$). This is perhaps not surprising as the relationship was based on 35 small watersheds throughout Michigan, with varying land use and hydrologic characteristics, but it is unclear whether the improvement in P-51 scores associated with the reduction in flashiness will be linear and follow the same slope as the calculated regression line. We include confidence intervals around the relationship (Fig. 3.6) to provide estimates of uncertainty in our analysis.

We also assume that the change in Flashiness Index is a linear function of the %DCIA. While there is undoubtedly a reduction in flashiness associated with a reduction in DCIA (Arnold and Gibbons 1996, Konrad and Booth 2005, Roy and Shuster 2009), it is unknown if the relationship is linear or if it changes once it reaches some critical threshold of DCIA. Hence, there may be a threshold beyond which reducing DCIA may not have the same benefit (with respect to reducing flashiness) as before reaching the threshold.

Although not directly related to the development of hydrologic targets, we also collected data on water quality, sediment loads, and stream geomorphology, which are all influenced by hydrology and all have potentially strong impacts on stream biota. Restoring a stream's hydrology to a more natural flow regime can improve water quality, as the nutrients, heavy metals, pesticides, and toxic organic compounds that accumulate on impervious surfaces can wash off into streams during storms (Sansalone and Cristina 2004, Johnson et al. 2011). We sampled only one storm event for water quality, but our data show that nutrients such as phosphorus and reduced forms of nitrogen, as well as heavy metals such as copper, zinc, and chromium are elevated, at least at some sites, during storm flow. Hence, we anticipate that restoring Ruddiman Creek to a more natural hydrology will benefit water quality, and at least indirectly, the biota.

Stream biota are negatively influenced by sediment because interstitial spaces become embedded, affecting feeding, refugia, and reproduction of sensitive invertebrates and fish (Waters 1995, Newcombe and Jensen 1996, Taulbee et al. 2009). A sediment loading model, FLOWSED, was used to: 1) calculate the current annual sediment load at each sampling location, 2) compare sediment transport rates among monitoring locations, and 3) estimate future conditions assuming a more stabilized hydrology resulting from the implementation of the BMP benchmark scenario. Model results indicated that the main branch delivered more sediment than the other two branches, and that 69% of the sediment load in the main branch was delivered by the storm sewer system. The north branch accounted for a minor amount of the total sediment load in the watershed, due to upstream sedimentation and low flow.

The geomorphic assessment revealed that streambed sediments were generally dominated by medium sand (250-500 µm) and that mean benthic organic matter measured in most streambed sediment cores was low (5% or less), suggesting that contaminants were unlikely to attach to these sediments. Scour chain installations revealed dynamic streambed conditions at the monitoring locations, with monthly changes evident at all sites; Main Branch 1 showed the greatest change in annual bed elevation (~18 cm). Habitat assessments, averaged over the four seasonal surveys, fell within the Rapid Bioassessment Protocols' (RBP) *suboptimal* habitat condition category at all sites. This relatively positive classification was unexpected given the observed and documented habitat degradation in Ruddiman Creek. It appears that the RBP may have overestimated habitat conditions. The RBP is qualitative and gives only a general idea of habitat quality. Some Ruddiman Creek sites tended to score high in metrics such as channel flow status, sinuosity, bank stability, vegetative protection, and riparian zone width; only 3 out of the 10 metrics assess substrate quality, which is one of the main habitat deficiencies in Ruddiman Creek.

The Integrated Assessment process, which was the overarching framework for our study, had mixed success. We had decent participation from municipalities and the general public, but it was a select group of dedicated individuals. The municipalities were interested and involved in the BMP selection process, but were clear that resource constraints were a major hurdle for implementation. While this does not come as a surprise, it cannot be ignored in the future, as

BMPs are being considered. The Drain Commissioner's Office provided numerous ideas and was enthusiastic about possible mechanisms to move implementation forward, but nothing concrete was ever formalized; given the potential influence of this Office, a more concentrated effort in teaming with the Drain Commissioner may be warranted. Ultimately, given that community involvement was voluntary and uncompensated, it was difficult to find "champions"; in the future, provision of incentives (financial or otherwise) might ensure more consistent input and involvement from different sectors.

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Appendix A – Stakeholder Steering Committee

STUDIES TO SUPPORT RUDDIMAN CREEK IMPLEMENTATION-READY TMDL

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Appendix B – Community Feedback

Stakeholders were asked to help select appropriate BMPs that would reduce flashiness in Ruddiman Creek, and ultimately lead to reduced sedimentation and improved biotic communities. They were asked to choose BMPs they felt would be most acceptable in their communities. Stakeholder meetings included discussions where feedback was given about which LID BMP options were optimal given the design requirements and available land in the Ruddiman Creek watershed.

Residential stakeholders gave feedback during their neighborhood association meetings, where they were presented with various residential stormwater BMPs, including rain barrels, rain gardens, porous pavement, extension curb planters, and bioswales. Residential input indicated that the majority of the residential communities favored rain barrels (74%; Fig. B.1). Rain gardens were accepted by 92% of respondents, if there were funding opportunities available to implement the rain gardens (Fig. B.1). Similarly, meandering sidewalks with bioswales had 100% acceptability, as long as funding was available for initial costs of implementation (Fig. B.1). Porous pavement was not favored due to the notion that residential areas do not have an adequate amount of pavement for the implementation to benefit the stream's hydrology (94% said no, even if funding was available; Fig. B.1). Curb extension stormwater planters were the least favored due to possible complications during snow removal (100% said this BMP would not work in their community; Fig. B.1). Other complications with the curb extension stormwater planters were ordinances that require parking on terraces (the area between the sidewalk and street) of roads during certain times of the year, possibly reducing the effectiveness to infiltrate runoff. Residents at these meetings were eager to implement LID BMPs that would help beautify their neighborhoods.

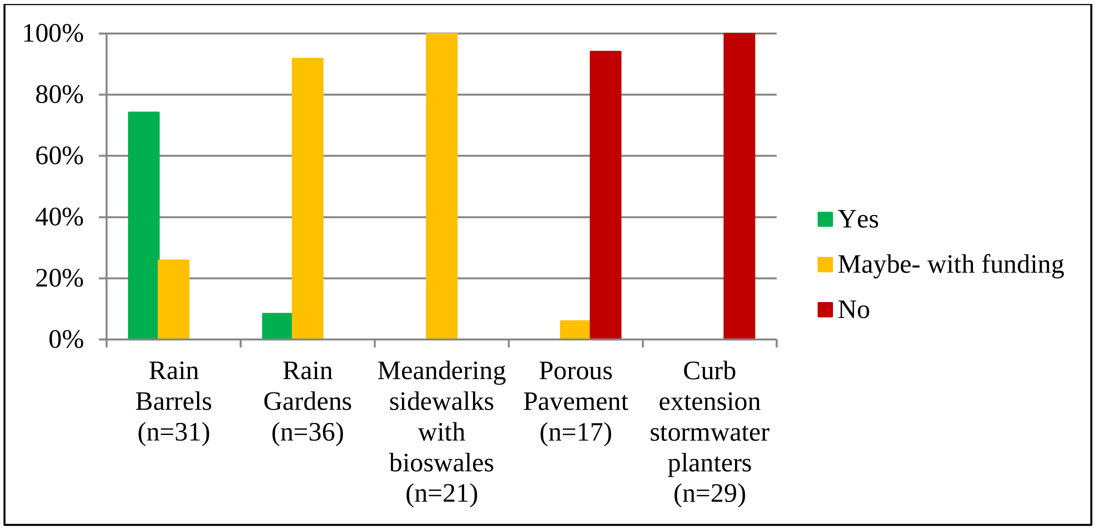

Fig. B.1 Glenside and Lakeside Neighborhood Association feedback on residential BMP options.

Input during stakeholder meetings entailed verbal feedback on LID BMP options presented by the project team (Table B.1; see www.gvsu.edu/wri/director/ruddiman to view presentations). Municipal input from the Muskegon Area Municipal Stormwater Committee (MAMSC) representatives indicated that tree plantings and regional retention to address direct discharges into waterways are important. It was noted that fertilizer, pesticides, and mowing riparian areas have been reduced, and the Muskegon County Road Commission has reduced the amount of salt used during snow removal to save on costs. The Department of Public Works (DPW) met with the project team to discuss potential property easements that could be used to collect stormwater before it enters the main branch of Ruddiman Creek. The long-term benefits of natural detention basins on stream ecosystems were recognized by municipalities. The municipalities and DPW would be willing to partner with local watershed and natural resource planning/management organizations on future grant proposals to help fund the LID BMPs that go beyond those required by their MS4 Phase II stormwater permit requirements. The BMP opportunity map provides the most effective geographic locations to implement LID BMPs (Appendix D).

Only one MAMSC municipal participant chose to also participate individually on the Stakeholder Committee. That was the City of Roosevelt Park (Anthony Chandler). The Muskegon County Drain Commissioner (Dave Fisher), also a member of the MAMSC, participated on the Stakeholder Committee. The City of Muskegon Heights and the City of Muskegon chose to participate on the stakeholder committee, but through individuals who were not MAMSC or DPW representatives. The City of Muskegon Heights provided a staff person from their Planning Department (Reatha Anderson and her designee); the City of Muskegon was represented by a City Commissioner (Steve Wisneski).

Early in the project, WMSRDC and FTC&H attended a MAMSC meeting to give information about the project and to gather input on the storm drain system. FTC&H followed up with the municipalities to review DPW maps to further determine the direction of flow within the storm system.

The project team and stakeholders representing the industrial sector discussed the potential limitations of implementable LID BMPs due to brownfield locations throughout the Ruddiman Creek watershed. Underdrains were considered a necessity for industrial LID BMPs to reduce the risk of groundwater contamination in highly degraded areas. Feedback on the benefits and drawbacks of LID BMP options was also given by local architect, engineer, construction, and landscape representatives based on their own experiences. Native plantings, tree plantings, rain gardens, and green roofs were generally acceptable. The LID BMP with the most drawbacks was porous pavement, due to its continuous maintenance to prevent clogging;

however, some stakeholders pointed out that new technologies have been developed to help clean porous pavement more effectively.

With the feedback received from various sectors (municipal, industrial, commercial, and residential), the project team modeled multiple scenarios during the final stakeholder meeting to help the stakeholders understand the beneficial impacts that LID BMPs could have on Ruddiman Creek's biotic community (Table B.1), and ultimately, for inclusion in the implementation-ready biota TMDL that will be developed by the MDEQ. By laying out a menu of options with detailed advantages and disadvantages, the project team had an understandable and scientifically-defensible series of options to evaluate with the Stakeholder Steering Committee. Further evaluations (i.e., efficiency and cost estimations) were conducted to identify the most environmentally and economically effective ways to reduce stormwater volumes and meet the TMDL hydrologic targets that will promote reductions in flashiness (Appendix C).

Table B.1 Structural best management practices (BMPs) appropriate for implementation in the Ruddiman Creek watershed.

	Grow Zones* **(I, C/I, R, M)**	**Tree Plantings*** **(I, C/I, R, M)**	**Rain Capture/ Reuse** **(I, C/I, R, M)**	**Bioretention/ Rain Garden** **(C/I, R, M)**	**Vegetated/ Bio Swales** **(I, C/I, M)**	**Pervious Pavement** **(I, C/I, R, M)**	**Green Roofs** **(I, C/I, M)**	**Subsurface Stormwater Retention/Detention** **(I, C/I, M)**
Description	Planting of native vegetation	Increased tree cover	Storing and reusing rain water	Landscaped surface depressions designed for the filtration or infiltration of stormwater	Stormwater conveyance channel designed for the filtration or infiltration of stormwater	Pavement that allows for filtration or infiltration of stormwater	Rooftops partially or completely covered with vegetation	Facilities underground to promote stormwater infiltration, filtration, or storage
Detail	• Upland or riparian native planting areas	• Tree canopy and forest cover has been shown to reduce stormwater runoff	• Structures that capture stormwater for the purpose of reuse	• Shallow landscaped surface depressions • Recommend using deep-rooted native plants • Overflow drain is necessary • Should be located at least 10 feet away from building	• Shallow stormwater channel that is densely planted with a variety of native grasses, shrubs, or trees • Check dams can be used to improve performance, especially in steeper areas	• Pervious pavements (concrete, asphalt, and pavers) slows rain water before entering storm drains and streams	• Rooftops covered with vegetation and soil or a growing media planted over a waterproof membrane • Allows the roof to function like a vegetated surface	• Underground aggregate-filled beds or vaults, tanks, large pipes, or other fabricated structures placed in aggregate-filled beds in the soil mantle to collect or filter stormwater
Where Effective	• Parks • Riparian corridors • Road medians • Grow zones are excellent opportunities for reducing local maintenance costs by converting turf or impervious areas to deep-rooted native vegetation	• Areas around impervious surfaces • Adjacent to surface water • Riparian corridors	• Rain barrels are well-suited for residential lots • Cisterns and other large storage tanks are more appropriate for commercial or industrial sites • Captured water can be re-used for a variety of applications, including irrigation and grey water uses in buildings	• Residential and commercial areas • Parking lots (use curb cuts to direct stormwater runoff to depressed areas or consider “inverted” islands rather than raised islands.)	• Vegetated swales typically treat runoff from highly impervious surfaces (e.g., roadways and parking lots) and re-enters storm drains	• Parking lots • Walking paths • Sidewalks • Playgrounds • Plazas • Basketball courts • Parking lanes • Bike paths • Bike lanes • Alleys • Driveways	• Green roofs are not common for residential homes • Schools, libraries, and commercial or industrial buildings are perfect candidates for installation • Flat roofs are preferred, but green roofs can be installed on pitched roofs when designed accordingly	• Under areas of high imperviousness to collect runoff • Perfect for land uses where extensive parking is needed and green space is not feasible
Mechanisms of Pollutant Reduction	• Slows runoff before entering streams or storm drains • Infiltration • Vegetative transpiration	• Stormwater volume reduction • Interception (rain water collects on leaves before becoming surface runoff) • Infiltration • Reduces stream erosion	• Stormwater volume reduction	• Filtration/ Infiltration to reduce stormwater volume • Vegetative transpiration	• Filtration to reduce stormwater volume • Settling of sediment transported from impervious surfaces • Vegetative transpiration	• Stormwater drains through the permeable surface where it is temporarily held in the voids of a stone bed or other storage reservoir, and then slowly releases into underdrains, or underlying soil	• Vegetative transpiration • Stormwater volume control	• Stormwater is temporarily stored within the voids of the stone bed and then slowly infiltrates into the underlying soil, or into underdrains in areas of soil contamination, or reused as grey water
Other Benefits	• Reduced maintenance costs compared to turf grass • Enhances aesthetics	• Improved air and water quality • Wildlife habitat • Enhances aesthetics • Heat reduction due to shading pavement	• Reduced use of potable water when reused • Energy savings • Money savings	• Enhances landscapes • Could fulfill landscaping requirements for site plan approval	• For new construction, swales are more cost effective than storm sewers for conveyance	• Reduced storm sewer costs for new construction • Recharges groundwater when soil is eligible for infiltration	• Reduces heating and cooling costs • Increases lifespan of roof • Heat island reduction • Habitat enhancement • Educational tool and sightseeing attraction	• Allows for various land uses above ground • Reduces storm sewer costs

*BMPs **not** modeled with the Scoping Tool.
Land uses most appropriate for listed BMP: I= Industrial; C/I= Commercial and/or Institutional; R= Residential; M= Municipal

Appendix C – BMP Effectiveness and Cost Estimations

C.1 Methods

A user-friendly, interactive BMP Cost Calculator was developed using Microsoft Excel® spreadsheet software to calculate BMP cost estimations based on various nationwide and local studies (available at www.gvsu.edu/wri/director/ruddiman).

We selected 6 LID BMPs for our analysis: constructed wetland, bioretention/rain garden, underground detention, porous pavement, rain barrel, and green roof. Although sensitivity values were not calculated for constructed wetlands since it was not one of the BMPs evaluated in the SWMM model (Appendix J), this BMP was included in the BMP Cost Calculator since cost information was readily available.

The direct initial costs and annual operation and maintenance (O&M) costs for the bioretention/rain garden, green roof, porous pavement, and constructed wetland BMPs were developed by taking the average of the cost values reported by the Minnesota Pollution Control Agency (2008), University of New Hampshire (2008), Alliance of Rouge Communities (2009), MacMullan et al. (2008), Fishbeck, Thompson, Carr & Huber, Inc. (FTC&H 2012), and MDEQ (2012). Cost values were reported per one acre (or per rain barrel, if applicable) of impervious surface area directly connected to a particular BMP. These values, with the exception of FTC&H and MDEQ's BMP costs for Michigan, were identified in a prior study addressing stormwater management in Spring Lake, MI (AWRI 2009). The direct initial cost and annual O&M cost for underground detention were obtained from StormTech (2012). The direct initial cost for rain barrels was obtained from Sears (2012), and the cost estimate for rain barrel maintenance was based on replacing 10% of initial hardware cost ($20) annually. Notably, many variables can affect construction cost and should be taken into account when estimating budgets.

Pollutant loads and pollutant load reductions were estimated using the event mean concentrations (EMCs) typically found in urban stormwater runoff. This conventional approach relies on published values of storm water pollutant concentrations by land use and BMP removal efficiencies for sediment. Other pollutants (i.e., nutrients, metals) are directly linked to the sediment in varying percentages. This approach was chosen because using the BMP Flashiness Index sensitivity values (Table 4.2) and the related sediment load reductions (Table 6.4) based on monitoring data was not feasible, due to the numerous assumptions that would have to be made to relate the Cost Calculator to the flow and sediment monitoring data. The benefit of using EMCs to estimate pollutant loads is that it is a uniform method to compare pollutant reductions among watersheds.

Total stormwater sediment load of each sub-catchment was calculated following the Water Quality Trading Rules as outlined in *Macatawa Watershed Modeled Pollutant Loads* (Fongers 2009). The EMC for total suspended solids (mg/L) was used to calculate the average annual sediment load given the annual stormwater runoff volume for a curve number (CN) value of 98 (i.e., impervious surface) (Fongers 2009). The EMC applied to the impervious surfaces in each of the Ruddiman Creek subcatchments was determined by calculating the average of the total suspended solids EMCs by land use type (Fongers 2009) (see table C.1). The resulting EMC of 91 mg/L of suspended solids is used as representative of urban impervious surfaces.

BMP efficiencies were obtained primarily from *Low Impact Development Manual for Michigan: A Design Guide for Implementers and Reviewers* (SEMCOG 2008), with the exception of a rain barrel, which was based on the assumptions used in the SWMM model (i.e., a rain barrel was only 16% efficient at removing impervious area, assuming the captured water was used for irrigation in pervious areas that were not connected to the storm sewer, and any overflow discharged back into the storm sewer; see Chapter 4.1). BMP efficiencies ranged from 16 to 95%, depending on the BMP chosen (see Table C.2)

The total stormwater sediment load reduction achieved by a particular BMP was calculated by multiplying the estimated sediment load of the sub-catchment by the percentage of the sub-catchment treated, and by BMP efficiency. Cost comparisons of each BMP implemented were calculated by dividing the total first year cost by either total pounds of sediment reduced or total DICA treated per sub-catchment.

Table C.1. Event mean concentration for total suspended solids.

Land use category	**TSS (mg/l)**
Commercial	77
High Density Residential	97
Medium Density Residential	70
Low Density Residential	70
Highways	141
User Defined TSS EMC (Average of above values):	91

Source: Water Quality Trading Rules (Fongers 2009).

Table C.2. Total suspended solids (TSS) removal efficiencies used in the BMP Cost Calculator.

BMP	**% TSS Removal**
Rain Barrel	16%*
Bioretenion / Rain Garden	80%
Green Roof	95%
Porous Pavement	82.5%
Constructed Wetlands	76%
Underground Detention	95%

Source:
Percent of total suspended solids removed based on Low Impact Development Manual for Michigan (SEMCOG, 2008).
* Percent of total suspended solids removed based on FTC&H rain barrel treatment assumption (see Chapter 4.1).

C.2 Results

This section provides an example of how the BMP Cost Calculator may be used to compare the cost to implement alternative combinations of BMPs. The example looks at two alternative BMP combinations that treat the percent of DCIA determined by the BMP benchmark scenario for NB of Ruddiman Creek. Recall that 62% of the DCIA in the NB is required to be treated to meet the TMDL target (Table 5.1).

Five BMPs (porous pavement, bioretention/rain garden, green roof, rain barrels, and underground detention) were used to evaluate the two alternatives. Alternative 1 is the BMP benchmark scenario and applies the BMPs uniformly over all sub-catchments (e.g., each BMP applied in sub-catchment NB-A treated 12.4% of the DCIA). Therefore, the five BMPs applied will treat a total of 62% (12.4% x 5) of the DCIA. Alternative 2 applies a different combination of BMPs, while treating the same amount of DCIA as Alternative 1. For instance, in sub-catchment NB-A, the DCIA is treated as follows: 24.8% routed to bioretention/rain gardens, 24.8% routed to constructed wetlands, 12.4% routed to underground detention, and 0% routed to porous pavement and green roofs, also resulting in treatment of 62% of the DCIA.

Alternative 1 is estimated to reduce approximately 3,400 pounds of suspended sediment with a total first year cost of $2.6 million (see Fig.C.1). Alternative 2 is estimated to reduce approximately 2,700 pounds of suspended sediment with a total first year cost of $265,000 (see Fig. C.2). This is a 10-fold reduction in cost between the two BMP alternatives and results in only a 20% reduction in sediment removal (700 pounds).

Results also indicate BMP cost-effectiveness as summarized in Table C.3. The total first year costs (direct initial cost plus O&M cost for the first year) by BMP type varied by over three orders of magnitude (Table C.3). Constructed wetlands and bioretention/rain gardens had the lowest first year costs and green roofs had the highest first year costs (Table C.3). Constructed wetlands had the lowest cost per pound of sediment reduced, and green roofs had the highest cost per pound of sediment reduced (Table C.3).

Table C.3. Estimated total first year costs per BMP.

BMP	Total First Year Cost per Pound of Suspended Sediment Reduced	Total First Year Cost per Acre Treated
Rain Barrel	$2	$125
Constructed wetland*	$38	$1300
Bioretention/rain garden	$55	$19,700
Underground detention	$210	$88,200
Porous pavement	$870	$321,800
Green roof	$1900	$819,700

*Not included in example shown below.

In summary, the BMP Cost Calculator provides a tool for watershed managers to compare alternative storm water treatment methods. As shown in the above example, the cost to provide essentially the same amount of treatment can vary greatly. To a great extent, BMP selection will be driven by economics. Additional factors such as the availability of useable land, materials, constructability, and public opinion should be considered when using the cost results to compare alternative treatment methods.

A detailed explanation of the BMP Cost Calculator tables is provided below.

Table 1 (Figures C.1 and C.2) is set up as follows:

- Column 1 provides a drop down list where the user selects a BMP to apply to a sub-catchment. The list of BMPs is referenced from *Column 8* of *Table 3*.
- Column 2 provides a drop down list where the user selects the sub-catchment. The list of sub-catchments is referenced from *Column 1* of *Table 3*.
- Column 3 provides a cell where the user can define the amount of DCIA treated by a selected BMP.
- Column 4 shows the direct initial cost of the applied BMP. The cost is calculated by multiplying Column 3 by the capital cost per acre DCIA referenced from *Column 9* of *Table 3*.
- Column 5 displays the calculated annual operations and maintenance costs associated with the selected BMP. This cost is calculated by multiplying Column 3 by the annual operation and maintenance cost per acre of DCIA referenced from *Column 10* of *Table 3*.
- Column 6 shows the total first year cost. This is calculated by adding Column 4 to Column 5. A summation of the costs for all implemented BMPs is found at the bottom of the column.
- Column 7 shows the percent of sub-catchment treated. This is calculated by dividing Column 2 from the available area in the sub-catchment referenced from *Column 2* of *Table 3.*

- Column 8 shows the efficiency of the selected BMP in percent referenced from *Column 11* of *Table 3.*
- Column 9 shows the annual sediment load in pounds referenced from *Column 7* of *Table 3.*
- Column 10 shows the total sediment load reduction in pounds predicted for the selected BMP. This is calculated by multiplying Columns 7, 8 and 9. A summation of the pounds of sediment reduction for all implemented BMPs is found at the bottom of the column.
- Column 11 shows the total first year cost per pound of sediment reduced. This is calculated by dividing Column 6 by Column 10.
- Column 12 show the total first year cost per acre treated. This is calculated by dividing Column 6 by Column 3.

Table 2 (Figures C.1 and C.2) reports the net annual sediment reduced in pounds referenced from *Column 10* of *Table 1.*

Table 3 (Fig. C.3) is a reference table used by the cells in Table 1.

- Column 1 is the name of the sub-catchment.
- Column 2 is the area of the sub-catchment in acres.
- Column 3 is the percent of the sub-catchment that is impervious.
- Column 4 displays the amount of impervious land in acres. This is calculated by multiplying Column 2 to Column 3.
- Column 5 is the event mean concentration that reflects the land use of the sub-catchment.
- Column 6 is the predicted volume of runoff from impervious land (CN=98).
- Column 7 is the sediment load in pounds for the sub-catchment. This is calculated by multiplying Columns 4, 5, and 6 by a constant value of 0.2666 as defined in the Water Quality Trading Rules (Fongers 2009).
- Column 8 lists the LID BMPs.
- Column 9 lists the capital cost per acre.
- Column 10 lists the annual operation and maintenance cost per acre.
- Column 11 lists the BMP sediment removal efficiencies in percent.

Ruddiman Creek Watershed: Alternative 1

Best Management Practice (BMP) Cost Estimates Calculator

Table 1: LID BMPs Estimated Costs and Sediment Reduction

Best Management Practice (BMP)	Sub-catchment (See map)	Acres of Impervious Surface Area Connected to BMP (*Or No. of Rain Barrels if applicable)	Direct Initial Cost[1]	Annual Operation & Maintenance (O&M) Cost[1]	Total First Year Cost (Direct Initial + O&M)	Percent of Sub-catchment Area Treated	BMP Efficiency[2]	Annual Sediment Load (lbs) of Sub-catchment[3]	Total Sediment Load Reduction (lbs) (Percent of Land Treated x BMP Efficiency x Sediment Load)	Total First Year Cost per Pound of Suspended Sediment Reduced	Total First Year Cost per Acre Treated (*Or per Rain Barrel, if applicable)
Porous Pavement	NB-A	0.5983774	$188,981.35	$3,590.26	$192,571.61	12.40%	82.50%	2167.26	221.71	$868.57	$321,823.00
Biorention/Rain Garden	NB-A	0.5983774	$11,634.25	$149.59	$11,783.85	12.40%	80.00%	2167.26	214.99	$54.81	$19,693.00
Green Roof	NB-A	0.5983774	$490,159.05	$359.03	$490,518.08	12.40%	95.00%	2167.26	255.30	$1,921.31	$819,747.00
Rain Barrel	NB-A	0.5983774	$73.00	$1.20	$74.20	12.40%	16.00%	2167.26	43.00	$1.73	$124.00
Underground Detention	NB-A	0.5983774	$50,263.70	$2,513.19	$52,776.89	12.40%	95.00%	2167.26	255.30	$206.72	$88,200.00
Porous Pavement	NB-B	0.5882000	$185,767.09	$3,529.20	$189,296.29	12.40%	82.50%	2130.43	217.94	$868.57	$321,823.00
Biorention/Rain Garden	NB-B	0.5882000	$11,436.37	$147.05	$11,583.42	12.40%	80.00%	2130.43	211.34	$54.81	$19,693.00
Green Roof	NB-B	0.5882000	$481,822.27	$352.92	$482,175.19	12.40%	95.00%	2130.43	250.96	$1,921.31	$819,747.00
Rain Barrel	NB-B	0.5882000	$71.76	$1.18	$72.94	12.40%	16.00%	2130.43	42.27	$1.73	$124.00
Underground Detention	NB-B	0.5882000	$49,408.80	$2,470.44	$51,879.24	12.40%	95.00%	2130.43	250.96	$206.72	$88,200.00
Porous Pavement	NB-C	0.8844000	$279,313.86	$5,306.40	$284,620.26	12.40%	82.50%	3203.23	327.69	$868.57	$321,823.00
Biorention/Rain Garden	NB-C	0.8844000	$17,195.39	$221.10	$17,416.49	12.40%	80.00%	3203.23	317.76	$54.81	$19,693.00
Green Roof	NB-C	0.8844000	$724,453.61	$530.64	$724,984.25	12.40%	95.00%	3203.23	377.34	$1,921.31	$819,747.00
Rain Barrel	NB-C	0.8844000	$107.90	$1.77	$109.67	12.40%	16.00%	3203.23	63.55	$1.73	$124.00
Underground Detention	NB-C	0.8844000	$74,289.60	$3,714.48	$78,004.08	12.40%	95.00%	3203.23	377.34	$206.72	$88,200.00
				Sum:	**$2,587,866.44**			**Sum:**	**3427.46**		

Table 2: Project Summary

Net Annual Sediment Reduced in Pounds
3427.46

Fig. C.1 Screenshot of Executed BMP Cost Calculator for Alternative 1.

Ruddiman Creek Watershed: Alternative 2

Best Management Practice (BMP) Cost Estimates Calculator

Table 1: LID BMPs Estimated Costs and Sediment Reduction

Best Management Practice (BMP)	Sub-catchment (See map)	Acres of Impervious Surface Area Connected to BMP (*Or No. of Rain Barrels if applicable)	Direct Initial Cost[1]	Annual Operation & Maintenance (O&M) Cost[1]	Total First Year Cost (Direct Initial + O&M)	Percent of Sub-catchment Area Treated	BMP Efficiency[2]	Annual Sediment Load (lbs) of Sub-catchment[3]	Total Sediment Load Reduction (lbs) (Percent of Land Treated x BMP Efficiency x Sediment Load)	Total First Year Cost per Pound of Suspended Sediment Reduced	Total First Year Cost per Acre Treated (*Or per Rain Barrel, if applicable)
Porous Pavement	NB-A	0.0000000	$0.00	$0.00	$0.00	0.00%	82.50%	2167.26	0.00	$0.00	$0.00
Biorention/Rain Garden	NB-A	1.1967548	$23,268.50	$299.19	$23,567.69	24.80%	80.00%	2167.26	429.99	$54.81	$19,693.00
Green Roof	NB-A	0.0000000	$0.00	$0.00	$0.00	0.00%	95.00%	2167.26	0.00	$0.00	$0.00
Rain Barrel	NB-A	1.1967548	$146.00	$2.39	$148.40	24.80%	16.00%	2167.26	86.00	$1.73	$124.00
Underground Detention	NB-A	0.5983774	$50,263.70	$2,513.19	$52,776.89	12.40%	95.00%	2167.26	255.30	$206.72	$88,200.00
Porous Pavement	NB-B	0.0000000	$0.00	$0.00	$0.00	0.00%	82.50%	2130.43	0.00	$0.00	$0.00
Biorention/Rain Garden	NB-B	1.1764000	$22,872.75	$294.10	$23,166.85	24.80%	80.00%	2130.43	422.67	$54.81	$19,693.00
Green Roof	NB-B	0.0000000	$0.00	$0.00	$0.00	0.00%	95.00%	2130.43	0.00	$0.00	$0.00
Rain Barrel	NB-B	1.1764000	$143.52	$2.35	$145.87	24.80%	16.00%	2130.43	84.53	$1.73	$124.00
Underground Detention	NB-B	0.5882000	$49,408.80	$2,470.44	$51,879.24	12.40%	95.00%	2130.43	250.96	$206.72	$88,200.00
Porous Pavement	NB-C	0.0000000	$0.00	$0.00	$0.00	0.00%	82.50%	3203.23	0.00	$0.00	$0.00
Biorention/Rain Garden	NB-C	1.7688000	$34,390.78	$442.20	$34,832.98	24.80%	80.00%	3203.23	635.52	$54.81	$19,693.00
Green Roof	NB-C	0.0000000	$0.00	$0.00	$0.00	0.00%	95.00%	3203.23	0.00	$0.00	$0.00
Rain Barrel	NB-C	1.7688000	$215.79	$3.54	$219.33	24.80%	16.00%	3203.23	127.10	$1.73	$124.00
Underground Detention	NB-C	0.8844000	$74,289.60	$3,714.48	$78,004.08	12.40%	95.00%	3203.23	377.34	$206.72	$88,200.00
				Sum:	**$264,741.32**			**Sum:**	**2669.42**		

Table 2: Project Summary

Net Annual Sediment Reduced in Pounds
2669.42

Fig. C.2 Screenshot of Executed BMP Cost Calculator for Alternative 2

Table 3: EMC Calculated Values and LID BMP Reference

Sub-catchment	Area (acres)	% Impervious land	Impervious land (acre)	User defined TSS EMC (mg/L)	Runoff volume from impervious land, CN= 98 (in/yr)	Load of suspended solid from impervious land (lbs)	BMP	Capital Cost per 1 Acre of Impervious Surface Area[1]	Annual Operation & Maintenance Cost per 1 Acre of Impervious Surface Area[1]	% Efficiency, e[3]
SS3-A	65.1	18.0%	11.7	91	21.78	5262.75	Rain Barrel	$122.00	$2.00	16.00%
SS3-B	99.8	24.6%	24.6	91	21.78	11026.17	Biorention/Rain Ga	$19,443.00	$250.00	80.00%
SS3-C	340.9	6.4%	21.8	91	21.78	9798.65	Green Roof	$819,147.00	$600.00	95.00%
SS2-A	166.1	9.6%	15.9	91	21.78	7161.43	Porous Pavement	$315,823.00	$6,000.00	82.50%
SS2-B	174.1	10.1%	17.6	91	21.78	7897.31	Constructed Wetlar	$12,962.00	$30.00	76.00%
SS2-C	145.6	8.7%	12.7	91	21.78	5689.05	Underground Deter	$84,000.00	4200	95%
SS1	159.6	51.0%	81.4	91	21.78	36556.30				
MB1-A	103.8	28.9%	30.0	91	21.78	13472.69				
MB1-B	72.3	49.8%	36.0	91	21.78	16170.63				
MB1-C	97.1	44.3%	43.0	91	21.78	19318.89				
MB2	114.9	15.0%	17.2	91	21.78	7740.53				
NB-A	150.8	3.2%	4.8	91	21.78	2167.26				
NB-B	26.8	17.7%	4.7	91	21.78	2130.43				
NB-C	44.3	16.1%	7.1	91	21.78	3203.23				
WB1-A	107.4	18.6%	20.0	91	21.78	8971.73				
WB1-B	258	7.8%	20.1	91	21.78	9038.02				
WB2-A	293.5	8.4%	24.7	91	21.78	11072.52				
WB2-B	119.1	48.5%	57.8	91	21.78	25942.55				
WB3	130.7	5.0%	6.5	91	21.78	2934.98				

1.The direct initial costs and annual O&M costs for the bioretention/rain garden, green roof, porous pavement, constructed wetland BMPs are an average of the cost values reported by the Minnesota Pollution Control Agency (2008), University of New Hampshire (2008), Alliance of Rouge Communities (2009), MacMullan et al. (2008), Fishbeck, Thompson, Carr & Huber, Inc. (FTC&H, 2012), and MDEQ (2012). These values, with the exception of FTC&H and MDEQ's BMP costs for Michigan, were reported in the "Alternative Stormwater Management Practices that Address the Environmental, Social, and Economic Aspects of Water Resources in the Spring Lake Watershed (MI) - Final Project Report" (AWRI 2009). The direct initial cost and annual O&M cost for underground detention were obtained from StormTech (2012). The direct initial cost for rain barrels was obtained from Sears (2012), and the cost estimate for rain barrel maintenance was based on replacing 10% of initial hardware cost ($20) annually. Notably, many variables can affect construction cost and should be taken into account when estimating budgets.

2. BMP efficiencies were obtained from the *Low Impact Development Manual for Michigan: A Design Guide for Implementors and Reviewers* (2008).

3. Total sediment load (lbs) of each sub-catchment was calculated following the Water Quality Trading Rules as outlined in the Michigan Department of Environmental Quality report "Macatawa Watershed Modeled Pollutant Loads" (2009). An event mean concentration of total suspended solids (mg/l) is assumed to reflect an average annual sediment load given the annual storm water runoff volume. The assigned event mean concentration is an average of total suspended solids concentrations per land use of each sub-catchment. The annual runoff volume per sub-catchment is based on the acreage of impervious surface connected to a BMP.

Table 3: LID BMP Reference and Calculated Values

Sub-catchment	Area (acres)	% Impervious land	Impervious land (acre)	TSS mg/L per Sub-catchment, EMC (mg/L)	Average Annual Runoff Volume: R (in/yr)	Load per acre, L (Lbs/acre)	Load of suspended solid from impervious land (lbs)	BMP	Capital Cost per 1 Acre of Impervious Surface Area[1]	Annual Operation & Maintenance Cost per 1 Acre of Impervious Surface Area[1]	% Efficiency, e[3]
SS3-A	65.1	18.0%	11.7	91	21.78	449.12	5262.75	Rain Barrel	$122.00	$2.00	16.00%
SS3-B	99.8	24.6%	24.6	91	21.78	449.12	11026.17	Biorention/Rain Gard	$19,443.00	$250.00	80.00%
SS3-C	340.9	6.4%	21.8	91	21.78	449.12	9798.65	Green Roof	$819,147.00	$600.00	95.00%
SS2-A	166.1	9.6%	15.9	91	21.78	449.12	7161.43	Porous Pavement	$315,823.00	$6,000.00	82.50%
SS2-B	174.1	10.1%	17.6	91	21.78	449.12	7897.31	Constructed Wetland	$12,962.00	$30.00	76.00%
SS2-C	145.6	8.7%	12.7	91	21.78	449.12	5689.05	Underground Detenti	$84,000.00	4200	95%
SS1	159.6	51.0%	81.4	91	21.78	449.12	36556.30				
MB1-A	103.8	28.9%	30.0	91	21.78	449.12	13472.69				
MB1-B	72.3	49.8%	36.0	91	21.78	449.12	16170.63				
MB1-C	97.1	44.3%	43.0	91	21.78	449.12	19318.89				
MB2	114.9	15.0%	17.2	91	21.78	449.12	7740.53				
NB-A	150.8	3.2%	4.8	91	21.78	449.12	2167.26				
NB-B	26.8	17.7%	4.7	91	21.78	449.12	2130.43				
NB-C	44.3	16.1%	7.1	91	21.78	449.12	3203.23				
WB1-A	107.4	18.6%	20.0	91	21.78	449.12	8971.73				
WB1-B	258	7.8%	20.1	91	21.78	449.12	9038.02				
WB2-A	293.5	8.4%	24.7	91	21.78	449.12	11072.52				
WB2-B	119.1	48.5%	57.8	91	21.78	449.12	25942.55				
WB3	130.7	5.0%	6.5	91	21.78	449.12	2934.98				

1.The direct initial costs and annual O&M costs for the bioretention/rain garden, green roof, porous pavement, constructed wetland BMPs are an average of the cost values reported by the Minnesota Pollution Control Agency (2008), University of New Hampshire (2008), Alliance of Rouge Communities (2009), MacMullan et al. (2008), Fishbeck, Thompson, Carr & Huber, Inc. (FTC&H, 2012), and MDEQ (2012). These values, with the exception of FTC&H and MDEQ's BMP costs for Michigan, were reported in the "Alternative Stormwater Management Practices that Address the Environmental, Social, and Economic Aspects of Water Resources in the Spring Lake Watershed (MI) - Final Project Report" (AWRI 2009). The direct initial cost and annual O&M cost for underground detention were obtained from StormTech (2012). The direct initial cost for rain barrels was obtained from Sears (2012), and the cost estimate for rain barrel maintenance was based on replacing 10% of initial hardware cost ($20) annually. Notably, many variables can affect construction cost and should be taken into account when estimating budgets.

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Fig. C.3 Screenshot of Reference Table used for BMP Cost Calculator for Alternatives 1 and 2.

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Appendix D – BMP Opportunity Map

D.1 Methods

Sub-catchments that could provide the greatest opportunity for flashiness reduction were determined using R-B Flashiness Index sensitivity coefficients. The sensitivity of the R-B Flashiness Index to the amount of area treated by BMPs (Appendix J) was computed using the SWMM model at every stream monitoring location to understand the effectiveness of BMP implementation in each upstream sub-catchment. At three key monitoring locations (MB1, NB, and WB2; see Chapter 3.3) the sensitivity coefficients (Chapter 4.2, Appendix J) were multiplied by the total directly connected impervious area (DCIA) within the sub-catchment (see Appendix M) to compute the total amount of R-B Flashiness Index reduction possible. These values were then converted into a zero to one rating to provide a relative measure of flashiness reduction (zero is no reduction and one is maximum reduction). The results are shown in Table D.1 and mapped in Figure D.1 using ESRI™ ArcView. These zero to one ratings were found to be independent of BMP type (e.g., green roofs had the same zero to one rating as rain gardens, etc.). Each branch was calculated independently; thus, BMP opportunity values can be compared only within each branch, not between branches.

D.2 Results

The BMP Opportunity Map (Fig D.1) shows the zero to one ratings described above. Geographic locations of BMP opportunities based on 1.0 (red=most effective) to 0.1 (dark green=least effective) describe areas where BMPs would be most beneficial (Fig D.1). As expected, the areas with the highest DCIA percentages provide the best opportunities. These subcatchments were SS1, NB-C and WB2-B in the main, north, and west branches, respectively. Sub-catchments WB3, MB2, and Pond were assigned the lowest rating; treatment by BMPs in these sub-catchments will have no effect on the three key monitoring locations since they are located downstream of the monitoring locations. But, treatment by BMPs in these areas will still have a positive impact on Ruddiman Creek as a whole.

The BMP opportunity map is heavily influenced by the amount of (DCIA) within each sub-catchment (Appendix M). Therefore, the map can be used as a visual guide to identify where the greatest reduction in DCIA is needed, and where BMP implementation may be focused within a given branch.

While the map provides an indication of the relative need for BMPs to meet impervious reduction targets (see Chapter 5), the map should not be used to choose among several potential BMP sites. The best choice of individual site is always the one that treats the most DCIA with the lowest costs.

Table D.1 BMP Opportunity Values by Branch

Main Branch		West Branch		North Branch	
Sub-catchment	Opportunity Value	Sub-catchment	Opportunity Value	Sub-catchment	Opportunity Value
SS3-C	0.26	WB1-A	0.30	NB-A	0.58
SS3-B	0.26	WB1-B	0.33	NB-B	0.58
SS3-A	0.14	WB2-A	0.48	NB-C	1.00
SS2-C	0.15	WB2-B	1.00		
SS2-B	0.21	WB3	0.00		
SS2-A	0.19				
SS1	1.00				
MB1-A	0.26				
MB1-B	0.27				
MB1-C	0.32				
MB2	0.00				
Pond	0.00				

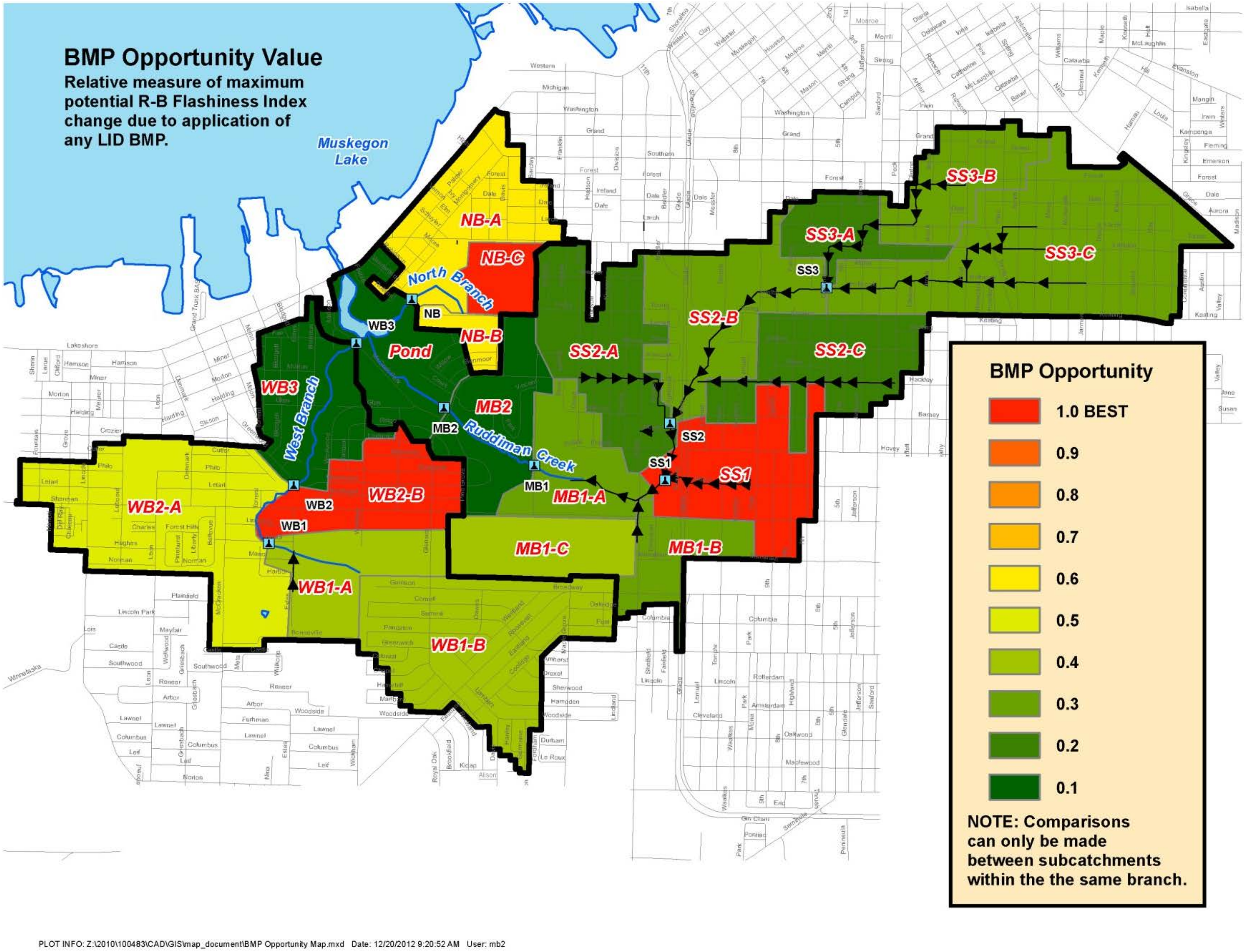

Fig. D.1 BMP opportunity map for the Ruddiman Creek watershed.

Appendix E – Land Use and Cover Update and Stream Delineation

The latest existing land use and cover dataset for Ruddiman Creek was created by AWRI for Muskegon County in 1998; however, a more recent update of the land use and cover dataset was created to identify land use changes since then. A 2008 Muskegon County digital orthophotograph (leaf-off, 0.5 inch pixel resolution at a scale of 1" = 100') from the Muskegon County Equalization Department was used as the base image for the land use and cover update process. Using ESRI™ ArcGIS 10.0, the existing 1998 land use and cover vector polygon data was overlaid onto the 2008 digital orthophotograph. The 2011 delineated Ruddiman Creek watershed boundary was then used to clip the Muskegon County 1998 land use and cover dataset for the project area. The 1998 land use and cover polygon for Ruddiman Creek watershed was then edited using the ArcGIS 10.0 toolset to create an updated 2008 land use and cover data layer that reflected the landscape changes apparent in the 2008 image within the watershed boundary. The photographic interpretation of the changes found in the 2008 orthophotograph were field verified by the project team, and any land use and cover attribute modifications were completed using the Michigan Land Cover/Use Classification System 2000 (MDNR 2002) to assess changes over time.

The project team delineated the watershed's surface hydrography during spring 2010. To complete this task, an AWRI field crew walked the stream corridor with a Thales/Magellan ProMark 3 GPS to collect GPS positions for the entire surface watercourse. The data were plotted using ESRI™ ArcGIS 10.0 and edited using the 2008 orthophotograph. Ruddiman Lagoon was also digitized using the 2008 orthophotograph to develop the most updated depiction of Ruddiman Creek's surface water.

References

Michigan Department of Natural Resources (MDNR). (2002) Michigan land cover/ use classification system- 2000. Updated in 2000 by the Michigan Land Use Classification and Referencing Committee.

Appendix F – Hydrographs from Monitoring Data

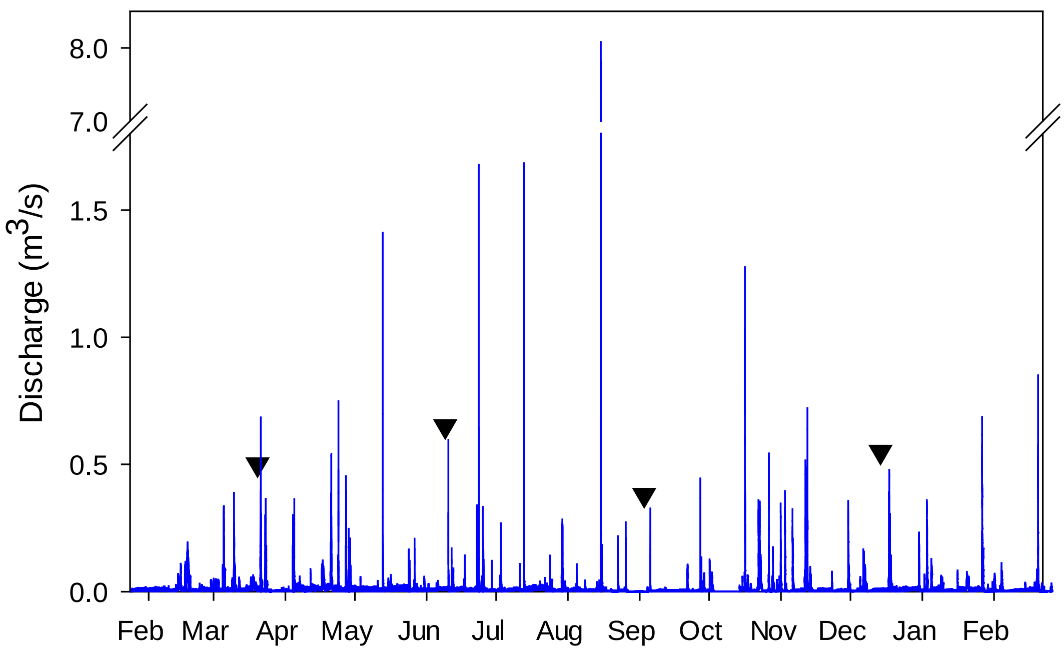

Fig. F.1. SS3 hydrograph from January 24, 2011-February 22, 2012. Inverted triangles indicate storm sampling events.

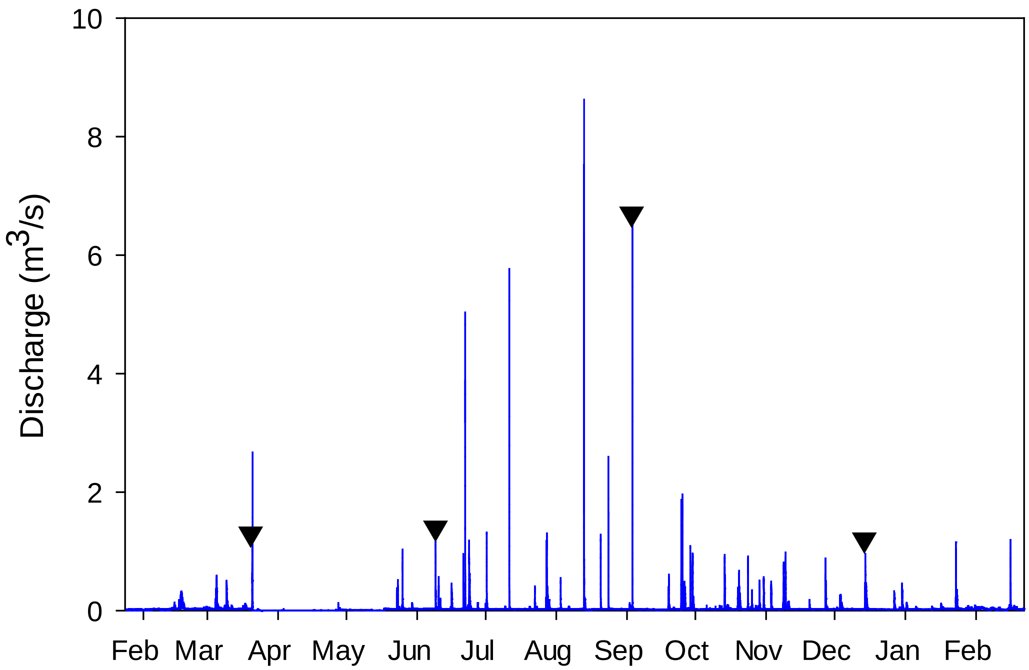

Fig. F.2. SS2 hydrograph from January 24, 2011-February 22, 2012. Inverted triangles indicate storm sampling events.

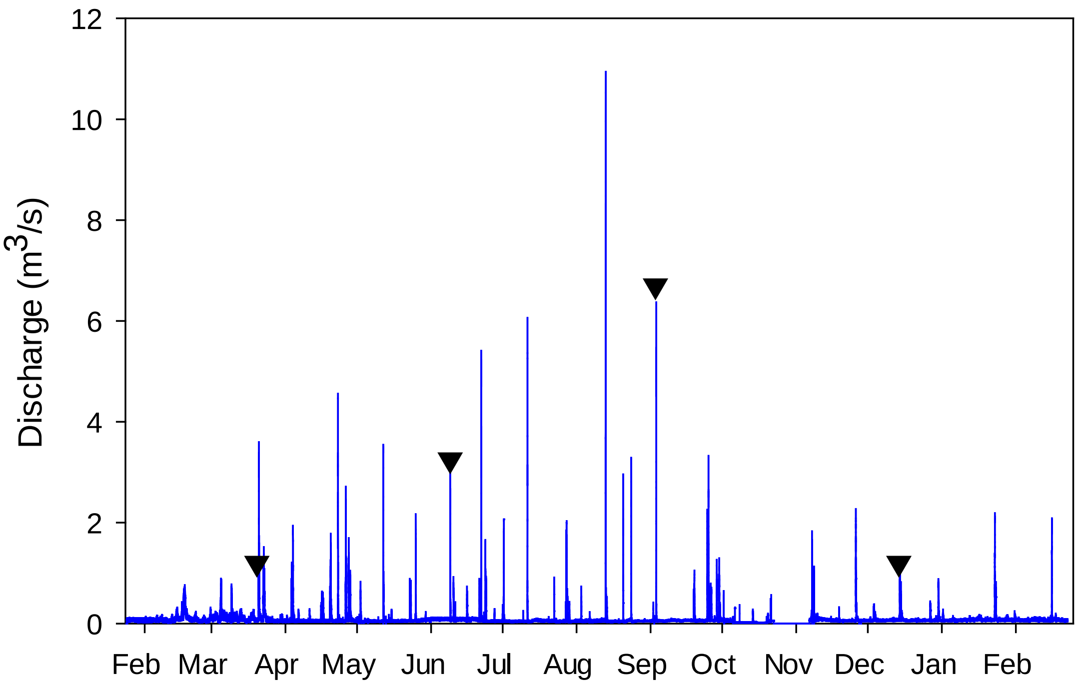

Fig. F.3. SS1 hydrograph from January 24, 2011-February 22, 2012. Inverted triangles indicate storm sampling events.

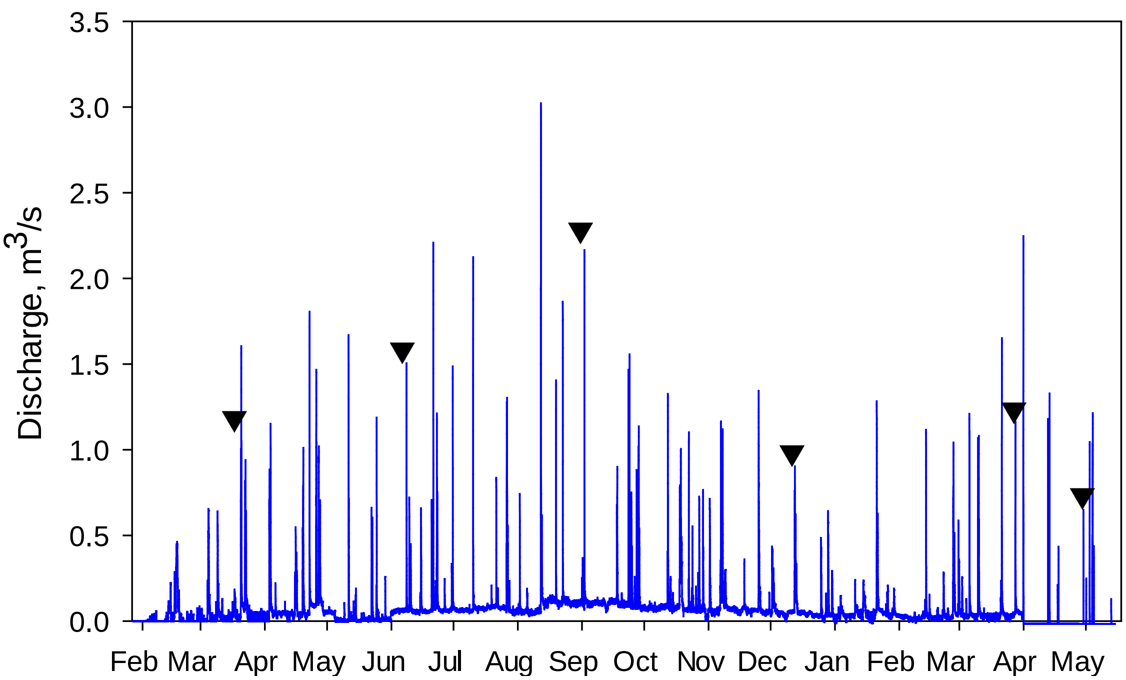

Fig. F.4. MB1 hydrograph from January 27, 2011-May 17, 2012. Inverted triangles indicate storm sampling events.

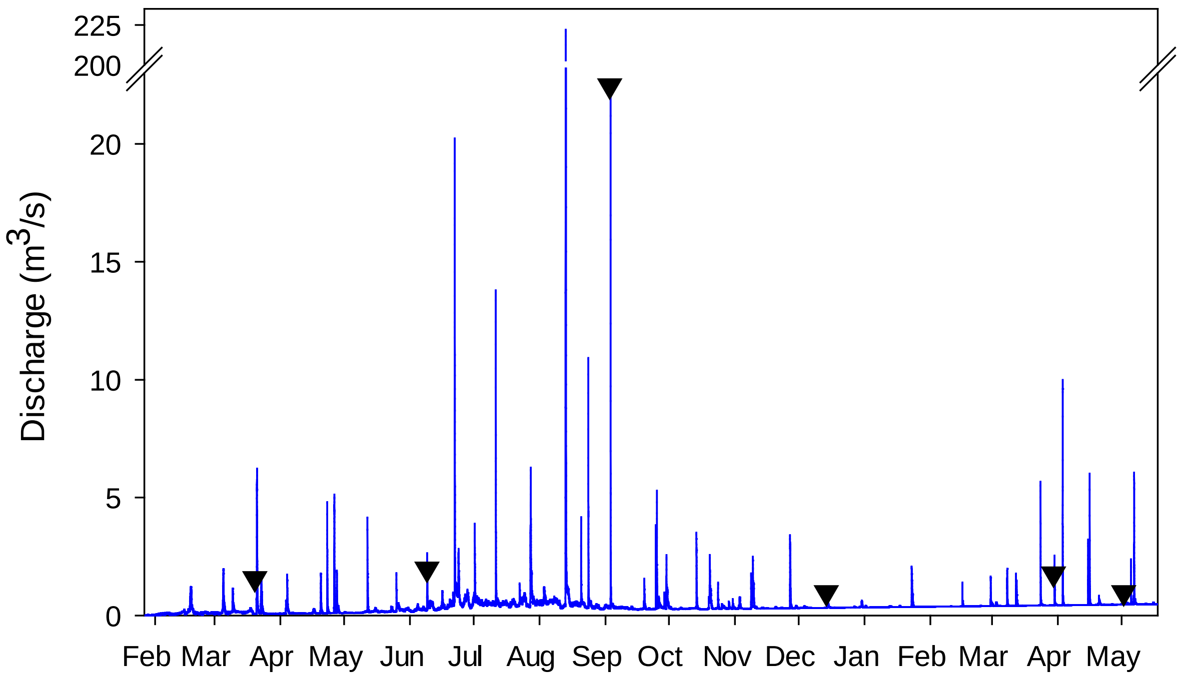

Fig. F.5. MB2 hydrograph from January 27, 2011-May 17, 2012. Inverted triangles indicate storm sampling events.

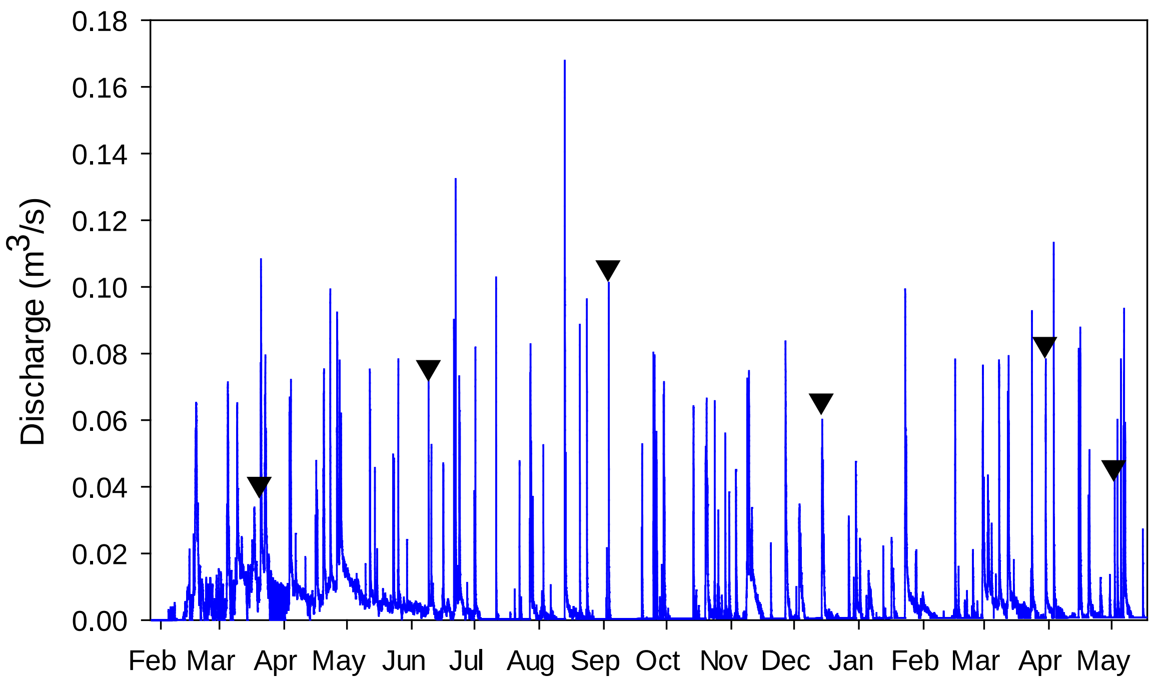

Fig. F.6. NB hydrograph from January 27, 2011-May 17, 2012. Inverted triangles indicate storm sampling events.

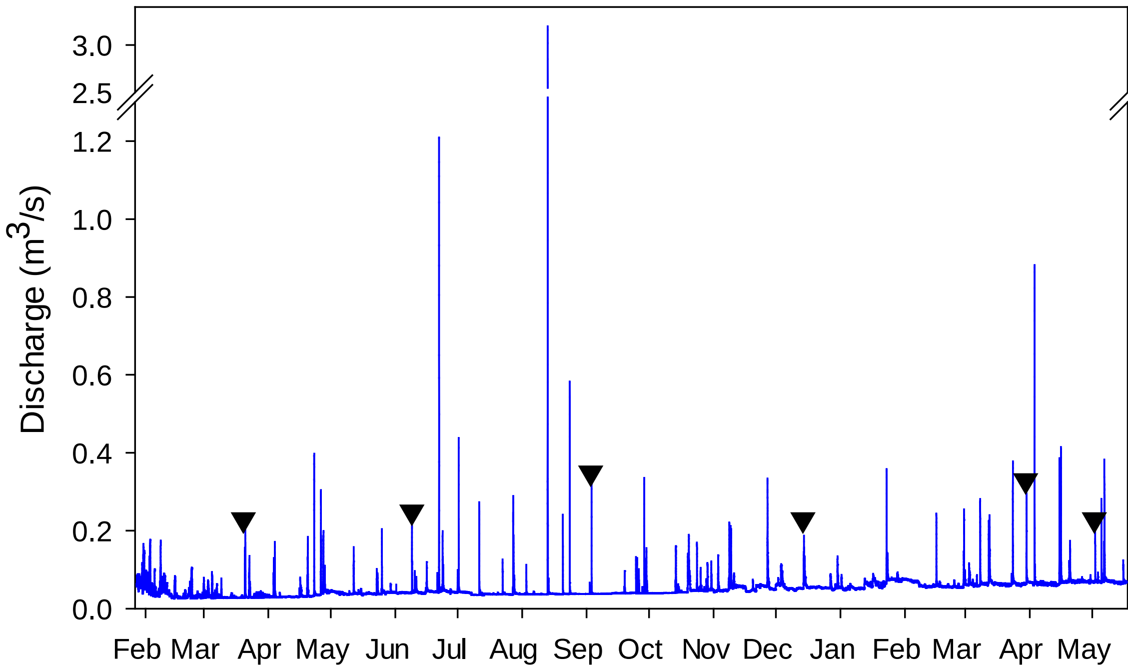

Fig. F.7. WB1 hydrograph from January 27, 2011-May 17, 2012. Inverted triangles indicate storm sampling events.

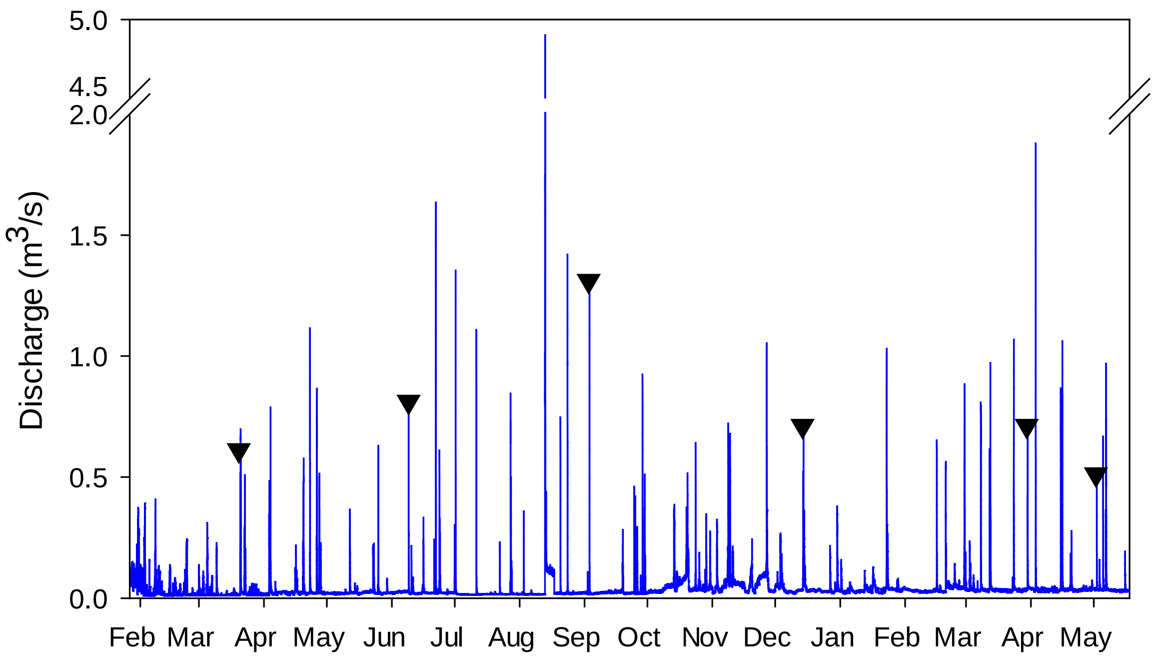

Fig. F.8. WB2 hydrograph from January 27, 2011-May 17, 2012. Inverted triangles indicate storm sampling events.

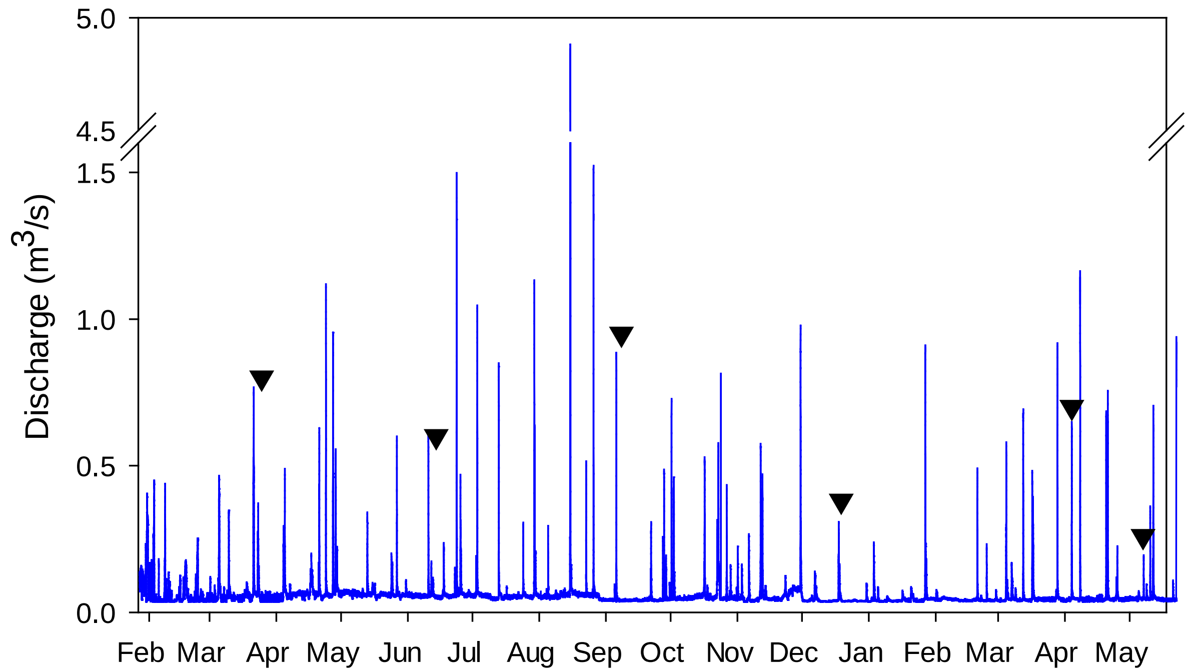

Fig. F.9. WB3 hydrograph from January 27, 2011-May 17, 2012. Inverted triangles indicate storm sampling events.

Appendix G – Water Quality

G.1 Methods

Water quality sampling occurred at the time of sediment sampling (i.e., baseflow and storm events). Refer to Chapter 2.3 for details.

Grab samples for biochemical oxygen demand (BOD) were collected in 1-L polyethylene bottles at tributary sites on the main branch and from storm sewers during all sampling events, as described Chapter 2.3.1. BOD was measured by filling an airtight 300-ml glass bottle with a well-mixed subsample and incubating it at 20ºC for 5 days (Method 405.1; USEPA 1983). Dissolved oxygen (DO) was measured with an Orion Autostir Oxygen/BOD Probe before and after incubation; BOD was computed as the difference between the initial and final DO readings. Each sample was analyzed at 100% concentration and at 3 levels of dilution with seeded (wastewater treatment plant influent), buffered dilution water. The BOD of the seeded dilution water was measured with each set of samples and determined to be < 1 mg/l. Differences in average storm event BOD among sites and were determined using Kruskal-Wallis one-way analysis of variance (ANOVA) on ranks, due to lack of normality and/or unequal variance. All statistical analyses were performed using SigmaPlot 12.3.

A suite of chemical and physical parameters were measured at tributary sites during each sampling event using a Yellow Springs Instruments Model 6600 Sonde. Parameters included DO, temperature, pH, redox potential (ORP), specific conductance (SpC), total dissolved solids (TDS), turbidity, and chlorophyll *a*. During baseflow monitoring trips, the sonde was submerged at each tributary site to one-half the water depth in the thalweg of the stream and allowed to equilibrate before measurements were logged. Baseflow measurements were taken between 9:30 a.m. and 3:30 p.m. During storm events, sondes were deployed at the most downstream site on each branch: NB, MB2, and WB3 (Fig. 2.1) and programmed to log data every 15 minutes throughout the event. Storm event measurements were taken at various times of day and night, depending on the occurrence of storms. Sondes were calibrated prior to each sampling trip according to protocols recommended by the manufacturer. In determining average baseflow conditions, outliers were excluded from the average when they varied more than 2.5 SD from the mean baseflow value (Lottig and Carpenter 2012).

Nutrients, metals, and polycyclic aromatic hydrocarbons (PAHs) were sampled during one summer baseflow event (August 23, 2011) and one summer storm event (September 3, 2011) at all tributary sites. Nutrient analyses included soluble reactive phosphorus (SRP), total phosphorus (TP), nitrate (NO_3), total Kjeldahl nitrogen (TKN), ammonia (NH_3); metals analyses included arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), selenium (Se), and zinc (Zn). The analytical methods are summarized in Table G.1. Briefly, SRP, TP, TKN, and NH_3 were analyzed on a Braun + Lubbe AA3 Segmented Flow Analyzer and NO_3 was analyzed on a Dionex ICS-1100 ion chromatograph (APHA 1992). Heavy metals, with the exception of Hg, were analyzed by acid digestion followed by graphite furnace atomic absorption spectroscopy using a Perkin Elmer AAnalyist 800 (USEPA 1999). Mercury was analyzed cold vapor atomic absorption spectroscopy (USEPA 1999) on a Perkin Elmer FIMS 400 system. PAH compounds were analyzed by solvent extraction followed by gas chromatography/mass spectrometry (GC/MS) using an Agilent 5890/5973 GC/MS (USEPA 1999). Grab samples were collected as previously described in 4-L glass jars and maintained at 4°C.

Table G.1. Laboratory analytical methods.

Parameter	Method	Reference	Detection Limit
BOD	Incubation @ 20°C with DO measurements	405.1*	1 mg/l
As	Graphite Furnace Atomic Absorption (GFAA)	7010**	0.005 mg/l
Cd			0.001 mg/l
Cr			0.01 mg/l
Cu			0.004 mg/l
Ni			0.020 mg/l
Se			0.050 mg/l
Zn			0.015 mg/l
Metals Digestion for GFAA	Acid digestion	3020a**	NA
Hg	Cold Vapor Atomic Absorption	7470a**	0.0002
Semivolatile Organics	GC/MS	8270**	1 ug/l
Nitrate	Ion Chromatography	4100 C***	0.01 mg/l
Soluble Reactive Phosphorus	Automated Ascorbic Acid	4500-P F*	0.01 mg/l
Total Phosphorus	Persulfate Digestion Automated Ascorbic Acid	4500-P B.5 and F*	0.01 mg/l
Ammonia	Automated Phenate	4500-NH_3 H*	0.01 mg/l
Total Kjeldahl Nitrogen	Autoclave Acid Digestion Automated Phenate	4500-N_{org} B*	0.1 mg/l

*USEPA 1983
**USEPA 1999
***APHA 1992

G.2 Results

Water temperature averaged 10-12 °C (50-54 °F) during baseflow over the 13-month monitoring period (Table G.2). The sites were generally well-oxygenated, with dissolved oxygen (DO) concentrations well above the minimum of 5 mg/L needed to support healthy biota. However, DO was low at NB (4-5 mg/L) during two baseflow events and one storm event. pH was approximately 8 over the study period, regardless of flow condition. Average conductivity was 842-1250 μs/cm during baseflow and 344-406 μs/cm during storm events, presumably due to dilution associated with runoff (Table G.2). Baseflow conductivity exceeded the 150-500 μs/cm range considered to support good mixed fisheries in streams (USEPA 1997), suggesting sub-optimal water quality conditions for fish. Elevated conductivity is a common symptom of an urbanized watershed and reflects point source and non-point source pollution from human activities (Paul and Meyer 2001); aquatic ecosystem conductivity values ≥ 600 μS/cm have been linked to human-induced stress (Hughes et al. 1998, Uzarski et al. 2005), suggesting general degradation of stream conditions in the Ruddiman Creek watershed. Average total dissolved solids (TDS), which is related to conductivity, ranged from 0.5-0.8 g/L during baseflow and from 0.2-0.3 g/L during storms (Table G.2). Conductivity and TDS both decreased in a downstream direction in the main branch and west branches during baseflow. Average oxidation-reduction potential (ORP) ranged from 285-325 mV during baseflow and from 231-327 mV during storm events (Table G.2). Turbidity was low during baseflow conditions, with average values ranging from 2-5 NTU. Average storm event turbidity was highest in the main branch (51 NTU), followed by the north branch (42 NTU; Table G.2). Turbidity levels over 100 NTU were common in the main and north branches during storm events, and associated with elevated suspended sediment concentrations.

In general, these water quality data are consistent with urban stream conditions. The high baseflow conductivity values and high storm event turbidity values are indicative of a watershed experiencing ecological stress.

Table G.2. Mean and standard deviation (SD) of select water quality parameters measured during baseflow (n=13) and storm (n=6) events. Storm flow measurements were taken only at the downstream-most sampling location on each branch of Ruddiman Creek. Baseflow measurements were taken between 9:30 a.m. and 3:30 p.m.; storm event measurements were taken at various times of day and night, depending on the occurrence of storms.

		Temp, C		Temp, F		DO, mg/L		pH		SpCond, uS/cm		ORP, mV		TDS, g/L		Turbidity, NTU	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Baseflow	MB1	11.62	3.85	52.91	22.94	8.97	1.73	7.78	0.15	1250	297	325	96	0.812	0.193	2.1	1.6
	MB2	11.28	5.27	52.31	22.65	9.85	1.43	7.77	0.17	1114	330	323	90	0.724	0.215	4.0	4.3
	NB	9.18	8.16	48.52	22.89	8.52	2.58	7.61	0.21	1017	218	301	101	0.661	0.142	5.5	7.2
	WB1	12.02	3.91	53.64	22.91	9.76	0.99	7.79	0.19	931	560	311	90	0.605	0.364	1.9	1.4
	WB2	10.75	4.70	51.34	22.32	9.15	1.35	7.65	0.16	842	221	285	102	0.547	0.143	1.9	1.2
	WB3	9.70	7.12	49.46	22.05	9.97	2.15	7.76	0.24	779	202	319	100	0.507	0.131	4.5	6.5
Storm flow	MB2	8.82	5.36	47.88	9.65	10.60	1.82	7.81	0.12	344	264	242	89	0.224	0.171	50.9	30.1
	NB	8.66	6.82	47.58	12.28	10.05	2.65	7.85	0.12	407	298	231	96	0.265	0.194	42.1	39.4
	WB3	9.30	5.90	48.75	10.63	9.62	2.09	8.24	1.50	426	158	327	33	0.277	0.103	37.7	26.7

Baseflow 5-day biochemical oxygen demand (BOD_5) ranged from 0.27-7.73 mg/L at tributary sites and from 0.13-29.60 mg/L at sewer sites. SS3 had the highest average BOD_5 during baseflow conditions (12.51 mg/L; Fig. G.1). During storm events, BOD_5 ranged from 15.33-64.87 mg/L at tributary sites and from 5.60-111.87 mg/L at sewer sites; storm event BOD_5 was not statistically different among sites (Fig. G.1). Tributary BOD_5 at baseflow was within range of what has been reported for urban streams in North Carolina (Mallin et al. 2006). Although *average* storm event BOD_5 was greater than what was reported for the City of Milwaukee (23 mg/L), the *range* of BOD_5 values was within that reported for Milwaukee (1-250 mg/L; Soonthornnonda and Cristensen 2005). By comparison, BOD_5 for raw wastewater ranges from 110-400 mg/L (Metcalf and Eddy 1991, Henze et al. 2001). The increased BOD_5 during storm events indicates an increased oxygen demand, and greater stress, associated with storm flow, which is consistent with the other water quality data measured in Ruddiman Creek.

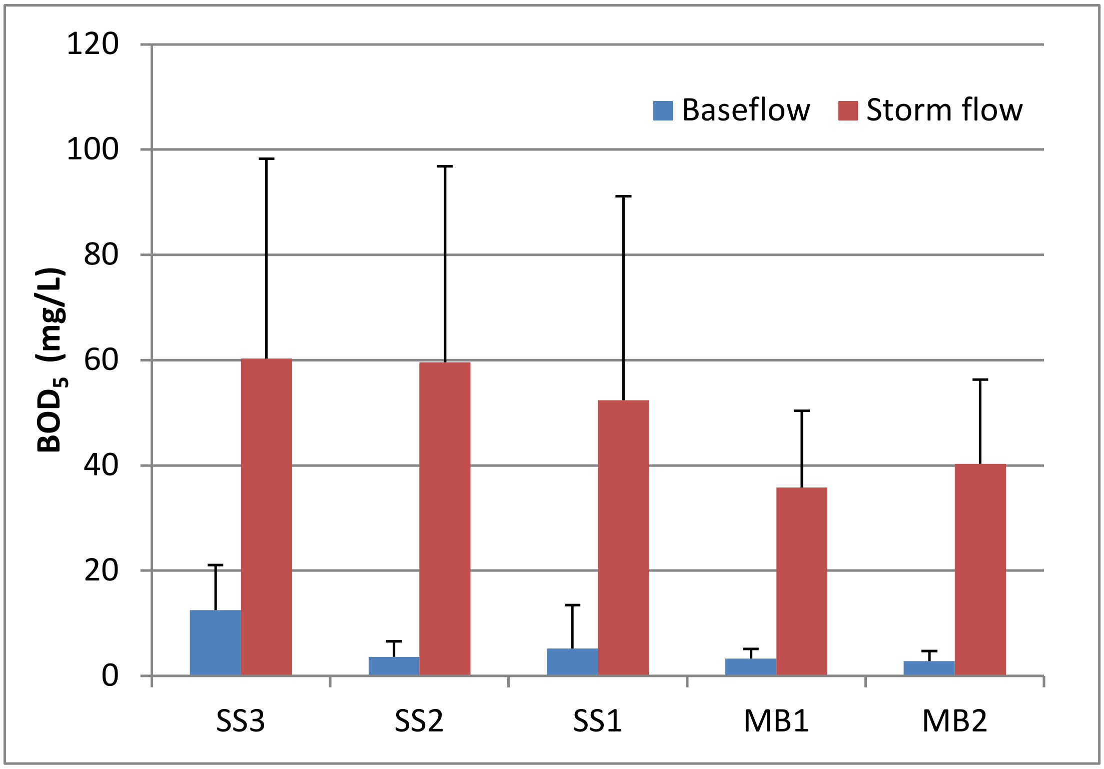

Fig. G.1. Mean (+SD) BOD_5 concentrations for baseflow and storm event samples over the study period. Data are presented from upstream (SS3) to downstream (MB2).

Nitrate concentrations measured during baseflow on August 23, 2011 ranged from 1.06-2.78 mg/L and were slightly higher than concentrations measured during the September 3, 2011 storm event (Table G.3). Baseflow nitrate concentrations reported for other urban streams, including nearby Little Black Creek, are considerably lower (0.12-0.77 mg/L; Mallin et al. 2006, Johnson et al. 2011) than those measured in Ruddiman Creek, and very similar to ranges measured in Muskegon Lake between 2003-2009 (0.01-0.70 mg/L; Gillett and Steinman 2011).

Ammonia concentrations ranged from 0.05-0.16 mg/L during baseflow and increased 3-17× during the storm event. Storm event ammonia concentrations in Ruddiman Creek were similar to raw stormwater concentrations reported for the City of Milwaukee (Soonthornnonda and Cristensen 2005), road runoff entering Little Black Creek (Johnson et al. 2011), and Muskegon Lake (Gillett and Steinman 2011; Table G.3); the increase with storm flow is consistent with results of Johnson et al (2011), and may reflect ammonia being liberated from sediment porewater, where reducing conditions are prevalent. Ammonia is the preferred form of N for uptake by autotrophs, so elevated concentrations may contribute to algal blooms in downstream receiving waters. Total Kjeldahl nitrogen (TKN) concentrations were similar among sites during baseflow, ranging from 0.41-0.59 mg/L, with the exception of NB, which was 0.78 mg/L (Table G.3). These concentrations are similar to the long-term average reported for Muskegon Lake (0.51 mg/L; Gillett and Steinman 2011). TKN increased 2× during the storm event at all sites except NB, where the increase was 1.3×.

Total phosphorus (TP) concentration was moderate at most sites during baseflow, ranging from 16-29 μg/L, but was considerably higher at NB (75 μg/L; Table G.3). It is unclear whether this tributary has a persistent P source or if this was a one-time event, but additional monitoring may be prudent. With the exception of NB, TP in Ruddiman Creek was lower than the range of baseflow concentrations reported for Little Black Creek (30-100 μg/L; Steinman et al. 2006) and Muskegon Lake (30 μg/L; Gillett and Steinman 2011). Storm event TP was greater than baseflow TP, with concentrations ranging from 25-130 μg/L (Table G.3). Johnson et al. (2011) reported similar storm event TP concentrations in nearby Little Black Creek.

Soluble reactive phosphorus (SRP) ranged from 6-31 μg/L during baseflow and from 19-128 μg/L during the storm event, with the highest concentrations measured at NB (Table G.3). Baseflow SRP was similar to the reported range for Little Black Creek (5-30 μg/L; Steinman et al. 2006) and Muskegon Lake, but storm event SRP was considerably higher than what was reported for Little Black Creek (9-11 μg/L; Johnson et al. 2011).

Metals with detectable concentrations at baseflow were copper (MB2, NB, WB1) and nickel (MB2; Table G.3), and these were well below the State of Michigan's water quality criteria for chronic effects to aquatic life (MDEQ 2011). Some sites had increases in cadmium, chromium, and nickel during the storm event, similar to the increases observed after storm events in Little Black Creek (Johnson et al. 2011; Table G.3). Copper concentrations exceeded Michigan's criteria for chronic effects (0.016 mg/L) at all sites during the storm event, and exceeded the criteria for acute effects (0.052 mg/L) at MB1, MB2, WB1, and WB2 (MDEQ 2011; Table G.3). Storm event copper concentrations were 3× greater than the maximum values reported for Little Black Creek (Johnson et al. 2011) at all sites except NB and WB3, where they fell within the range (Table G.3). Storm event zinc concentrations exceeded the WQS criteria for chronic effects (0.213 mg/L; MDEQ 2011) at MB1, MB2, WB1, and WB2 and were greater than the maximum concentration reported for Little Black Creek (Johnson et al. 2011; Table G.3), but did not exceed the WQS criteria for acute effects (0.422 mg/L).

Polycyclic aromatic hydrocarbons (PAHs) were below the detection limit in baseflow samples, but had measureable concentrations in storm samples from MB1, MB2, WB1, and WB2 (Table G.3). Total PAHs ranged from 4.5-42.1μg/L when they were detected, with the highest concentrations occurring in the main branch. At all sites with detectable PAHs, fluoranthene exceeded the WQS for chronic effects (1.6 μg/L; MDEQ 2011). Phenanthrene concentrations also exceeded the WQS for chronic effects (1.4 μg/L; MDEQ 2011) at MB1. Although the west branch total PAH concentrations were similar to those reported for Little Black Creek during storms (1-10 μg/L), the main branch concentrations were more similar to snowmelt values (14-41 μg/L) reported in the Little Black Creek study (Steinman et al. 2011; Table G.3).

Other studies have measured increases in metals and PAHs after storm events (Lee et al. 2004, Tiefenthaler et al. 2008), so these results were not unexpected and may contribute to biotic stress in the Ruddiman Creek watershed.

Table G.3. Nutrient, metal, and total PAH concentrations measured during one-time baseflow (8/23/11) and storm (9/3/11) events. Two samples were collected during the storm event at different points on the hydrograph. Data ranges for Muskegon Lake are based on collections made between 2003 and 2009 (see Gillett and Steinman [2011] for more details). Data ranges for Little Black Creek are from Johnson et al. (2011).

		NO_3-N mg/L	NH_3-N mg/L	TKN mg/L	SRP-P μg/L	TP-P μg/L	Ar mg/L	Cd mg/L	Cr mg/L	Cu mg/L	Ni mg/L	Se mg/L	Zn mg/L	Hg mg/L	PAHs μg/L
Base flow	MB1	2.27	0.16	0.47	13	26	<0.005	<0.001	<0.01	<0.004	<0.02	<0.005	<0.15	<0.0002	<1
	MB2	1.87	0.16	0.47	6	26	<0.005	<0.001	<0.01	0.009	0.041	<0.005	<0.15	<0.0002	<1
	NB	1.06	0.06	0.78	31	75	<0.005	<0.001	<0.01	0.004	<0.02	<0.005	<0.15	<0.0002	<1
	WB1	2.78	0.05	0.59	6	16	<0.005	<0.001	<0.01	0.006	<0.02	<0.005	<0.15	<0.0002	<1
	WB2	2.38	0.07	0.45	14	27	<0.005	<0.001	<0.01	<0.004	<0.02	<0.005	<0.15	<0.0002	<1
	WB3	1.80	0.07	0.41	17	29	<0.005	<0.001	<0.01	<0.004	<0.02	<0.005	<0.15	<0.0002	<1
	Little Black Creek	0.2-0.69	<0.01-0.13	--	<5-8	<10-24	--	<0.001	<0.001-0.002	<0.005-0.06	<0.005	--	<0.05	--	--
Storm flow	MB1	1.71	0.44	1.01	19	117	<0.005	0.001	0.049	0.059	0.021	<0.005	0.290	<0.0002	42.1
		1.02	0.52	0.93	61	72	<0.005	<0.001	<0.01	0.016	<0.02	<0.005	<0.15	<0.0002	<1
	MB2	1.28	0.52	0.99	43	51	<0.005	0.002	0.098	0.055	0.021	<0.005	0.250	0.0002	20.0
		1.19	0.49	0.85	50	62	<0.005	<0.001	0.021	0.020	<0.02	<0.005	<0.15	<0.0002	<1
	NB	1.12	0.64	1.06	128	130	<0.005	<0.001	<0.01	0.011	<0.02	<0.005	<0.15	<0.0002	<1
		0.76	0.24	0.78	40	51	<0.005	<0.001	<0.01	0.008	<0.02	<0.005	<0.15	<0.0002	<1
	WB1	0.79	0.87	1.27	22	25	<0.005	<0.001	0.031	0.068	0.031	<0.005	0.270	<0.0002	<1
		1.33	0.58	0.87	23	33	<0.005	<0.001	<0.01	0.020	<0.02	<0.005	<0.15	<0.0002	4.5
	WB2	1.60	0.37	0.99	24	34	<0.005	<0.001	0.028	0.060	<0.02	<0.005	0.240	<0.0002	10.3
		1.30	0.59	0.99	30	29	<0.005	<0.001	0.013	0.021	<0.02	<0.005	<0.15	<0.0002	<1
	WB3	1.30	0.46	0.81	41	34	<0.005	<0.001	0.011	0.022	<0.02	<0.005	<0.15	<0.0002	<1
		1.72	0.37	0.66	59	56	<0.005	<0.001	0.01	0.02	<0.02	<0.005	<0.15	<0.0002	<1
	Little Black Creek	0.55-0.58	0.16-0.22	--	9-11	40-90	--	<0.001	0.011-0.028	0.008-0.020	<0.005-0.008	--	<0.05-0.147	--	--
Muskegon Lake		0.01-0.7	0.01-0.16	0.18-2.00	3-60	10-90	--	--	--	--	--	--	--	--	--

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Appendix H – Geomorphology

H.1 Streambed Sediment Characterization

Streambed sediment sampling was conducted for benthic organic matter (BOM) and grain size analysis during a one-time sampling event (April 25, 2012). Sediment samples were collected using a 4-cm-diameter clear PVC core sampler inserted to a depth of ~10 cm into the streambed. BOM was quantified as the average ash-free dry mass of 5 replicate benthic core samples collected at equally-spaced locations along a transect, using the method of Steinman et al. (2006). Grain size was quantified from 3 benthic samples collected at equally-spaced locations near where BOM was sampled; grain size was determined as previously described. Differences in mean BOM among sites were analyzed using one-way analysis of variance (ANOVA); significant contrasts ($p<0.05$) were further analyzed using Holm-Sidak multiple comparison test. BOM data were log-transformed prior to analysis to achieve normal distribution and equal variance. All statistical analyses were performed using SigmaPlot 12.3.

Streambed sediments were generally dominated by medium sand (250-500 μm), but there was a substantial, albeit highly variable, gravel/cobble (>2 mm) fraction at MB2 and WB3 (Fig. H.1). Fine sand (125-250 μm) was the second most abundant fraction at MB1 and WB1. Very fine sand (63-125 μm) and silt/clay (<63 μm) were minor components of streambed sediment (Fig. H.1). Mean BOM measured in streambed sediment cores was 5% or less at all sites except NB, where it was 11% (Fig. H.2). NB had significantly greater mean BOM than MB2, WB1, and WB2 ($p=0.004$; Fig. H.2).

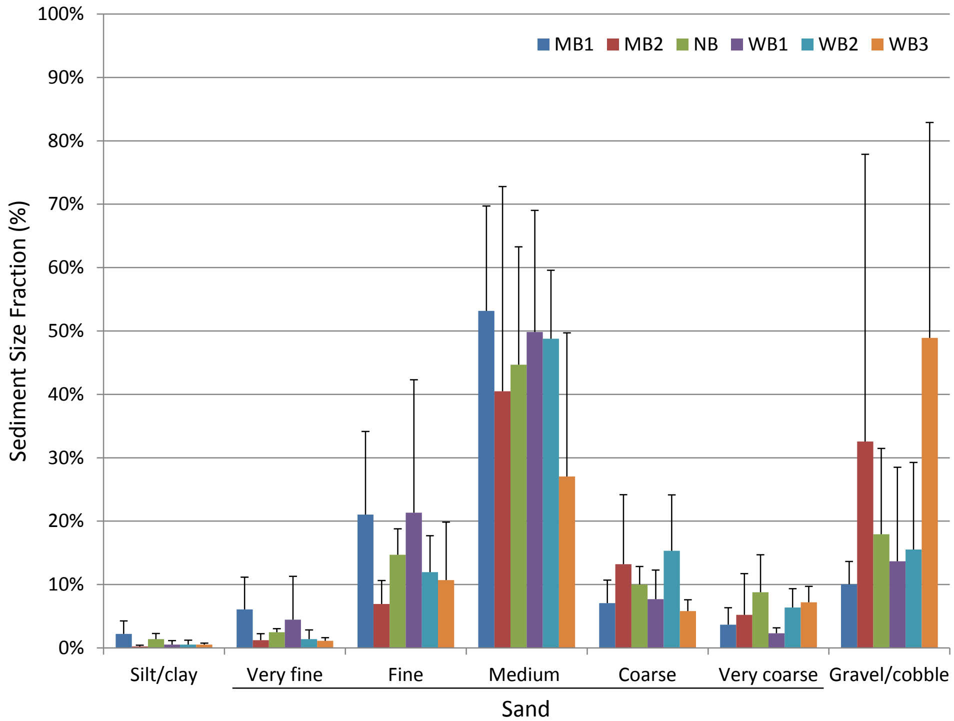


Fig. H.1. Mean (+SD) grain size distribution of streambed sediment cores (n=3).

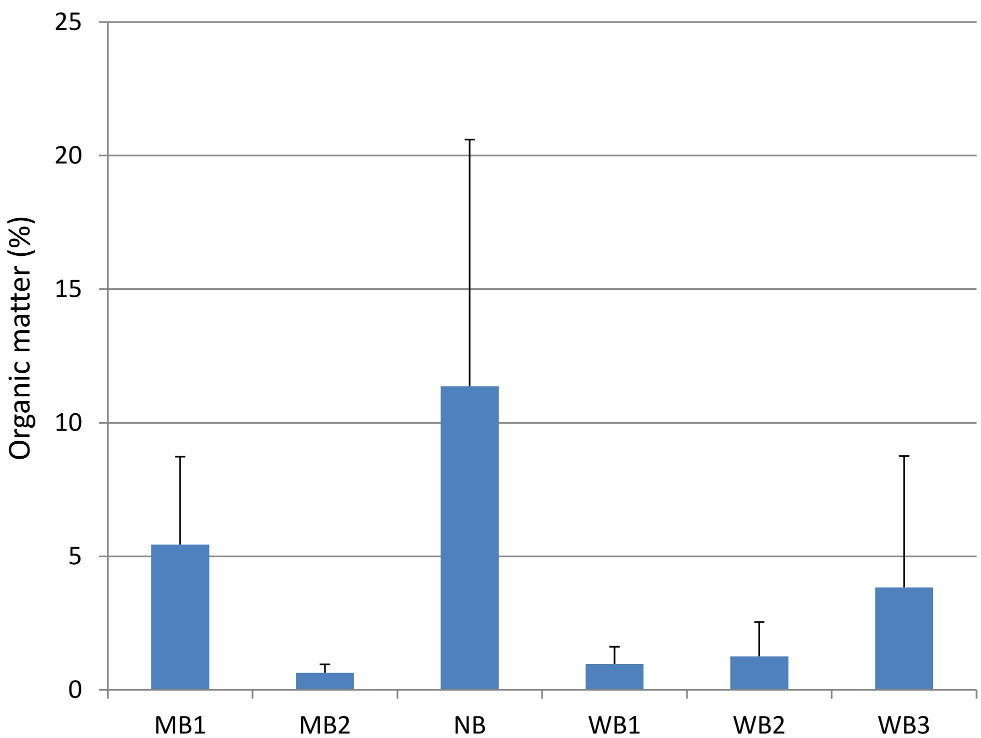


Fig. H.2. Mean (+SD) benthic organic matter measured in streambed sediment cores (n=5).

Scour chains were installed according to Bigelow (2003) at each of the tributary sites to measure depth of sediment deposition or scour over time. Upon installation, the initial elevation of the streambed (i.e., top of scour chain) was surveyed using a permanent benchmark. Scour chains were installed ~1m upstream of the stilling wells and a permanent marker was installed in the bank 90 degrees from the chain location. Positioning the chains in this way allowed for re-location of the chains if deposition occurred; metal debris in the streambed made the more common use of a metal detector for re-location impossible. Scour chains were monitored for sediment deposition and/or scour during each baseflow monthly field visit. Bed elevation was surveyed directly on top of the scour chain; the length of exposed chain was measured, if applicable. The change in bed elevation from one month to the next was used to determine the monthly fill (positive change) or scour (negative change) rate. Annual scour or fill rate was determined by subtracting the initial bed elevation from the final bed elevation. At the end of the sampling period, each scour chain was located and assessed for dynamic scour and fill, in which scour occurs first, exposing the chain, followed by burial by fill; this situation is demonstrated by a chain that is laid over 90 degrees under a layer of sediment. Scour chains found in this position were measured from the point at which they were bent to determine the depth of scour; the depth of fill was measured by bed survey.

Scour chain installations revealed dynamic streambed conditions at the monitoring locations (Fig. H.3). A combination of streambed scour and fill was measured over the study period at all sites. Sites MB2, NB, and WB1 experienced 3-5 cm/yr net accumulation of sediment; the greatest annual fill rate, 17 cm/yr, occurred at MB1 (Fig. H.3). WB2 and WB3 experienced a 7 cm/yr net loss of streambed sediment (Fig. H.3). Monthly bed elevation surveys at scour chain locations emphasized the short time scale at which bed elevation changes occurred; indeed, monthly scour rates were as high as 14 cm/mo at MB2 while monthly fill rates were as high as 11 cm/mo at WB1 (Table H.1). Sites NB and WB3 tended to have the lowest monthly change in bed elevation among the sites (Table H.1). Streambed sediments at the scour chain locations were predominately medium sand (250-500 μm), except at WB3 where gravel/cobble (>2 mm) was the dominant size fraction (Fig. H.4); the larger sediment size may have accounted for the greater stability in bed elevation at WB3, but not at NB, where sediment grain size was much finer, on average. See Appendix H.2 for more information about the geomorphic characteristics of each site.

Wetted perimeter was determined at tributary sites during all sampling events by measuring the distance covered by water (stream bank and bottom) across each transect.

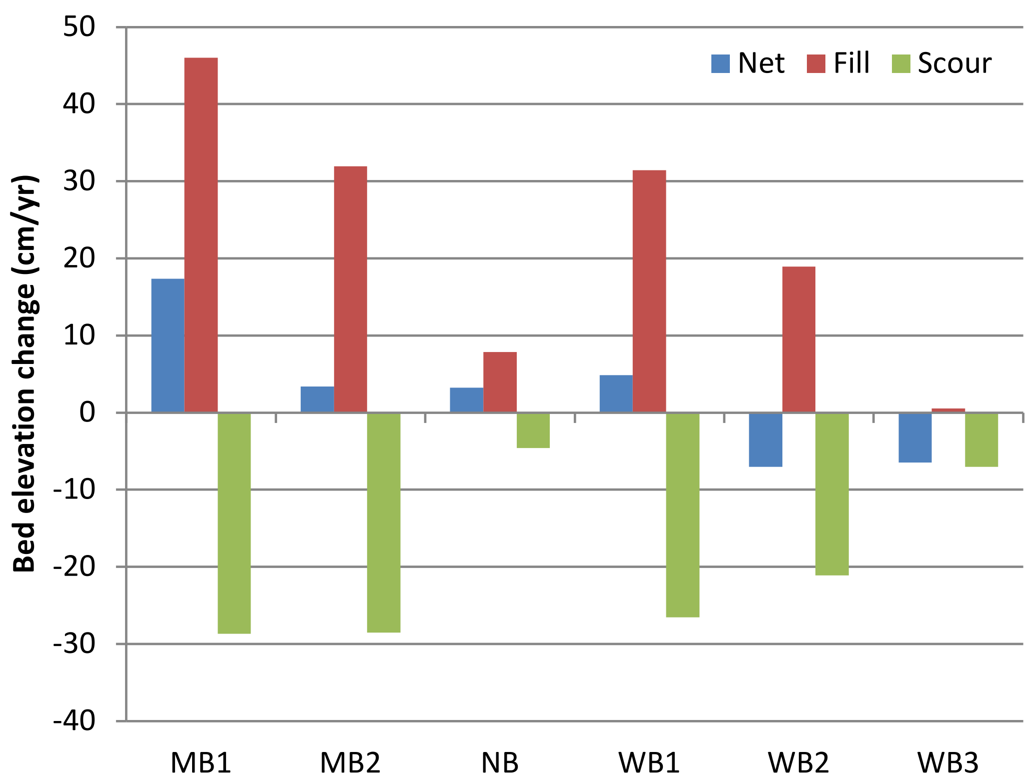


Fig. H.3. Annual change in bed elevation at scour chain installations over the study period.

Table H.1. Monthly change in bed elevation at scour chain installations over the study period. Dashes indicate no data available due to measurement error.

	Fill [+] or scour [-] rate (cm/mo)					
Month	**MB1**	**MB2**	**NB**	**WB1**	**WB2**	**WB3**
April	6.5	4.4	--	-3.0	5.0	0.0
May	6.4	-1.6	--	11.3	-5.4	0.0
June	8.4	8.0	2.6	-9.8	-0.5	0.0
July	-3.5	-14.0	-1.8	-1.0	-5.0	0.0
August	-1.4	4.2	0.0	4.2	0.5	0.0
September	-6.8	-5.5	-1.4	-2.0	0.7	--
October	4.8	2.4	-0.3	3.1	-4.4	-1.6
November	7.2	1.7	0.0	2.2	7.8	-3.3
December	-7.8	-7.8	--	7.8	-8.3	0.5
January	6.6	4.4	2.1	-5.3	3.1	--
February	-9.3	-2.1	-1.0	-2.6	2.1	0.0

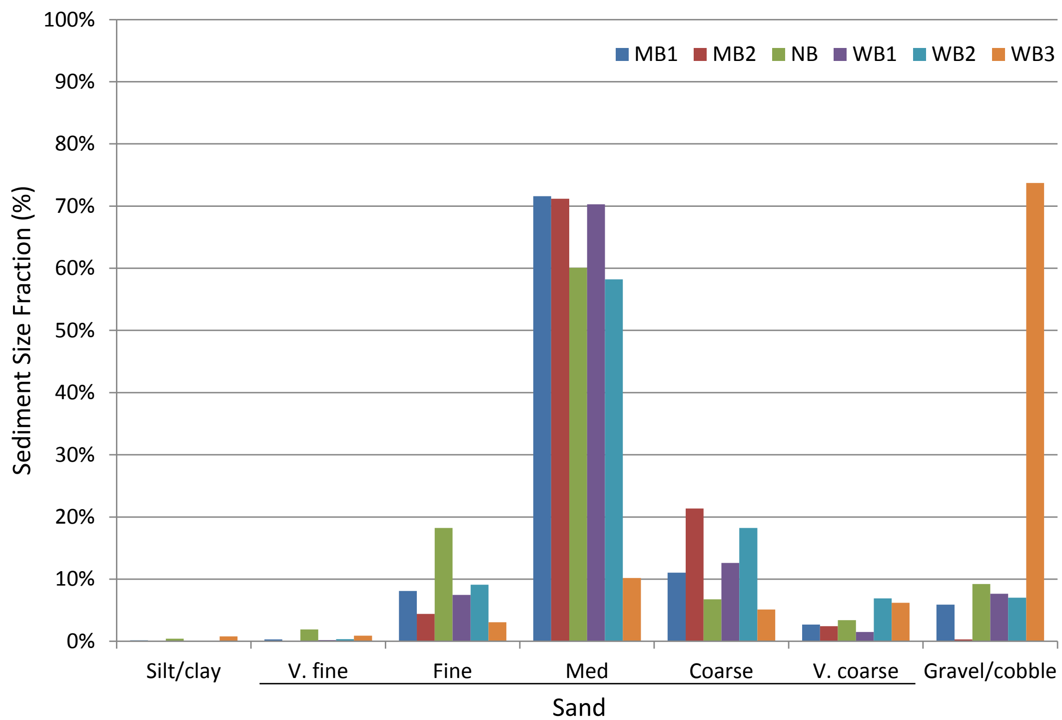


Fig. H.4. Grain size distribution of streambed sediment in cores taken near scour chain installations.

H.2 Geomorphic Assessment

A geomorphic assessment of seven locations within the watershed was performed on April 9, 2012. The purpose of this assessment was to draw greater inferences about the overall health/stability of the stream channel, as well as substantiate geomorphic monitoring data (e.g., sediment sampling, scour chains). The geomorphic assessment also provided a comparative measure of stability between stream reaches.

A rapid assessment survey was performed at WB2, MB1 (Fig. 2.1), and at a reference site near McGraft Park on the west branch. Data collected included: identification of bankfull elevation (where possible), plan view drawings, a longitudinal profile over a length of approximately 20 bankfull widths, and cross section analysis. Longitudinal profile data included thalwag elevation, water surface elevation, top of sediment (if applicable), bankfull elevation (where possible), and top of right and left stream banks. Cross section determination for each location included bankfull width, bankfull height, thalwag, water surface, and top of bank elevations. General characterization of the channel substrate and riparian communities were also documented.

These data were analyzed to classify each stream channel according to Rosgen stream classification. This classification is based on the entrenchment ratio (ratio of flood-prone width to bankfull width), bankfull width to depth ratio, sinuosity, slope, and substrate (Rosgen 2006).

A visual assessment was performed at WB1, WB3, MB2, and NB monitoring locations (Fig. 2.1). This included a qualitative evaluation of the general stability of the monitoring location and how well the site represented the overall condition of the reach.

West Branch Ruddiman Creek Summary

The west branch of Ruddiman Creek appears to be relatively stable, and is classified as a Rosgen C-Type stream with moderate width to depth ratio and an accessible floodplain. Most of the areas of minor instability are located in more urbanized sections of the watercourse where direct alterations have been made to the stream system.

West Branch: Downstream of WB1

Upstream of Sherman Boulevard, the creek flows through a series of ravines that are separated by roadway embankment culverts. The stream is fairly linear and the floodplain appears accessible, although the channel is slightly incised in a few locations. The scour chain data associated with WB1 are inconclusive, showing both minor scouring and aggradation of the channel bottom. The exposure of additional links in the scour chain suggests that the channel bottom is active (i.e., movement of bed material is occurring); however, overall the reach appears relatively stable.

West Branch: Site WB-2

The stream enters a series of culverts, pipes, and concrete-lined canals between Sherman

Boulevard and site WB2, which is located just upstream of the abandoned railroad grade. WB2 is located along a relatively stable and short (300-linear feet) stretch of open channel. While some minor scour was present, especially along the toe of bank, the channel is well connected to the floodplain, which is aiding channel stability at this location. The scour chain data collected at WB2 suggest that the channel bottom may be down-cutting (degrading) slightly; however, the rock grade control structure immediately upstream of the culvert under the railroad embankment appears to be preventing any major head-cut advancement.

The west branch of Ruddiman Creek was quite stable downstream of the abandoned railroad embankment. The channel meanders through a broad valley with well-connected floodplain. A reference reach survey was conducted along the west branch near McGraft Park.

West Branch: Reference Reach near McGraft Park

WB3 was located along a short channelized reach, immediately downstream of McGraft Park Road near the confluence with Ruddiman Lagoon. Scour chain data indicate that this site is prone to degradation; however, the data collected were not representative of the overall stability of the west branch due to its proximity to the road culvert, foreign (riprap) substrate, and atypical channel dimension. The reach could benefit from additional forms of energy dissipation, channel stabilization, and modifications to the culvert.

Main Branch

Ruddiman Creek

Summary

Main Branch: Site MB1

The upstream portion of the main branch from Barclay Street to Glenside Boulevard appeared to be in an evolutionary state of down-cutting and lateral expansion. Scour chain data at MB1 suggest the channel is aggrading; however, these results most likely represent a localized condition, common to depositional areas along the main branch. The channel near MB1 was moderately incised with a bank-height-ratio of approximately 1.2 (Table H.2). While the channel's bankfull width is only slightly wider than reference conditions measured along the west branch, the mean bankfull depth is more than twice that of the west branch reference site (Table H.2). The resulting lower width to depth ratio suggests the channel may be incised and unstable. Bank scour and sloughing provided further evidence that the channel is actively down-cutting (degrading). In addition, the presence of point bars and mid channel bars provide evidence that the channel may be laterally expanding as higher flows with greater shear stresses and erosive potential are being confined to the channel. As the channel continues to down-cut and widen, depositional features will continue to form. As a result of the unstable conditions at the MB1 site, bankfull dimensions could not be accurately assessed.

Main Branch: Downstream of Glenside (Site MB2)

Downstream of Glenside Boulevard, the main branch is influenced by backwater from Ruddiman Lagoon, resulting in decreased sediment transport capacity. Given the combined effects of upstream channel degradation (erosion and increased sediment supply) and inefficiency of the downstream channel to transport sediment, it is not surprising that the scour chain data at site MB2 indicate the channel bottom may be slightly aggrading.

North Branch Ruddiman Creek Summary

While the monitoring location NB appeared fairly stable, the upper reaches of the north branch are unstable.

North Branch: Downstream of Laketon Ave. – Degradation (Perched Outlets typical of Channel Down-Cutting)

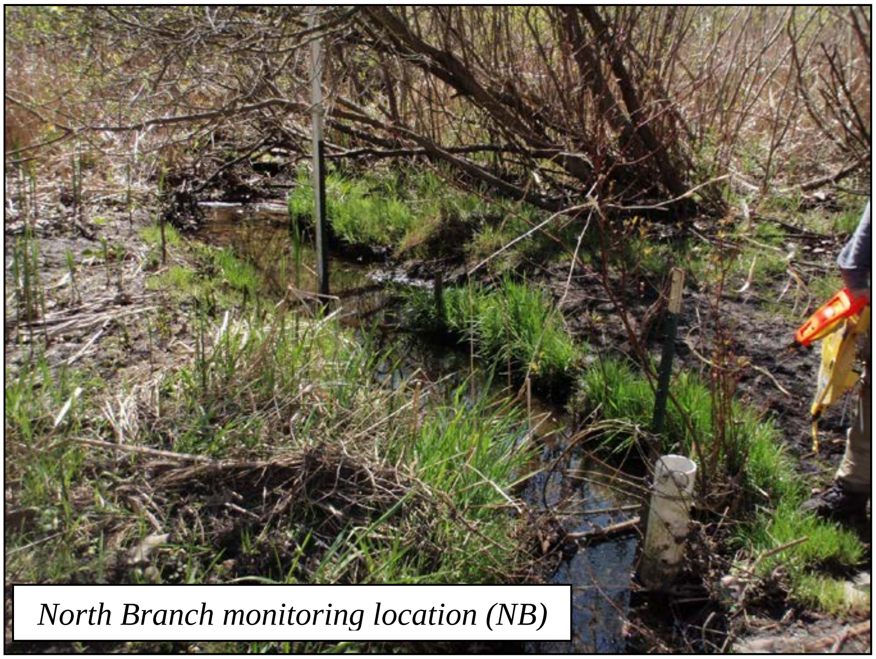
The upstream portion of the north branch near Laketon Avenue is severely degraded. The channel is actively down-cutting and transporting large amounts of sediment downstream.

North Branch: Downstream of Laketon Ave. – Stream bank erosion and down-cutting

The increased sediment supply downstream can be seen in the form of point bars and mid channel bars, which reduce in magnitude downstream toward site NB.

Overall, the channel downstream of site NB appears to be fairly stable with dense vegetation and well-connected wetland floodplain. Scour chain data suggest the streambed may still be aggrading slightly; however, the relatively low width to depth ratio

North Branch: Downstream of Laketon Ave. – Aggradation (Point Bars and Mid Channel Bars)



of the channel appears to be efficiently transporting sediment.

A summary of the data collected as part of the geomorphic assessment, as well as an overall assessment in regard to the stability of each monitoring location, is provided in Table H.2.

Table H.2 Bankfull Dimensions, Stream Classification, and Overall Geomorphic Stability

Location	Bankfull Dimensions						Rosgen Stream Type	Bank Height Ratio	Scour Chain *(feet)*	Overall Geomorphic Stability *(Aggrading, Degrading, or Stable)*
	XS Area *(sq. ft.)*	Width *(feet)*	Depth *(feet)*	Entrenchment Ratio	W/D Ratio	Slope *(%)*				
WB-1	NA	NA	NA	NA	NA	0.5%	NA	NA	0.1	*Inconclusive (Exposed Links)*
WB-2	17.5	14.2	1.2	> 2.2	12	0.5% - 2%	C	1+	-0.2	*Inconclusive (Exposed Links)*
WB-REF	14.4	15.8	0.9	> 2.2	17	0.2%	C	1	NA	*Stable (Reference Reach)*
WB-3	NA	NA	NA	NA	NA	NA	NA	NA	-0.2	*Degrading (DS Culvert)*
MB-1*	40	16.8	2.4	> 2.2	7	0.1%	Unstable	1.2	0.5	*Degrading (Locally Aggrading)*
MB-2	NA	NA	NA	NA	NA	NA	NA	NA	0.1	*Aggrading (Pond Backwater)*
NB	NA	NA	NA	NA	Low	NA	E	NA	0.1	*Stable (Slightly Aggrading)*

XS Area= Cross-sectional area
Depth= Bankfull mean depth
Entrenchment Ratio = Ratio of the flood-prone width to the bankfull width
W/D = Width to Depth Ratio; Ratio of the bankfull width to bankfull mean depth
Bank Height Ratio = Ratio of the bankfull depth to bank height
Scour Chain = Net change in elevation of channel bottom over monitoring period
NA = Not available, field data were not collected.
**MB-1 - Channel is degrading (unstable), bankfull dimensions cannot be accurately assessed*

H.3 Work Index

The Work Index is a way to quantify the erosive work associated with velocities and shear stresses acting along the channel bank. The critical issue for channel stability is not just the magnitude of these shear stresses, but the amount of work done by the shear stresses. The erosive work is a function of both shearing stress and time. It is calculated by multiplying the bank shear stress by the velocity in excess of some critical velocity and integrating it over the period of modeling and analysis (FTC&H 2006, 2008).

The Work Index is used to compare the erosive work at a given stream location under varying land use or stormwater management conditions. Since it is used for comparison only, parameters that are unchanged under different flow conditions at a given location are usually ignored. This results in the following expression:

$$W' = \int_{time} (d - d_c) V dt$$

where d is the depth of flow, d_c is the critical depth for bed mobility, and V is the stream velocity (MacRae 1992, 1996). The larger the Work Index, the more erosion potential there is.

The critical depth for bed mobility is closely related to the bankfull depth, since streambank erosion begins as flow conditions approach bankfull conditions. As a result, the critical depth was approximated as a fraction of the bankfull depth. Previous studies suggest that using 75% of the bankfull depth produces reasonable results (FTC&H 2006, 2008).

The actual numerical value of the Work Index has limited value—it is the change in value associated with land use or stormwater management changes that is important. The Work Index was computed at the key monitoring locations MB1, NB, and WB2 (see Chapter 3.2.2) for both the existing conditions, as well as the BMP benchmark scenario. Velocity and depth time series were computed by the SWMM model. Table H.3 provides the percent reduction in Work Index associated with the benchmark scenario. These results show that there should be a substantial reduction in the potential for streambank erosion associated with implementation of the BMP benchmark scenario, which was used as the basis for calculating the TMDL hydrologic targets (see Chapter 5.4).

Table H.3. Predicted reduction in Work Index under the BMP benchmark scenario, when compared to the Work Index under current conditions.

Monitoring Location	% Reduction in Work Index
MB1	31%
NB	31%
WB2	69%

The predicted reduction in Work Index is an additional verification that reducing flashiness through implementation of the BMP benchmark scenario will not unintentionally increase the erosive force on the stream channel, which could lead to further channel instability, degraded habitat, and negative impacts to biota. This is important because, although the BMP benchmark scenario addresses the flashy flows in Ruddiman Creek, the treatment provided by any given BMP may not necessarily reduce runoff volume. Runoff volume is a factor known to be critical for stream stability (SEMCOG 2008). When peak flows are reduced, but flow volume is not reduced, the duration of flow is increased, which can increase the work (shear stress over time) exerted on a channel.

H.4 Habitat Assessment

Stream habitat was characterized at each tributary site in May 2011, August 2011, February 2012, and April 2012 according to Barbour et al. (1999). A 50-m reach was evaluated at each site, with the mid-point of the reach located at the permanently-marked transect used for monitoring (Fig. 2.1). Average percent substrate composition and average habitat assessment scores were calculated for each site over the four assessment periods. In the absence of a reference reach for comparison, habitat assessment scores were evaluated against the Rapid Bioassessment Protocols' (RBP) condition categories (Barbour et al. 1999).

Habitat assessment scores, averaged over the four seasonal surveys, ranged from 101-144 and fell within the RBP suboptimal habitat condition category at all sites (Barbour et al. 1999; Fig. H.5). Based on observed and documented habitat degradation in Ruddiman Creek, it appears that the RBP overestimated the habitat conditions during our surveys. The RBP is qualitative and gives only a general idea of habitat quality. Some sites tended to score high in the individual metrics, such as channel flow status, sinuosity, bank stability, vegetative protection, and riparian zone width. Only 3 out of the 10 metrics assess substrate quality, which is one of the main habitat deficiencies in Ruddiman Creek.

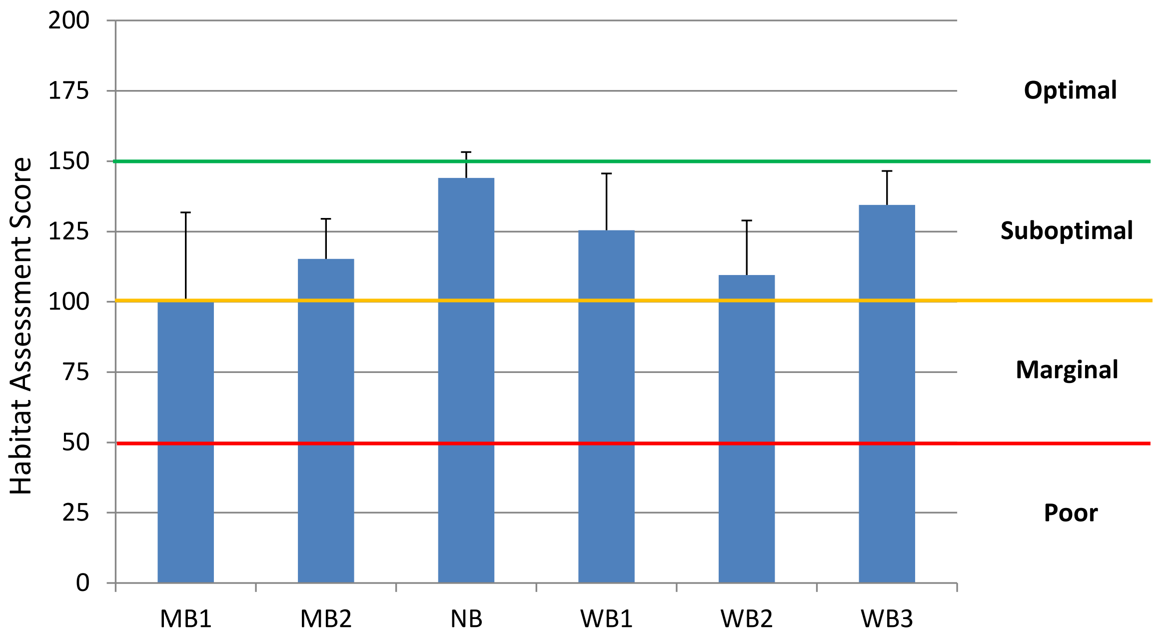


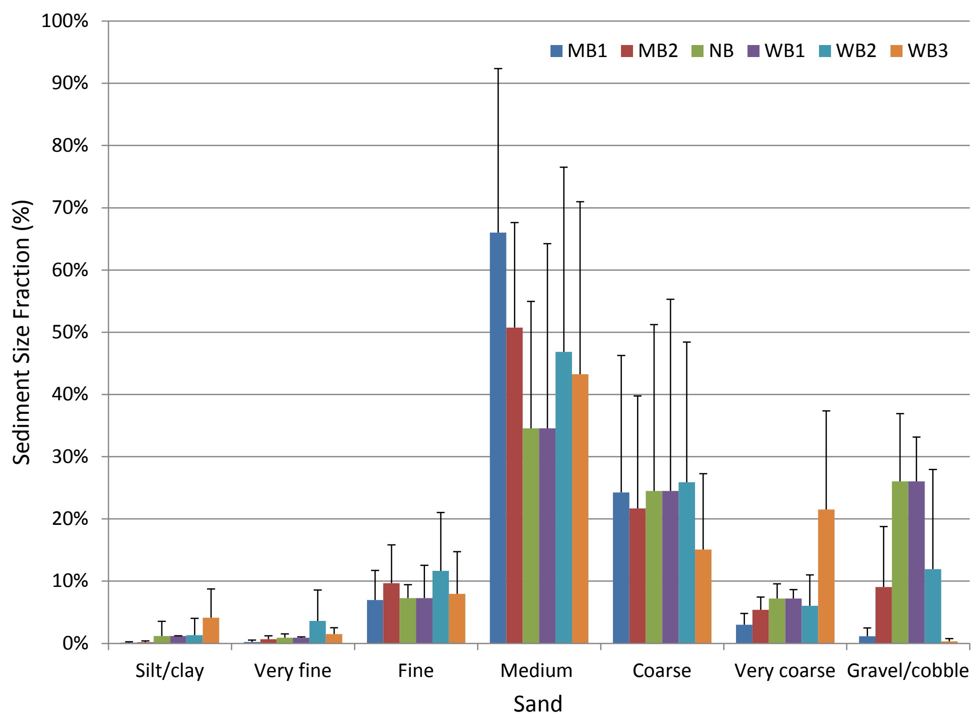
Figure H.5. Average (+SD) habitat assessment score as determined by Rapid Bioassessment Protocols (RBP; n=4). Horizontal lines on the figure show the boundaries for habitat condition categories given in the RBP (Barbour et al. 1999).

H.5 Grain Size of Bedload

Grain size distribution of bedload sediment was determined by dry sieving using the following size categories: gravel/cobble (>2 mm); very coarse sand (1-2 mm); coarse sand (0.5-1 mm); medium sand (250-500 μm); fine sand (125-250 μm); very fine sand (63-125 μm); and silt/clay (<63 μm). Bedload samples were dried at 105ºC for 8 hours and weighed to determine dry mass. Percent sediment dry weight (% size fraction) was determined for each of the grain size fractions. Grain size samples excluded from analysis of mean values included those with dry mass <0.25 g and those whose % size factions deviated from 100% by >±30% when summed across all of the size fractions.

Grain size distribution of bedload was similar among sites during baseflow and storm events, with medium sand (250-500 μm) being the dominant size fraction (Fig. H.6). Coarse sand (0.5-1 mm) and gravel/cobble (>2 mm) were the second most abundant size fractions. Very fine sand (63-125 μm) and silt/clay (<63 μm) were minor components of bedload during baseflow and storms (Fig. H.6).

A) Baseflow



B) Storm flow

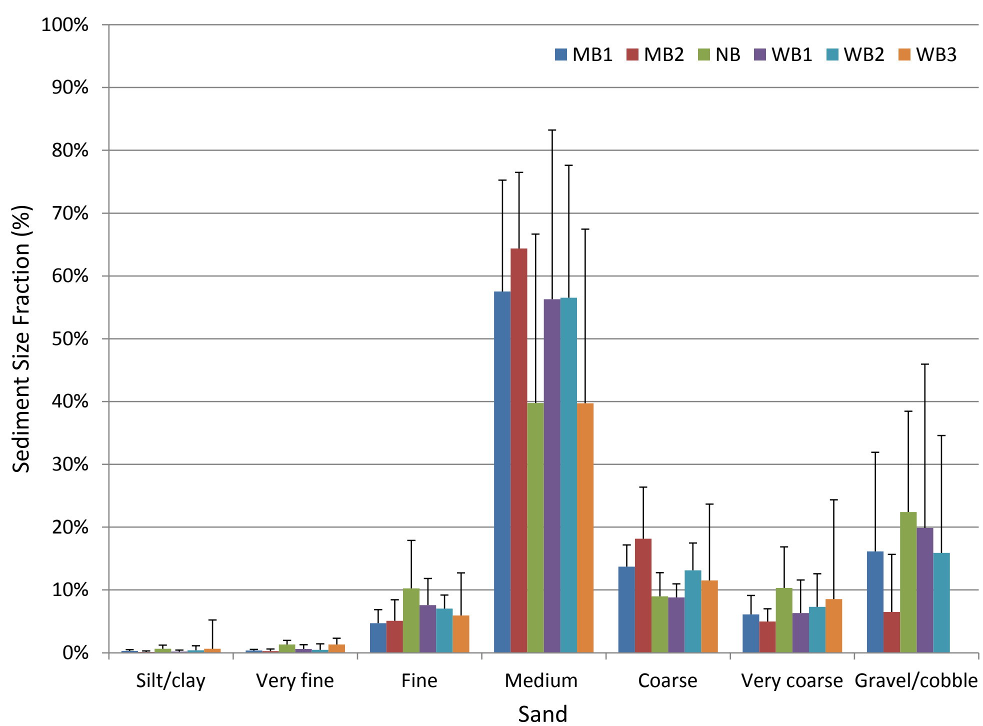


Fig. H.6. Average (+SD) grain size distribution of bedload under A) baseflow and B) storm flow conditions.

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Appendix I – Impacts of Climate Change

The SWMM model developed for this project is based on current climate conditions. Improvements made to the flow regime by way of stormwater BMPs could be counteracted by climate change (i.e., more extreme downpours and dramatic increases in extreme-heat days; Sousounis and Grover 2002, Kling et al. 2003). Furthermore, the biotic community itself may be impacted directly by climate change with more extreme runoff events (Mackey 2012).

The primary meteorological input to the SWMM model is the rainfall record. Global climate models, or general circulation models (GCMs), have been developed to model the impact of climate change. They can be used to compute both the temperature and precipitation deviations from the current climate. There is considerable uncertainty in the predictive ability of GCMs, especially with respect to downscaling at the regional level (Hanrahan et al. 2010).

Given these uncertainties, a simple approach was taken to understand the impact of climate change on Ruddiman Creek's hydrology. First, Muskegon area precipitation was projected based on several general circulation models (GCMs) under a high greenhouse gas emissions scenario (A1B), as defined by the Intergovernmental Panel on Climate Change. The A1 scenario family is based on a future world of rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies. The A1B scenario assumes energy comes from a balance of fossil and non-fossil intensive sources. Next, the precipitation record used to compute the R-B Flashiness Index values was scaled up based on projections from GCMs. Finally, data from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al. 2007) were downscaled (Maurer et al. 2009) using the biascorrection/spatial downscaling method (Wood et al. 2004) to a 0.5 degree grid, based on the 1950-1999 gridded observations of Adam and Lettenmaier (2003).

The benchmark BMP scenario was run using SWMM for both current climate conditions as well as those projected for the end of the century. The average projected precipitation increase from 2012 to 2100 is 14.2% (Fig. J.1). The precipitation values used as input to the SWMM model were simply increased by 14.2% to simulate the climate conditions at the end of this century. To simplify the analysis, this 14.2% increase was evenly distributed over all rainfall events. It is understood that climate change will result in precipitation increases concentrated in a few major events. We recognize that this approach will not account for those episodic events with precipitation values much larger than 14.2%, but the approach also magnifies the flashiness that would be associated with the more frequent, low precipitation events. The climate change runs were made using the 12-year record of rainfall (Table J.1).

Table J.1 shows the impact of climate change on the R-B Flashiness Index. For the current climate (2012), it gives the current modeled value (no BMPs) along with the target reduction. Since the benchmark scenario was run for a 12-year period, the value is slightly different than the benchmark value using 1-year of rainfall data. The table also provides the benchmark values assuming for the increased precipitation expected by the year 2100, as well as the loss in target reduction.

At all three key monitoring locations (MB1, NB, and WB2; see Chapter 3.3), gains made by application of BMPs were at least partially lost due to climate change. Losses in target reduction are expected to be 11%, 49%, and 9 % at MB1, NB, and WB2, respectively.

While the analysis is quite simplified, it does indicate that the BMP benefits in reducing flashiness are likely to be offset to varying degrees by anticipated climate change. Planners and resource managers should build flexibility into their BMP design and consider climate adaptation strategies as they move forward. Direct implications might be 1) an increase in the size of detention/retention to accommodate the increased runoff and/or 2) a greater amount of impervious area that requires treatment (i.e., revising DCIA targets in the future).

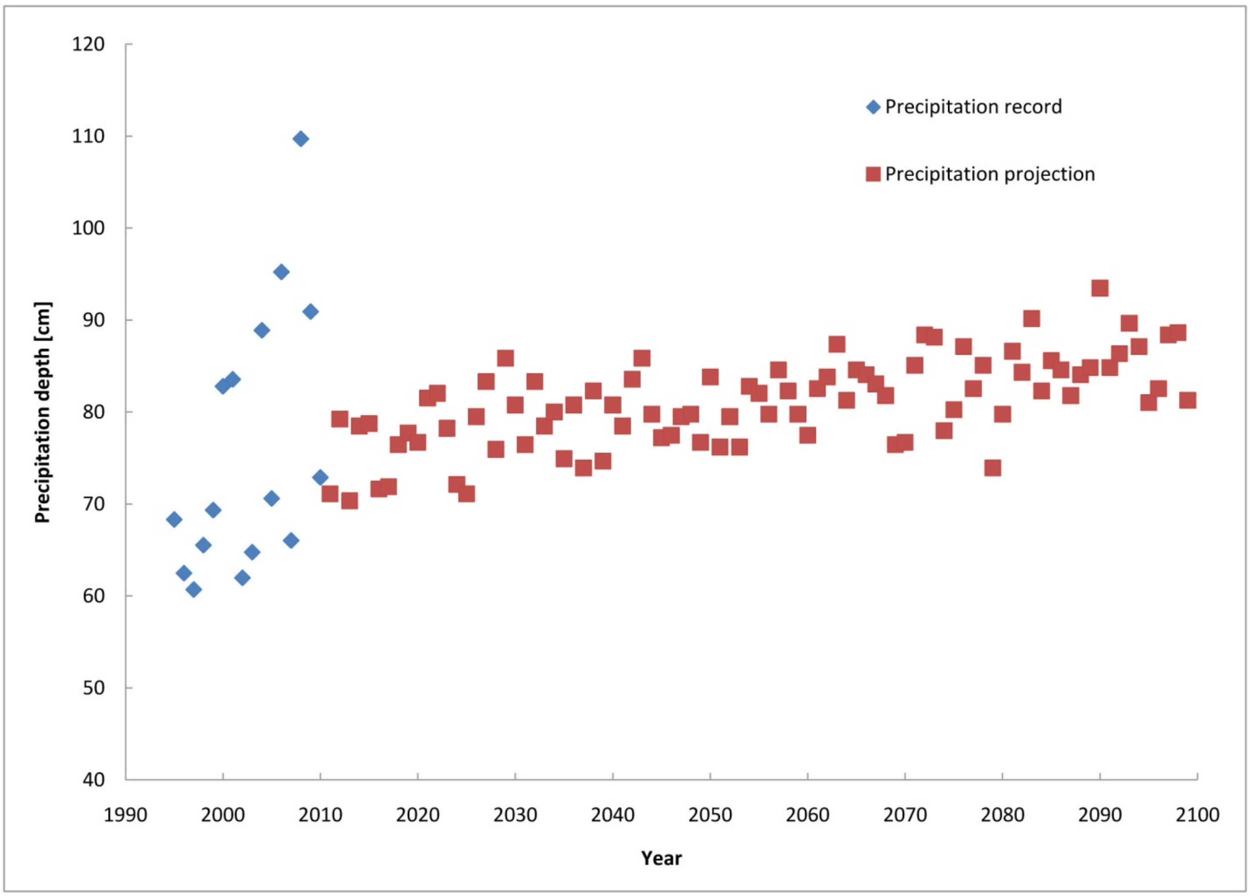

Fig. I.1. Precipitation projection under climate change from 2012-2100.

Table I.1 Changes in R-B Flashiness Index values due to implementation of the BMP benchmark scenario and from climate change

Case		R-B Flashiness Index		
Climate	BMP scenario	MB1	NB	WB2
2012	No BMPs	0.56	0.74	0.60
	Targeted reduction	-0.12	-0.24	-0.24
	Benchmark using 1-year rainfall record	0.44	0.50	0.36
	Benchmark using 12-year rainfall record	**0.44**	**0.49**	**0.34**
2100	**Benchmark using 12-year rainfall record**	**0.49**	**0.73**	**0.37**
	Loss in target reduction	**11%**	**49%**	**9%**

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Appendix J – R-B Flashiness Index Sensitivity Values

See Chapter 4.2 for discussion of how these values were computed.

Table J.1. Sensitivity values for green roofs by sub-catchment and monitoring location. All sensitivity values have units 1/ha (1/ac).

Green Roof								
Sub-catchment	Monitoring Location		Sub-catchment	Location	Sub-catchment	Monitoring Location		
	MB1	MB2		NB		WB1	WB2	WB3
SS3-A	0.003205 (0.001297)	0.002615 (0.001058)	NB-A	0.062268 (0.025199)	WB1-A	0.009871 (0.003995)	0.005505 (0.002228)	0.003822 (0.001547)
SS3-B	0.002939 (0.001189)	0.002446 (0.000990)	NB-B	0.062875 (0.025445)	WB1-B	0.010646 (0.004308)	0.006103 (0.002470)	0.004089 (0.001655)
SS3-C	0.003205 (0.001297)	0.002628 (0.001063)	NB-C	0.064130 (0.025952)	WB2-A		0.007407 (0.002997)	0.004190 (0.001695)
SS2-A	0.003301 (0.001336)	0.002588 (0.001047)			WB2-B		0.006507 (0.002633)	0.004107 (0.001662)
SS2-B	0.003274 (0.001325)	0.002558 (0.001035)			WB3			0.003970 (0.001607)
SS2-C	0.003277 (0.001326)	0.002555 (0.001034)						
SS1	0.003400 (0.001376)	0.002672 (0.001081)						
MB1-A	0.002356 (0.000953)	0.001936 (0.000783)						
MB1-B	0.002086 (0.000844)	0.001757 (0.000711)						
MB1-C	0.002074 (0.000839)	0.001735 (0.000702)						
MB2		0.002380 (0.000963)						

Table J.2. Sensitivity values for rain gardens by sub-catchment and monitoring location. All sensitivity values have units 1/ha (1/ac).

Rain Garden								
Sub-catchment	Monitoring Location		Sub-catchment	Location	Sub-catchment	Monitoring Location		
	MB1	MB2		NB		WB1	WB2	WB3
SS3-A	0.004302 (0.001741)	0.003290 (0.001331)	NB-A	0.045677 (0.018485)	WB1-A	0.012840 (0.005196)	0.008968 (0.003629)	0.005146 (0.002082)
SS3-B	0.004096 (0.001658)	0.003181 (0.001287)	NB-B	0.046206 (0.018699)	WB1-B	0.013090 (0.005297)	0.009283 (0.003757)	0.005255 (0.002127)
SS3-C	0.004327 (0.001751)	0.003296 (0.001334)	NB-C	0.094272 (0.038150)	WB2-A		0.009752 (0.003947)	0.005072 (0.002052)
SS2-A	0.004184 (0.001693)	0.003130 (0.001267)			WB2-B		0.009600 (0.003885)	0.005352 (0.002166)
SS2-B	0.004146 (0.001678)	0.003092 (0.001251)			WB3			0.004311 (0.001744)
SS2-C	0.003999 (0.001618)	0.003004 (0.001216)						
SS1	0.004402 (0.001781)	0.003345 (0.001354)						
MB1-A	0.003600 (0.001457)	0.002751 (0.001113)						
MB1-B	0.003452 (0.001397)	0.002690 (0.001089)						
MB1-C	0.003366 (0.001362)	0.002625 (0.001062)						
MB2		0.003040 (0.001230)						

Table J.3. Sensitivity values for porous pavement/ underground detention by sub-catchment and monitoring location. All sensitivity values have units 1/ha (1/ac).

Porous Pavement/ Underground Detention								
Sub-catchment	Monitoring Location		Sub-catchment	Location	Sub-catchment	Monitoring Location		
	MB1	MB2		NB		WB1	WB2	WB3
SS3-A	0.002509 (0.001016)	0.001898 (0.000768)	NB-A	0.053972 (0.021842)	WB1-A	0.005270 (0.002133)	0.003822 (0.001547)	0.002115 (0.000856)
SS3-B	0.002275 (0.000921)	0.001761 (0.000713)	NB-B	0.055166 (0.022325)	WB1-B	0.005992 (0.002425)	0.004384 (0.001774)	0.002394 (0.000969)
SS3-C	0.002537 (0.001027)	0.001937 (0.000784)	NB-C	0.058967 (0.023863)	WB2-A		0.005573 (0.002255)	0.002436 (0.000986)
SS2-A	0.002557 (0.001035)	0.001844 (0.000746)			WB2-B		0.004637 (0.001877)	0.002344 (0.000949)
SS2-B	0.002558 (0.001035)	0.001841 (0.000745)			WB3			0.002118 (0.000857)
SS2-C	0.002614 (0.001058)	0.001853 (0.000750)						
SS1	0.002687 (0.001087)	0.001946 (0.000788)						
MB1-A	0.001623 (0.000657)	0.001211 (0.000490)						
MB1-B	0.001393 (0.000564)	0.001050 (0.000425)						
MB1-C	0.001367 (0.000553)	0.001040 (0.000421)						
MB2		0.001634 (0.000661)						

Table J.4. Sensitivity values for infiltration BMPs by sub-catchment and monitoring location. All sensitivity values have units 1/ha (1/ac).

Infiltration								
Sub-catchment	Monitoring Location		Sub-catchment	Location	Sub-catchment	Monitoring Location		
	MB1	MB2		NB		WB1	WB2	WB3
SS3-A	0.002994 (0.001212)	0.002531 (0.001024)	NB-A	0.058171 (0.023541)	WB1-A	0.011875 (0.004806)	0.005047 (0.002042)	0.004329 (0.001752)
SS3-B	0.002738 (0.001108)	0.002416 (0.000978)	NB-B	0.057614 (0.023316)	WB1-B	0.012697 (0.005138)	0.005722 (0.002316)	0.004617 (0.001868)
SS3-C	0.003058 (0.001238)	0.002650 (0.001073)	NB-C	0.054463 (0.022041)	WB2-A		0.007136 (0.002888)	0.004731 (0.001914)
SS2-A	0.003068 (0.001242)	0.002541 (0.001028)			WB2-B		0.006032 (0.002441)	0.004697 (0.001901)
SS2-B	0.003064 (0.001240)	0.002529 (0.001024)			WB3			0.004764 (0.001928)
SS2-C	0.003082 (0.001247)	0.002497 (0.001010)						
SS1	0.003230 (0.001307)	0.002714 (0.001098)						
MB1-A	0.002142 (0.000867)	0.001928 (0.000780)						
MB1-B	0.001812 (0.000733)	0.001688 (0.000683)						
MB1-C	0.001792 (0.000725)	0.001654 (0.000670)						
MB2		0.002380 (0.000963)						

Table J.5. Sensitivity values for rain barrels by sub-catchment and monitoring location. All sensitivity values have units 1/ha (1/ac).

Rain Barrel								
Sub-catchment	Monitoring Location		Sub-catchment	Location	Sub-catchment	Monitoring Location		
	MB1	MB2		NB		WB1	WB2	WB3
SS3-A	0.000479 (0.000194)	0.000405 (0.000164)	NB-A	0.009307 (0.003767)	WB1-A	0.001900 (0.000769)	0.000808 (0.000327)	0.000693 (0.000280)
SS3-B	0.000438 (0.000177)	0.000386 (0.000156)	NB-B	0.009218 (0.003731)	WB1-B	0.002031 (0.000822)	0.000916 (0.000371)	0.000739 (0.000299)
SS3-C	0.000489 (0.000198)	0.000424 (0.000172)	NB-C	0.008714 (0.003526)	WB2-A		0.001142 (0.000462)	0.000757 (0.000306)
SS2-A	0.000491 (0.000199)	0.000407 (0.000165)			WB2-B		0.000965 (0.000391)	0.000752 (0.000304)
SS2-B	0.000490 (0.000198)	0.000405 (0.000164)			WB3			0.000762 (0.000308)
SS2-C	0.000493 (0.000200)	0.000400 (0.000162)						
SS1	0.000517 (0.000209)	0.000434 (0.000176)						
MB1-A	0.000343 (0.000139)	0.000308 (0.000125)						
MB1-B	0.000290 (0.000117)	0.000270 (0.000109)						
MB1-C	0.000287 (0.000116)	0.000265 (0.000107)						
MB2		0.000381 (0.000154)						

Appendix K – Surface Water Assessment Section Procedure 51 scoring summary

The abundance and diversity of aquatic macroinvertebrate communities are commonly used as indicators of the overall quality of a stream. Although the current study did not examine macroinvertebrate community structure, prior assessments of the macroinvertebrate communities within the Ruddiman Creek watershed were completed by the MDEQ in 2009 and 2011. The MDEQ collected macroinvertebrate samples from 6 sites on June 4, 2009 (Lipsey 2009) and July 15, 2011 (Knoll and Lipsey 2012): three sites on the main branch, two sites on the west branch, and one site the north branch.

Sample collections and the scoring and interpretation of data followed the Surface Water Assessment Section Procedure 51 (P-51) (MDEQ 2008), which describes qualitative biological and habitat survey protocols for wadeable streams. P-51 is accepted by both federal and state agencies as an accurate, consistent, and repeatable sampling and analytical protocol for Michigan streams.

A set of 9 metrics are used to score community data in comparison to sites considered as excellent within the Southern Michigan/Northern Indiana Drift Plains ecoregion. Each metric is given a score of 1 (better than average), 0 (average), or -1 (outside of 2 standard deviations from average). Scores for each metric are summed for a final site score. The MDEQ uses the P-51 Microsoft Excel® spreadsheet to calculate the following 9 metrics for each station, which provide a qualitative rating of the macroinvertebrate community:

- **Total number of taxa**. Taxa richness and species diversity are standard indicators of healthy and stable biological communities. This metric evaluates the total number of taxa found and rates diverse systems higher than monotypic communities.

- **Number of mayfly taxa**. The total number of mayfly taxa is used as an overall indicator of stream quality. Mayflies are, as a group, considered to be intolerant to pollution. Their presence, in abundance, is therefore rated high in this metric.
- **Number of caddisfly taxa**. Like mayflies, caddisflies are pollution intolerant. Areas containing high numbers of caddisflies are given higher metric values. However, several species can tolerate varying degrees of habitat degradation.
- **Number of stonefly taxa**. Stoneflies are the most sensitive to, and intolerant of, poor water quality. Their presence is often an indicator of excellent water quality.
- **Percent mayfly composition**. This metric weights the presence of mayflies in relation to the total number of species found. As with the total number of mayfly taxa, the percent composition of mayflies can drastically decline with stream quality degradation.
- **Percent caddisfly composition**. This metric weights the number of caddisflies found in relation to the total number of species found within the sample area.
- **Percent contribution of dominant taxa**. This metric calculates the ratio of the number of dominant taxa found to the total number of organisms collected. The results provide an indication of community structure and balance. Those areas dominated by few species, or composed of several taxa but strongly dominated by one, indicate lower quality systems.
- **Percent isopods, snails, and leeches**. Taxa from these 3 groups are tolerant to a wide variety and range of environmental conditions. High percent abundance of these animals is a good indicator of degraded stream habitats and low water quality.
- **Percent surface air breathers**. Surface dependent taxa refers to invertebrates that obtain oxygen through direct atmospheric exchange, usually at the air/water interface.

High abundance of these animals is an indication of diurnal oxygen changes or other biological or chemical oxygen use. These taxa are also found in streams with higher temperatures and lower, erratic flows that typically have low or fluctuating dissolved oxygen concentrations.

This process results in a score based upon a scale of -9 to 9; -9 to -5 is rated as poor, -4 to 4 is rated as acceptable, and a score greater than 4 is rated as excellent. Generally speaking, flowing waters which harbor a high diversity of macroinvertebrates, including taxa sensitive to pollution (e.g., mayfly, caddisfly, and stonefly taxa), are of high water and habitat quality. Water bodies with low macroinvertebrate diversity often have very high numbers of tolerant organisms, due to their ability to thrive in degraded conditions with little competition or predation.

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Appendix L – Scoping Tool pages

This section details the use of the BMP Scoping Tool described in Chapter 4.3. The Scoping Tool was developed as a Microsoft Excel® application that enables the user to estimate the change in R-B Flashiness Index associated with implementation of various storm water management BMPs. It also shows the predicted change in P-51 macroinvertebrate score at the 3 key stream monitoring locations (MB1, WB2, and NB), based on the P-51 vs. Flashiness Index regression described in Chapter 3.3.

Figure L.1 shows a screen shot of the BMP inventory sheet. The example shown is the data used to develop the BMP "benchmark" scenario that was used to determine hydrologic targets. Since this scenario focused on flashiness change at the 3 key locations, no data were entered for sub-catchments MB2 and WB3, which are downstream of the locations of interest. BMPs in sub-catchments WB3 and MB2 will not reduce the RB Flashiness Index at the monitoring locations; however, BMPs in these two sub-catchments will still have a positive impact on Ruddiman Creek.

In the BMP inventory sheet, the user can input their own BMP configuration to be evaluated. The information in each row describes the BMPs within a single sub-catchment. If desired, multiple rows can be used for a single sub-catchment allowing different combinations of BMPs, with differing percentages, to be tested. The inventory sheet has the following 10 columns:

- Column 1 - Site Description: The user may enter any text information to identify the site or BMP scenario.
- Column 2 – Sub-catchment: This is a pull-down menu allowing the user to select the sub-catchment in which the BMPs are implemented

- Column 3 - Use this BMP?: This is a “Yes/No” pull-down menu allowing the user to easily “turn off” any BMP description without having to delete the BMP data.
- Columns 4 through 10: This is the BMP description. The user provides the number of rain barrels or the acreage treated by a specific BMP. If regional detention is implemented in a downstream sub-catchment then the percentage of untreated impervious area can be included. Multiple BMPs can be described in a single row of the table.

Figure L.2 shows a screen shot of part of the output page. Shown here are three tables.

- The BMP summary table provides a BMP summary organized by sub-catchment. If multiple rows are used for a single sub-catchment in the inventory sheet then these are combined into a single row in the summary table. In addition to repeating BMP data from the inventory sheet, this table provides the total area, directly connected impervious area, and the percentage of the directly connected impervious area committed (i.e., treated). If more than 100% is committed a warning message is shown.
- The R-B Flashiness Index table shows the estimated reduction in R-B Flashiness Index associated with the BMP scenario. The R-B Flashiness Index reduction is computed for each BMP type at the 3 key monitoring locations (MB1, WB2, and NB).
- The P-51 Macroinvertebrate Score table shows the current P-51 value along with the estimated value after implementation of BMPs at the 3 key monitoring locations.

Figure L.3 shows a screen shot of the P-51 Macroinvertebrate Score versus R-B Flashiness Index plot. This plot graphically shows the improvement in P-51 scores at monitoring locations MB1, WB2, and NB (red dots) as the implementation of BMPs results in a reduced Flashiness Index.

Ruddiman Creek Watershed ***BMP Inventory Sheet***									
Site Description	Sub-catchment	Use this BMP?	Number of Rain Barrels	Porous Pavement area [ac]	Directly connected impervious area treated by Rain Garden [ac]	Green Roof area [ac]	Directly connected impervious area treated by infiltration [ac]	Impervious area treated by underground detention [ac]	Percent of untreated directly connected impervious area captured by downstream regional retention or detention
36% treatment along the Main Branch	SS3-A	Yes		0.85	0.85	0.85	0.85	0.85	
36% treatment along the Main Branch	SS3-B	Yes		1.79	1.79	1.79	1.79	1.79	
36% treatment along the Main Branch	SS3-C	Yes		1.59	1.59	1.59	1.59	1.59	
36% treatment along the Main Branch	SS2-A	Yes		1.16	1.16	1.16	1.16	1.16	
36% treatment along the Main Branch	SS2-B	Yes		1.28	1.28	1.28	1.28	1.28	
36% treatment along the Main Branch	SS2-C	Yes		0.92	0.92	0.92	0.92	0.92	
36% treatment along the Main Branch	SS1	Yes		5.93	5.93	5.93	5.93	5.93	
36% treatment along the Main Branch	MB1-A	Yes		2.19	2.19	2.19	2.19	2.19	
36% treatment along the Main Branch	MB1-B	Yes		2.62	2.62	2.62	2.62	2.62	
36% treatment along the Main Branch	MB1-C	Yes		3.14	3.14	3.14	3.14	3.14	
59% treatement along the North Branch	NB-A	Yes		0.57	0.57	0.57	0.57	0.57	
59% treatement along the North Branch	NB-B	Yes		0.56	0.56	0.56	0.56	0.56	
59% treatement along the North Branch	NB-C	Yes		0.85	0.85	0.85	0.85	0.85	
77% treatment along the West Branch	WB1-A	Yes		3.09	3.09	3.09	3.09	3.09	
77% treatment along the West Branch	WB1-B	Yes		3.11	3.11	3.11	3.11	3.11	
77% treatment along the West Branch	WB2-A	Yes		3.81	3.81	3.81	3.81	3.81	
77% treatment along the West Branch	WB2-B	Yes		8.94	8.94	8.94	8.94	8.94	

Fig L.1: Screenshot of Input Page of the Executed BMP Scoping Tool for the Benchmark Scenario. Percentages in Column 1 correspond to the percent of committed (treated) DCIA in the branch.

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Ruddiman Creek Watershed

R-B Flashiness and P-51 Macroinvertebrate Score Estimates

BMP Summary

Subshed Name	Subshed area [ac]	Dircectly connected impervious area [ac]	Number of Rain Barrels	Porous Pavement area [ac]	Directly connected impervious area treated by Rain Garden [ac]	Green Roof area [ac]	Directly connected impervious area treated by infiltration [ac]	Impervious area treated by underground detention [ac]	Directly connected impervious area treated by regional detention or retention [ac]	Percent directly connected impervious area committed	Available directly connected impervious area exceeded?
SS3-A	65.1	11.7	0	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	0.0	36%	
SS3-B	99.8	24.6	0	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**	0.0	36%	
SS3-C	340.9	21.8	0	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	0.0	36%	
SS2-A	166.1	15.9	0	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**	0.0	36%	
SS2-B	174.1	17.6	0	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**	0.0	36%	
SS2-C	145.6	12.7	0	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	0.0	36%	
SS1	159.6	81.4	0	**5.9**	**5.9**	**5.9**	**5.9**	**5.9**	0.0	36%	
MB1-A	103.8	30.0	0	**2.2**	**2.2**	**2.2**	**2.2**	**2.2**	0.0	36%	
MB1-B	72.3	36.0	0	**2.6**	**2.6**	**2.6**	**2.6**	**2.6**	0.0	36%	
MB1-C	97.1	43.0	0	**3.1**	**3.1**	**3.1**	**3.1**	**3.1**	0.0	36%	
MB2	114.9	17.2	0	0.0	0.0	0.0	0.0	0.0	0.0	0%	
NB-A	150.8	4.8	0	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	0.0	59%	
NB-B	26.8	4.7	0	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	0.0	59%	
NB-C	44.3	7.1	0	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	0.0	59%	
WB1-A	107.4	20.0	0	**3.1**	**3.1**	**3.1**	**3.1**	**3.1**	0.0	77%	
WB1-B	258.0	20.1	0	**3.1**	**3.1**	**3.1**	**3.1**	**3.1**	0.0	77%	
WB2-A	293.5	24.7	0	**3.8**	**3.8**	**3.8**	**3.8**	**3.8**	0.0	77%	
WB2-B	119.1	57.8	0	**8.9**	**8.9**	**8.9**	**8.9**	**8.9**	0.0	77%	
WB3	130.7	6.5	0	0.0	0.0	0.0	0.0	0.0	0.0	0%	

RB Flashiness Index

Location -->		MB1	WB2	WB3	NB
Pre-BMP value		**0.569**	**0.598**	0.350	**0.724**
R-B Flashiness Index change due to BMPs	Rain Barrel	0.000	0.000	0.000	0.000
	Porous Pave	0.019	0.036	0.018	0.045
	Rain Garden	0.035	0.073	0.040	0.053
	Green Roof	0.025	0.050	0.031	0.051
	Infiltration	0.023	0.046	0.036	0.045
	UG Detention	0.019	0.036	0.018	0.045
	Reg ret/det	0.000	0.000	0.000	0.000
	Total	0.120	0.240	0.143	0.240
Post-BMP value		**0.449**	**0.358**	**0.207**	**0.484**

P-51 Macroinvertebrate Score

Location -->	MB1	WB2	WB3	NB
Pre-BMP value	-5.0	-6.0	-6.0	-6.0
Estimated Post-BMP	-4.0	-4.0		-4.0

Fig L.2: Screenshot of the Results Page of the Executed BMP Scoping Tool for the Benchmark Scenario. Yellow highlights show pre- and post-BMP values of the R-B Flashiness Index and P-51 Macroinvertebrate scores.

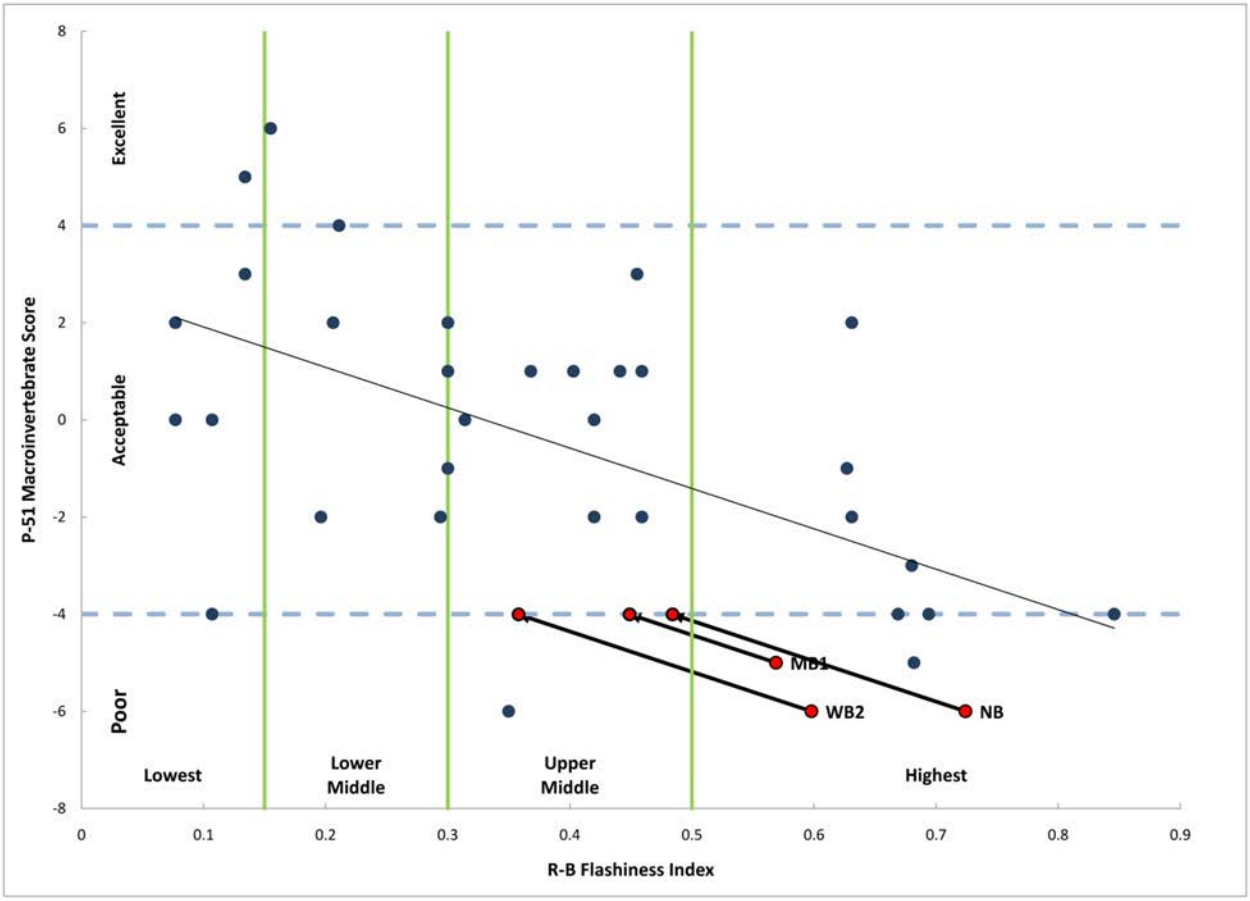


Fig L.3: Screenshot of P-51 Macroinvertebrate Score versus R-B Flashiness Index plot from the Executed BMP Scoping Tool for the Benchmark Scenario.

Appendix M – Directly Connected Impervious Area (DCIA) Summary

Branch	Sub-catchment	Total Area, ha (ac)	Current Total DCIA, ha (ac) *	Current Percent DCIA by Sub-catchment	Percent DCIA Treated (Benchmark Scenario + MOS)	Target Percent DCIA
Main	SS3-A	26 (65)	4.7 (11.7)	18.0%	42%	12%
	SS3-B	40 (100)	9.9 (24.6)	24.6%		
	SS3-C	138 (341)	8.8 (21.8)	6.4%		
	SS2-A	67 (166)	6.5 (15.9)	9.6%		
	SS2-B	70 (174)	7.1 (17.6)	10.1%		
	SS2-C	59 (146)	5.1 (12.7)	8.7%		
	SS1	65 (160)	32.9 (81.4)	51.0%		
	MB1-A	42 (104)	12.1 (30.0)	28.9%		
	MB1-B	29 (72)	14.6 (36.0)	49.8%		
	MB1-C	39 (97)	17.4 (43.0)	44.3%		
	All**	576 (1424)	119.3 (294.7)	20.7%		
North	NB-A	61 (151)	2.0 (4.8)	3.2%	62%	2.9%
	NB-B	11 (27)	1.9 (4.7)	17.7%		
	NB-C	18 (44)	2.9 (7.1)	16.1%		
	All**	90 (222)	6.8 (16.7)	7.5%		
West	WB1-A	43 (107)	8.1 (20.0)	18.6%	82%	2.8%
	WB1-B	104 (258)	8.1 (20.1)	7.8%		
	WB2-A	119 (294)	10.0 (24.7)	8.4%		
	WB2-B	48 (119)	23.4 (57.8)	48.5%		
	All**	315 (778)	49.6 (122.5)	15.7%		

* Total DCIA presented in this table is taken from the calibrated combined SWMM model to produce the same volume of runoff as that measured over the 12-month monitoring period. Variations in DCIA by sub-catchment were adjusted upward or downward using aerial photography for use in the full SWMM model, and collectively equal the total impervious area from the calibrated combined model.

** "All" represents data for the entire branch.

Appendix N – R-B Flashiness Index values for 41 small watersheds (≤78 km2 [30 mi2]) from Fongers et.al. (2007). NS = not significant; n/a = not applicable.

Major Watershed	Watershed Number	Gage Number	Lat (Gage)	Long (Gage)	STORET #	Lat (STORET)	Long (STORET)	Gage Description	Total Drainage Area (mi^2)	Average R-B Flashiness Index Value	Quartile Rank	Flashi-ness Trend	p Value	First water year analyzed (gage)	Last water Year (gage)	Biosurvey Report #s	Year of Data Collection	P-51 Score	P-51 Rating
Chocolay	43	4044583						Cherry Creek Near Harvey, MI	10	0.006	lowest	NS	NS	1966	1981			no data	no data
Portage	55	4001000	47.923056	-89.145	420085	47.9231	-89.145	Washington Creek At Windigo, MI	13	0.225	lower middle	NS	NS	1965	2003			no data	no data
Escanaba	46	4058200	46.411111	-87.624167	520252	47.23003	-88.38276	Schweitzer Creek Near Palmer, MI	24	0.211	lower middle	NS	NS	1961	2004	01/010	2000	4	Accept-able
Escanaba	46	4058300	46.4025	-87.544167	520380	46.40232	-87.54472	Warner Creek Near Palmer, MI	14	0.196	lower middle	NS	NS	1962	1978	n/a	2005	-2	Accept-able
Menominee	50	4065600	45.930833	-87.971667	220125	45.9323	-87.9702	Pine Creek Near Iron Mountain, MI	16	0.156	lower middle	NS	NS	1972	1981			no data	no data
Grand	14	4111500	42.609167	-84.319167	330360	42.60917	-84.31861	Deer Creek Near Dansville, MI	16	0.368	upper middle	NS	NS	1954	2004	03/025	2003	1	Accept-able
Grand	14	4112000	42.675833	-84.363889	330253	42.68304	-84.38081	Sloan Creek Near Williamston, MI	10	0.455	upper middle	NS	NS	1955	2004	03/025	2003	3	Accept-able
Grand	14	4113097	42.755556	-84.652778	230195	42.75532	-84.65315	Carrier Creek Near Lansing, MI	10	0.459	upper middle	NS	NS	1975	1980	02/002	2001	-2	Accept-able
Grand	14	4113097	42.755556	-84.652778	230199	42.75237	-84.65516	Carrier Creek Near Lansing, MI	10	0.459	upper middle	NS	NS	1975	1980	11/001	2009	1	Accept-able
Grand	14	4113097	42.755556	-84.652778	230247	42.74477	-84.65244	Carrier Creek Near Lansing, MI	10	0.459	upper middle	NS	NS	1975	1980	11/001	2009	-2	Accept-able

Appendix N (continued)

Major Watershed	Watershed Number	Gage Number	Lat (Gage)	Long (Gage)	STORET #	Lat (STORET)	Long (STORET)	Gage Description	Total Drainage Area (mi^2)	Average R-B Flashiness Index Value	Quartile Rank	Flashi-ness Trend	p Value	First water year analyzed (gage)	Last water Year (gage)	Biosurvey Report #s	Year of Data Collection	P-51 Score	P-51 Rating
Grand	14	4117000	42.565833	-85.093611	080239	42.56498	-85.09368	Quaker Brook Near Nashville, MI	8	0.3	lower middle	NS	NS	1955	2004	02/001	1998	1	Accept-able
Grand	14	4117000	42.565833	-85.093611	080240	42.55729	-85.09436	Quaker Brook Near Nashville, MI	8	0.3	lower middle	NS	NS	1955	2004	02/001	1998	2	Accept-able
Grand	14	4117000	42.565833	-85.093611	080256	42.56610	-85.09360	Quaker Brook Near Nashville, MI	8	0.3	lower middle	NS	NS	1955	2004	98/029	1993 and 1994	-1	Accept-able
Grand	14	4117000	42.565833	-85.093611	080265	42.57789	-85.09436	Quaker Brook Near Nashville, MI	8	0.3	lower middle	NS	NS	1955	2004	09/061	2008	2	Accept-able
Kalamazoo	17	4106180	42.204444	-85.591111	390567	42.20969	-85.58654	Portage Creek At Portage, MI	15	0.077	lowest	more flashy	0.02	1983	2004	97/046	1993	0	Accept-able
Kalamazoo	17	4106300	42.246111	-85.575	390106	42.25959	-85.57695	Portage Creek Near Kalamazoo, MI	20	0.107	lowest	NS	NS	1988	2003	11/004	2009	0	Accept-able
Kalamazoo	17	4106300	42.246111	-85.575	390584	42.2465	-85.58	Portage Creek Near Kalamazoo, MI	20	0.107	lowest	NS	NS	1988	2003	05/064	2004	-4	Accept-able
Kalamazoo	17	4106320	42.235278	-85.648333				West Fork Portage Creek Near Oshtemo, MI	15	0.064	lowest	more flashy	<0.005	1976	1996			no data	no data
Kalamazoo	17	4106400	42.244444	-85.614444	390605	42.24409	-85.61412	West Fork Portage Creek At Kalamazoo, MI	21	0.077	lowest	more flashy	<0.005	1975	2004	11/004	2009	2	Accept-able

Appendix N (continued)

Major Watershed	Watershed Number	Gage Number	Lat (Gage)	Long (Gage)	STORET #	Lat (STORET)	Long (STORET)	Gage Description	Total Drainage Area (mi^2)	Average R-B Flashiness Index Value	Quartile Rank	Flashi-ness Trend	p Value	First water year analyzed (gage)	Last water Year (gage)	Biosurvey Report #s	Year of Data Collection	P-51 Score	P-51 Rating
Muskegon	22	4122100	43.288611	-86.222778	610525	43.28888	-86.22304	Bear Creek Near Muskegon, MI	17	0.206	lower middle	less flashy	<0.005	1966	2003	08/058	2001	no data	no data
Muskegon	22	4122100	43.288611	-86.222778	610526	43.29208	-86.21370	Bear Creek Near Muskegon, MI	17	0.206	lower middle	less flashy	<0.006	1966	2003	08/058	2001	no data	no data
Muskegon	22	4122100	43.288611	-86.222778	610661	43.29688	-86.20952	Bear Creek Near Muskegon, MI	17	0.206	lower middle	less flashy	<0.007	1966	2003	10/014	2006	2	Accept-able
St. Joseph	34	4097200	42.155556	-85.613333				Gourdneck Creek Near Schoolcraft, MI	8	0.094	lowest	NS	NS	1964	1972			no data	no data
Belle	3	4160570	43.030278	-83.067222	440167	43.03010	-83.06720	North Branch Belle River At Imlay City, MI	16	0.294	lower middle	NS	NS	1966	2001	07/069	2002	-2	Accept-able
Clinton	12	4160800	42.72	-83.353611	630680	42.71984	-83.35349	Sashabaw Creek Near Drayton Plains, MI	21	0.134	lowest	NS	NS	1960	2004	05/124	2005	3	Accept-able
Clinton	12	4160800	42.72	-83.353611	631077	42.71448	-83.35373	Sashabaw Creek Near Drayton Plains, MI	21	0.134	lowest	NS	NS	1960	2004	n/a	2009	5	Excellent
Clinton	12	4161100	42.667222	-83.200556	631032	42.65917	-83.20083	Galloway Creek Near Auburn Heights, MI	17	0.314	upper middle	more flashy	<0.005	1972	1991	95/026	1994	no data	no data
Clinton	12	4161100	42.667222	-83.200556	631032	42.65917	-83.20083	Galloway Creek Near Auburn Heights, MI	17	0.314	upper middle	more flashy	<0.006	1972	1991	n/a	2009	0	Accept-able

Appendix N (continued)

Major Watershed	Watershed Number	Gage Number	Lat (Gage)	Long (Gage)	STORET #	Lat (STORET)	Long (STORET)	Gage Description	Total Drainage Area (mi^2)	Average R-B Flashiness Index Value	Quartile Rank	Flashi-ness Trend	p Value	First water year analyzed (gage)	Last water Year (gage)	Biosurvey Report #s	Year of Data Collection	P-51 Score	P-51 Rating
Clinton	12	4161580	42.800833	-83.090278	500012	42.8008	-83.0917	Stony Creek Near Romeo, MI	24	0.17	lower middle	more flashy	<0.005	1984	2004			no data	no data
Clinton	12	4162900	42.541944	-83.047778				Big Beaver Creek Near Warren, MI	21	0.848	highest	more flashy	<0.005	1971	1988			no data	no data
Clinton	12	4163400	42.601389	-83.071389				Plum Brook At Utica, MI	17	0.541	highest	NS	NS	1966	2004			no data	no data
Clinton	12	4163500	42.583611	-83.030556				Plum Brook Near Utica, MI	24	0.497	highest	NS	NS	1954	1966			no data	no data
Clinton	12	4164010	42.916389	-83.045	440059	42.91712	-83.04528	North Branch Clinton River at Almont, MI	10	0.42	upper middle	NS	NS	1963	1968	n/a	1999	0	Accept-able
Clinton	12	4164010	42.916389	-83.045	440172	42.91649	-83.04471	North Branch Clinton River at Almont, MI	10	0.42	upper middle	NS	NS	1963	1968	92/253	1991	no data	no data
Clinton	12	4164010	42.916389	-83.045	440175	42.92052	-83.03515	North Branch Clinton River at Kidder/Almont Rd.	10	0.42	upper middle	NS	NS	1963	1968	05/124	2005	-2	Accept-able
Clinton	12	4164100	42.8225	-83.020278	500434	42.81708	-83.00891	East Pond Creek At 33 Mile Rd.	21	0.155	lowest	NS	NS	1966	2004	05/124	2005	6	Excellent
Clinton	12	4164200	42.794722	-82.882778	500435	42.79127	-82.88212	Coon Creek at 31 Mile Rd.	9	0.489	upper middle	NS	NS	1966	1970	92/289	1992	no data	no data

Appendix N (continued)

Major Watershed	Watershed Number	Gage Number	Lat (Gage)	Long (Gage)	STORET #	Lat (STORET)	Long (STORET)	Gage Description	Total Drainage Area (mi^2)	Average R-B Flashiness Index Value	Quartile Rank	Flashi-ness Trend	p Value	First water year analyzed (gage)	Last water Year (gage)	Biosurvey Report #s	Year of Data Collection	P-51 Score	P-51 Rating
Clinton	12	4164250	42.761667	-82.901111	500566	42.76139	-82.90092	Tupper Brook at Ray Center, MI	9	0.669	highest	NS	NS	1960	1964	no report yet, data only	2009	-4	Accept-able
Clinton	12	4164300	42.845833	-82.885	500293	42.84622	-82.88463	East Branch Coon Creek Prospect u/s Armada, MI	13	0.631	highest	NS	NS	1959	2004	05/124	2005	2	Accept-able
Clinton	12	4164300	42.845833	-82.885	500294	42.83362	-82.88445	East Branch Coon Creek North Road	13	0.631	highest	NS	NS	1959	2004	no report yet, data only	2009	2	Accept-able
Clinton	12	4164300	42.845833	-82.885	500431	42.83800	-82.88774	East Branch Coon Creek At North Road	13	0.631	highest	NS	NS	1959	2004	n/a	1991	no data	no data
Clinton	12	4164300	42.845833	-82.885	500456	42.85067	-82.88174	East Branch Coon Creek Armada Center Road	13	0.631	highest	NS	NS	1959	2004	n/a	1999	-2	Accept-able
Clinton	12	4164350	42.806667	-82.852222	500473	42.80723	-82.85248	Highbank Creek Near 32 Mile Road	15	0.68	highest	NS	NS	1965	1970	n/a	2004	-3	Accept-able
Clinton	12	4164400	42.710833	-82.858889				Deer Creek at Meade, MI	13	0.76	highest	NS	NS	1961	1965			no data	no data
Clinton	12	4164450	42.687222	-82.920556	500557	42.68719	-82.92038	McBride Drain Near Macomb, MI	6	0.682	highest	NS	NS	1960	1964	no report yet, data only	2009	-5	Poor
Clinton	12	4164600	42.700833	-82.995556	500568	42.70089	-82.99562	Middle Branch Clinton River At Schoenherr Rd Near Macomb, MI	22	0.441	upper middle	NS	NS	1965	1969	no report yet, data only	2009	1	Accept-able

Appendix N (continued)

Major Watershed	Watershed Number	Gage Number	Lat (Gage)	Long (Gage)	STORET #	Lat (STORET)	Long (STORET)	Gage Description	Total Drainage Area (mi^2)	Average R-B Flashiness Index Value	Quartile Rank	Flashi-ness Trend	p Value	First water year analyzed (gage)	Last water Year (gage)	Biosurvey Report #s	Year of Data Collection	P-51 Score	P-51 Rating
Clinton	12	4165200	42.6275	-82.952778				Gloede Ditch Near Waldenburg, MI	16	0.461	upper middle	NS	NS	1960	1964			no data	no data
Rifle	30	4140000	44.335	-84.068333	650073	44.33426	-84.06835	Prior Creek Near Selkirk, MI	21	0.237	lower middle	NS	NS	1951	1972	94/030	1994	no data	no data
Rifle	30	4141000	44.307778	-84.086944	650129	44.30739	-84.08470	South Branch Shepards Creek Near Selkirk, MI	1	0.627	highest	NS	NS	1952	1978	n/a	2009	-1	Accept-able
Rouge	31	4166200	42.457778	-83.2675	631047	42.46754	-83.26054	Evans Ditch At Southfield, MI	10	0.846	highest	more flashy	<0.005	1959	2003	09/001	2005 and 2006	-4	Accept-able
Rouge	31	4166300	42.464444	-83.369722	631054	42.46176	-83.36701	Upper River Rouge At Farmington, MI	18	0.403	upper middle	more flashy	<0.005	1958	2004	09/001	2005	1	Accept-able
Saginaw	32	4148160	43.024167	-83.625556	250323	43.02560	-83.63510	Gilkey Creek, Center Road	7	0.694	highest	NS	NS	1970	1983	n/a	2008	-4	Accept-able
Saginaw	32	4148160	43.024167	-83.625556	250474	43.01918	-83.61419	Gilkey Creek, East Court St.	7	0.694	highest	NS	NS	1970	1983	01/032	1998	-4	Accept-able
Saginaw	32	4148200	42.8275	-83.628333				Swartz Creek Near Holly, MI	12	0.14	lowest	NS	NS	1956	1975			no data	no data
Saginaw	32	4148720	43.17	-83.834167				Brent Run Near Montrose, MI	21	0.478	upper middle	NS	NS	1970	1983			no data	no data

Appendix O – Ruddiman Creek Remediation Area Maps

Fig. O.1. Ruddiman Pond remediation area. Map source: USEPA (2011).

Fig. O.2. Glenside Boulevard remediation map. Map source: USEPA (2011).

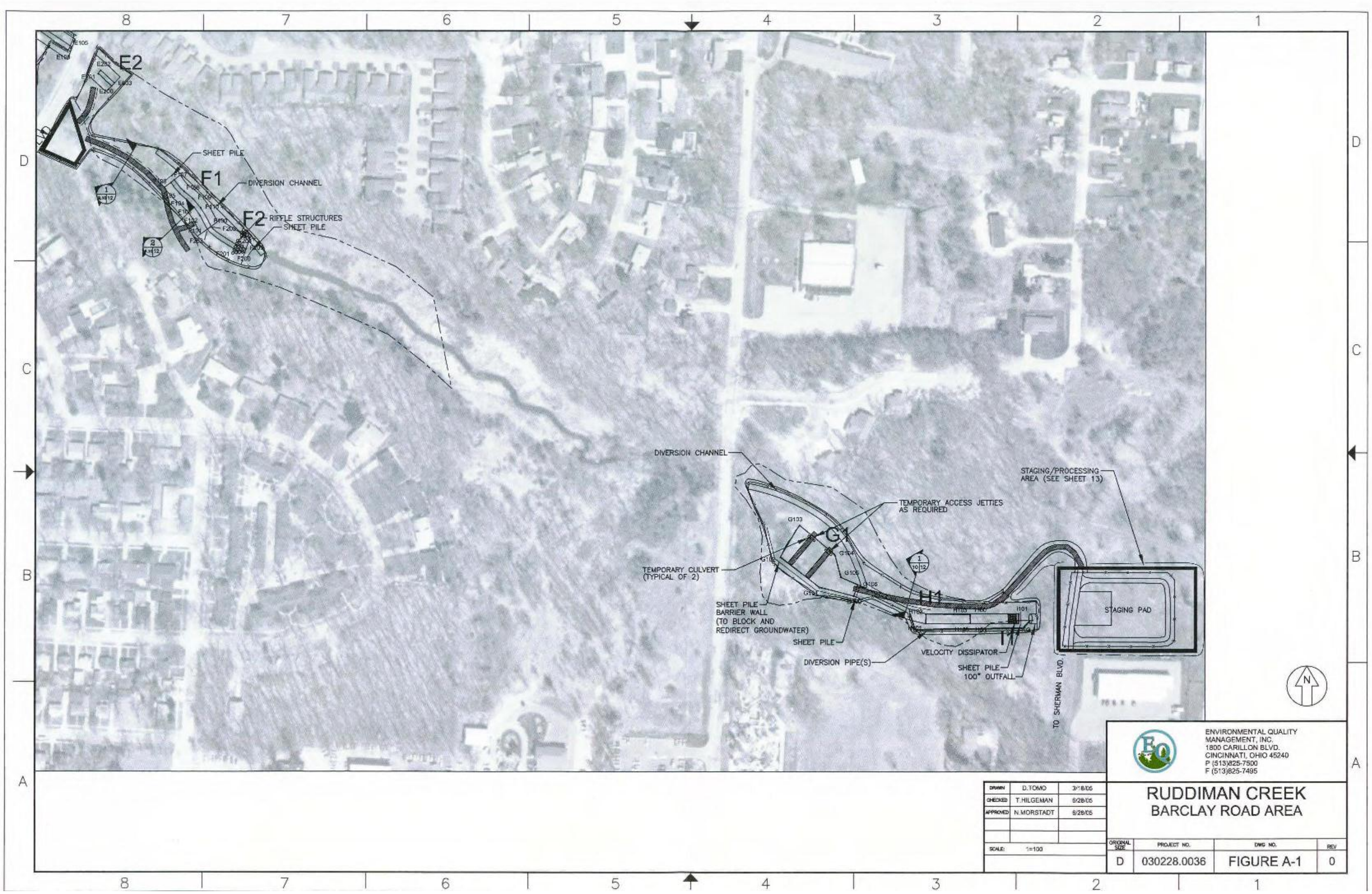


Fig. O.3. Barclay Street remediation area map. Map source: USEPA (2011).

References

U.S. Environmental Protection Agency (USEPA). (2011). Remediation of the Ruddiman Creek main branch and pond. Muskegon County, Michigan. Great Lakes Legacy Act Program. U.S. Environmental Protection Agency Great Lakes National Program Office. Chicago, IL. March 2011. 101 pp.

Appendix P – Flow Duration Curves

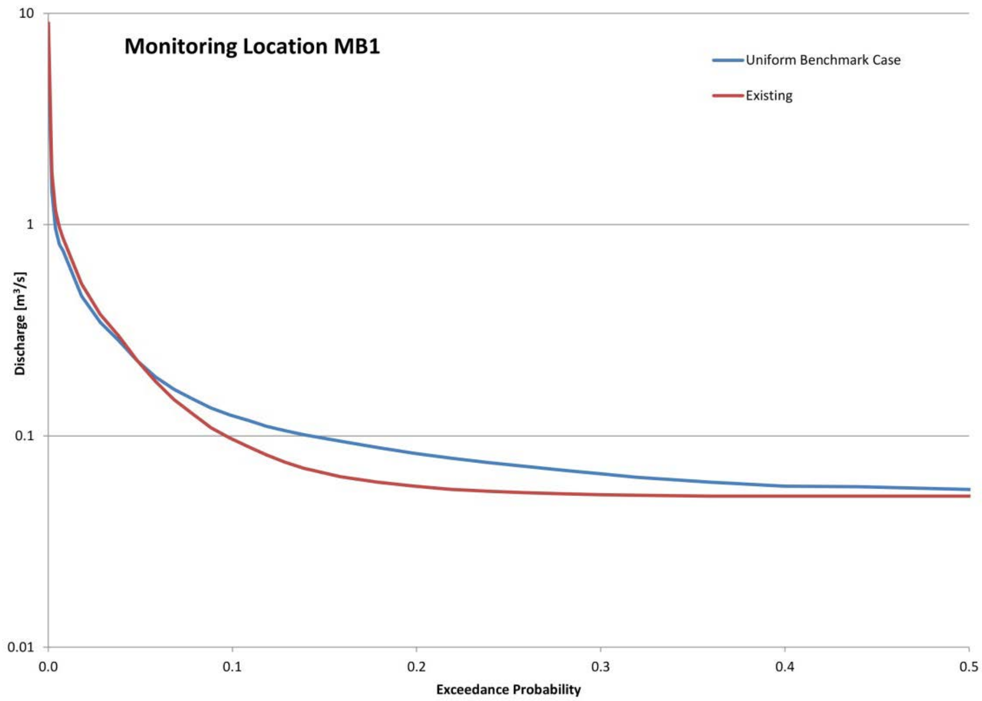


Figure P.1. Existing (red line) and projected (uniform benchmark case; blue line) flow duration curves for the key monitoring location MB1.

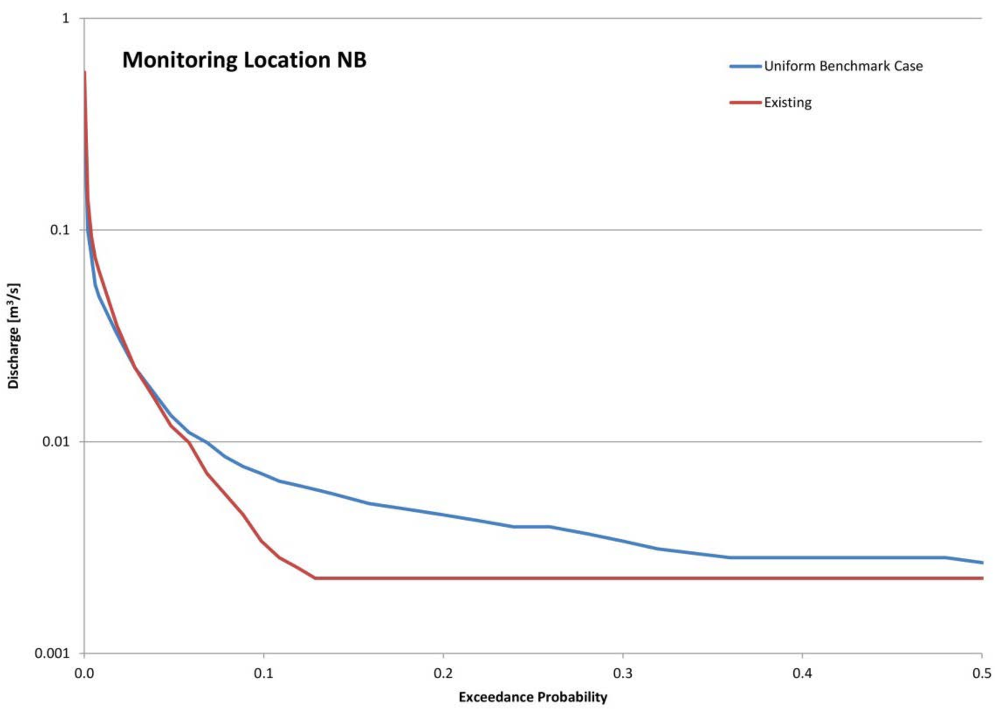


Figure P.2. Existing (red line) and projected (uniform benchmark case; blue line) flow duration curves for the key monitoring location NB.

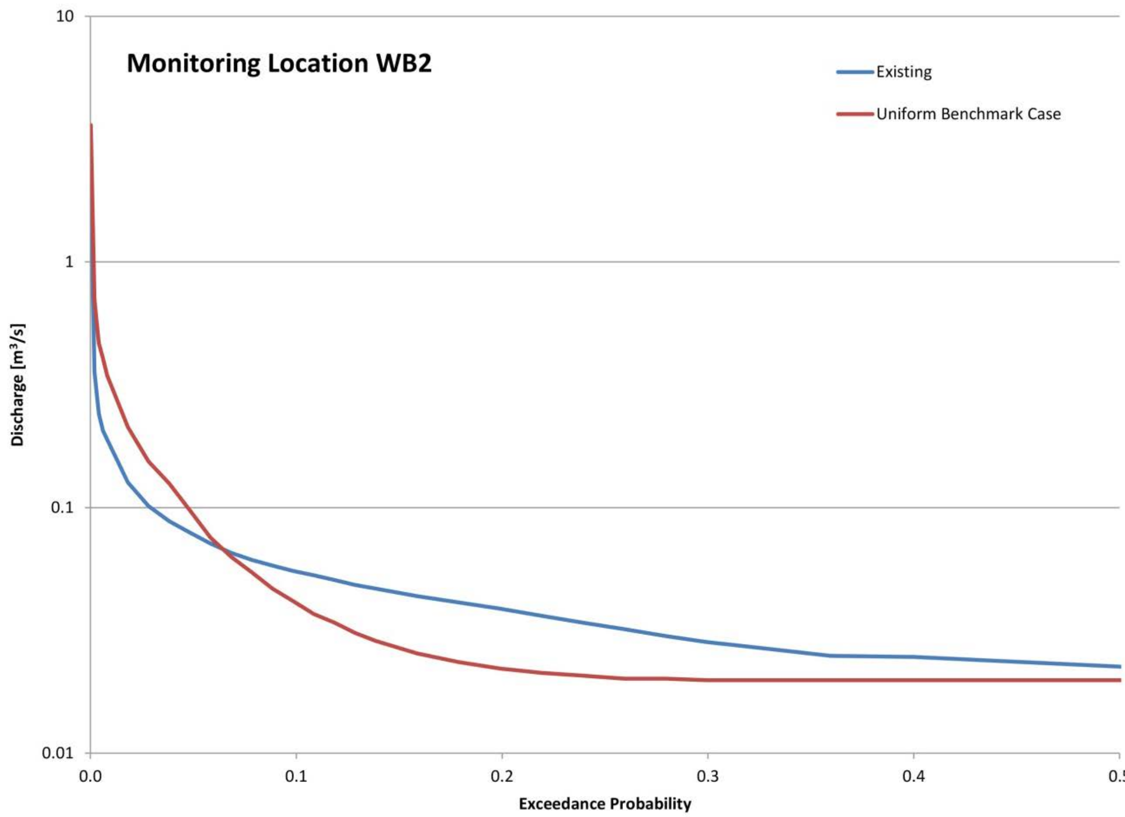


Figure P.3. Existing (blue line) and projected (uniform benchmark case; red line) flow duration curves for the key monitoring location WB2.

Appendix Q – FLOWSED Worksheets

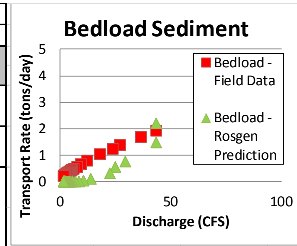
Stream:	Main Branch - Ruddiman Creek			Location:	MB-1 Existing Conditions		Date:	10/12/12
Observers:	DF2			Gage Station #:	NA	Stream Type:	Valley Type:	

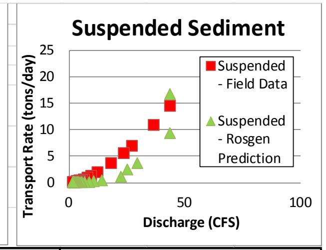
Equation type	Intercept	Coefficient	Exponent	Form (e.g., Linear, Power, etc.)	Equation name	Bankfull Discharge	Bankfull Bedload	Bankfull Suspended
1. Bedload (dimensionless)	-0.0113	1.0139	2.1929	Non-Linear	"Good/Fair" Pagosa	40 cfs	0.019052 kg/s	116.8 mg/l
2. Suspended sediment (dimensionless)	0.0636	0.9326	2.4085	Non-Linear	"Good/Fair" Pagosa		1.81 ton/day	3.65E-06 tn/cf
3. User-defined relations (bedload)	0	125.746	0.6972	Power	Field Data			
4. User-defined relations (suspended sediment)	0	13.297	0.5891	Power	Field Data	Notes: Utilizes Reduced Flow up to Measured Limits of Sediment Data.		

Dimensioned Flow-Duration Curve							Sediment Field Data				Calculate	Sediment Yield from Field Data		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(9)	(11)	(12)	(13)	(14)	(15)
Flow exceedence	Daily mean discharge	Mid-ordinate	Time increment (percent)	Time increment (days)	Mid-ordinate streamflow	Dimension-less streamflow	Suspended Sediment Conc.	Suspended sediment discharge	Bedload Tansport Rate	Bedload	Time adjusted streamflow	Suspended sediment [(5)×(9)]	Bedload sediment [(5)×(11)]	Suspended + bedload [(13)+(14)]
(%)	(cfs)	(%)	(%)	(days)	(cfs)	(Q/Q_{bkf})	(mg/l)	(tons/day)	(kg/d)	(tons/day)	(cfs)	(tons)	(tons)	(tons)
0.0%	62.08													
0.2%	62.08	0.1%	0%	0.67	62.08	1.55	151	25	2236	2	0.11	17	2	19
0.4%	41.20	0.1%	0%	0.75	51.64	1.29	136	19	1967	2	0.11	14	2	16
0.6%	34.47	0.1%	0%	0.75	37.84	0.95	113	12	1583	2	0.08	9	1	10
0.8%	30.43	0.1%	0%	0.75	32.45	0.81	103	9	1423	2	0.07	7	1	8
2%	18.53	0.5%	1%	3.67	24.48	0.61	87	6	1169	1	0.25	21	5	26
3%	13.29	0.5%	1%	3.67	15.91	0.40	68	3	866	1	0.16	11	3	14
4%	10.50	0.5%	1%	3.67	11.90	0.30	57	2	707	1	0.12	7	3	10
5%	8.03	0.5%	1%	3.67	9.27	0.23	49	1	594	1	0.09	5	2	7
6%	6.38	0.5%	1%	3.67	7.21	0.18	43	1	498	1	0.07	3	2	5
7%	5.24	0.5%	1%	3.67	5.81	0.15	37	1	429	0	0.06	2	2	4
8%	4.49	0.5%	1%	3.67	4.87	0.12	34	0	379	0	0.05	2	2	3
9%	3.86	0.5%	1%	3.67	4.18	0.10	31	0	341	0	0.04	1	1	3
10%	3.45	0.5%	1%	3.67	3.66	0.09	29	0	310	0	0.04	1	1	2
11%	3.14	0.5%	1%	3.67	3.30	0.08	27	0	289	0	0.03	1	1	2
12%	2.87	0.5%	1%	3.67	3.01	0.08	25	0	271	0	0.03	1	1	2
13%	2.65	0.5%	1%	3.67	2.76	0.07	24	0	255	0	0.03	1	1	2
14%	2.48	0.5%	1%	3.67	2.57	0.06	23	0	242	0	0.03	1	1	2
16%	2.26	1.0%	2%	7.33	2.37	0.06	22	0	229	0	0.05	1	2	3
18%	2.13	1.0%	2%	7.33	2.20	0.05	21	0	218	0	0.04	1	2	3
20%	2.04	1.0%	2%	7.33	2.09	0.05	20	0	210	0	0.04	1	2	3
22%	1.97	1.0%	2%	7.33	2.01	0.05	20	0	204	0	0.04	1	2	2
24%	1.93	1.0%	2%	7.33	1.95	0.05	20	0	200	0	0.04	1	2	2
26%	1.90	1.0%	2%	7.33	1.92	0.05	19	0	198	0	0.04	1	2	2
28%	1.88	1.0%	2%	7.33	1.89	0.05	19	0	196	0	0.04	1	2	2
30%	1.86	1.0%	2%	7.33	1.87	0.05	19	0	195	0	0.04	1	2	2
32%	1.85	1.0%	2%	7.33	1.86	0.05	19	0	193	0	0.04	1	2	2
36%	1.83	2.0%	4%	14.63	1.84	0.05	19	0	192	0	0.07	1	3	4
40%	1.83	2.0%	4%	14.63	1.83	0.05	19	0	192	0	0.07	1	3	4
44%	1.83	2.0%	4%	14.63	1.83	0.05	19	0	192	0	0.07	1	3	4
48%	1.83	2.0%	4%	14.63	1.83	0.05	19	0	192	0	0.07	1	3	4
52%	1.83	2.0%	4%	14.63	1.83	0.05	19	0	192	0	0.07	1	3	4
56%	1.83	2.0%	4%	14.63	1.83	0.05	19	0	192	0	0.07	1	3	4
60%	1.83	2.0%	4%	14.63	1.83	0.05	19	0	192	0	0.07	1	3	4
70%	1.83	5.0%	10%	36.50	1.83	0.05	19	0	192	0	0.18	3	8	11
80%	1.83	5.0%	10%	36.50	1.83	0.05	19	0	192	0	0.18	3	8	11
90%	1.83	5.0%	10%	36.50	1.83	0.05	19	0	192	0	0.18	3	8	11
100%	1.83	5.0%	10%	36.50	1.83	0.05	19	0	192	0	0.18	3	8	11
											Annual totals:	132 (tons/yr)	99 (tons/yr)	231 (tons/yr)
			100%	*365*	*days*									

Figure Q.1. FLOWSED worksheet for existing conditions at key monitoring location MB1.

Stream:	Main Branch - Ruddiman Creek			Location:	MB-1 BMP Benchmark Scenario			Date:	10/16/12
Observers:	DF2			Gage Station #:	NA	Stream Type:		Valley Type:	
Equation type	**Intercept**	**Coefficient**	**Exponent**	**Form (e.g., Linear, Power, etc.)**	**Equation name**	**Bankfull Discharge**		**Bankfull Bedload**	**Bankfull Suspended**
1. Bedload (dimensionless)	**-0.0113**	**1.0139**	**2.1929**	**Non-Linear**	**"Good/Fair" Pagosa**	**40** cfs		**0.019052** kg/s	**116.8** mg/l
2. Suspended sediment (dimensionless)	**0.0636**	**0.9326**	**2.4085**	**Non-Linear**	**"Good/Fair" Pagosa**			**1.81** ton/day	**3.65E-06** tn/cf
3. User-defined relations (bedload)	**0**	**125.746**	**0.6972**	**Power**	**Field Data**	Notes: Utilizes Reduced Flow up to Measured Limits of Sediment Data. Rosgen Estimated Sediment Load is less than Measured - Indicating Potential Channel Instablility			
4. User-defined relations (suspended sediment)	**0**	**13.297**	**0.5891**	**Power**	**Field Data**				





Dimensioned Flow-Duration Curve							**Sediment Field Data**				**Calculate**	**Sediment Yield from Field Data**			**Rosgen Sediment Rating Curves**				**Sediment Yield from Rosgen**		
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(9)**	**(11)**	**(12)**	**(13)**	**(14)**	**(15)**	**(8)**	**(9)**	**(10)**	**(11)**	**(13)**	**(14)**	**(15)**
Flow exceedence	**Daily mean discharge**	**Mid-ordinate**	**Time increment (percent)**	**Time increment (days)**	**Mid-ordinate streamflow**	**Dimension-less streamflow**	**Suspended Sediment Conc.**	**Suspended sediment discharge**	**Bedload Tansport Rate**	**Bedload**	**Time adjusted streamflow**	**Suspended sediment [(5)×(9)]**	**Bedload sediment [(5)×(11)]**	**Suspended + bedload [(13)+(14)]**	**Dimension-less suspended sediment discharge**	**Suspended sediment discharge**	**Dimension-less bedload discharge**	**Bedload**	**Suspended sediment [(5)×(9)]**	**Bedload sediment [(5)×(11)]**	**Suspended + bedload [(13)+(14)]**
(%)	**(cfs)**	**(%)**	**(%)**	**(days)**	**(cfs)**	**(Q/Q_{bkf})**	**(mg/l)**	**(tons/day)**	**(kg/d)**	**(tons/day)**	**(cfs)**	**(tons)**	**(tons)**	**(tons)**	**(S/S_{bkf})**	**(tons/day)**	**(b_s/b_{bkf})**	**(tons/day)**	**(tons)**	**(tons)**	**(tons)**
0.0%	43.63																				
0.2%	43.63	0.1%	0%	0.67	43.63	1.09	123	14	1749	2	0.08	10	1	11	1.21	17	1.22	2	11	1	13
0.4%	29.54	0.1%	0%	0.75	36.59	0.91	111	11	1547	2	0.08	8	1	9	0.82	9	0.82	1	7	1	8
0.6%	25.04	0.1%	0%	0.75	27.29	0.68	93	7	1261	1	0.06	5	1	6	0.43	4	0.43	1	3	1	3
0.8%	22.52	0.1%	0%	0.75	23.78	0.59	86	6	1145	1	0.05	4	1	5	0.33	2	0.31	1	2	0	2
2%	14.05	0.5%	1%	3.67	18.29	0.46	74	4	954	1	0.18	13	4	17	0.21	1	0.17	0	4	1	5
3%	10.54	0.5%	1%	3.67	12.30	0.31	58	2	723	1	0.12	7	3	10	0.12	0	0.06	0	2	0	2
4%	8.62	0.5%	1%	3.67	9.58	0.24	50	1	608	1	0.10	5	2	7	0.09	0	0.03	0	1	0	1
5%	6.89	0.5%	1%	3.67	7.76	0.19	44	1	524	1	0.08	3	2	6	0.08	0.2	0.02	0.03	1	0	1
6%	5.77	0.5%	1%	3.67	6.33	0.16	39	1	455	1	0.06	2	2	4	0.07	0.1	0.01	0.01	1	0	1
7%	5.11	0.5%	1%	3.67	5.44	0.14	36	1	410	0	0.05	2	2	4	0.07	0.1	0.00	0.00	0	0	0
8%	4.53	0.5%	1%	3.67	4.82	0.12	34	0	376	0	0.05	2	2	3	0.07	0.1	0.00	0.00	0	0	0
9%	4.17	0.5%	1%	3.67	4.35	0.11	32	0	350	0	0.04	1	1	3	0.07	0.1	0.00	0.00	0	0	0
10%	3.90	0.5%	1%	3.67	4.04	0.10	30	0	333	0	0.04	1	1	3	0.07	0.1	0.00	0.00	0	0	0
11%	3.66	0.5%	1%	3.67	3.78	0.09	29	0	318	0	0.04	1	1	2	0.07	0.1	0.00	0.00	0	0	0
12%	3.47	0.5%	1%	3.67	3.57	0.09	28	0	305	0	0.04	1	1	2	0.07	0.1	0.00	0.00	0	0	0
13%	3.32	0.5%	1%	3.67	3.40	0.08	27	0	295	0	0.03	1	1	2	0.07	0.1	0.00	0.00	0	0	0
14%	3.21	0.5%	1%	3.67	3.27	0.08	27	0	287	0	0.03	1	1	2	0.07	0.1	0.00	0.00	0	0	0
16%	2.99	1.0%	2%	7.33	3.10	0.08	26	0	277	0	0.06	2	2	4	0.07	0.1	0.00	0.00	0	0	0
18%	2.81	1.0%	2%	7.33	2.90	0.07	25	0	264	0	0.06	1	2	4	0.07	0.1	0.00	0.00	0	0	0
20%	2.66	1.0%	2%	7.33	2.74	0.07	24	0	254	0	0.05	1	2	3	0.07	0.1	0.00	0.00	0	0	0
22%	2.54	1.0%	2%	7.33	2.60	0.07	23	0	245	0	0.05	1	2	3	0.06	0.1	0.00	0.00	0	0	0
24%	2.42	1.0%	2%	7.33	2.48	0.06	23	0	237	0	0.05	1	2	3	0.06	0.1	0.00	0.00	0	0	0
26%	2.32	1.0%	2%	7.33	2.37	0.06	22	0	229	0	0.05	1	2	3	0.06	0.0	0.00	0.00	0	0	0
28%	2.23	1.0%	2%	7.33	2.28	0.06	22	0	223	0	0.05	1	2	3	0.06	0.0	0.00	0.00	0	0	0
30%	2.16	1.0%	2%	7.33	2.20	0.05	21	0	218	0	0.04	1	2	3	0.06	0.0	0.00	0.00	0	0	0
32%	2.10	1.0%	2%	7.33	2.13	0.05	21	0	213	0	0.04	1	2	3	0.06	0.0	0.00	0.00	0	0	0
36%	2.04	2.0%	4%	14.63	2.07	0.05	20	0	209	0	0.08	2	3	5	0.06	0.0	0.00	0.00	1	0	1
40%	2.00	2.0%	4%	14.63	2.02	0.05	20	0	205	0	0.08	2	3	5	0.06	0.0	0.00	0.00	1	0	1
44%	1.96	2.0%	4%	14.63	1.98	0.05	20	0	202	0	0.08	2	3	5	0.06	0.0	0.00	0.00	1	0	1
48%	1.93	2.0%	4%	14.63	1.95	0.05	20	0	200	0	0.08	2	3	5	0.06	0.0	0.00	0.00	1	0	1
52%	1.90	2.0%	4%	14.63	1.92	0.05	19	0	198	0	0.08	1	3	5	0.06	0.0	0.00	0.00	1	0	1
56%	1.87	2.0%	4%	14.63	1.89	0.05	19	0	196	0	0.08	1	3	5	0.06	0.0	0.00	0.00	1	0	1
60%	1.84	2.0%	4%	14.63	1.86	0.05	19	0	193	0	0.07	1	3	5	0.06	0.0	0.00	0.00	1	0	1
70%	1.83	5.0%	10%	36.50	1.84	0.05	19	0	192	0	0.18	3	8	11	0.06	0.0	0.00	0.00	1	0	1
80%	1.83	5.0%	10%	36.50	1.83	0.05	19	0	192	0	0.18	3	8	11	0.06	0.0	0.00	0.00	1	0	1
90%	1.83	5.0%	10%	36.50	1.83	0.05	19	0	192	0	0.18	3	8	11	0.06	0.0	0.00	0.00	1	0	1
100%	1.83	5.0%	10%	36.50	1.83	0.05	19	0	192	0	0.18	3	8	11	0.06	0.0	0.00	0.00	1	0	1
			100%	*365 days*							**Annual totals:**	**103** (tons/yr)	**99** (tons/yr)	**202** (tons/yr)				**Annual totals:**	**47** (tons/yr)	**6** (tons/yr)	**52** (tons/yr)

Figure Q.1. FLOWSED worksheet for <u>projected</u> conditions resulting from the BMP benchmark scenario at key monitoring location MB1.

Stream:	North Branch - Ruddiman Creek			Location:	NB-1 Existing Conditions			Date:	10/16/12
Observers:	DF2			Gage Station #:	NA	Stream Type:		Valley Type:	

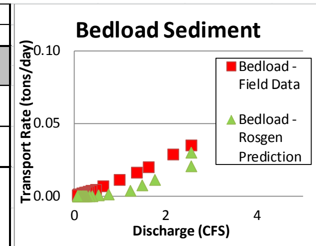
Equation type	Intercept	Coefficient	Exponent	Form (e.g., Linear, Power, etc.)	Equation name	Bankfull Discharge	Bankfull Bedload	Bankfull Suspended
1. Bedload (dimensionless)	-0.0113	1.0139	2.1929	Non-Linear	"Good/Fair" Pagosa	3 cfs	0.000448 kg/s	54.8 mg/l
2. Suspended sediment (dimensionless)	0.0636	0.9326	2.4085	Non-Linear	"Good/Fair" Pagosa		0.04 ton/day	1.71E-06 tn/cf
3. User-defined relations (bedload)	0	10.1048	1.2218	Power	Field Data			
4. User-defined relations (suspended sediment)	0	26.0252	0.6772	Power	Field Data	Notes: Bankfull Not Identified (Estimated)		

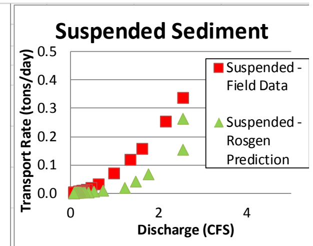
Dimensioned Flow-Duration Curve							Sediment Field Data				Calculate	Sediment Yield from Field Data		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(9)	(11)	(12)	(13)	(14)	(15)
Flow exceedence	Daily mean discharge	Mid-ordinate	Time increment (percent)	Time increment (days)	Mid-ordinate streamflow	Dimension-less streamflow	Suspended Sediment Conc.	Suspended sediment discharge	Bedload Tansport Rate	Bedload	Time adjusted streamflow	Suspended sediment [(5)×(9)]	Bedload sediment [(5)×(11)]	Suspended + bedload [(13)+(14)]
(%)	(cfs)	(%)	(%)	(days)	(cfs)	(Q/Q_{bkf})	(mg/l)	(tons/day)	(kg/d)	(tons/day)	(cfs)	(tons)	(tons)	(tons)
0.0%	4.96													
0.2%	4.96	0.1%	0%	0.67	4.96	1.65	77	1	71	0	0.01	1	0	1
0.4%	3.28	0.1%	0%	0.75	4.12	1.37	68	1	57	0	0.01	1	0	1
0.6%	2.61	0.1%	0%	0.75	2.95	0.98	54	0	38	0	0.01	0	0	0
0.8%	2.27	0.1%	0%	0.75	2.44	0.81	48	0	30	0	0.01	0	0	0
2%	1.25	0.5%	1%	3.67	1.76	0.59	38	0	20	0	0.02	1	0	1
3%	0.79	0.5%	1%	3.67	1.02	0.34	26	0	10	0	0.01	0	0	0
4%	0.58	0.5%	1%	3.67	0.69	0.23	20	0	6	0	0.01	0	0	0
5%	0.42	0.5%	1%	3.67	0.50	0.17	16	0	4	0	0.01	0	0	0
6%	0.35	0.5%	1%	3.67	0.39	0.13	14	0	3	0	0.00	0	0	0
7%	0.25	0.5%	1%	3.67	0.30	0.10	12	0	2	0	0.00	0	0	0
8%	0.20	0.5%	1%	3.67	0.23	0.08	9	0	2	0	0.00	0	0	0
9%	0.16	0.5%	1%	3.67	0.18	0.06	8	0	1	0	0.00	0	0	0
10%	0.12	0.5%	1%	3.67	0.14	0.05	7	0	1	0	0.00	0	0	0
11%	0.10	0.5%	1%	3.67	0.11	0.04	6	0	1	0	0.00	0	0	0
12%	0.09	0.5%	1%	3.67	0.10	0.03	5	0	1	0	0.00	0	0	0
13%	0.08	0.5%	1%	3.67	0.09	0.03	5	0	0	0	0.00	0	0	0
14%	0.08	0.5%	1%	3.67	0.08	0.03	5	0	0	0	0.00	0	0	0
16%	0.08	1.0%	2%	7.33	0.08	0.03	5	0	0	0	0.00	0	0	0
18%	0.08	1.0%	2%	7.33	0.08	0.03	5	0	0	0	0.00	0	0	0
20%	0.08	1.0%	2%	7.33	0.08	0.03	5	0	0	0	0.00	0	0	0
22%	0.08	1.0%	2%	7.33	0.08	0.03	5	0	0	0	0.00	0	0	0
24%	0.08	1.0%	2%	7.33	0.08	0.03	5	0	0	0	0.00	0	0	0
26%	0.08	1.0%	2%	7.33	0.08	0.03	5	0	0	0	0.00	0	0	0
28%	0.08	1.0%	2%	7.33	0.08	0.03	5	0	0	0	0.00	0	0	0
30%	0.08	1.0%	2%	7.33	0.08	0.03	5	0	0	0	0.00	0	0	0
32%	0.08	1.0%	2%	7.33	0.08	0.03	5	0	0	0	0.00	0	0	0
36%	0.08	2.0%	4%	14.63	0.08	0.03	5	0	0	0	0.00	0	0	0
40%	0.08	2.0%	4%	14.63	0.08	0.03	5	0	0	0	0.00	0	0	0
44%	0.08	2.0%	4%	14.63	0.08	0.03	5	0	0	0	0.00	0	0	0
48%	0.08	2.0%	4%	14.63	0.08	0.03	5	0	0	0	0.00	0	0	0
52%	0.08	2.0%	4%	14.63	0.08	0.03	5	0	0	0	0.00	0	0	0
56%	0.08	2.0%	4%	14.63	0.08	0.03	5	0	0	0	0.00	0	0	0
60%	0.08	2.0%	4%	14.63	0.08	0.03	5	0	0	0	0.00	0	0	0
70%	0.08	5.0%	10%	36.50	0.08	0.03	5	0	0	0	0.01	0	0	0
80%	0.08	5.0%	10%	36.50	0.08	0.03	5	0	0	0	0.01	0	0	0
90%	0.08	5.0%	10%	36.50	0.08	0.03	5	0	0	0	0.01	0	0	0
100%	0.08	5.0%	10%	36.50	0.08	0.03	5	0	0	0	0.01	0	0	0
			100%	365	days					Annual totals:		3 (tons/yr)	1 (tons/yr)	4 (tons/yr)

Figure Q.3. FLOWSED worksheet for existing conditions at key monitoring location NB.

Stream:	Main Branch - Ruddiman Creek				Location:	NB-1 BMP Benchmark Scenario			Date:	10/16/12
Observers:	DF2				Gage Station #:	NA	Stream Type:		Valley Type:	

Equation type	Intercept	Coefficient	Exponent	Form (e.g., Linear, Power, etc.)	Equation name	Bankfull Discharge	Bankfull Bedload	Bankfull Suspended
1. Bedload (dimensionless)	-0.0113	1.0139	2.1929	Non-Linear	"Good/Fair" Pagosa	3 cfs	0.000448 kg/s	54.8 mg/l
2. Suspended sediment (dimensionless)	0.0636	0.9326	2.4085	Non-Linear	"Good/Fair" Pagosa		0.04 ton/day	1.71E-06 tn/cf
3. User-defined relations (bedload)	0	10.1048	1.2218	Power	Field Data			
4. User-defined relations (suspended sediment)	0	26.0252	0.6772	Power	Field Data	Notes: Bankfull Not Identified (Estimated)		





Dimensioned Flow-Duration Curve							Sediment Field Data				Calculate	Sediment Yield from Field Data			Rosgen Sediment Rating Curves				Sediment Yield from Rosgen		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(9)	(11)	(12)	(13)	(14)	(15)	(8)	(9)	(10)	(11)	(13)	(14)	(15)
Flow exceedence	Daily mean discharge	Mid-ordinate	Time increment (percent)	Time increment (days)	Mid-ordinate streamflow	Dimension-less streamflow	Suspended Sediment Conc.	Suspended sediment discharge	Bedload Tansport Rate	Bedload	Time adjusted streamflow	Suspended sediment [(5)×(9)]	Bedload sediment [(5)×(11)]	Suspended + bedload [(13)+(14)]	Dimension-less suspended sediment discharge	Suspended sediment discharge	Dimension-less bedload discharge	Bedload	Suspended sediment [(5)×(9)]	Bedload sediment [(5)×(11)]	Suspended + bedload [(13)+(14)]
(%)	(cfs)	(%)	(%)	(days)	(cfs)	(Q/Q_{bkf})	(mg/l)	(tons/day)	(kg/d)	(tons/day)	(cfs)	(tons)	(tons)	(tons)	(S/S_{bkf})	(tons/day)	(b_s/b_{bkf})	(tons/day)	(tons)	(tons)	(tons)
0.0%	2.55																				
0.2%	2.55	0.1%	0%	0.67	2.55	0.85	49	0	32	0	0.00	0	0	0	0.69	0	0.70	0	0	0	0
0.4%	1.76	0.1%	0%	0.75	2.16	0.72	44	0	26	0	0.00	0	0	0	0.48	0	0.48	0	0	0	0
0.6%	1.48	0.1%	0%	0.75	1.62	0.54	36	0	18	0	0.00	0	0	0	0.28	0	0.25	0	0	0	0
0.8%	1.23	0.1%	0%	0.75	1.36	0.45	32	0	15	0	0.00	0	0	0	0.20	0	0.17	0	0	0	0
2%	0.74	0.5%	1%	3.67	0.99	0.33	26	0	10	0	0.01	0	0	0	0.13	0	0.08	0	0	0	0
3%	0.53	0.5%	1%	3.67	0.64	0.21	19	0	6	0	0.01	0	0	0	0.09	0	0.02	0	0	0	0
4%	0.40	0.5%	1%	3.67	0.47	0.16	15	0	4	0	0.00	0	0	0	0.07	0	0.01	0	0	0	0
5%	0.33	0.5%	1%	3.67	0.37	0.12	13	0	3	0	0.00	0	0	0	0.07	0.0	0.00	0.00	0	0	0
6%	0.28	0.5%	1%	3.67	0.31	0.10	12	0	2	0	0.00	0	0	0	0.07	0.0	0.00	0.00	0	0	0
7%	0.25	0.5%	1%	3.67	0.27	0.09	11	0	2	0	0.00	0	0	0	0.07	0.0	0.00	0.00	0	0	0
8%	0.23	0.5%	1%	3.67	0.24	0.08	10	0	2	0	0.00	0	0	0	0.07	0.0	0.00	0.00	0	0	0
9%	0.21	0.5%	1%	3.67	0.22	0.07	9	0	2	0	0.00	0	0	0	0.07	0.0	0.00	0.00	0	0	0
10%	0.20	0.5%	1%	3.67	0.21	0.07	9	0	1	0	0.00	0	0	0	0.07	0.0	0.00	0.00	0	0	0
11%	0.19	0.5%	1%	3.67	0.20	0.07	9	0	1	0	0.00	0	0	0	0.06	0.0	0.00	0.00	0	0	0
12%	0.18	0.5%	1%	3.67	0.19	0.06	8	0	1	0	0.00	0	0	0	0.06	0.0	0.00	0.00	0	0	0
13%	0.18	0.5%	1%	3.67	0.18	0.06	8	0	1	0	0.00	0	0	0	0.06	0.0	0.00	0.00	0	0	0
14%	0.17	0.5%	1%	3.67	0.18	0.06	8	0	1	0	0.00	0	0	0	0.06	0.0	0.00	0.00	0	0	0
16%	0.16	1.0%	2%	7.33	0.17	0.06	8	0	1	0	0.00	0	0	0	0.06	0.0	0.00	0.00	0	0	0
18%	0.15	1.0%	2%	7.33	0.16	0.05	7	0	1	0	0.00	0	0	0	0.06	0.0	0.00	0.00	0	0	0
20%	0.14	1.0%	2%	7.33	0.15	0.05	7	0	1	0	0.00	0	0	0	0.06	0.0	0.00	0.00	0	0	0
22%	0.14	1.0%	2%	7.33	0.14	0.05	7	0	1	0	0.00	0	0	0	0.06	0.0	0.00	0.00	0	0	0
24%	0.13	1.0%	2%	7.33	0.14	0.05	7	0	1	0	0.00	0	0	0	0.06	0.0	0.00	0.00	0	0	0
26%	0.12	1.0%	2%	7.33	0.13	0.04	6	0	1	0	0.00	0	0	0	0.06	0.0	0.00	0.00	0	0	0
28%	0.11	1.0%	2%	7.33	0.12	0.04	6	0	1	0	0.00	0	0	0	0.06	0.0	0.00	0.00	0	0	0
30%	0.11	1.0%	2%	7.33	0.11	0.04	6	0	1	0	0.00	0	0	0	0.06	0.0	0.00	0.00	0	0	0
32%	0.10	1.0%	2%	7.33	0.11	0.04	6	0	1	0	0.00	0	0	0	0.06	0.0	0.00	0.00	0	0	0
36%	0.10	2.0%	4%	14.63	0.10	0.03	5	0	1	0	0.00	0	0	0	0.06	0.0	0.00	0.00	0	0	0
40%	0.10	2.0%	4%	14.63	0.10	0.03	5	0	1	0	0.00	0	0	0	0.06	0.0	0.00	0.00	0	0	0
44%	0.09	2.0%	4%	14.63	0.10	0.03	5	0	1	0	0.00	0	0	0	0.06	0.0	0.00	0.00	0	0	0
48%	0.09	2.0%	4%	14.63	0.09	0.03	5	0	1	0	0.00	0	0	0	0.06	0.0	0.00	0.00	0	0	0
52%	0.09	2.0%	4%	14.63	0.09	0.03	5	0	1	0	0.00	0	0	0	0.06	0.0	0.00	0.00	0	0	0
56%	0.09	2.0%	4%	14.63	0.09	0.03	5	0	1	0	0.00	0	0	0	0.06	0.0	0.00	0.00	0	0	0
60%	0.08	2.0%	4%	14.63	0.09	0.03	5	0	0	0	0.00	0	0	0	0.06	0.0	0.00	0.00	0	0	0
70%	0.08	5.0%	10%	36.50	0.08	0.03	5	0	0	0	0.01	0	0	0	0.06	0.0	0.00	0.00	0	0	0
80%	0.08	5.0%	10%	36.50	0.08	0.03	5	0	0	0	0.01	0	0	0	0.06	0.0	0.00	0.00	0	0	0
90%	0.08	5.0%	10%	36.50	0.08	0.03	5	0	0	0	0.01	0	0	0	0.06	0.0	0.00	0.00	0	0	0
100%	0.08	5.0%	10%	36.50	0.08	0.03	5	0	0	0	0.01	0	0	0	0.06	0.0	0.00	0.00	0	0	0
											Annual totals:	2 (tons/yr)	0 (tons/yr)	2 (tons/yr)				Annual totals:	1 (tons/yr)	0 (tons/yr)	1 (tons/yr)
			100%	365 days																	

Figure Q.4. FLOWSED worksheet for projected conditions resulting from the BMP benchmark scenario at key monitoring location NB.

Stream:	West Branch - Ruddiman Creek	Location:	WB-2 Existing Conditions	Date:	10/16/12
Observers:	DF2	Gage Station #:	NA	Stream Type:	Valley Type:

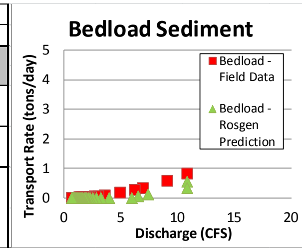
Equation type	Intercept	Coefficient	Exponent	Form (e.g., Linear, Power, etc.)	Equation name	Bankfull Discharge	Bankfull Bedload	Bankfull Suspended
1. Bedload (dimensionless)	**-0.0113**	**1.0139**	**2.1929**	**Non-Linear**	**"Good/Fair" Pagosa**	**50 cfs**	**0.191878 kg/s**	**263.9 mg/l**
2. Suspended sediment (dimensionless)	**0.0636**	**0.9326**	**2.4085**	**Non-Linear**	**"Good/Fair" Pagosa**		**18.27 ton/day**	**8.25E-06 tn/cf**
3. User-defined relations (bedload)	**0**	**6.0017**	**2.0255**	**Power**	**Field Data**			
4. User-defined relations (suspended sediment)	**0**	**11.7314**	**0.7958**	**Power**	**Field Data**	Notes: Utilized Reduced Flow up to Measured Limits of Sediment Data. Bankfull Flow > Max. Discharge		

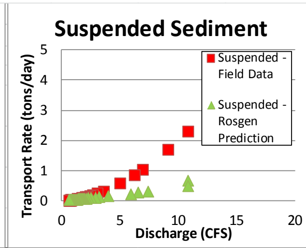
Dimensioned Flow-Duration Curve							Sediment Field Data				Calculate	Sediment Yield from Field Data		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(9)	(11)	(12)	(13)	(14)	(15)
Flow exceedence	Daily mean discharge	Mid-ordinate	Time increment (percent)	Time increment (days)	Mid-ordinate streamflow	Dimension-less streamflow	Suspended Sediment Conc.	Suspended sediment discharge	Bedload Tansport Rate	Bedload	Time adjusted streamflow	Suspended sediment [(5)×(9)]	Bedload sediment [(5)×(11)]	Suspended + bedload [(13)+(14)]
(%)	(cfs)	(%)	(%)	(days)	(cfs)	(Q/Q_{bkf})	(mg/l)	(tons/day)	(kg/d)	(tons/day)	(cfs)	(tons)	(tons)	(tons)
0.0%	24.70													
0.2%	24.70	0.1%	0%	0.69	24.70	0.49	151	10	3974	4	0.05	7	3	10
0.4%	16.50	0.1%	0%	0.73	20.60	0.41	130	7	2751	3	0.04	5	2	7
0.6%	14.32	0.1%	0%	0.75	15.41	0.31	103	4	1528	2	0.03	3	1	4
0.8%	12.16	0.1%	0%	0.75	13.24	0.26	92	3	1124	1	0.03	2	1	3
2%	7.51	0.5%	1%	3.67	9.84	0.20	72	2	615	1	0.10	7	2	10
3%	5.44	0.5%	1%	3.67	6.48	0.13	52	1	264	0	0.07	3	1	4
4%	4.42	0.5%	1%	3.67	4.93	0.10	42	1	152	0	0.05	2	1	3
5%	3.44	0.5%	1%	3.67	3.93	0.08	35	0	96	0	0.04	1	0	2
6%	2.66	0.5%	1%	3.67	3.05	0.06	28	0	57	0	0.03	1	0	1
7%	2.22	0.5%	1%	3.67	2.44	0.05	24	0	37	0	0.02	1	0	1
8%	1.92	0.5%	1%	3.67	2.07	0.04	21	0	26	0	0.02	0	0	1
9%	1.65	0.5%	1%	3.67	1.79	0.04	19	0	19	0	0.02	0	0	0
10%	1.47	0.5%	1%	3.67	1.56	0.03	17	0	15	0	0.02	0	0	0
11%	1.30	0.5%	1%	3.67	1.39	0.03	15	0	12	0	0.01	0	0	0
12%	1.20	0.5%	1%	3.67	1.25	0.03	14	0	9	0	0.01	0	0	0
13%	1.09	0.5%	1%	3.67	1.15	0.02	13	0	8	0	0.01	0	0	0
14%	1.01	0.5%	1%	3.67	1.05	0.02	12	0	7	0	0.01	0	0	0
16%	0.90	1.0%	2%	7.33	0.96	0.02	11	0	5	0	0.02	0	0	0
18%	0.83	1.0%	2%	7.33	0.87	0.02	10	0	4	0	0.02	0	0	0
20%	0.78	1.0%	2%	7.33	0.81	0.02	10	0	4	0	0.02	0	0	0
22%	0.75	1.0%	2%	7.33	0.77	0.02	9	0	3	0	0.02	0	0	0
24%	0.73	1.0%	2%	7.33	0.74	0.01	9	0	3	0	0.01	0	0	0
26%	0.71	1.0%	2%	7.33	0.72	0.01	9	0	3	0	0.01	0	0	0
28%	0.71	1.0%	2%	7.33	0.71	0.01	9	0	3	0	0.01	0	0	0
30%	0.70	1.0%	2%	7.33	0.71	0.01	9	0	3	0	0.01	0	0	0
32%	0.70	1.0%	2%	7.33	0.70	0.01	9	0	3	0	0.01	0	0	0
36%	0.70	2.0%	4%	14.63	0.70	0.01	9	0	3	0	0.03	0	0	0
40%	0.70	2.0%	4%	14.63	0.70	0.01	9	0	3	0	0.03	0	0	0
44%	0.70	2.0%	4%	14.63	0.70	0.01	9	0	3	0	0.03	0	0	0
48%	0.70	2.0%	4%	14.63	0.70	0.01	9	0	3	0	0.03	0	0	0
52%	0.70	2.0%	4%	14.63	0.70	0.01	9	0	3	0	0.03	0	0	0
56%	0.70	2.0%	4%	14.63	0.70	0.01	9	0	3	0	0.03	0	0	0
60%	0.70	2.0%	4%	14.63	0.70	0.01	9	0	3	0	0.03	0	0	0
70%	0.70	5.0%	10%	36.50	0.70	0.01	9	0	3	0	0.07	1	0	1
80%	0.70	5.0%	10%	36.50	0.70	0.01	9	0	3	0	0.07	1	0	1
90%	0.70	5.0%	10%	36.50	0.70	0.01	9	0	3	0	0.07	1	0	1
100%	0.70	5.0%	10%	36.50	0.70	0.01	9	0	3	0	0.07	1	0	1
											Annual totals:	**40** (tons/yr)	**14** (tons/yr)	**54** (tons/yr)
			100%	*365*	*days*									

Figure Q.5. FLOWSED worksheet for existing conditions at key monitoring location WB2.

Stream:	West Branch - Ruddiman Creek	Location:	WB-2 Benchmark Scenario			Date:	10/16/12
Observers:	DF2	Gage Station #:	NA	Stream Type:		Valley Type:	

Equation type	Intercept	Coefficient	Exponent	Form (e.g., Linear, Power, etc.)	Equation name	Bankfull Discharge	Bankfull Bedload	Bankfull Suspended
1. Bedload (dimensionless)	-0.0113	1.0139	2.1929	Non-Linear	"Good/Fair" Pagosa	40 cfs	0.122105 kg/s	220.9 mg/l
2. Suspended sediment (dimensionless)	0.0636	0.9326	2.4085	Non-Linear	"Good/Fair" Pagosa		11.63 ton/day	6.9E-06 tn/cf
3. User-defined relations (bedload)	0	6.0017	2.0255	Power	Field Data			
4. User-defined relations (suspended sediment)	0	11.7314	0.7958	Power	Field Data	Notes: Utilized Reduced Flow up to Measured Limits of Sediment Data. Bankfull Flow > Measured Max. Discharge		





Dimensioned Flow-Duration Curve							Sediment Field Data				Calculate	Sediment Yield from Field Data			Rosgen Sediment Rating Curves				Sediment Yield from Rosgen		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(9)	(11)	(12)	(13)	(14)	(15)	(8)	(9)	(10)	(11)	(13)	(14)	(15)
Flow exceedence	Daily mean discharge	Mid-ordinate	Time increment (percent)	Time increment (days)	Mid-ordinate streamflow	Dimension-less streamflow	Suspended Sediment Conc.	Suspended sediment discharge	Bedload Tansport Rate	Bedload	Time adjusted streamflow	Suspended sediment [(5)×(9)]	Bedload sediment [(5)×(11)]	Suspended + bedload [(13)+(14)]	Dimension-less suspended sediment discharge	Suspended sediment discharge	Dimension-less bedload discharge	Bedload	Suspended sediment [(5)×(9)]	Bedload sediment [(5)×(11)]	Suspended + bedload [(13)+(14)]
(%)	(cfs)	(%)	(%)	(days)	(cfs)	(Q/Q_{bkf})	(mg/l)	(tons/day)	(kg/d)	(tons/day)	(cfs)	(tons)	(tons)	(tons)	(S/S_{bkf})	(tons/day)	(b_s/b_{bkf})	(tons/day)	(tons)	(tons)	(tons)
0.0%	10.86																				
0.2%	10.86	0.1%	0%	0.69	10.86	0.27	78	2	752	1	0.02	2	1	2	0.10	1	0.05	1	0	0	1
0.4%	7.40	0.1%	0%	0.73	9.13	0.23	68	2	529	1	0.02	1	0	2	0.09	0	0.03	0	0	0	1
0.6%	6.53	0.1%	0%	0.75	6.97	0.17	55	1	306	0	0.01	1	0	1	0.08	0	0.01	0	0	0	0
0.8%	5.98	0.1%	0%	0.75	6.26	0.16	50	1	246	0	0.01	1	0	1	0.07	0	0.01	0	0	0	0
2%	3.99	0.5%	1%	3.67	4.99	0.12	42	1	155	0	0.05	2	1	3	0.07	0	0.00	0	1	0	1
3%	3.26	0.5%	1%	3.67	3.63	0.09	33	0	81	0	0.04	1	0	2	0.07	0	0.00	0	1	0	1
4%	2.88	0.5%	1%	3.67	3.07	0.08	29	0	58	0	0.03	1	0	1	0.07	0	0.00	0	0	0	0
5%	2.56	0.5%	1%	3.67	2.72	0.07	26	0	46	0	0.03	1	0	1	0.07	0.1	0.00	0.00	0	0	0
6%	2.32	0.5%	1%	3.67	2.44	0.06	24	0	37	0	0.02	1	0	1	0.06	0.1	0.00	0.00	0	0	0
7%	2.14	0.5%	1%	3.67	2.23	0.06	22	0	30	0	0.02	0	0	1	0.06	0.1	0.00	0.00	0	0	0
8%	1.99	0.5%	1%	3.67	2.07	0.05	21	0	26	0	0.02	0	0	1	0.06	0.1	0.00	0.00	0	0	0
9%	1.90	0.5%	1%	3.67	1.95	0.05	20	0	23	0	0.02	0	0	0	0.06	0.1	0.00	0.00	0	0	0
10%	1.81	0.5%	1%	3.67	1.86	0.05	19	0	21	0	0.02	0	0	0	0.06	0.1	0.00	0.00	0	0	0
11%	1.72	0.5%	1%	3.67	1.77	0.04	18	0	19	0	0.02	0	0	0	0.06	0.1	0.00	0.00	0	0	0
12%	1.65	0.5%	1%	3.67	1.69	0.04	18	0	17	0	0.02	0	0	0	0.06	0.1	0.00	0.00	0	0	0
13%	1.59	0.5%	1%	3.67	1.62	0.04	17	0	16	0	0.02	0	0	0	0.06	0.1	0.00	0.00	0	0	0
14%	1.53	0.5%	1%	3.67	1.56	0.04	17	0	15	0	0.02	0	0	0	0.06	0.1	0.00	0.00	0	0	0
16%	1.43	1.0%	2%	7.33	1.48	0.04	16	0	13	0	0.03	0	0	1	0.06	0.1	0.00	0.00	0	0	0
18%	1.34	1.0%	2%	7.33	1.39	0.03	15	0	12	0	0.03	0	0	1	0.06	0.1	0.00	0.00	0	0	0
20%	1.26	1.0%	2%	7.33	1.30	0.03	14	0	10	0	0.03	0	0	0	0.06	0.0	0.00	0.00	0	0	0
22%	1.17	1.0%	2%	7.33	1.22	0.03	14	0	9	0	0.02	0	0	0	0.06	0.0	0.00	0.00	0	0	0
24%	1.10	1.0%	2%	7.33	1.14	0.03	13	0	8	0	0.02	0	0	0	0.06	0.0	0.00	0.00	0	0	0
26%	1.03	1.0%	2%	7.33	1.07	0.03	12	0	7	0	0.02	0	0	0	0.06	0.0	0.00	0.00	0	0	0
28%	0.97	1.0%	2%	7.33	1.00	0.03	12	0	6	0	0.02	0	0	0	0.06	0.0	0.00	0.00	0	0	0
30%	0.93	1.0%	2%	7.33	0.95	0.02	11	0	5	0	0.02	0	0	0	0.06	0.0	0.00	0.00	0	0	0
32%	0.89	1.0%	2%	7.33	0.91	0.02	11	0	5	0	0.02	0	0	0	0.06	0.0	0.00	0.00	0	0	0
36%	0.87	2.0%	4%	14.63	0.88	0.02	11	0	5	0	0.04	0	0	0	0.06	0.0	0.00	0.00	0	0	0
40%	0.83	2.0%	4%	14.63	0.85	0.02	10	0	4	0	0.03	0	0	0	0.06	0.0	0.00	0.00	0	0	0
44%	0.80	2.0%	4%	14.63	0.82	0.02	10	0	4	0	0.03	0	0	0	0.06	0.0	0.00	0.00	0	0	0
48%	0.78	2.0%	4%	14.63	0.79	0.02	10	0	4	0	0.03	0	0	0	0.06	0.0	0.00	0.00	0	0	0
52%	0.75	2.0%	4%	14.63	0.77	0.02	9	0	3	0	0.03	0	0	0	0.06	0.0	0.00	0.00	0	0	0
56%	0.73	2.0%	4%	14.63	0.74	0.02	9	0	3	0	0.03	0	0	0	0.06	0.0	0.00	0.00	0	0	0
60%	0.70	2.0%	4%	14.63	0.72	0.02	9	0	3	0	0.03	0	0	0	0.06	0.0	0.00	0.00	0	0	0
70%	0.70	5.0%	10%	36.50	0.70	0.02	9	0	3	0	0.07	1	0	1	0.06	0.0	0.00	0.00	1	0	1
80%	0.70	5.0%	10%	36.50	0.70	0.02	9	0	3	0	0.07	1	0	1	0.06	0.0	0.00	0.00	1	0	1
90%	0.70	5.0%	10%	36.50	0.70	0.02	9	0	3	0	0.07	1	0	1	0.06	0.0	0.00	0.00	1	0	1
100%	0.70	5.0%	10%	36.50	0.70	0.02	9	0	3	0	0.07	1	0	1	0.06	0.0	0.00	0.00	1	0	1
			100%	365 days							Annual totals:	20 (tons/yr)	5 (tons/yr)	25 (tons/yr)				Annual totals:	16 (tons/yr)	1 (tons/yr)	16 (tons/yr)

Figure Q.6. FLOWSED worksheet for <u>projected</u> conditions resulting from the BMP benchmark scenario at key monitoring location WB2.