U.S. Army Corps of Engineers
Detroit District

Clinton River Sediment Transport Modeling Study

Prepared by
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Prepared for:

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LIST OF ACRONYMS

ADE	Alternating Direction Explicit
ADE-PC	Alternating Direction Explicit with Prediction-Correction
AOC	Area of Concern
ASCE	American Society of Civil Engineers
AVSWAT	ArcView SWAT
BASINS	Better Assessment Science Integrating Point & Nonpoint Sources
BMP	Best Management Practice
CN	Curve Number
CRWC	Clinton River Watershed Council
CWMS	Clinton River Watershed Modeling System
DEM	Digital Elevation Model
DEQ	Department of Environmental Quality
EFDC	Environmental Fluid Dynamics Computer Code
ELP	Empirically based, Lumped Parameter models
EPA	Envrionmental Protection Agency
ERDC	Engineer Research and Development Center
GA	Green and Ampt
GAR	Green and Ampt with Redistribution
GIS	Geographic Information System
GSSHA	Gridded Surface-Subsurface Hydrologic Analysis
HC	Hydraulic Conductivity
HD	Hydrodynamic
HRU	Hydrologic Response Unit
MLGA	Multi-layer Green and Ampt
MUSLE	Modified Universal Soil Loss Equation
NED	National Elevation Dataset
NLCD	National Land Cover Dataset
NOAA	National Oceanic and Atmospheric Agency
NPS	Non-point Source
NRCS	Natural Resources Conservation Service
NSI	National Sediment Inventory
NWS	National Weather Service
PCB	Polychlorinated Biphenyl
PDE	Partial Differential Equation
PDP	Physically-based, Distributed Parameter Models
PE	Point Explicit
RAP	Remedial Action Plan
SCS	Soil Conservation Service
SEMCOG	Southeast Michigan Council of Governments
SSL	Suspended Sediment Load
ST	Sediment Transport
STORET	STOrage and RETrieval
SWAT	Soil Water Assment Tool
SWRRB	Simulator for Water Resources in Rural Basins
TIN	Triangulated Irregular Network
TMDL	Total Maximum Daily Load
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USDA-ARS	United States Department of Agriculture - Agriculatural Research Station
USEPA	United States Environmental Protection Agency
USGS	United States Geologic Survey
USLE	Universal Soil Loss Equation
WCS	Watershed Characterization System
WERF	Water Environmental Research Foundation
WY	Water Year

EXECUTIVE SUMMARY

The U.S. Army Corps of Engineers is directed to develop sediment transport models for tributaries to the Great Lakes that discharge to Federal navigation channels or Areas of Concern (AOCs). These models are being developed to assist State and local resource agencies in evaluating alternatives for soil conservation and non-point source pollution prevention in the tributary watersheds. The ultimate goal is to support State and local measures that will reduce the loading of sediments to navigation channels and AOCs, and thereby reduce the costs for navigation maintenance and sediment remediation. This report includes a description of the Clinton River Watershed and the modeling tools that were developed and tested during the course of this study.

The Clinton River is located just north of Detroit in southeastern Michigan. The main channel traverses 80 miles (128 km) from its headwaters in the western portion of the watershed, to Lake St. Clair near the city of Mt. Clemens. The watershed covers 760 square miles (1,968 km^2) of southeastern Michigan, including portions of Oakland and Macomb Counties and small areas of St. Clair and Lapeer Counties. The watershed is home to more than 1.6 million people in 56 municipalities. The southern portion of the watershed is dominantly urban, the middle section is undergoing rapid development of suburban land use, and the northern region is primarily agricultural and forested. The condition of the river and its tributaries varies dramatically, from runoff and pollution problems in urban areas, to healthier waters with thriving trout fisheries in rural areas.

The diversion canal in the downstream reach of the river is an important control on water and sediment movement in the lower watershed, and it also has a significant impact on sediment delivery to Lake St. Clair. The intent of the diversion canal was to alleviate flooding problems in Mt. Clemens. The diversion is controlled by an adjustable weir, which allows for the necessary flood conveyance in times of excess river flow, while forcing the flow down the original river channel during low flow. A detailed investigation of the impact of the canal and diversion structure on water and sediment transport is provided in Section 6 of this report.

There are no direct measurements of soil erosion or sediment delivery within the Clinton River Watershed. However, it is possible to estimate likely sediment yield and sediment delivery ratio for the Clinton River Watershed using basic relationships found in general watershed geomorphology literature. In addition, sediment yield estimates were generated using the Clinton River Watershed Model System (CWMS) developed during this study. There is a broad range in sediment yield estimates due to the large variation in methodologies used to estimate watershed soil erosion and channel sediment loads.

To assess potential management problems and to evaluate a wide range of best management practices (BMPs), a set of computational tools were used to study watershed hydrology, soil erosion, sediment delivery, river channel hydrodynamics and sediment transport. These models provide a general understanding of the hydrologic and geomorphic behavior of the watershed, allowing the prediction of the relative effects of changing land use and the effectiveness of different best management practice (BMP) strategies on subwatershed scale, soil erosion and sediment yield.

The three hydrologic models (WCS, SWAT, GSSHA) in the CWMS simulate overland flow generation, sediment detachment (soil erosion) and sediment yield from the watershed. They use input data from the Clinton River Watershed GIS and use a variety of modeling approaches to represent watershed processes. Each model has a different range of applicability and all three were necessary to characterize the different aspects of watershed processes examined in this study.

Land use and land use change are key factors governing soil erosion and sediment yield in this watershed. Cultivated and grazed land is shown to be the greatest non-point source of sediment, while developed land leads to flashy river flow. Urban and suburban development is likely to increase soil erosion (especially from construction sites) in the future, and this may be combined with greater riverbed and bank erosion from a flashier river regime to increase sediment yield. However, a reduction in the amount of sediment available for transport once an area is urbanized may serve to counteract this.

Urbanization affects soil erosion rates by potentially reducing the sediment available to be entrained from hillslopes, although this depends on many factors, such as the nature of the storm drainage system, degree of buffering, type of sewer outfalls, housing lot structure, etc. While process-response models suggest an inverse relationship between urbanization, soil erosion and sediment yield, these models ignore the mitigating effect of intrabasinal storage and/or sediment conveyance rates. In particular, increased flashiness of the urban hydrograph may be enough to trigger river channel instability and therefore increased channel erosion may balance reduced hillslope erosion.

Many watersheds have experienced high population growth rates during the post-war period, yet sediment yields are not strongly correlated to population or new housing development. Sediment yield, in general, is strongly controlled by the occurrence of peak flows. This implies that changes in sediment conveyance rates can mask changes in land use practices and vice-versa. In a broader context, this underscores the need to address anthropogenic impacts on watershed sediment yield when considering BMP actions. Obviously, future sediment yield is an important component in land use planning, and to state simply that urbanization reduces sediment yield would undermine the need for careful consideration of process interactions as urban development takes place.

Increased sedimentation rates may also be expected in the relatively flat, lower section of the watershed as development continues. These factors serve to stress the importance of appropriate choices of BMPs in this watershed and highlight the utility of using a numerical modeling approach for evaluating their implementation.

Direct assessment of sediment yield and sediment delivery from empirical evidence was not possible in the Clinton River Watershed. Comparison of catchment baseline conditions (such as drainage area; effective precipitation etc.) with empirical relationships established by other studies give estimates of sediment yield in the order of 200-600 t/km^2 yr^{-1}.

The SWAT model predicts average net erosion for the years 1990-1994 of 380 t/km^2 yr^{-1}. This value seems reasonable, compared to the empirical estimates above. Mean annual sediment delivery at the SWAT model outlet (near gage #04165500) for 1990-1994 was 539,000 t/yr, giving an estimated sediment yield of 270 t/km^2 yr^{-1}.

Estimates of watershed sediment load using rating curves for the most downstream station in other Great Lakes watersheds have suggested sediment yields of 15-100 t/km^2 yr^{-1}. Mean daily suspended sediment load at USGS Gage #04165500 is 82.8 t/day, suggesting a mean annual suspended sediment delivery in the region of 30,000 t/yr. This leads to an estimate of mean annual suspended sediment yield of 16 t/km^2 yr^{-1} at this point in the watershed. The main cause of lack of agreement between sediment yields derived from empirical relationships, model predictions and rating curve analysis is unclear at present. This ambiguity reflects the lack of sediment load data within the watershed.

Substantial portions of the watershed have undergone a shift from primarily agricultural to urban land use. A flashiness index was computed for all stream gage records in the Clinton River Watershed that had a minimum of 20 years of data. The results indicate that several of the gages in the southern portion of the watershed have shown marked increases in flashiness since 1970. Other gages have remained steady or show minor decreases in flashiness with time. As expected, this suggests that there is a close link between the development of land in the southern part of the watershed and an increase in flashiness. The reduction in flashiness elsewhere in the catchment may be explained by a shift from agricultural to forestland use causing a decline in overland flow, through flow and therefore rapid hydrograph response.

There are several processes by which increased flashiness in hydrograph response may increase sediment loads in the watershed. Increased flashiness suggests increased overland flow, increasing erosion rates and increasing sediment transport from hillslope to channel. This may be balanced by a shift from agricultural to urban land uses, which may reduce sediment supply at the hillslope scale. Urban runoff may contain significant amounts of sediment, pollutants and nutrients if stormflow through sewers is left untreated before it discharges into the river channel. In addition, developed land has often meant the eradication of buffer strips by riparian landowners, which may cause a significant increase in the amount of sediment reaching a river channel.

A wide variety of BMP alternatives were evaluated using the CWMS. The large-scale effects of changing land use over time on watershed sediment yield and sediment delivery were investigated using the SWAT model. Analysis of the relative effectiveness of riparian buffer strips was the most extensive of the BMP analyses. Different buffer widths and vegetative types were evaluated for different land use types surrounding the buffer zone using the GSSHA model. This analysis identified the most effective vegetative types for buffer implementations as well as sensitivity to the different vegetation types and buffer widths. Variations in vegetation cover did not produce as much variation in sediment delivery as changes to buffer width.

Change in urban density was evaluated by changing lot sizes within the GSSHA hydrologic model. GSSHA predicted that with increasing urban density, runoff plays a more important role in erosion than the available sediment for erodibility. In other words, although the erodible soil would be reduced with urbanization (lawns and driveways) the increased runoff provides a more erosive mechanism for sediment transport.

In an ideal situation there would be sufficient sediment and flow data to calibrate the models. It is usually the case that these data are very limited, thus a more thorough quantitative calibration of the model is of questionable merit until further sediment load data are available. However, the lack of final calibration of the model system does not necessarily diminish the usefulness of the system in BMP planning as the system still allows for comparison of different management options and scenarios.

The different numerical models implemented for this watershed have different functional advantages and disadvantages; thus the generation of a watershed modeling system provides the advantage of a versatile and integrated tool to aid in the management of the basin. It is recommended that this set of tools is applied with due diligence since the interpretation of model results requires experience in the fields of hydrology, geomorphology and sediment dynamics.

SWAT is a very useful tool for long-term, large-scale watershed modeling. The input data for SWAT are readily available and the model can be calibrated to measured data with a reasonable amount of effort. The ability of SWAT to simulate nutrients and contaminants makes it a valuable tool for comprehensive watershed management and BMP evaluation.

The application of GSSHA at a subwatershed scale provided results reasonably similar to measured flow data. The effort required for this analysis is relatively high and should be applied for short-term simulations such as storm events or hypothetical situations to evaluate land use changes. The application of GSSHA to assess wetlands and sediment traps was not effective with the current version. However, a new edition of GSSHA, which has the built-in capability to account for wetlands, lakes and reservoirs, is released as a beta version.

The three-dimensional channel hydrodynamics and sediment transport model EFDC was useful in assessing hydrodynamics and sediment transport in the Lower Clinton River. However, it is a computationally intensive tool and should be applied for very specific purposes such as assessing the impact of the inflatable weir on channel sedimentation. Increased urbanization and flashiness of the river system (especially without adequate BMPs to compensate) may cause further challenges to the management of water and sediment in the Lower Clinton River. This is in turn related to management of the inflatable weir. EFDC could play an important role in informing the future active control of the weir to address related sedimentation and flooding issues.

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1.0 INTRODUCTION

1.1 Purpose

The U.S. Army Corps of Engineers is directed to develop sediment transport models for tributaries to the Great Lakes that discharge to Federal navigation channels or Areas of Concern (AOCs). These models are being developed to assist State and local resource agencies in evaluating alternatives for soil conservation and non-point source pollution prevention in the tributary watersheds. The ultimate goal is to support State and local measures that will reduce the loading of sediments to navigation channels and AOCs, and thereby reduce the costs for navigation maintenance and sediment remediation. This report includes a description of the Clinton River Watershed and the modeling tools that were developed and tested during the course of this study.

1.2 Watershed Description

The Clinton River is located just north of Detroit in southeastern Michigan. The main channel traverses 80 miles (128 km) from its headwaters in the western portion of the watershed, to Lake St. Clair near the city of Mt. Clemens. The watershed covers 760 square miles (1,968 km^2) of southeastern Michigan, including portions of Oakland and Macomb Counties and small areas of St. Clair and Lapeer Counties. The basin has two distinct topographic regions, the upper half, which has more relief and steeper channels, and the lower half, characterized by flatter topography and channel slopes. Although the entire basin covers parts of four counties, the two regions coincidentally occupy different political boundaries as well. The upper region lies predominantly in Oakland and Lapeer Counties, and the lower region in Macomb and St. Clair Counties (Figure 1.1).

The watershed is home to more than 1.6 million people in 56 municipalities. The urban development status within the watershed is varied: the southern portion is urban, the middle section is made up of rapidly developing suburbs and the northern region is rural. The condition of the river and its tributaries varies dramatically, from runoff and pollution problems in urban areas, to healthier waters with thriving trout fisheries in rural areas. Sediment, stormwater quantity, and bacteria continue to be the most prominent pollutants challenging water quality and habitat.

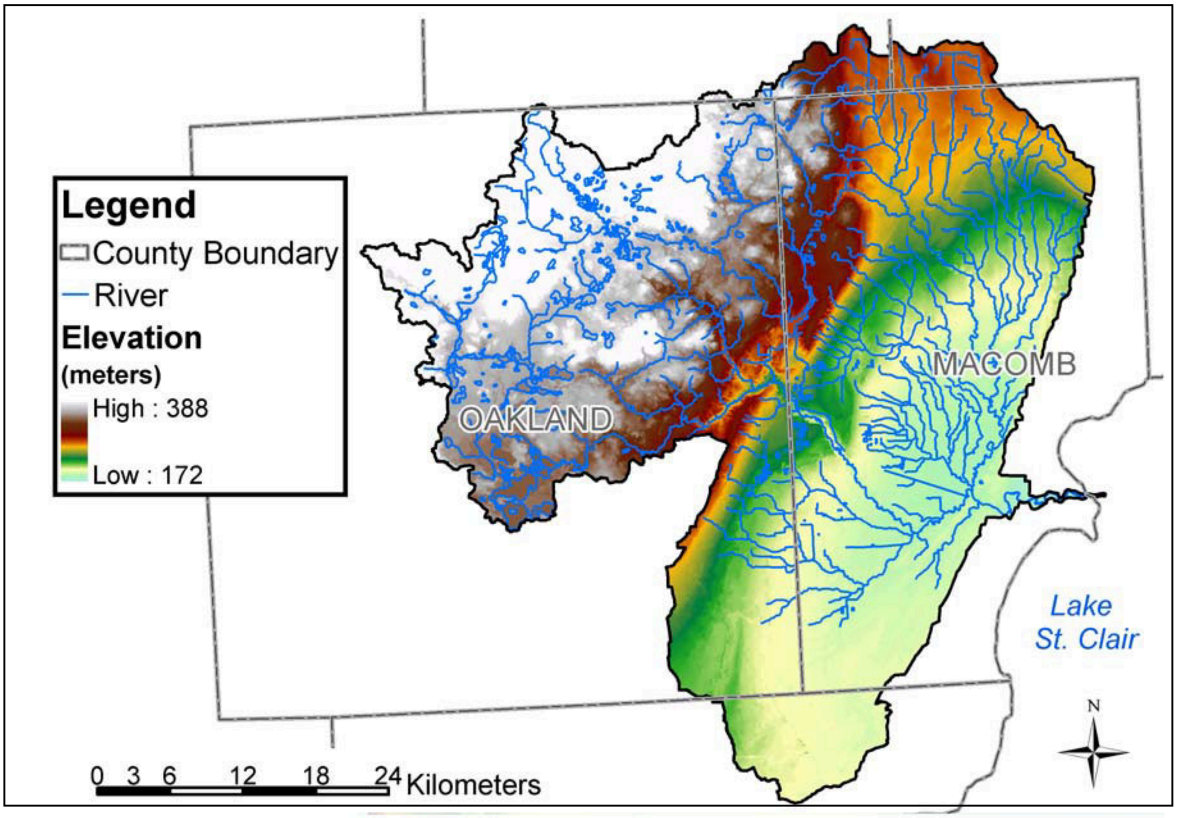

Figure 1.1 Basin Topography

The diversion canal in the downstream reach of the river is an important control on water and sediment movement in the lower watershed, and it also has a significant impact on sediment delivery to Lake St. Clair. The intent of the diversion canal was to alleviate flooding problems in Mt. Clemens. While the diversion canal provided flooding relief, it has required modification in more recent years to facilitate active control over the diversion. The control is provided by an adjustable weir, which allows for the necessary conveyance in times of excess river flow, while forcing the flow down the original river channel during low flow. The structure (as originally built) diverted too much of the low flow down the bypass channel, which resulted in unacceptably low flow rates down the original channel during dry weather. The same phenomenon was also partially responsible for the buildup of sediments upstream of the diversion structure. A detailed investigation of the impact of the canal and diversion structure on water and sediment transport is provided in Section 6 of this report.

1.3 Clinton River Watershed Sediment Delivery

Sediment in a river can be transported by two processes: suspension and bedload transport. Suspended sediment load in the watershed is usually dominated by clay- and silt-sized particles. Typical natural processes involved in the erosion and delivery of suspended sediment are:

- Overland flow;
- Sheet and rill erosion;
- Gully erosion;
- Riverbed erosion;
- River bank erosion, particularly shearing of fine material by river flow, and bank collapse.

These processes are generally distinguished into channel and non-channel sources and also into point and non-point sources. They may be accelerated by human activity in the catchment, as agriculture, industry and construction tend to mobilize and supply additional sediment to the watershed. In agricultural regions, soil loss from cultivated areas may dominate watershed suspended sediment delivery.

The relative contributions of the above different processes vary with location in the watershed. Headwaters of the catchment have steeper slopes without floodplains, and these areas are strongly coupled to channels (i.e. there are few sediment sinks between the source areas and the channel). Non-point sources therefore tend to dominate these areas and sediment is largely from non-channel sources. This may have implications for other watershed management issues, such as non-point source contaminant movement in upper watershed zones. Further downstream, wider floodplains increase temporary sediment storage and the channel becomes increasingly decoupled from the surrounding hillslopes. In these areas, in-channel sediment sources dominate.

Various sediment sinks also exist in the catchment. These may be either natural or anthropogenic, and they are often classified into temporary or permanent sinks. An example of the former would be channel storage of sediment in bar deposits, as sediment may be stored for a period of time before being remobilized by a high magnitude event. An example of a permanent sink would be the abstraction of sand or gravel from the channel for use as construction material. Natural sediment sources and sinks are listed in Table 1.1, and anthropogenic sources and sinks are listed in Table 1.2. The natural processes listed in Table 1.1 are likely to be heavily modified by human activity, which may lead to acceleration or reduction of erosion and delivery rates, depending on the type and extent of the modification.

1.3.1 Terminology

The terms ‘sediment yield’ and ‘sediment delivery’ have often been used synonymously, while in other instances have been used to describe different aspects of watershed sediment movement. This section therefore provides definitions of these (and related) terms in order to be consistent throughout this report.

Sediment production (a.k.a. total denudation) is the amount of material made available for transport by weathering processes in a catchment. Note that weathering is an in-situ process and does not imply a movement of sediment through the watershed.

Net erosion is the amount of material mobilized in the catchment by hillslope erosion processes such as sheet and rill erosion. It is synonymous with '**soil erosion**' in this report. While wind erosion can be a significant geomorphic agent in some areas, it was not included in any numerical calculations in this report, and is excluded from soil erosion estimates. Erosion typically has the units of tons/year. Soil erosion may also be expressed as a specific value (i.e. total amount divided by area of measurement) in tons/square mile/year.

Sediment yield is the amount of sediment passing a specified channel location and is influenced by a number of geomorphic processes. It may be substantially less than the amount actually eroded in the basin. Sediment yield is expressed as the total sediment volume delivered to a specified location in the basin, divided by the effective drainage area above that location for a specified period of time. Yield typically has the units of cubic meters/square kilometer/year or tons/square mile/year. Occasionally it is also necessary to estimate yield from a watershed from individual storm events of specified frequency. In some watersheds, single event sediment yields often exceed average annual values by several orders of magnitude.

Sediment delivery is the amount of sediment per year reaching the watershed outlet. It usually has the units of cubic meters/year or tons/year.

Sediment delivery ratio is the sediment yield divided by the gross amount of erosion occurring in the watershed upstream. This typically has values of less than 1.

1.3.2 Sediment Yield and Sediment Delivery

There are no direct measurements of net erosion, sediment yield and sediment delivery within the Clinton River Watershed. However, it is possible to estimate likely sediment yield and sediment delivery ratios for the Clinton River Watershed using basic relationships found in general watershed geomorphology literature. These estimates are intended as background information for the study due to the lack of sediment transport data, and the consequential lack of model calibration data.

Table 1.1 Examples of Natural Sources and Sinks of Sediment

Sources	Sinks
Upland sheet and rill erosion	Colluvial deposition
Upland gully erosion	Redistribution on upland valley slopes
Channel bank erosion (several mechanisms)	Floodplain storage
Channel bed scour	Channel storage
Animal action (e.g. burrowing)	Lakes
Landslides	

Table 1.2 Examples of Anthropogenic Sources and Sinks of Sediment

Sources	Sinks
Cultivated land	Dams and reservoirs
Managed Forests	Sand and gravel extraction
Forest roads	Hedgerow planting
Urban areas – including drainage systems	Vegetation management
Removal of vegetation for construction	Conservation activities
Roads and road drainage systems	Agricultural management (e.g. agroforestry,
Construction sites	contour cultivation, etc.)
Mining	
Mining – Indirect (e.g. land devegetated by smelter fumes	
Spoil Heaps	
Vegetation fires	
Channel modification	
Mismanagement	
Indirect effects (e.g. devegetation through climate change)	

Suspended sediment is normally the dominant component of sediment yield, with the exception of very extreme storm events. Langbein and Schumm (1958) developed a general relationship between effective precipitation and sediment yield for group-averaged data from the United States (Figure 1.2). Effective precipitation is that part of the total hydrograph which constitutes 'quickflow', as in the definition of the Unit Hydrograph (see Dunne & Leopold, 1978 for a review). Effective precipitation is also called 'quickflow', or 'precipitation excess', and is a notion of Hortonian Overland Flow: i.e. it is the proportion of precipitation that is 'effective' in producing rapid response streamflow (stormflow).

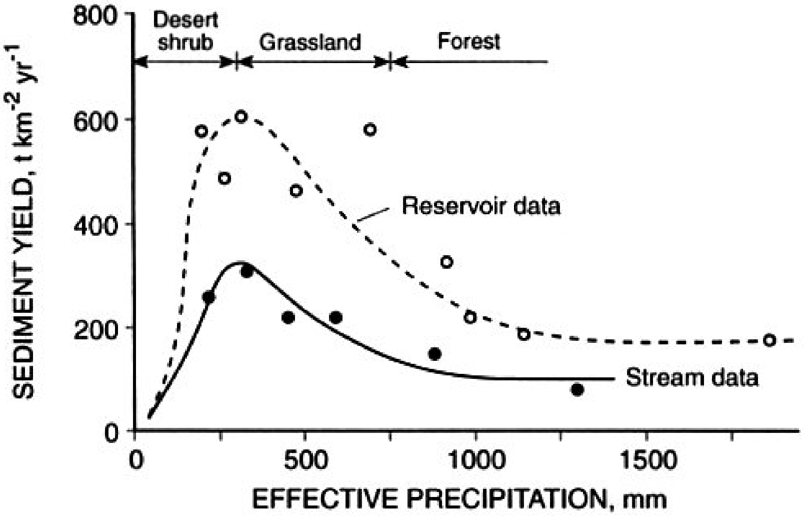

Figure 1.2 Relationship of Sediment Yield to Effective Precipitation (Langbein and Schumm, 1958; Knighton, 1998)

Macomb and Oakland Counties have a mean annual precipitation of 31.5 inches (800mm). 60-70% of this was assumed to be effective precipitation. This estimation was loosely on the SCS curve method (USDA-SCS, 1972). The SCS method requires information concerning the cropping practice, soil characteristics, pre-rainfall moisture status, and the rainfall amount. A visual appraisal of SCS curves suggested that a value of 60-70% was reasonable for this catchment as a first-order approximation. Hydrograph separation was outside the scope of this study and would not have improved confidence in the estimates in this section, given the high degree of approximation involved. The effective precipitation was therefore estimated to be in the range of 480-560 mm, giving an estimated yield of around 200-550 t km^{-2} yr^{-1}. There is a broad range in this estimate due to the large difference in sediment load estimates, depending on whether reservoir or river sediment load data are used to evaluate the relationship. This difference is methodological, and may depend on many issues (such as how reservoirs trap sediment, underestimating channel transport, etc.).

For the relationship established by Walling and Kleo (1979; Figure 1.3), the estimated sediment yield for the Clinton River Watershed would be approximately 200 t km^{-2} yr^{-1}. Langbein and Schumm's relationship was established for semi-arid regions in the American southwest, whereas Walling and Kleo reviewed the validity of the Langbein relationship for a broader range of climatic regimes. While the two relationships are similar in the lower range of precipitation values, Walling and Kleo suggest there is another peak in yield at 1500 mm mean annual precipitation. This is due to vegetation dynamics changing with climate (1300-1500 mm precipitation = Mediterranean and 2500mm = tropical monsoon). Walling and Kleo's analysis may apply more to climates with strong seasonality, and Langbein and Schumm's may be more continental, but both give similar predictions of yield for the Clinton River Watershed.

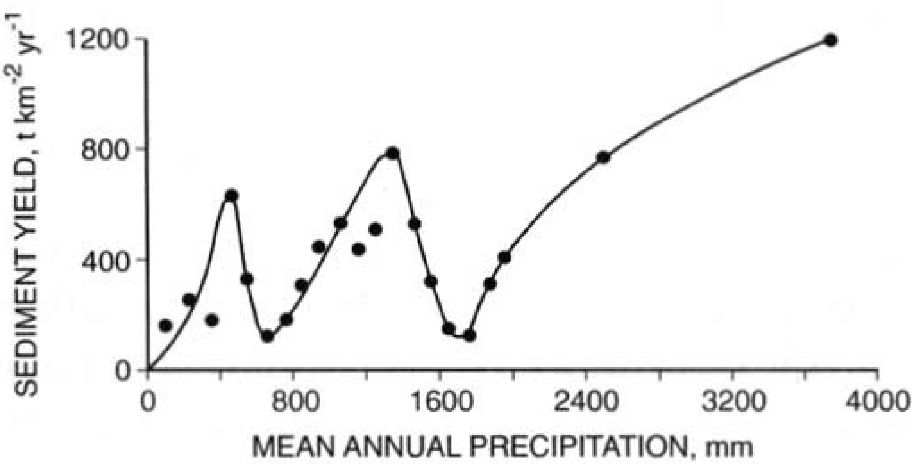

Figure 1.3 Relationship of Sediment Yield to Mean Annual Precipitation (Walling and Kleo, 1979)

The yields suggested by empirical relationships are markedly higher than the yields generated by analysis of sediment rating curves and river gage data from other Great Lakes watersheds (Table 1.3). That figures may in part differ from the large number of dams in these systems, which will reduce yields significantly below natural basins of similar size.

Table 1.3 Summary of Sediment Yields from Other Studies

Watershed	Drainage Area (km^2)	Mean Annual Sediment Yield ($t\ km^{-2}\ yr^{-1}$)
Saginaw River (MI)	22,360	20
St. Joseph River (MI/IN)	12,400	15
Sandusky River (OH)	3,250	75
Black River (OH)	1,200	100
Nemadji River (MN/WI)	1,125	25
Menomonee River (WI)	350	40

The gross sediment yield from a basin will generally represent a small amount of the net erosion within a catchment, since much of the eroded material within a catchment will be deposited before reaching the outlet. The sediment delivery ratio is dependent on a wide range of natural and anthropogenic factors, including:

- Climate;

- Drainage area;
- Basin topography;
- Lithologic structure;
- Vegetation cover;
- Land use and land management.

The relationship between drainage area and sediment delivery ratio for several areas of the world is shown in Figure 1.4. Estimating from relationship six in Figure 1.4, with a drainage area of approximately 2,000 km^2, the expected sediment delivery ratio for the Clinton River Watershed would be approximately 10%.

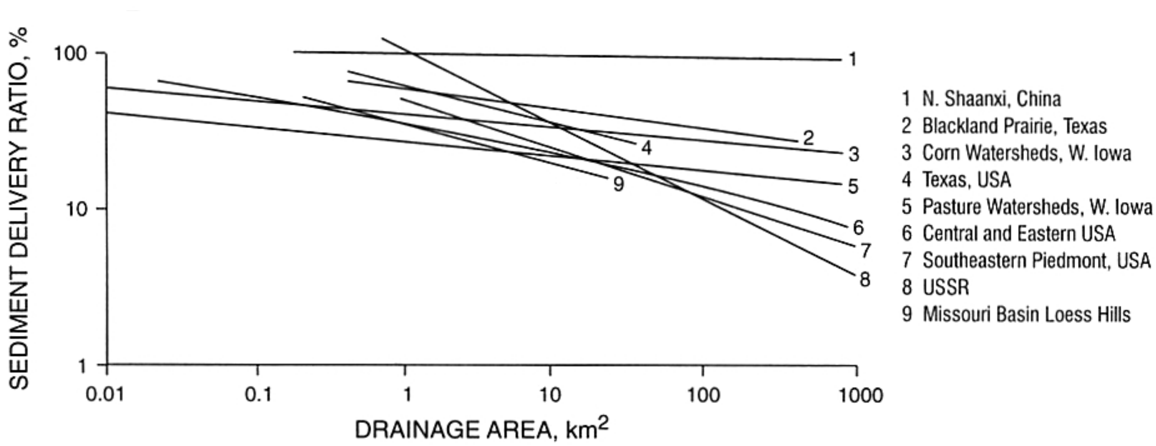

Figure 1.4 Relationship Between Drainage Area and Sediment Delivery Ratio for Different Parts of the World (Walling, 1983; Knighton, 1998)

1.4 Clinton River Watershed Modeling System

To assess the problems outlined above, a set of computational tools were used to evaluate watershed hydrology, net erosion, sediment delivery, river channel hydrodynamics and sediment transport. These models were developed to gain a general understanding of the hydrologic and geomorphic behavior of the watershed and to predict the effects of changing land use and the effectiveness of different best management practice (BMP) strategies on subwatershed scale erosion and sediment delivery. Models were calibrated against river flow and sediment transport records, reservoir sedimentation surveys and harbor dredging records. A summary of the models contained in the Clinton River Watershed Modeling System (CWMS) is presented in Table 1.3. A flow chart outlining the functionality of the CWMS is shown in Figure 1.5, and a map of model domain coverage is shown in Figure 1.6. The range of applicability of each model, the types of management issues each model addresses and the scale and complexity of the processes they represent are summarized in Figure 1.7.

Table 1.4 Summary of Models in the Clinton River Watershed Modeling System

Acronym	Model name	Agency	Processes
SWAT	Soil Water Assessment Tool	USDA / EPA	Hydrology Soil Erosion Sediment Delivery
WCS	Watershed Characterization System	EPA	Hydrology Sediment Yield Sediment Delivery
GSSHA	Gridded Surface-Subsurface Hydrologic Analysis	USACE	Hydrology 1D River Hydrodynamics and Sediment Transport Sediment Yield Sediment Delivery
EFDC	Environmental Fluid Dynamics Computer Code	USEPA	3D River Hydrodynamics Sediment Erosion, Transport and Deposition

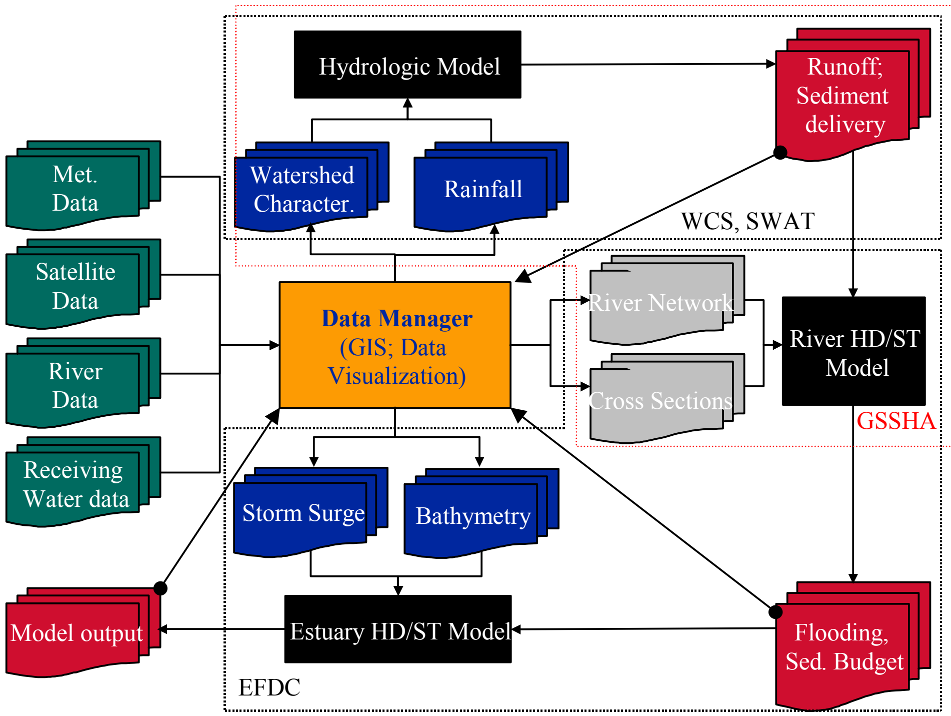

Figure 1.5 General Outline of the Clinton River Watershed Modeling System

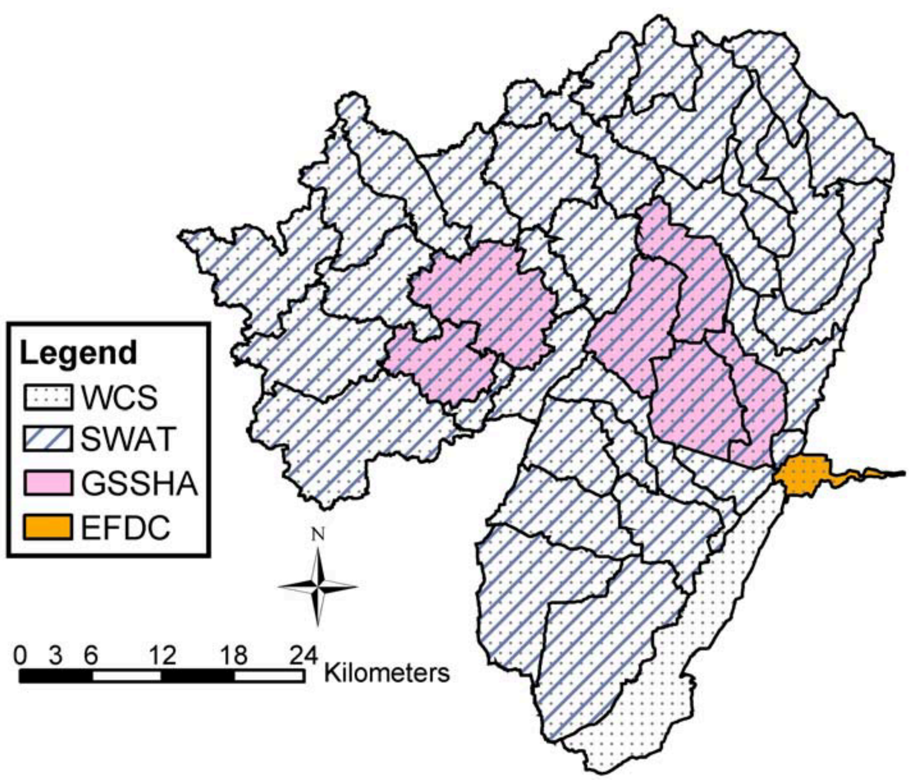

Figure 1.6 Coverage of Model Domains in the Clinton River Watershed Modeling System

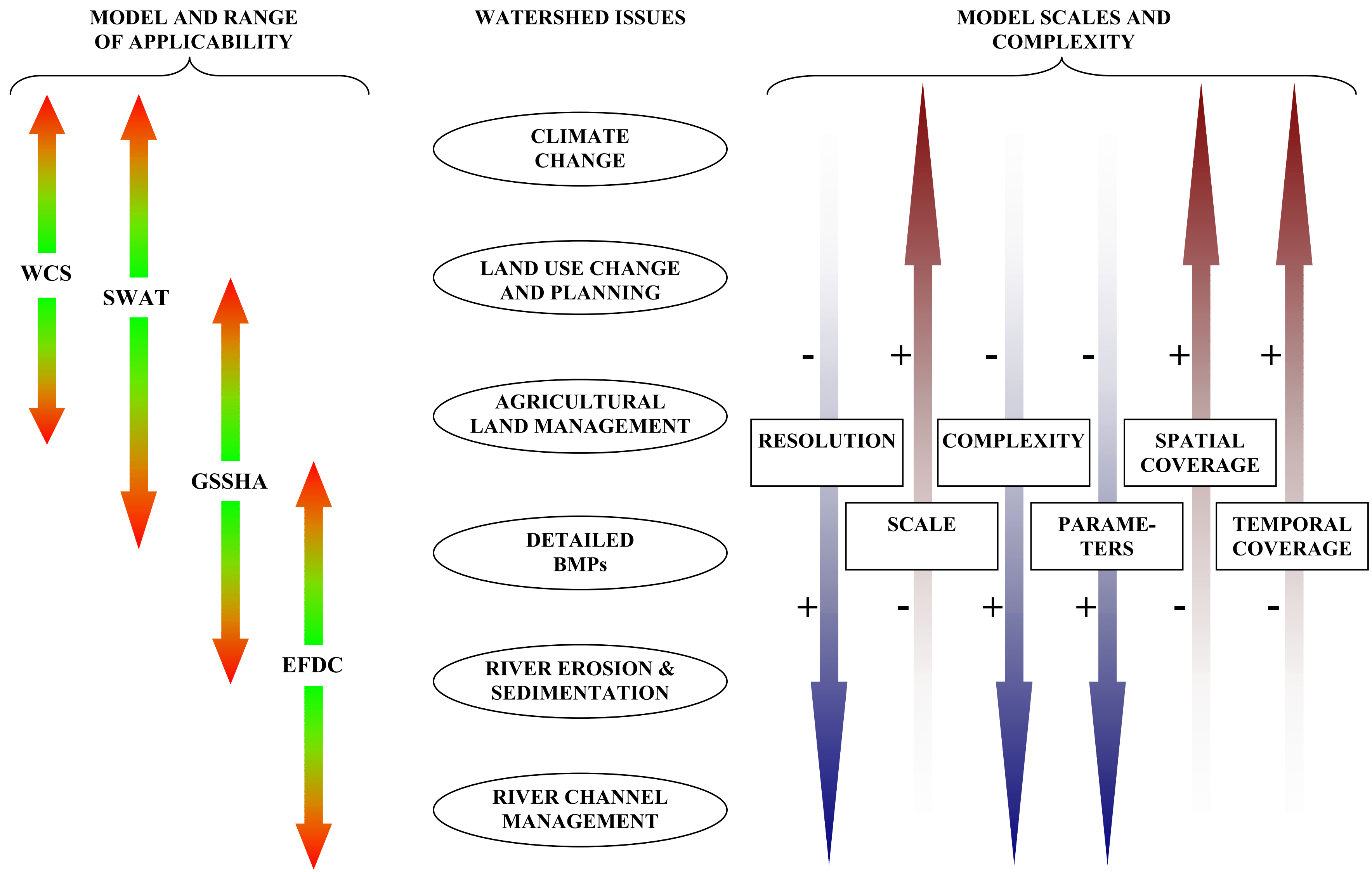

Figure 1.7 Clinton River Watershed Modeling System

1.4.1 Hydrologic Modeling

The three hydrologic models (WCS, SWAT, GSSHA) in the CWMS simulate overland flow generation, soil erosion and sediment delivery from the watershed. They use input data from the Clinton River Watershed GIS and use a variety of modeling approaches to represent watershed processes (Table 1.5). Each model has a different range of applicability and all three were necessary to characterize different aspects of watershed processes examined in this study.

Table 1.5 Summary of CWMS Hydrological Models

Model	Developer	Hydrology	Soil Erosion	Sediment Delivery	Spatial Resolution	Applicability
GSSHA	USACE	PDP / Multi-dimensions	USLE based	Yang (1973) method	Varies details / small catchments	Event / detail plan / detail design
SWAT	USDA/EPA	ELP / PDP	MUSLE	Process / Channel Sediment Routing	Medium / large watershed	Continuous / overview / agriculture practices / climate change / land use
WCS	EPA	ELP	USLE	Distance- and area-based equations	Large watershed	Annual based / quick overview

(ELP - Empirically based, lumped parameter models; PDP - Physically-based, distributed parameter models; USLE – Universal soil loss equation; MUSLE – Modified USLE)

The Watershed Characterization System (WCS) is an Arcview-based system designed to provide tools and an initial set of watershed data for characterizing and thereby understanding a watershed. It can be used to assist users in completing the watershed characterization phase required in developing Total Maximum Daily Loads (TMDLs). This may include:

- Characterization of the physical and hydrologic properties of the watershed, such as soil, land use, elevation, climate, and streamflow.
- Evaluation of ambient water quality conditions, including inventory of monitoring stations and statistical analysis of observed data.

- Assessment of potential sources of impairment, such as permitted dischargers, crop and livestock agriculture, mining, silviculture, and populated places, and preliminary estimation of pollutant loads from these sources.

WCS provides a simple and rapid method for estimating soil erosion and catchment sediment delivery on an average annual basis. For the Clinton River Watershed, results were determined for 41 subbasins within the Clinton River Watershed, based on 1992 land use data. When WCS is used for its intended purpose, in predicting long-term erosion and sediment delivery rates, it performs satisfactorily since the model is based on annual USLE predictions and basic empirical sediment delivery relationships. However, it should not be used on shorter timescales or for event-based predictions. The coarse nature of the WCS grid (30 m) also makes it unsuitable for detailed examinations of best management practices. Section 3.3 contains more detail on the WCS model.

The WCS model was valuable in carrying out a rapid, initial assessment of watershed sediment movement. However, it is limited in that it only predicts average annual sediment delivery rates, which may be predicted in a more flexible manner using SWAT. WCS is therefore not included in the Clinton River Watershed Modeling System that accompanies this report.

The objective of SWAT is to predict the impact of management decisions on water and sediment yields in large complex watersheds. Variation in land use and management conditions over long periods of time can be represented. While the project scope did not include a whole-watershed model using SWAT, this was included instead of the 1D HEC-6 river modeling, which was originally scoped. SWAT is particularly good at modeling NPS-pollution loads from agricultural practices, and routines for urban sediment loads are currently being improved. The grid resolution for SWAT in this project was 30 m. SWAT also has a good interface with GIS software (ArcView), making it suitable for end-user applications. It is physically based and it needs basin-specific data on weather; soil properties; topography; vegetation and land management practices.

SWAT is a continuous time model - not ideally suited to simulate detailed (sub-daily), single-event flood routing. To achieve detailed single-event forecasts, the GSSHA model was set up for the Paint Creek, and Galloway Creek and Middle Branch subbasins of the watershed. A more detailed description of the SWAT model is given in Section 4.2.

Gridded Surface Subsurface Hydrologic Analysis (GSSHA) is a finite difference two-dimensional hydrologic model. Features include 2D overland flow, 1D streamflow, 1D infiltration, 2D groundwater, and full coupling between the groundwater, vadoze zone, streams, and overland flow. GSSHA can run in both single event and long-term modes. The fully coupled groundwater to surface water interaction allows GSSHA to model both Hortonian (infiltration-excess) and Non-Hortonian (saturated) areas.

The GSSHA model is a physically-based, distributed-parameter hydrologic model intended to identify runoff mechanisms and simulate surface water flows in watersheds. The GSSHA model is capable of simulating streamflow generated from Hortonian runoff, saturated source areas, exfiltration, and groundwater discharge to streams. The model employs mass-conserving solutions of partial differential equations (PDEs) and closely links the hydrologic compartments to assure an overall mass balance and correct feedback. GSSHA grid size was 5 m for detailed appraisal of BMP activities and 50-70 m for evaluation of the hydrology of Paint Creek and Galloway Creek. Section 4.4 contains a detailed technical description of the GSSHA model.

1.5 Channel Hydrodynamic and Sediment Transport Modeling

A 3-D hydrodynamic and sediment transport model (EFDC) was constructed of the lower river to assess sedimentation issues in the Lower Clinton River. Environmental Fluid Dynamics Code (EFDC) is a three-dimensional model for the simulation of hydrodynamics, sediment transport, bed change and water quality in rivers, lakes, coastal waters and open seas. The model integrates hydrodynamics, sediment transport, and water quality and can account for the interaction of sediment and water quality.

The main objective of the EFDC modeling exercise was to assess sedimentation processes in the Clinton River from upstream of the hydraulic structure at the flow diversion to the river mouth. The structure at the flow diversion is an inflatable weir that may be raised or lowered according to prevalent flow conditions. The operation of this weir diverts a portion of the river flow into a bypass channel to alleviate flooding in the lower river. Sedimentation may occur upstream of the structure, and in the lower river channel, either as a result of operation of the structure, or due to river low flow conditions or lake seiches. A 3-D model was necessary to accurately simulate flow given the bathymetric complexity of the area, especially around the diversion, and to be able to evaluate features such as flow reversal. EFDC also provides the capability to support future water quality assessment.

This model has the capability for future revisions to input data based on the watershed modeling described in previous sections. For example, revised discharge-sediment rating curves derived from different SWAT land use scenarios could be used to derive new input time series data for EFDC. The EFDC scenarios could then be used to predict likely future sedimentation rates in the lower river with changing watershed sediment yields as a result of urbanization upstream.

1.6 Summary

In summary, the remainder of the report is divided into the following sections:

2.	Data Collection	An identification of data, previous reports and local issues.
3.	Sediment Budget	An initial review of sources, sediment transport pathways and sinks in the watershed.
4.	Hydrology and Sediment Delivery Model Development	Description of setup and testing for SWAT and GSSHA.
5.	Assessment of Best Management Practices	Example applications of the models for evaluating BMPs related to sediment load.
6.	Detailed Instream Sediment Modeling	Description of setup, testing and application the 3D hydrodynamic, sediment transport and morphologic model EFDC for the Lower Clinton River.
7.	Model Integration Description	Recommendation for applications of the different watershed model components.
8.	Conclusions	Discussion of findings on the sediment transport characteristics of the watershed and the ability of the model components to represent these characteristics and anthropogenic influences that can alter these characteristics.

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2.0 DATA COLLECTION

2.1 Introduction

While primary data collection was not a mandate of this study, several sources of data were used throughout this study. These sources included consultation with local stakeholders, review of previous studies, and collation of digital data from a variety of sources. The following sections describe the various data sources in detail.

2.2 Stakeholders Meeting Summary

A stakeholders meeting was held on November 27, 2001 to introduce this study; to provide a forum for sedimentation issues; and to discuss sources of data that could be used to develop numerical models of the hydrologic and geomorphologic processes of the watershed. A number of issues related to the hydrologic and/or geomorphologic condition of the Clinton River Watershed were discussed at the meeting. These issues included:

- The change of the hydrologic response of the basin related to urbanization;
- Bank failure adjacent to landfill – causing exposure of heretofore buried trash;
- Sediment buildup at spillway site – possibly due to changing flow patterns;
- Water quality in Lake St. Clair – noticeable change since construction of spillway;
- Increased urbanization, as evidence by the demolition of Mt. Clemens Rose Gardens;
- Distinct difference in topography between Oakland and Macomb Counties;
- Apparent difference in predominant sediment gradation between counties;
- Leaching of pollutants from existing and potential Superfund sites.

It is noted that it is not the intention of 516e project authorization to specifically solve local problems or issues, but instead to develop a tool that is appropriate for local watershed managers to address as many of the sediment related issues as possible.

2.3 Background and Previous Studies

The Great Lakes Water Quality Agreement between the United States and Canada decreed that Remedial Action Plans (RAP) be developed for 43 Great Lakes basin Areas of Concern. The Clinton River was designated an Area of Concern in 1985 because of contamination by conventional pollutants, including high fecal coliform bacteria and nutrients; high total dissolved solids; sediment contaminants, heavy metals, PCBs, oil and grease; and because of impacted biota. The original AOC boundaries were defined as the main branch of the Clinton River downstream of the Red Run Drain, and the spillway.

The initial Clinton River RAP document was completed in 1988. The authors concluded that most of the identified problems in the Clinton River were localized, and not impacting the Great Lakes. The 1988 RAP recommended 23 actions to address environmental degradation. During 1994, a RAP Team and three technical work groups (Point Sources/Non-point Sources, Habitat, and Contaminated Sediments) convened to direct effort towards RAP activities and to develop the RAP Update. The AOC boundaries were redefined to encompass the entire watershed. This resulted in a set of 84 recommended actions in the 1995 RAP Update. Work group members were again convened in 1997 to produce the 1998 RAP Update. Two new groups were also added (Recreation and Education/Public Outreach). The work groups were asked to share recent information relevant to any of the RAP recommended actions, including new legislation and regulations, new agency programs, and current funding sources. Each of the 84 actions in the 1995 Update was reviewed and some revised. New recommendations were added.

2.4 Data Sources

Several data sources were identified at the stakeholder meeting which included the following types:

- GIS data (land use, soils, topography, digital orthophotos, hydrography);
- Hydrologic data (precipitation, river flow, historic flood levels);
- Water quality data (suspended sediment) and sediment data;
- Anecdotal flood data (photos, location of debris jams);
- Additional topographic and geologic data (stream cross-sections, soils).

The sources of data included several organizations/agencies:

- Macomb County Planning Commission – digital orthophotography;
- Oakland County Planning Department – GIS data, including updated hydrography map overlays with year 2000 overlays;
- Southeastern Michigan Council of Governments (SEMCOG) – information developed for a workshop/meeting on soil erosion control, other planning information;
- United States Geological Survey (USGS) – sedimentation study and data for watershed, river flow data from gages;
- Michigan Department of Environmental Quality – various modeling data, including TR20 hydrology, and HEC-2 and HEC-RAS for flood profile computations;

- USACE, in conjunction with Environmental Protection Agency (EPA) – sediment sampling data for the Clinton River;
- Water quality data available through the STORET database (EPA).

2.4.1 Suspended Sediment Data

There is a limited inventory of suspended sediment data for the Clinton River. The most comprehensive data set was from the USGS Gage site #04165500 (Clinton River at Moravian Drive at Mt. Clemens). Suspended sediment samples were collected and analyzed at irregular intervals over a 20-year period, from WY1975 through WY1994. Although this data set was not complete, the quantity was sufficient to perform statistical regressions of flow vs. total sediment and specific sediment fractions (see Section 6.2.3).

2.4.2 Precipitation Data

Precipitation data for this study were obtained from two sources, the Southeast Michigan Council of Government (SEMCOG), and the National Oceanic and Atmospheric Administration / National Weather Service (NOAA/NWS). The SEMCOG rain gages have been continuously operating since 1988, and are given in an hourly basis. The NOAA/NWS gage network includes a small number of gages in the watershed, including daily and hourly gage values. The locations of these gages are shown in Figure 2.1.

The SEMCOG data are available on a website hosted by Michigan State University, http://climate.geo.msu.edu/semcog/sem/mainsem.html. The website for the NOAA/NWS data is http://dipper.nws.noaa.gov/hdsb/data/archived/legacy/stainv.html.

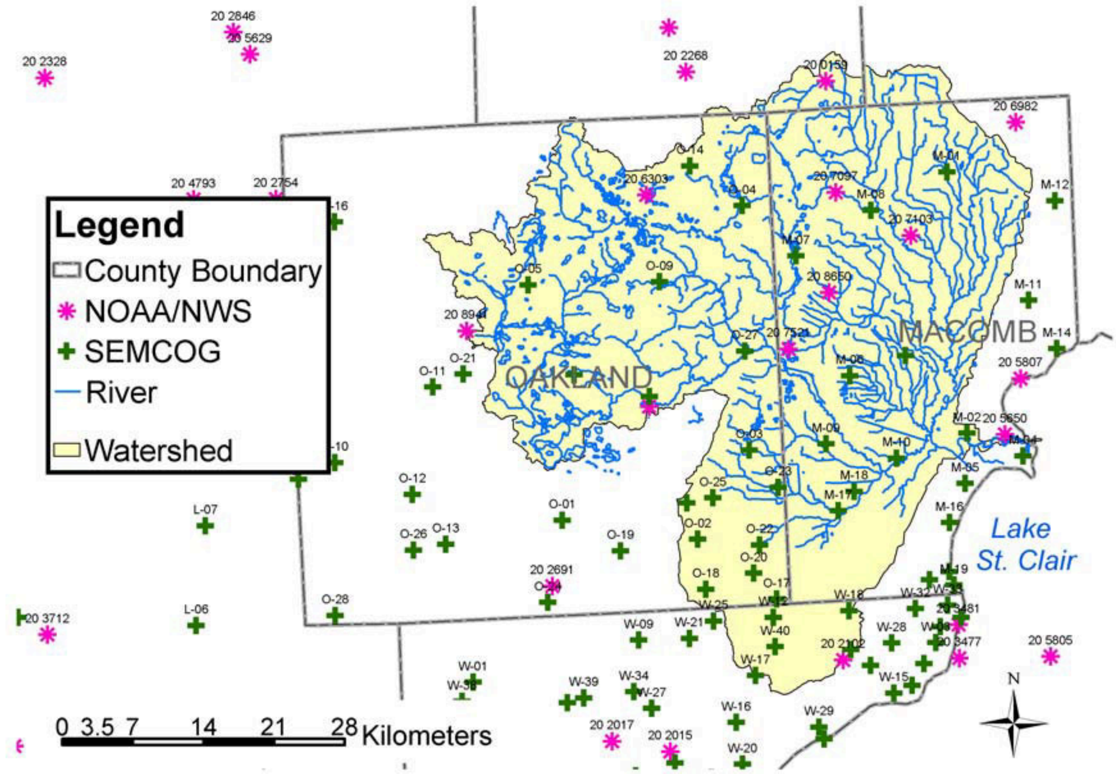

Figure 2.1 Locations of Precipitation Gages

2.4.3 Discharge Data

Discharge data for this study were obtained from the USGS through their streamflow data portal at http://nwis.waterdata.usgs.gov/mi/nwis/discharge. A summary of the stream gage location is shown in Figure 2.2, and Table 2.1 summarizes available gage data.

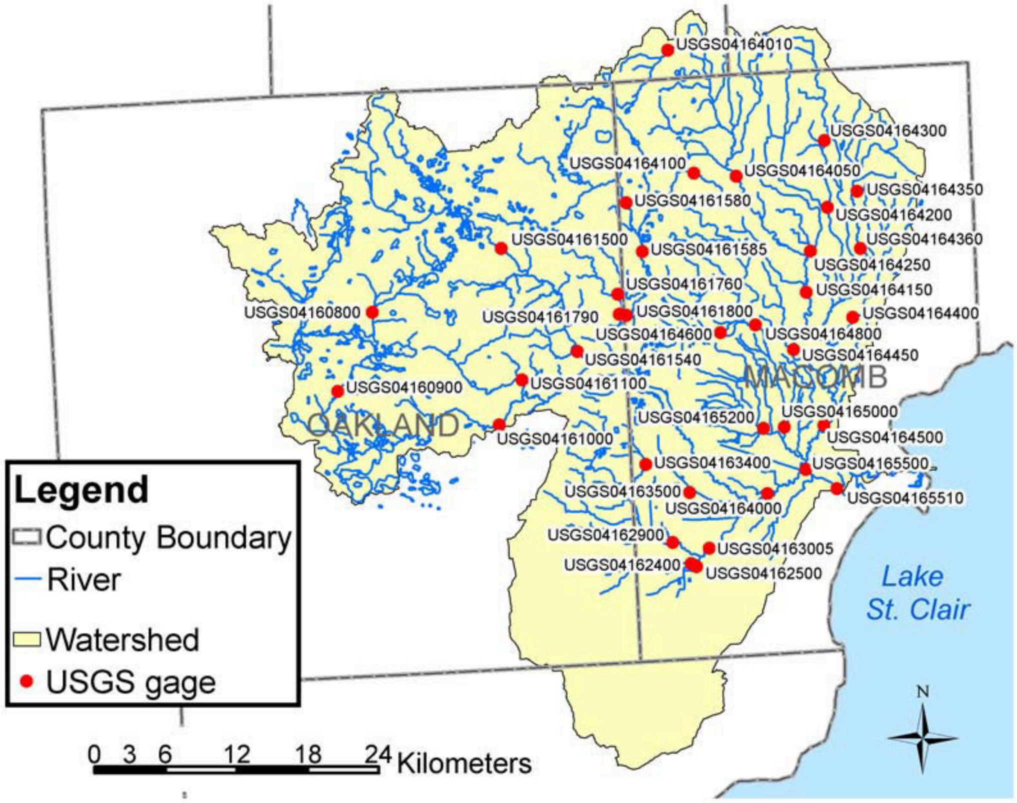

Figure 2.2 USGS Streamflow Gages

Table 2.1 USGS Flow Gage Stations Within the Clinton River Watershed

Gage #	Site Name	Area Km^2	From	To
04160800	SASHABAW CREEK NEAR DRAYTON PLAINS, MI	54	10/1/1959	9/30/2003
04160900	CLINTON RIVER NEAR DRAYTON PLAINS, MI	205	10/1/1959	9/30/2003
04161000	CLINTON RIVER AT AUBURN HILLS, MI	319	5/1/1935	9/30/2002
04161100	GALLOWAY CREEK NEAR AUBURN HEIGHTS, MI	46	10/1/1959	9/30/1991
04161500	PAINT CREEK NEAR LAKE ORION, MI	100	10/1/1955	9/30/1991
04161540	PAINT CREEK AT ROCHESTER, MI	184	10/1/1959	9/30/2003
04161580	STONY CREEK NEAR ROMEO, MI	66	10/1/1964	9/30/2003
04161800	STONY CREEK NEAR WASHINGTON, MI	177	7/1/1958	9/30/2003
04161820	CLINTON RIVER AT STERLING HEIGHTS, MI	800	10/1/1978	9/30/2003
04162000	RED RUN NEAR ROYAL OAK, MI	95	10/1/1966	9/30/1968
04162010	RED RUN NEAR WARREN, MI	0	10/1/1979	9/30/1988
04162400	RED RUN AT VAN DYKE RD NR WARREN, MI	113	1/1/1954	9/30/1957
04162900	BIG BEAVER CREEK NEAR WARREN, MI	61	10/1/1958	9/30/1988
04163000	BIG BEAVER CREEK AT VAN DYKE RD AT WARREN, MI	65	1/1/1954	9/30/1958
04163400	PLUM BROOK AT UTICA, MI	43	7/1/1965	9/30/2003
04163500	PLUM BROOK NEAR UTICA, MI	59	1/1/1954	9/30/1966
04164000	CLINTON RIVER NEAR FRASER, MI	1150	6/1/1947	9/30/2003
04164010	NORTH BRANCH CLINTON RIVER AT ALMONT, MI	25	10/1/1962	9/30/1968
04164050	N BRANCH CLINTON RIVER AT 33 MILE RD NR ROMEO, MI	129	10/1/1964	9/30/1969
04164100	EAST POND CREEK AT ROMEO, MI	56	9/1/1958	9/30/2003
04164150	N BRANCH CLINTON RIVER AT 27 MILE RD NR MEADE, MI	232	10/1/1967	9/30/1972
04164200	COON CREEK AT NORTH AVENUE NEAR ARMADA, MI	26	10/1/1965	10/13/1970
04164250	TUPPER BROOK AT RAY CENTER, MI	22	10/1/1959	9/30/1964
04164300	EAST BRANCH COON CREEK AT ARMADA, MI	34	10/1/1958	9/30/2003
04164350	HIGHBANK CREEK AT 32 MILE ROAD NEAR ARMADA, MI	39	8/24/1965	9/30/1970
04164360	EAST BRANCH COON C AT 29-MILE RD NR NEW HAVEN, MI	93	10/1/1967	9/30/1972
04164400	DEER CREEK AT 25 1/2 MILE ROAD NEAR MEADE, MI	33	9/1/1960	9/30/1965
04164450	MCBRIDE DRAIN AT 24 MILE ROAD NEAR MACOMB, MI	15	10/1/1959	9/30/1964
04164500	NORTH BRANCH CLINTON RIVER NEAR MT. CLEMENS, MI	515	6/1/1947	9/30/2003
04164600	MIDDLE BR CLINTON R AT SCHOENHERR RD NR MACOMB, MI	57	10/1/1964	9/30/1969
04164800	MIDDLE BRANCH CLINTON RIVER AT MACOMB, MI	106	10/1/1962	10/7/1982
04165200	GLOEDE DITCH NEAR WALDENBURG, MI	41	10/1/1959	9/30/1964
04165500	CLINTON RIVER AT MORAVIAN DRIVE AT MT. CLEMENS, MI	1901	5/1/1934	9/30/2003

2.5 GIS Data

GIS data layers were available from numerous sources and were used for basemap analysis as well as for input into watershed numerical models. One main source of base GIS data for the Clinton River Watershed was the BASINS dataset developed by the EPA. This dataset is freely available for download from the BASINS website: http://www.epa.gov/docs/ostwater/BASINS/. The GIS layers included in this dataset are:

Spatially Distributed Data

- Land use/land cover;
- Urbanized areas;
- Populated place locations;
- Reach File Version 1 (RF1);
- Soils (STATSGO);
- Elevation (DEM);
- National Elevation Dataset (NED);
- Major roads;
- USGS hydrologic unit boundaries (accounting unit, cataloging unit);
- Dam sites;
- EPA regional boundaries;
- State boundaries;
- County boundaries;
- Federal and Indian Lands;
- Ecoregions.

Environmental Monitoring Data

- Water quality monitoring station summaries;
- Water quality observation data;
- Bacteria monitoring station summaries;
- Weather station sites;
- USGS gaging stations;
- Fish Consumption advisories;
- National sediment inventory (NSI);
- Shellfish classified areas;
- Clean Water Needs Survey.

Point Source Data

- Industrial Facilities Discharge (IFD) sites;
- BASINS 3 Permit Compliance System (PCS) sites and loadings;
- BASINS 2 Permit Compliance System (PCS) sites and loadings;

- Toxic Release Inventory (TRI) sites;
- CERCLIS-Superfund National Priority List (NPL) sites;
- Resource Conservation and Recovery Information System (RCRIS) sites;
- Mineral Industry Locations.

Data used in the watershed numerical models include DEM, land use, soils, roads and gaging stations. Digital orthophotos and satellite imagery were also collected for the project area. GIS projects were set up as part of the numerical model development containing only those data sets necessary for model input. A separate GIS project was created in ArcView 8.x, which includes all the BASINS data as well as all additional GIS data collected as part of this project. A detailed listing of all GIS data layers can be found in the Clinton River Watershed Model Users Manual.

3.0 SEDIMENT BUDGET

3.1 Introduction

The purpose of defining a sediment budget is to better understand the sources, pathways and sinks (deposits) of sediment within a watershed system. The transport of sediment out of the watershed can then be seen as a culmination of the various processes mobilizing sediment within the basin and of the deposition and storage of sediment within the basin. Of the total sediment mobilized within a catchment, often only a small amount reaches the watershed outlet. The remainder is usually deposited in temporary storage to be remobilized in subsequent events (see Section 1.3). The active processes in the catchment may then be thought of in two categories: those associated with sediment mobilization (soil erosion; river channel erosion) and those associated with sediment delivery.

Due to the limitations of the available data, a fully quantitative sediment budget analysis was not possible. Instead several analyses were done in order to identify potential sources and sinks of sediment using data readily available.

The remainder of this section provides a discussion of: key aspects of sediment delivery in this watershed (3.2); a discussion of the changing flashiness of the streamflow within the watershed and implications for sediment transport (3.3); rating curve analysis (3.4); the use of the Watershed Characterization System (WCS) Sediment Tool to provide an initial understanding of the erosion and sediment yield characteristics (3.5); aerial photography review to evaluate any visible changes to the stream network (3.6); and an overall summary (3.7).

3.2 Key Aspects of Sediment Delivery in the Clinton River Watershed

A review of available literature and GIS datasets has revealed the following general comments on sediment movement through the Clinton River Watershed:

- Land use in the northern part of the watershed is mainly agricultural (Figure 3.1);
- Cultivated and grazed land elevates sediment supply above natural levels, and it is generally the greatest source of non-point source sediment, above mixed agricultural/forest and forest land use (Figure 3.2);
- Developed land in the south of the watershed (Figure 3.3) will be the source of flashy river flows and urban sediment (see Section 3.3);
- About half of the river's flow is treated wastewater from six municipal wastewater treatment plants (EPA, 2004). This water may be deficient in sediment but may have elevated nutrient levels;

- Oakland County leads the state in new construction, and Macomb County is also undergoing rapid urbanization. Construction site runoff is a major source of sand and silt in catchments undergoing urbanization;
- Non-point source control plan for the Bear Creek urban subwatershed is currently under implementation;
- Combined sewer overflows are still experienced in the watershed. This can lead to flushing of large amounts of urban sediment into the river system during storm events;
- The weir upstream from Mt. Clemens causes sedimentation upstream. This issue was raised at the Stakeholder Meeting (see Section 2.2). Discussion of this is provided in Section 6;
- High Total Dissolved Solids (TDS) levels have been reported in the Clinton River Watershed;
- Stormwater runoff is probably the single greatest source of water quality degradation (EPA, 2004);
- Stream Habitat Inventory completed by CRWC in 1997 identified erosion at road crossings and need for stricter enforcement of construction site erosion control;
- In 1996, CRWC completed a two-year streambank erosion control project at five sites on Paint Creek;
- Forests in the upper area of the watershed may provide a significant sediment source, depending on management techniques. However, dams and reservoirs in this region may be acting as traps for a large amount of this sediment (Figure 3.4);
- A key cause of sedimentation is the low gradient in lower watershed (Figure 3.5). This means that sand is likely to only be transported during high flows.

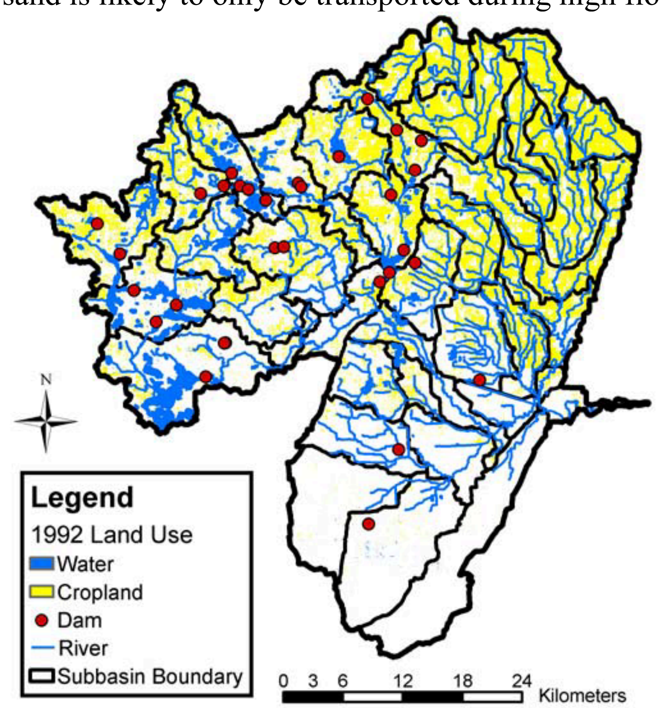

Figure 3.1 Distribution of Cropland in the Clinton River Watershed

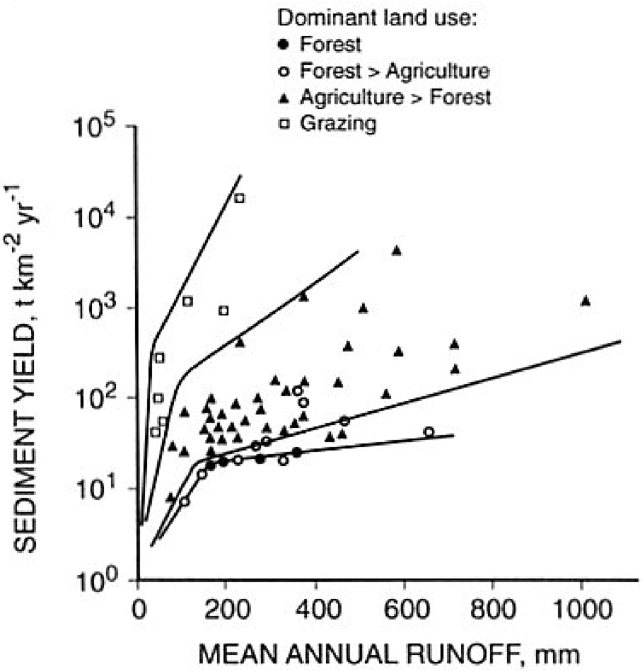

Figure 3.2 Mean Annual Runoff for Four Different Land Use Types (Dunne, 1979)

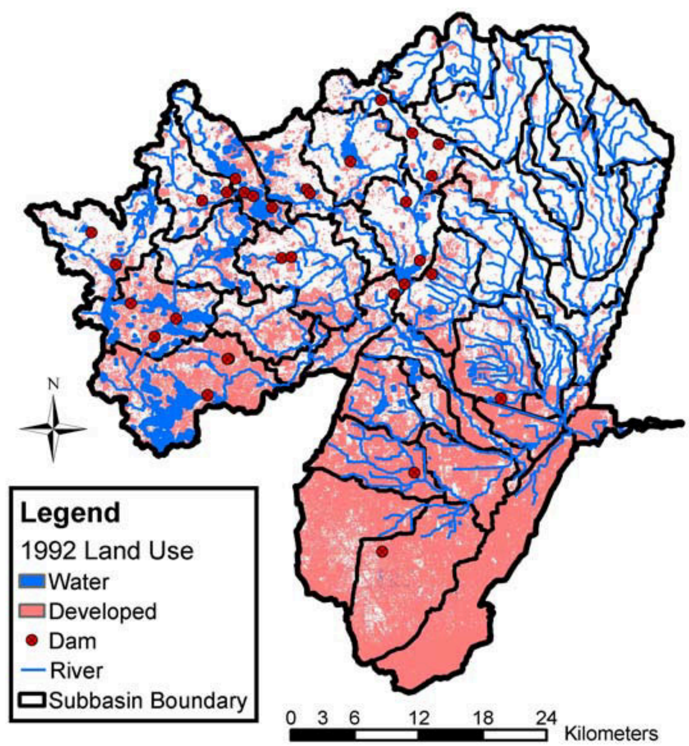

Figure 3.3 Distribution of Developed Land in the Clinton River Watershed

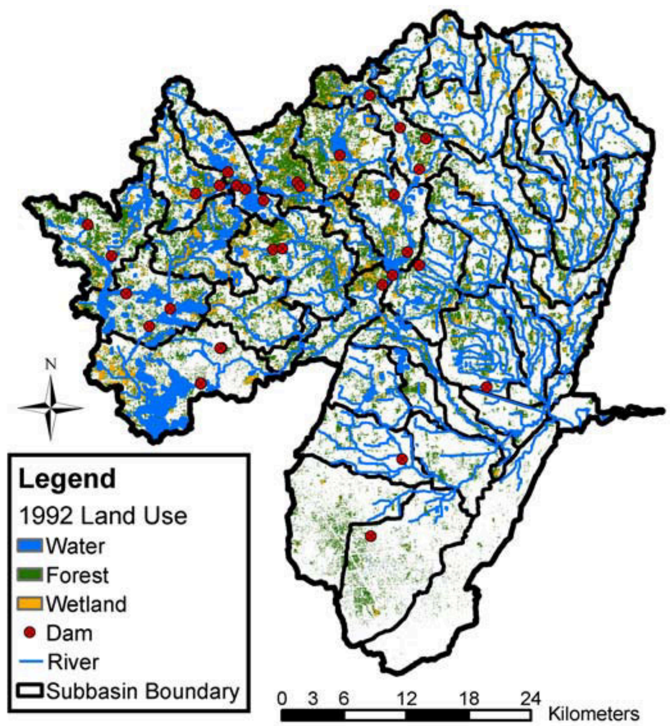

Figure 3.4 Distribution of Forests and Wetlands in the Clinton River Watershed

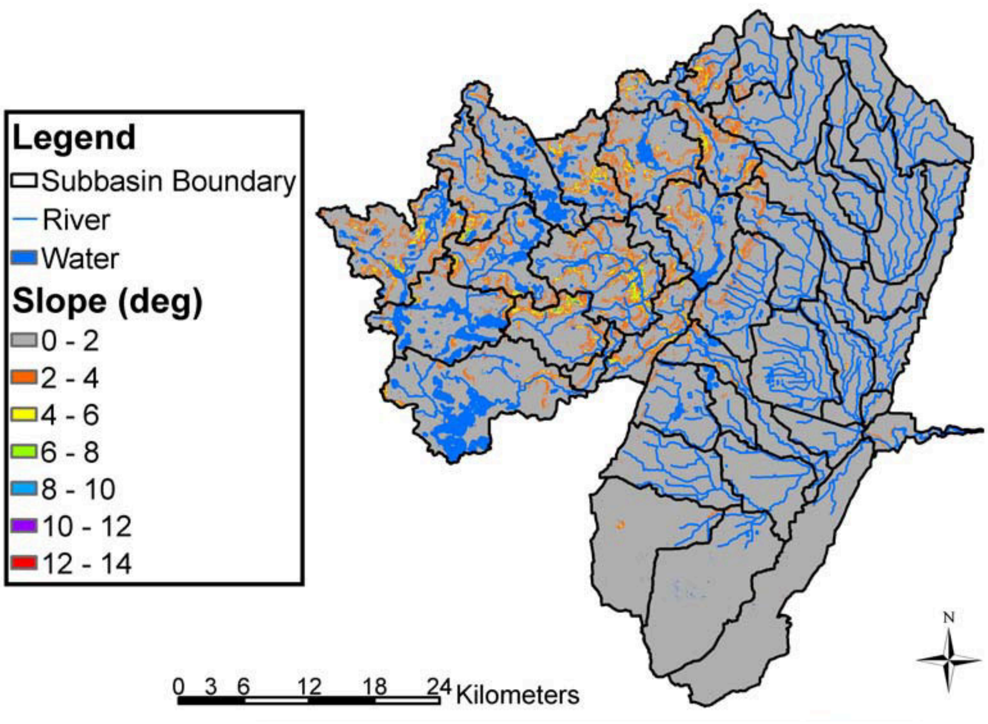

Figure 3.5 Variation of Surface Slope in the Clinton River Watershed

3.3 Flashiness Analysis

A preliminary assessment of the Clinton River Watershed was performed to determine if there have been any significant changes to the hydrologic processes over the last 30 to 40 years. Substantial portions of the watershed have undergone transformations from primarily agricultural to urbanized land use, especially within the last 10 to 15 years. A common response to land use changes is a decreased basin hydrologic response, which results in higher peak flows and velocities. Although channels undergo continual changes due to the erosive forces of the streamflow, an increase in the frequency of higher flows and velocities accelerates the channel degradation process. An important consideration in discerning whether the observable channel erosion is progressing at a "natural" rate is an objective quantification of the basin response over a long period of time.

One common metric used to characterize the change in basin response is a stream flashiness index. In this analysis, the flashiness index used was based on a method described in a paper by researchers from Heidelberg University (Baker, et al, 2004) in the Journal of American Water Resources Association. Flashiness is a characterization that quantifies the time response of a river to a rainfall event. A high degree of flashiness indicates that a river is quick to respond, usually both on the rising and falling limbs of the flow vs. time curve. Highly flashy rivers are typified by basins with steeper or rolling topography, and often with lower permeable soils, or basins with significant impervious areas. Conversely, rivers that are lower in flashiness are typically flatter terrain, and often have highly permeable soils with a high degree of shallow groundwater contribution to the base streamflow. As is the case for the characterization for hydrologic and climatologic trends, long-term records are required for meaningful analysis.

The flashiness index used in this analysis was the following equation:

$$\text{Flashiness Index} = \frac{\sum_{t=1}^{n} \left| q_{t-1} - q_t \right|}{\sum_{t=1}^{n} q_t} \tag{1}$$

This index is a ratio of the absolute value of the sum of the daily flow changes to the sum of the total daily flows. Although this index may vary spatially for a particular year, the temporal trend of this index is a relative indication of basin response to rainfall and is a good indicator of hydrologic changes in the watershed.

The flashiness index was computed for all streamgage records in the Clinton River Watershed that had a minimum of 20 years of record. In most cases, the gage records that were analyzed were operational from the 1960s through the present. It is also interesting to note that the precipitation over the same period actually had a small (albeit statistically insignificant) decrease.

The results indicate that several of the gages in the southern portion of the watershed have shown marked increases in flashiness since 1970. Others have remained steady or show minor decreases with time. The spatial distribution of the gage sites analyzed in this study is shown in Figure 3.6, with the 1992 land use shown in the background. The summary of the analysis is shown at Table 3.1, and the graphs of the index over time are shown in Figures 3.7a-f.

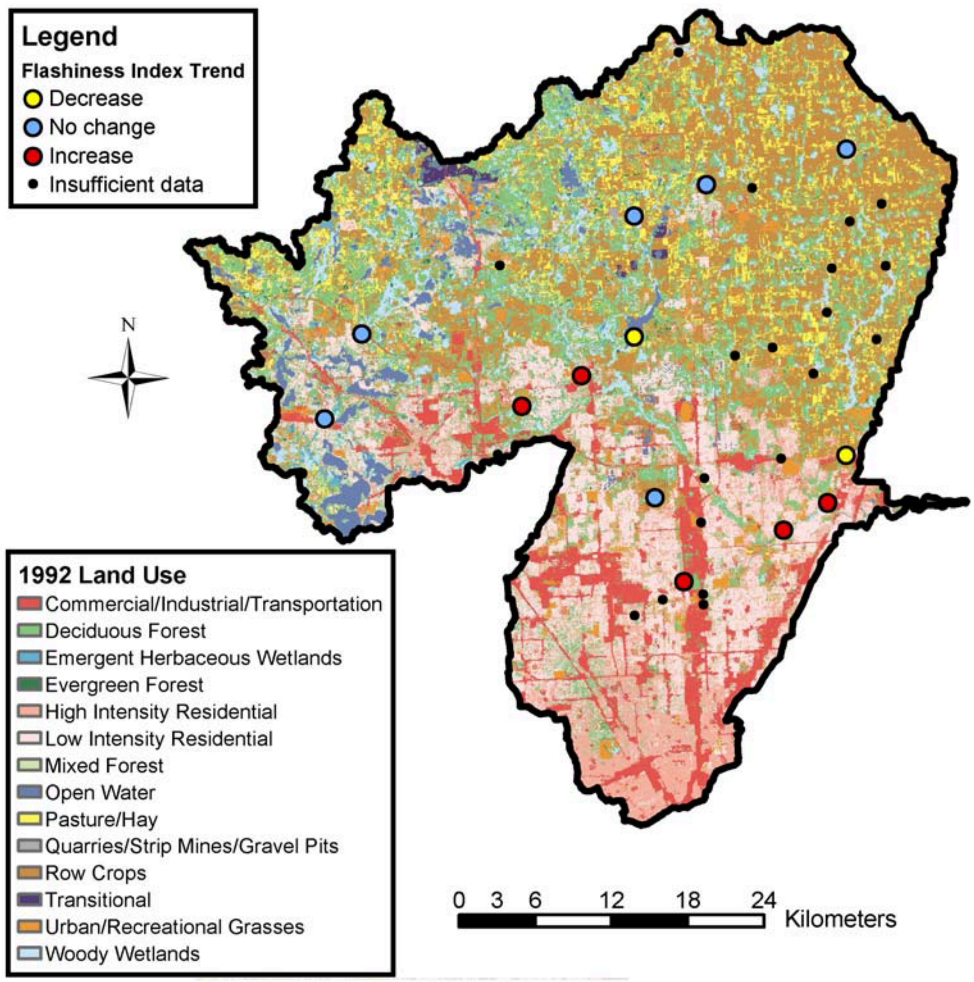

Figure 3.6 Summary of Changes in River Flashiness

Table 3.1 Trends in River Flashiness in the Clinton River Watershed

Gage Name	Gage Number	Trend
Clinton River near Fraser	04164000	Increase
Clinton River at Mt. Clemens	04165500	Increase
Paint Creek at Rochester	04161540	Increase
Galloway Creek near Auburn Hts	04161100	Increase
Big Beaver Creek near Warren	04162900	Increase
Stony Creek near Romeo	04161580	No Significant Change
Coon Creek E. Branch at Armada	04164300	No Significant Change
Sashabaw Creek near Drayton Plains	04160800	No Significant Change
Clinton River near Drayton Plains	04160900	No Significant Change
Plum Brook at Utica	04163400	No Significant Change
East Pond Creek at Romeo	04164100	No Significant Change
Stony Creek near Washington	04161800	Slight Decrease
North Branch Clinton River near Mt. Clemens	04164500	Slight Decrease

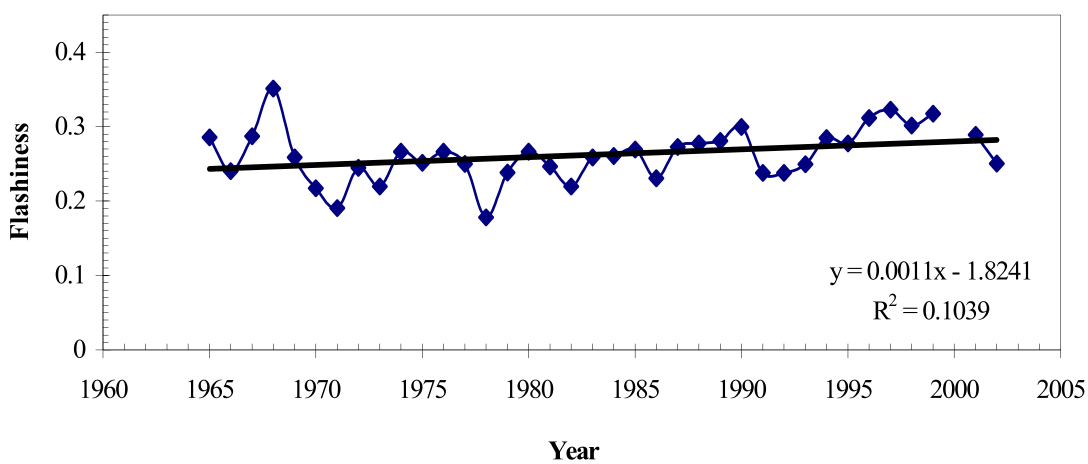

Figure 3.7a Gage # 04165500 Clinton River at Mt. Clemens

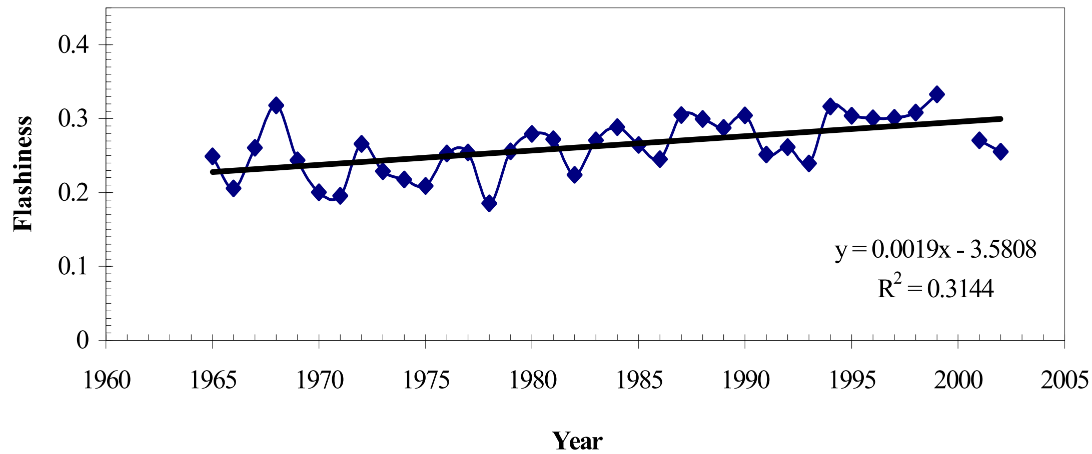

Figure 3.7b Gage # 04164000 Clinton River Near Fraser

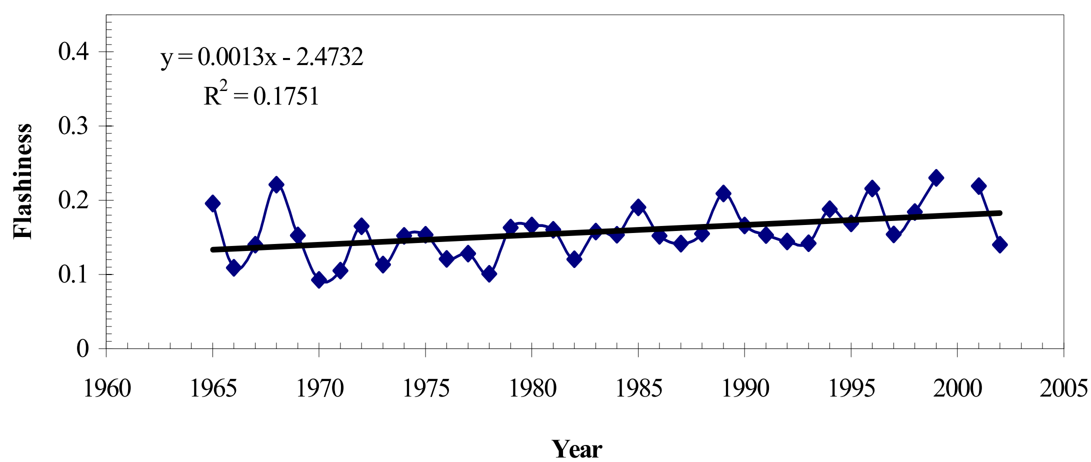

Figure 3.7c Gage # 04161540 Paint Creek at Rochester

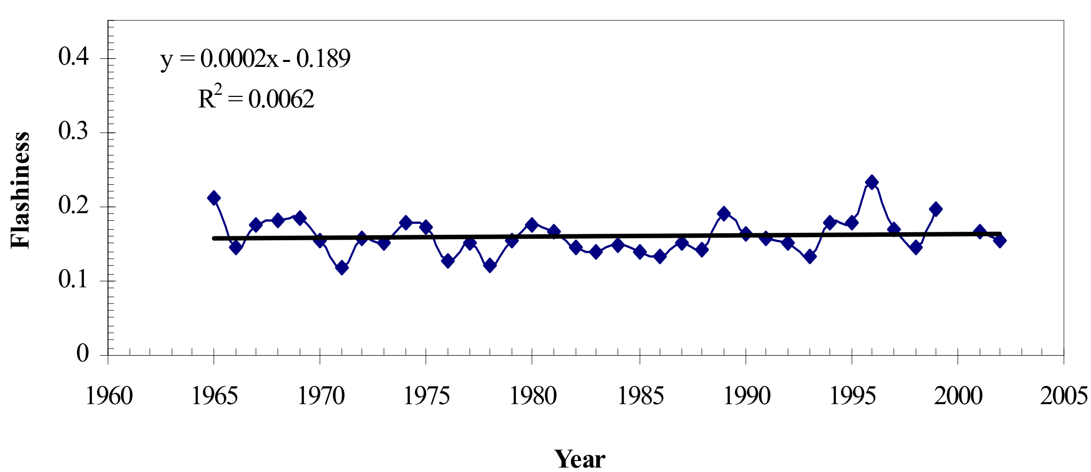

Figure 3.7d Gage # 04161580 Stony Creek Near Romeo

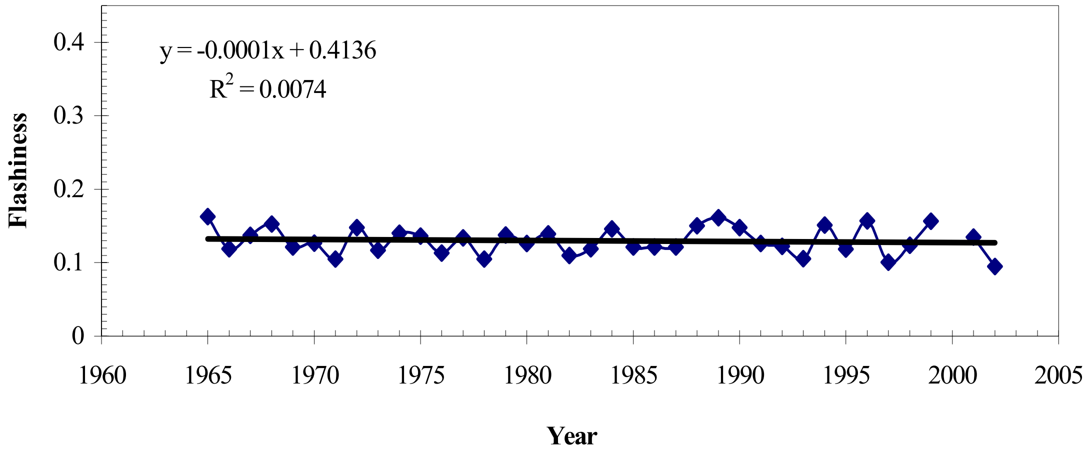

Figure 3.7e Gage # 04160800 Sashabaw Creek Near Drayton Plains

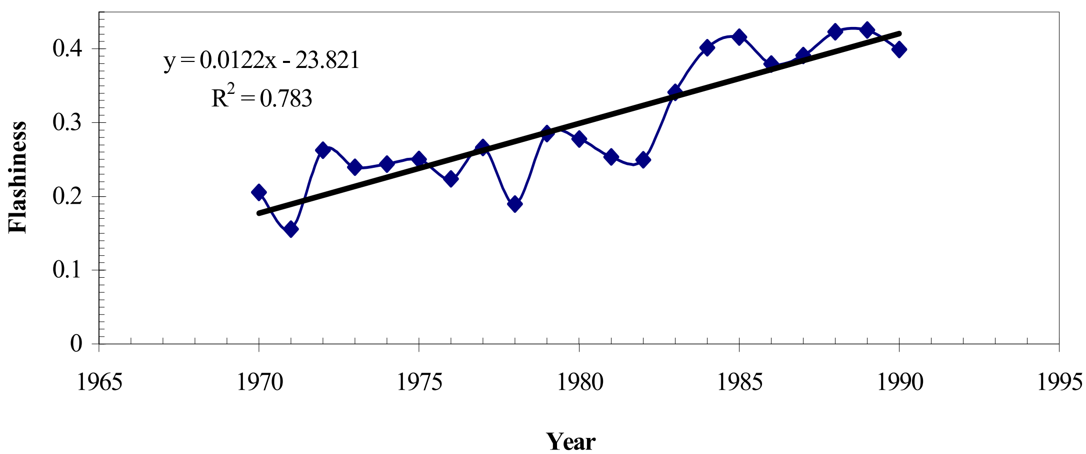

Figure 3.7f Gage # 04161100 Galloway Creek Near Auburn Hts.

3.4 Rating Curve Analysis

Daily discharge data from the USGS Gage #04165500 at Mt. Clemens were compared to available suspended sediment sampling at the same site. The sediment sampling at the gage covers most of the range of observed river discharge. A set of discharge-suspended sediment load (Qs) relationships (i.e. rating curves) was generated using the available data. Figure 3.8 shows a strong correlation between discharge and total suspended sediment load (SSL), and a pair of upper and lower limits assigned to the dataset. These relationships were used to generate discharge-based suspended sediment load time series (Figure 3.9).

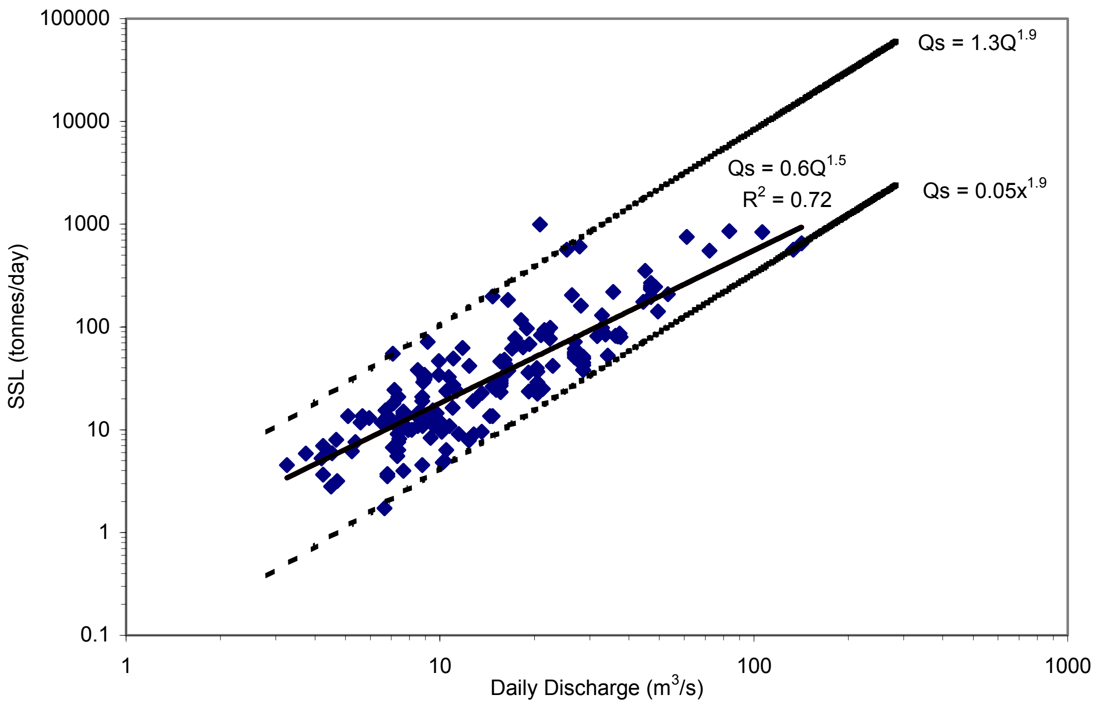

Figure 3.8 Relationship Between Suspended Sediment Load and Daily Discharge at USGS Gage # 04165500

The mean daily suspended sediment load for the rating curve was 56.2 t day^{-1}, giving an estimated mean annual sediment load of 20,500 t yr^{-1}. The estimated mean annual suspended sediment loads based on the upper and lower boundaries of the dataset were 146,300 t yr^{-1} and 8,500 t yr^{-1}, respectively. These values compare well with the values estimated from empirical relationships (Section 1.3.2), bearing in mind they do not include bedload transport.

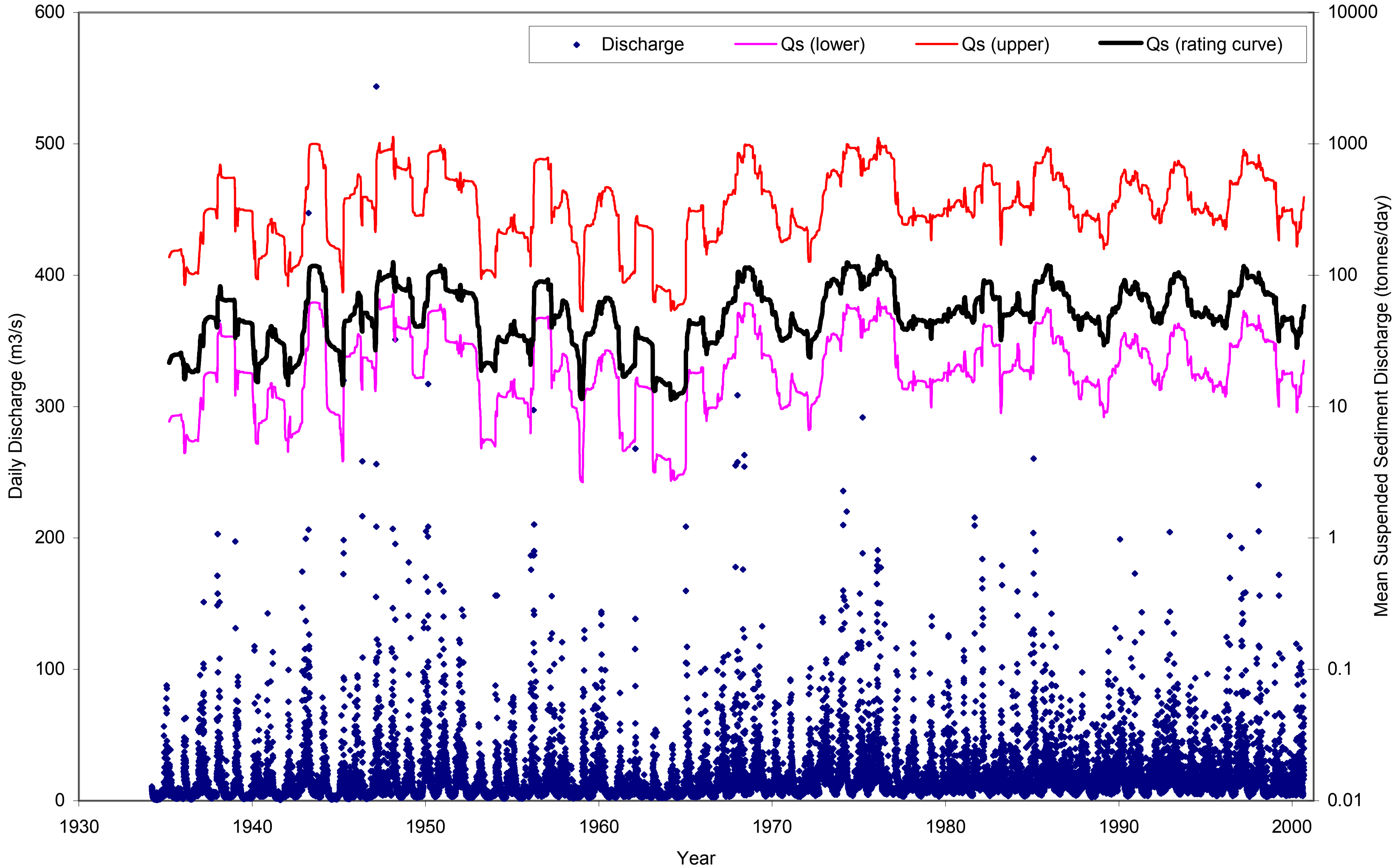

Figure 3.9 Mean Suspended Sediment Discharge Estimated from Rating Curve and Discharge Record

3.5 Watershed Characterization System

To determine the potential impacts of upland sources on sediment delivery, a numerical model of the entire watershed was developed using Watershed Characterization System (WCS). WCS is an ArcView-based system that provides users with several tools for characterizing the physical and hydrologic properties of a watershed. WCS is distributed by the U.S. Environmental Protection Agency (EPA) and can be used as part of the initial watershed characterization phase of the TMDL process. Currently, the EPA is only offering WCS and the associated data sets for those states in EPA Region 4. However, the majority of the input data needed for WCS is readily available for download from the Internet, so a customized version of WCS for the Clinton River Watershed, which is located in EPA Region 5, was set up. WCS was implemented early in the project to quickly gain a general appreciation for the sediment yield and delivery characteristics of the watershed.

The WCS sediment tool extension uses the Universal Soil Loss Equation (USLE) to estimate the total potential erosion and its spatial distribution for each subwatershed. In addition, the fraction of the potentially eroded sediment that reaches the stream is estimated using one of four sediment delivery equations built in to the WCS Sediment Tool. The delivery equations calculate sediment delivery as a function of the distance of the source grid cell from the stream and/or the difference in elevation. Using this extension in addition to the core WCS functions, the user is quickly able to evaluate the magnitude and spatial extent of erosion and sediment load within a watershed, as well as to evaluate alternative management scenarios considering such things as land use changes; road and silviculture practices; riparian zone characteristics; human disturbances (e.g. construction areas); on-site BMPs such as cropping practices; and off-site BMPs such as ponds and filter strips.

The following is a list of GIS data types required to develop a WCS model as well as the specific layer used for the Clinton River modeling:

- Land Use: 1992 National Land Cover Data Set;
- Digital elevation model (DEM): 30-meter BASINS DEM;
- Soils: STATSGO soils from the NRCS;
- USGS Stream Gages: USGS stream gage locations from BASINS dataset;
- River linework: RF3 file from USEPA;
- Subwatersheds: HUC14 watersheds;
- Roads: ESRI 2000 TIGER/Line Data.

Further information regarding the GIS data layers and their sources can be found in the accompanying Clinton River Watershed Model User Manual.

Using the information in the GIS data layers, soil erosion, sediment yield and delivery calculations were done for each HUC14 watershed within the Clinton River basin using

WCS. Since sediment calibration data were not available, the WCS results are meant to be used as a preliminary tool to assess possible sources of sediment within the watershed.

The WCS results for annual soil erosion per unit area and net subbasin erosion per year for each HUC14 subbasin are shown in Figure 3.10. In addition, pie charts of 1992 land use are shown for each subbasin. The sediment erosion estimates underline the important role of land use in determining erosion rates from land. This is expected, as land use is directly related to one of the main parameters in the USLE. The urban areas have the lowest erosion rate due to the amount of non-erodible surfaces, the more forested areas have the next highest rate and the agricultural subwatersheds have the highest soil erosion rate per year. Figure 3.11 shows the results for sediment yield per year and delivery per year for each HUC14 subbasin. These results show that some subbasins are delivering more sediment to the stream channels than others due not only to the factors affecting erosion rates, but also to those factors affecting delivery, which include distance to stream and area of watershed. The results plotted in Figures 3.10 and 3.11 are listed in Table A.1 in Appendix A, and the subbasin numbers are given in Figure A.1.

The net erosion predictions from WCS for each subbasin were plotted against the percentage of cropland in each basin and the percentage of developed land in each basin. Figures 3.12 and 3.13 show the trends in the results. The figures show that as the amount of cropland increases in a watershed, the amount of erosion also increases; the opposite is true for developed land, again due to the amount of non-erodible land in urban/developed areas. An exponential decay in erosion is expected with increasing urbanization. It should be noted that it was assumed there were no conservation measures being practiced on the cropland. If there were, erosion values would tend to be less.

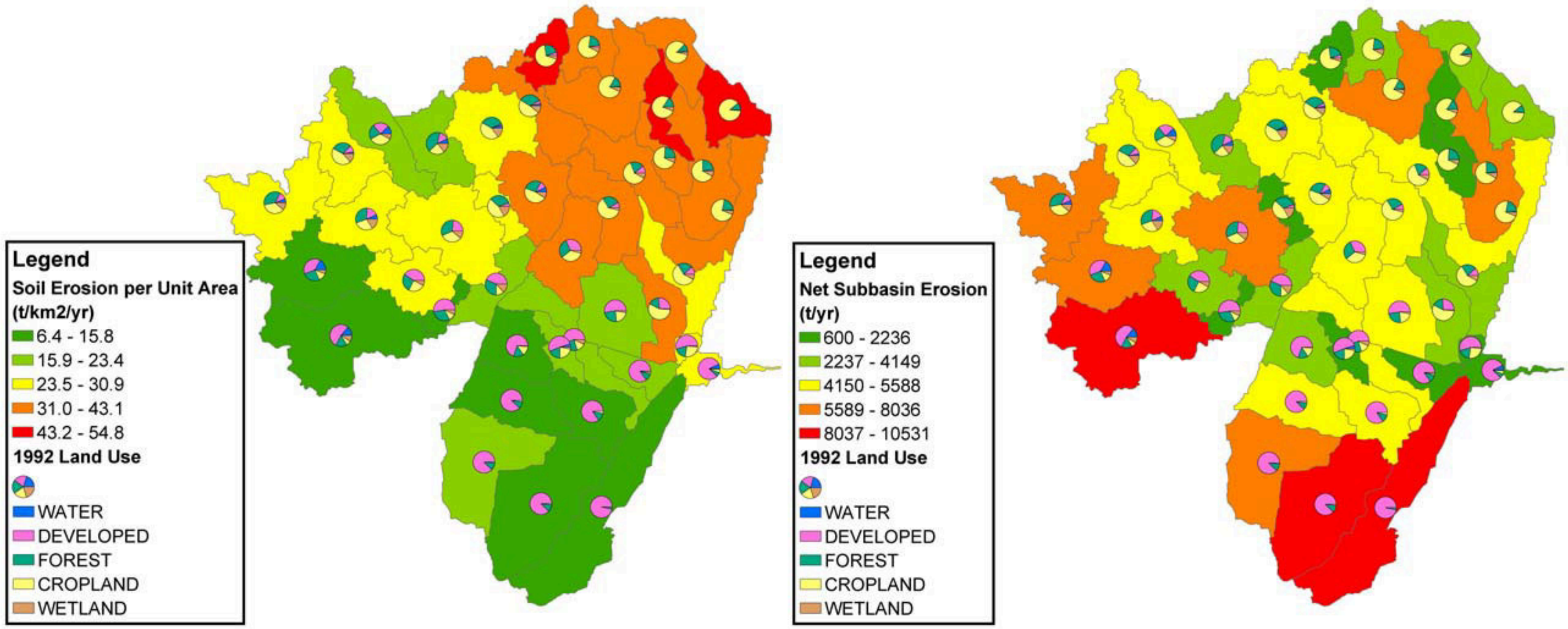

Figure 3.10 WCS Soil Erosion Results for HUC14 Subbasins

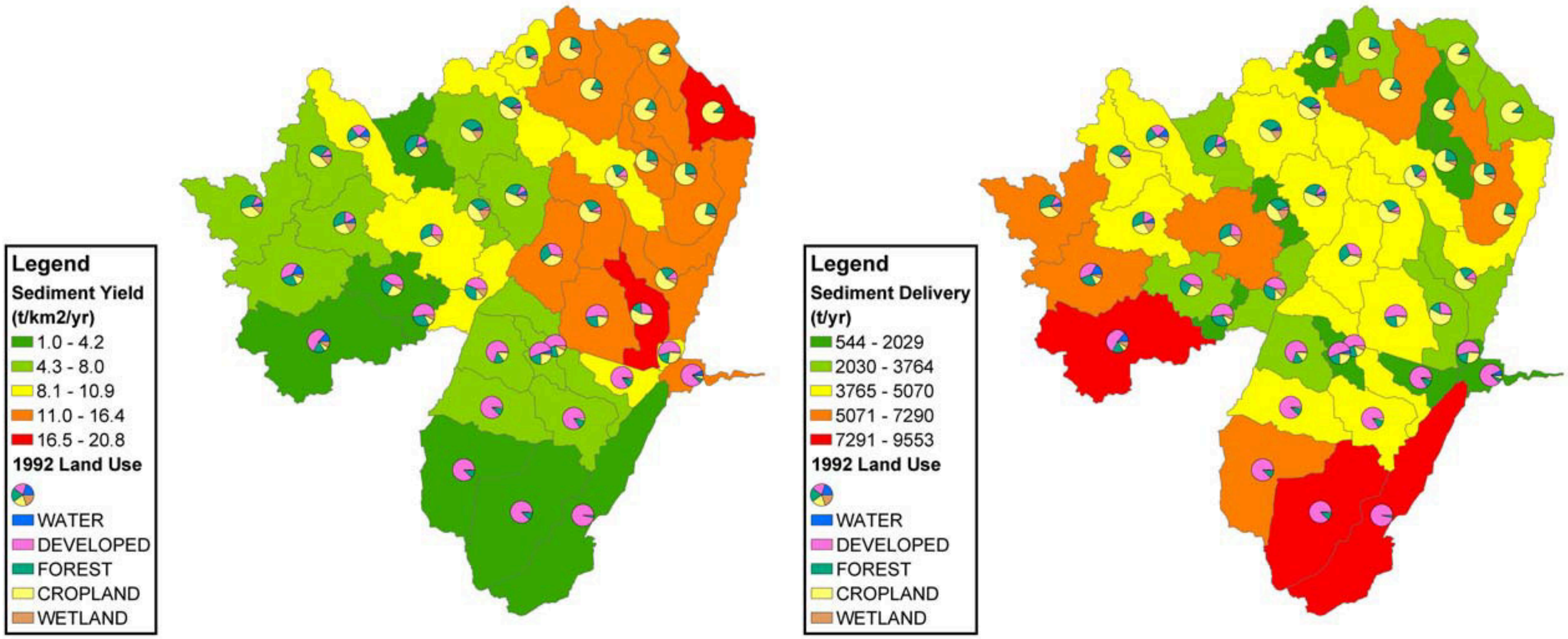

Figure 3.11 WCS Sediment Yield and Delivery Results for HUC14 Subbasins

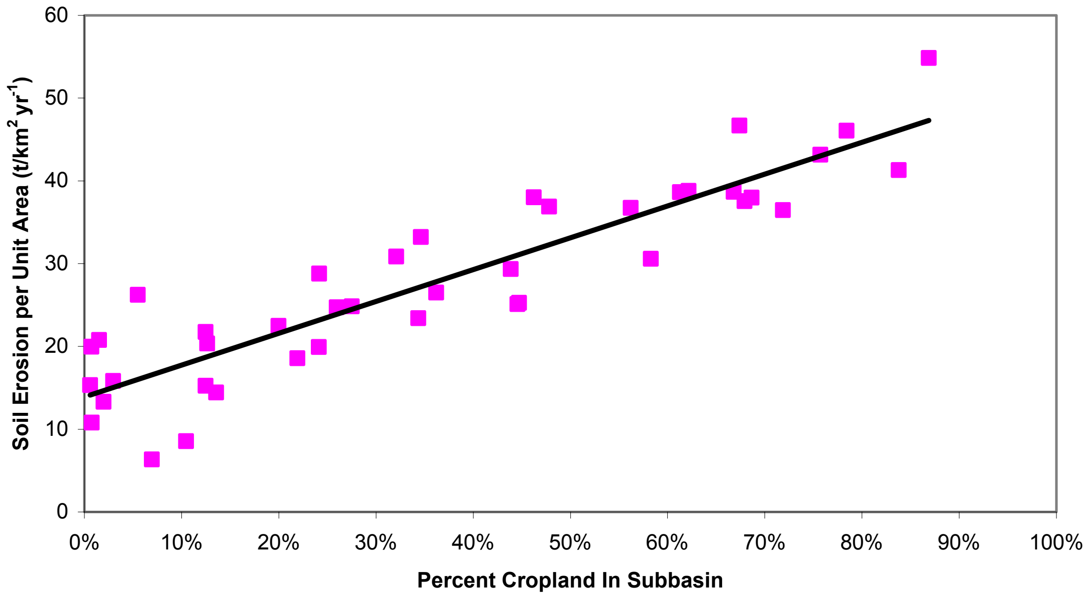

Figure 3.12 Relationship Between Percentage of Cropland in a Subbasin and Erosion Predicted by WCS

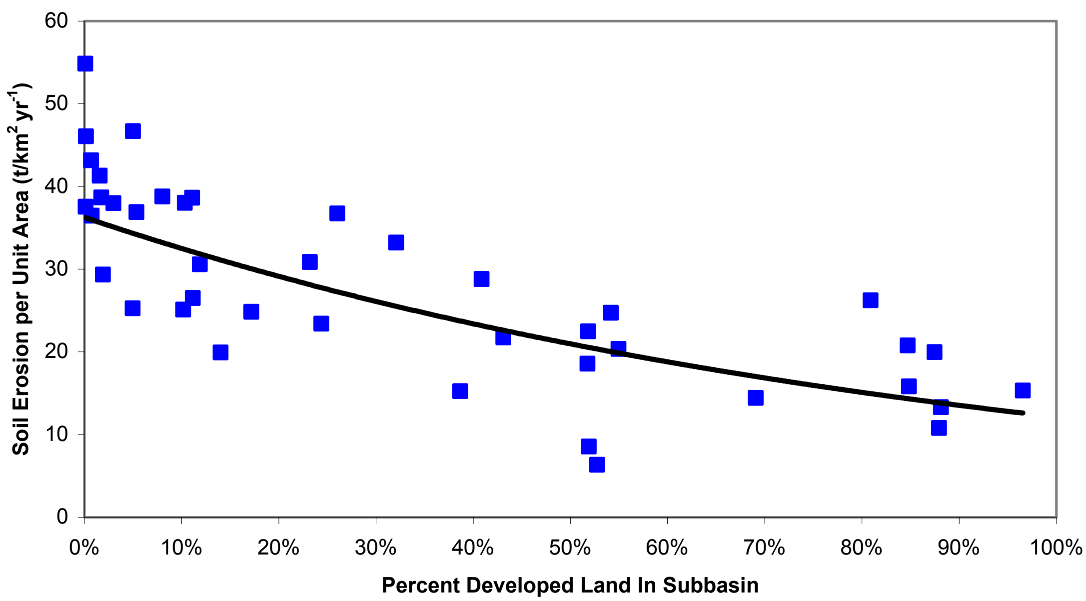

Figure 3.13 Relationship Between Percentage of Developed Land in a Subbasin and Erosion Predicted by WCS

WCS has no in-channel sediment routing capabilities, therefore these results cannot be used to determine the total amount of sediment transported to the mouth of the Clinton River. However, the WCS results can help identify areas where sediment problems are likely to occur and where more attention is warranted. Measurements of sediment load or more process-based models are required to more accurately quantify actual subbasin sediment loads.

3.6 Aerial Photography Evaluation

Detailed two-feet resolution digital orthophotographs of Oakland Country were examined for evidence of riverbank erosion. The Paint Creek subcatchment was evaluated in detail as ongoing riverbank erosion has been reported in this area. However, resolution of the digital orthophotos was not sufficient to consistently identify bank erosion. Pictures taken in 2002 from Dodge Park in Sterling Heights, just downstream from the Sterling Heights gage showed near vertical and overhanging banks (Figure 3.14). However, evidence of bank erosion in this region was difficult to obtain with any degree of consistency from the latest (1999-2000) digital orthophotos (Figure 3.15), most likely due to the vertical aspect of the air photos, but possibly also due to time difference between the orthophotos and site photographs.

In particular, the outsides of high sinuosity meander bends were examined for evidence of bank erosion. These regions would be expected to have actively eroding banks, as the channel would progressively undercut the outer bank in areas where bank protection was absent. Erosion was not apparent in these areas, which is likely due to vertical cliff faces not registering on the photographs. In-channel features such as point and mid-channel bars (which would suggest active channel sediment transport) were not abundantly present on the photographs. This may be because water levels were high at the time of survey, drowning out such features, or because river flow regime and boundary materials precluded the development of these forms.

In order to conduct a full aerial photograph analysis of bank erosion, a full set of digital photographs over different time frames would be necessary. This would allow riverbank linework to be determined for each time frame so that changes in river planform and planform geometry could be evaluated, which was beyond the scope of the present study. However, the review of existing reports on this watershed suggests that the effects of riverbank erosion and sediment yield are minor, compared to non-point sources, such as agricultural and urban sediment yield. These latter factors became the key area of focus for the evaluation of BMPs in this watershed (Section 5).

Figure 3.14 Bank Erosion in Sterling Heights Park. Source: MDNR

Figure 3.15 1999-2000 Digital Orthophoto of Sterling Heights Park

3.7 Summary

A review of previous studies has identified several aspects relating to sediment delivery in the Clinton River Watershed. Land use and land use change are key factors in sediment yield and sediment delivery in this watershed. Cultivated and grazed lands are the greatest non-point sources of sediment, while developed land leads to flashy river flow. Urban and suburban development is likely to increase sediment yield and delivery (especially from construction sites) in the short term, but lower soil erosion rates due to the presence of impermeable surfaces may lead to lower long-term yields. However, this reduction may be counterbalanced by greater riverbed and bank erosion from a flashier river regime. Increased sedimentation rates may also be expected in the relatively flat, lower section of the watershed as development continues.

Direct assessment of sediment yield and sediment delivery from empirical evidence was not possible in the Clinton River Watershed. Analysis of aerial photographs to determine the likely contribution of river bank erosion to watershed sediment yield was inconclusive, but review of other reports and available evidence suggest that this was not a dominant factor in the Clinton River Watershed. Cross-sectional data from different time periods would allow thorough evaluation of likely bank erosion, but data suitable for this analysis were not forthcoming during this study.

Comparison of catchment baseline conditions (such as drainage area; effective precipitation etc.) with empirical relationships established by other studies give estimates of net erosion in the order of 200-600 t km^{-2} yr^{-1} and sediment delivery to the watershed outlet of around 40,000-120,000 t yr^{-1}. Rating curve analysis of suspended sediment load at Mt. Clemens suggests mean annual suspended sediment load is in the region of 20-30,000 t yr^{-1}. This appears to concur with the empirical estimates, given that bedload is not accounted for in the rating curve analysis.

WCS estimated a mean sediment yield for each subbasin of 27.9 t km^{-2} yr^{-1}, which is an order of magnitude lower than expected. This may reflect the fact that WCS was not calibrated or validated against empirical data. The WCS model was superceded by the SWAT model analysis (Section 4), and WCS is therefore not supplied as a deliverable in the model system.

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4.0 HYDROLOGY AND SEDIMENT DELIVERY MODEL DEVELOPMENT

4.1 Introduction

This section focuses on the application of numerical modeling tools for the understanding and quantification of hydrologic and sediment transport processes occurring at the Clinton River Watershed.

Numerical models often provide a cost effective tool for the analysis of complex processes over large areas and long time periods. The two numerical models applied for the study of hydrology and sediment yield for this watershed are SWAT (Soil and Water Assessment Tool) and GSSHA (Gridded Surface Subsurface Hydrologic Analysis), both of which have different applications, advantages and disadvantages.

This section describes the theory for each model (Sections 4.2 and 4.4) and then provides application examples for each model (Sections 4.3 and 4.5) where results for the Clinton River Watershed and some of its sub basins are reported.

A comparison between model results, as well as advantages and disadvantages, is presented in Section 7.

4.2 SWAT Model Description

The Soil and Water Assessment Tool (SWAT) is a watershed-scale numerical model for the simulation of water, sediment, nutrient and pesticide movement in surface and subsurface systems. SWAT aids in prediction of the impacts of climate and vegetative changes, reservoir management, groundwater withdrawals, water transfer, land use change and watershed management practices on water, sediment and chemical dynamics in complex watershed systems. Land use and management conditions can be varied over long time periods, making the model a particularly useful tool to aid in the implementation of BMPs. SWAT is a continuous-time model, intended for the prediction of long-term water and sediment yields from a watershed.

SWAT is a physically-based numerical model requiring input of climatic, soil property, topographic, vegetation, land use and land management data. SWAT uses these data to predict water, nutrient and sediment movement through the watershed, along with vegetation growth. In order to characterize and predict the effects of watershed management on yields, SWAT can be used to analyze the watershed by subdividing the area into homogenous parts. SWAT then analyzes the behavior of each part, before examining how each part interacts with the watershed as a whole. SWAT uses a daily time step, continuous for 1 to 100 years. There are several advantages of this approach over regression-based approaches:

- SWAT may be used to quantitatively predict the long-term effects of land use, climate or vegetation changes on watershed sediment delivery and water quality. It is therefore highly useful in the analysis of certain BMPs.

- The use of Hydrologic Response Units (HRUs; see below) is computationally efficient, allowing for large watersheds to be simulated over long periods of time.

- Most data inputs are available free-of charge from government agencies.

4.2.1 SWAT Model Background

SWAT was developed at the USDA-Agricultural Research Service (ARS) by Dr. Jeff Arnold. This model is based on the SWRRB (Simulator for Water Resources in Rural Basins; Arnold et al., 1990) model for application to large, complex rural basins. SWRRB is a distributed version of CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems; Knisel, 1980), which can be applied to a basin with a maximum of 10 subbasins. SWAT is an extended and improved version of SWRRB, running simultaneously in several hundred subbasins. SWAT also includes elements of GLEAMS (Groundwater Loading Effects on Agricultural Management Systems; Leonard et al., 1987), and EPIC (Erosion-Productivity Impact Calculator; Williams et al., 1984).

The ArcView pre- and post-processor interface for SWAT, AVSWAT, has been developed by Blackland Research Center, a Texas Agricultural Experiment Station part of Texas A&M University System in Temple, Texas, in collaboration with Grassland Soil and Water Research Lab, a USDA-ARS laboratory in Temple, Texas (Di Luzio, et al., 2004).

4.2.2 Characterization of Processes Using SWAT

SWAT allows a wide range of different physical processes to be simulated in a watershed. These processes are briefly summarized in this section. A detailed discussion of each procedure is contained in Appendix B**.**

SWAT divides a watershed into subbasins. The use of subbasins in a simulation is beneficial when different areas of the watershed are dominated by land uses or soils dissimilar enough in properties to impact hydrology. Input data for each subbasin are grouped into the following categories:

- climate;
- hydrologic response units (HRUs);
- ponds and wetlands;
- groundwater;
- main channel draining the subbasin;
- soils;
- vegetation (land cover);
- land use and land management.

Hydrologic response units are areas within each subbasin that have been lumped together to comprise a single land cover, soil and management combination.

The hydrologic component of the SWAT model is based on the water balance equation:

$$SW_t = SW_o + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}\right) \quad (2)$$

where SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content on day i (mm H_2O), t is the time (days), R_{day} is the amount of precipitation on day i (mm H_2O), Q_{surf} is the amount of surface runoff on day i (mm H_2O), E_a is the amount of evapotranspiration on day i (mm H_2O), W_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm H_2O), and Q_{gw} is the amount of return flow on day i (mm H_2O).

The water balance equation is the driving force behind all the processes accounted for in the watershed simulation. In order to accurately predict the movement of pesticides, sediments or nutrients, the hydrologic cycle simulated by the model must conform to what is happening in the watershed. SWAT simulates the hydrology of a watershed in two distinct phases:

- Land Phase -The land phase of the hydrologic cycle controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each subbasin.

- Water Phase -The water or routing phase of the hydrologic cycle, which can be defined as the movement of water, sediments, etc. through the channel network of the watershed to the outlet.

A distributed SCS curve number is generated for the computation of overland flow runoff volume, given by the standard SCS runoff equation (USDA, 1986). A soil database is used to obtain information on soil type, texture, depth and hydrologic classification. In SWAT, soil profiles can be divided into ten layers. Infiltration is defined in SWAT as precipitation minus runoff. Infiltration moves into the soil profile where it is routed through the soil layers. A storage routing flow coefficient is used to predict flow through each soil layer, with flow occurring when a layer exceeds field capacity. When water percolates past the bottom layer, it enters the shallow aquifer zone (Arnold et al., 1993).

Channel transmission loss and pond/reservoir seepage replenishes the shallow aquifer while the shallow aquifer interacts directly with the stream. Flow to the deep aquifer system is effectively lost and cannot return to the stream (Arnold et al., 1993). The irrigation algorithm developed for SWAT allows irrigation water to be transferred from any reach or reservoir to any other in the watershed. Based on surface runoff calculated using the SCS runoff equation, excess surface runoff not lost to other functions makes its way to the channels where it is routed downstream. Sediment yield used for instream transport is determined from the Modified Universal Soil Loss Equation (MUSLE) (Arnold, 1992). For sediment routing in SWAT, deposition calculations are based on fall velocities of various sediment sizes. Rates of channel degradation are determined from Bagnold's (1977) stream power equation. Sediment size is estimated from the primary particle size distribution (Foster et al., 1980) for soils the SWAT model obtains from the STATSGO (USDA 1992) database. Stream power also is accounted for in the sediment routing routine, and is used for calculation of re-entrainment of loose and deposited material in the system until all of the material has been removed.

4.2.3 ArcView SWAT Interface - AVSWAT

AVSWAT (ArcView SWAT) is a complete preprocessor, interface and postprocessor of the hydrological model SWAT (Di Luzio, 2004). The current version of AVSWAT runs in conjunction with ArcView 3.x. The user is provided with a set of numerical routines for watershed delineation, definition and editing of the hydrological and agricultural management inputs, running and calibration of the model. The extension and the model are user-friendly tools for the watershed scale assessment and control of the agricultural and urban sources of water pollution.

AVSWAT is organized in several linked tools grouped in the following categories:

(1) Watershed delineation;

(2) Land use and soil definition;

(3) Editing of model databases;

(4) Definition of weather stations;

(5) Input parameterization and editing;

(6) Model run;

(7) Read and map-chart results;

(8) Calibration tool.

A more detailed description of these tools is provided in the SWAT users manual.

4.3 Clinton River Watershed SWAT Results

A SWAT model was created for the Clinton River Watershed. The portion of the river and watershed below the diversion canal was not included in this model because SWAT cannot simulate multiple outlets from the same watershed. This lower portion of the river was modeled with a 3D model of hydrodynamics and sediment dynamics as described in Section 6. The area modeled in SWAT is shown in Figure 4.1. This model was created using AVSWAT.

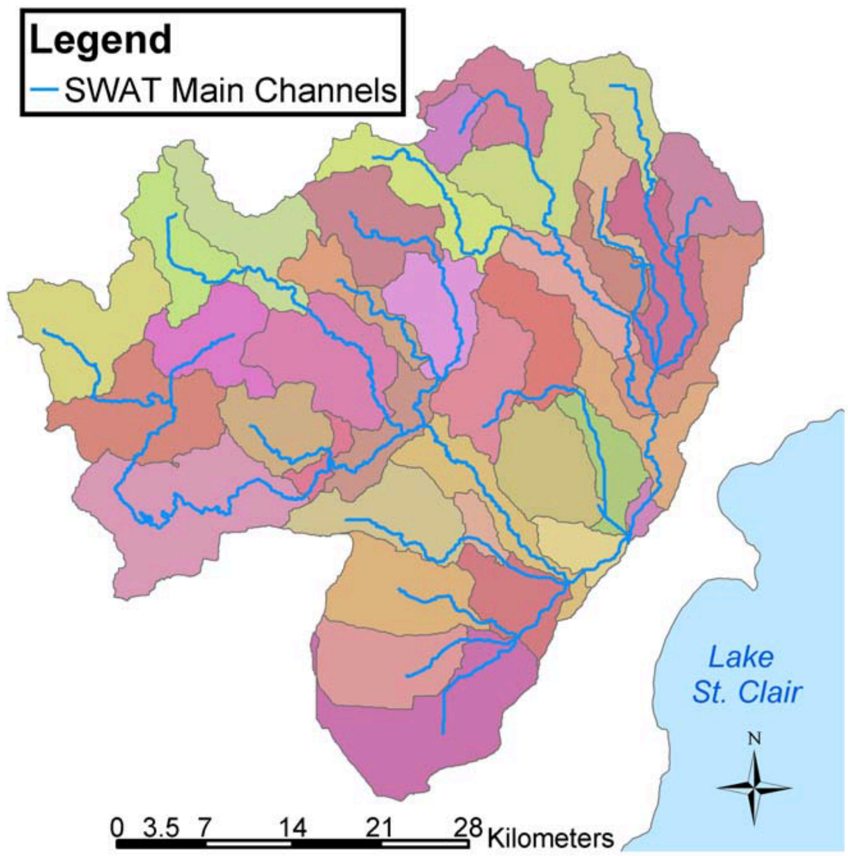

Figure 4.1 Clinton River Subbasins Modeled in SWAT

The GIS data layers necessary to create the SWAT input files are a DEM, land use coverage and soils coverage. The DEM was obtained from the BASINS dataset and was preprocessed using ArcHydro Tools which is a non-proprietary package. The land use utilized was the 1992 National Land Cover Dataset (NLCD). Each NLCD land use category was assigned a SWAT land cover/plant type. AVSWAT has several land cover/plant types built-in, each having a pre-defined set of model parameters. These default parameter values were used for the Clinton River SWAT modeling. A table of

NLCD land use and corresponding SWAT land cover/plant type is given in Table 2.1 in the Clinton River Watershed Model User Manual.

In addition to the GIS layers, the SWAT model also requires climate data for the simulation period. AVSWAT has a built-in national climate database that can be used to fulfill the climate data requirements, which include rainfall, temperature, solar radiation, wind speed and relative humidity. Since the spatial distribution of this national climate database is relatively coarse, it is advantageous to use local climate data when and where available. For the Clinton River Watershed SWAT model, the national climate database data for rainfall and temperature were replaced with data from local weather stations. Daily rainfall data were obtained from Michigan's SEMCOG stations while daily maximum and minimum temperature measurements from the Selfridge Air National Guard Base in Mt. Clemens were used. The map in Figure 4.2 shows the precipitation and temperature data gage locations utilized for this simulation.

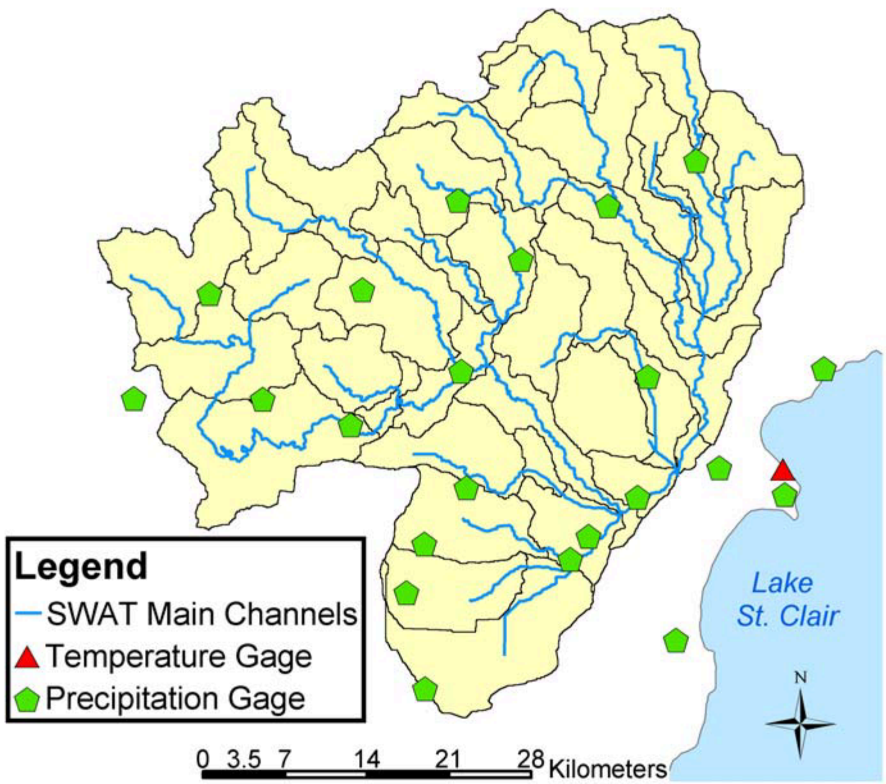

Figure 4.2 SWAT Precipitation and Temperature Stations

After the model was setup using the 1992 NLCD, preliminary calibration of the model hydrology was undertaken using USGS streamflow measurements at Gage 04165500 (Figure 2.2), which is at the same location as the SWAT model outlet. A baseflow filter program was used on the USGS streamflow data to determine the average annual ratio of baseflow to surface runoff for calibration of the simulated baseflow in SWAT. The particular baseflow filter program used was obtained from the SWAT website and is based on the methodology outlined in Arnold and Allen (1999) and Arnold, et al. (1995).

The Clinton River SWAT model was roughly calibrated to annual water yield and baseflow values; further refinement was done to simulate monthly water yields and daily values for particular events. Figures 4.3 to 4.5 show the yearly, monthly and daily flow comparisons between SWAT and the USGS measurements.

By adjusting some of the calibration parameters in SWAT, good agreement was reached with the measured flow data at the USGS stream gage. The largest discrepancies occurred in the winter and spring months. As it stands, the Clinton River SWAT model does not replicate snowmelt events accurately; to improve these results, more detailed local temperature and precipitation data are required. Predicted daily sediment delivery predictions are plotted for 1992 in Figure 4.6.

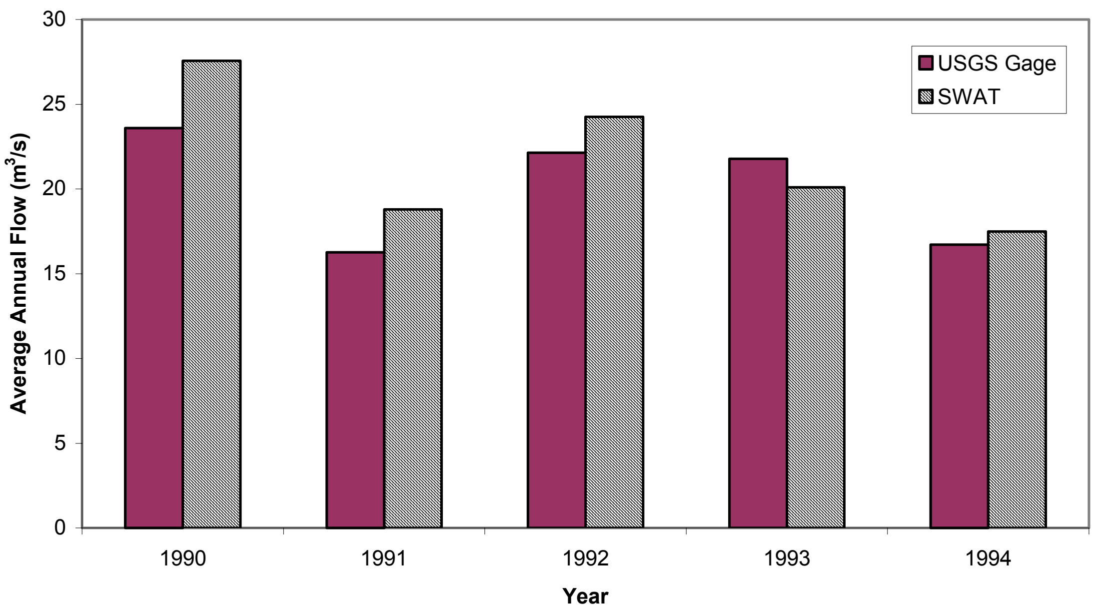

Figure 4.3 Average Annual Flow Comparison of SWAT Results and USGS Measurements

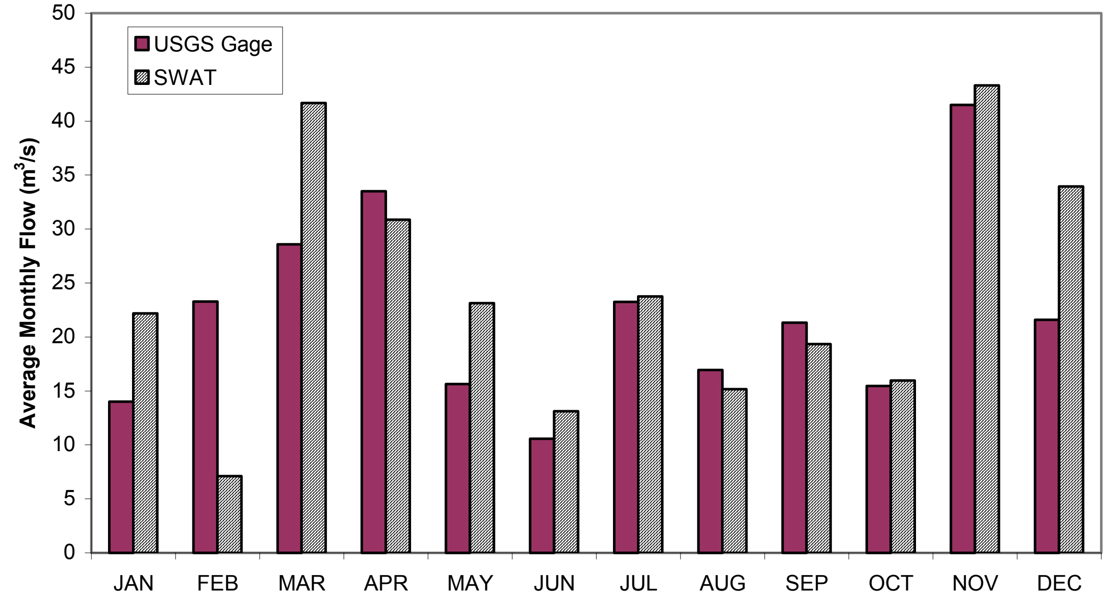

Figure 4.4 Average Monthly Flow Comparison of SWAT Results and USGS Measurements

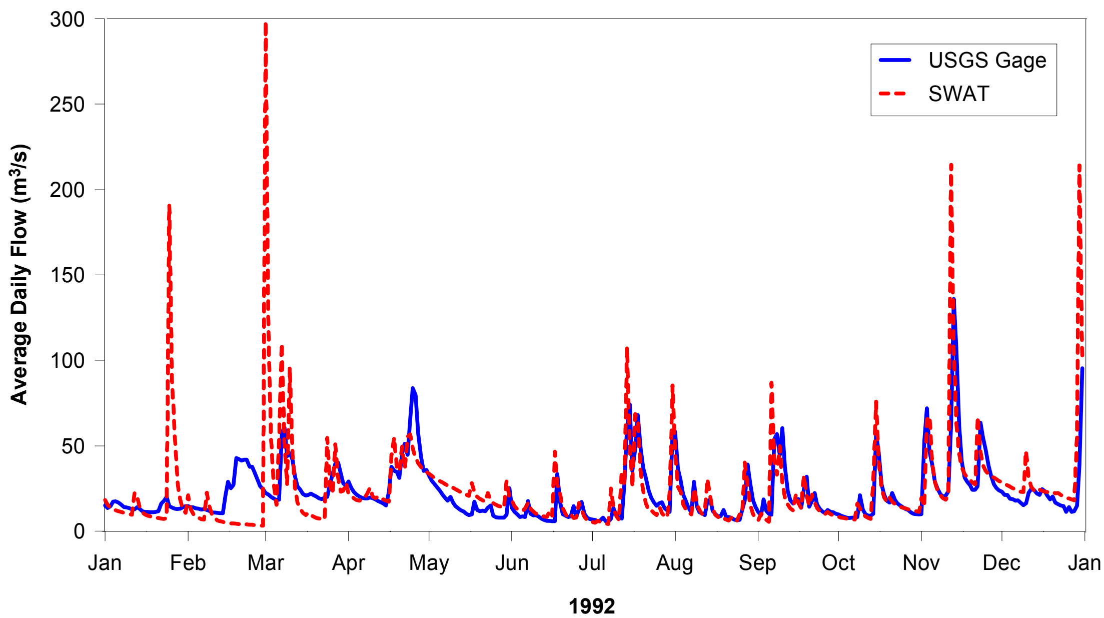

Figure 4.5 Average Daily Flow Comparison of SWAT Results and USGS Measurements

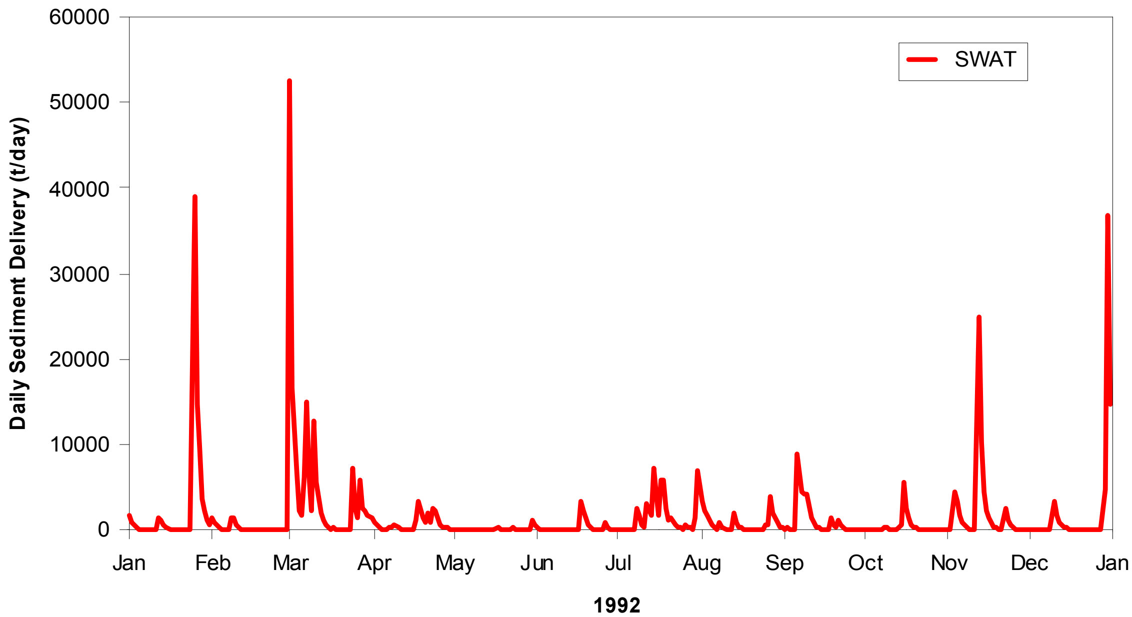

Figure 4.6 SWAT Model Daily Sediment Delivery Results for 1992

The SWAT model, based on the MUSLE, does not output net erosion from the land; instead, it calculates the amount of sediment that reaches the main channel in the subbasin. Thus, annual erosion per unit area (that is delivered to the channel) and sediment yield at the outlet of the Clinton River Watershed SWAT model are presented in Table 4.1.

Table 4.1 SWAT Results for Net Erosion and Sediment Yield for Clinton River Watershed

Year	Net Erosion ($t/km^2.yr^{-1}$)	Sediment Yield ($t/km^2.yr^{-1}$)
1990	799	505
1991	296	200
1992	345	263
1993	221	180
1994	256	187

Due to the lack of measured data, the sediment component of SWAT was not calibrated; therefore the results provide a relativistic estimate only.

A similar calibration process for the model hydrology was completed using the 1978 land use data and climate data from 1976 – 1980. With the calibrated model, climate data from 1990 – 1994 was run through the model with 1978 land use to see what relative difference the change in land use from 1978 to 1992 had on sediment delivery. The land use breakdown for the 1978 and 1992 data is shown in Figures 4.7 and 4.8. While there was little change in the percentage of urban/developed area, these charts show that the portion of the watershed used for agriculture increased by 10 %. It should be noted that the 1978 and 1992 land use data sets had different resolutions, thus the relative changes in specific land use types are approximate.

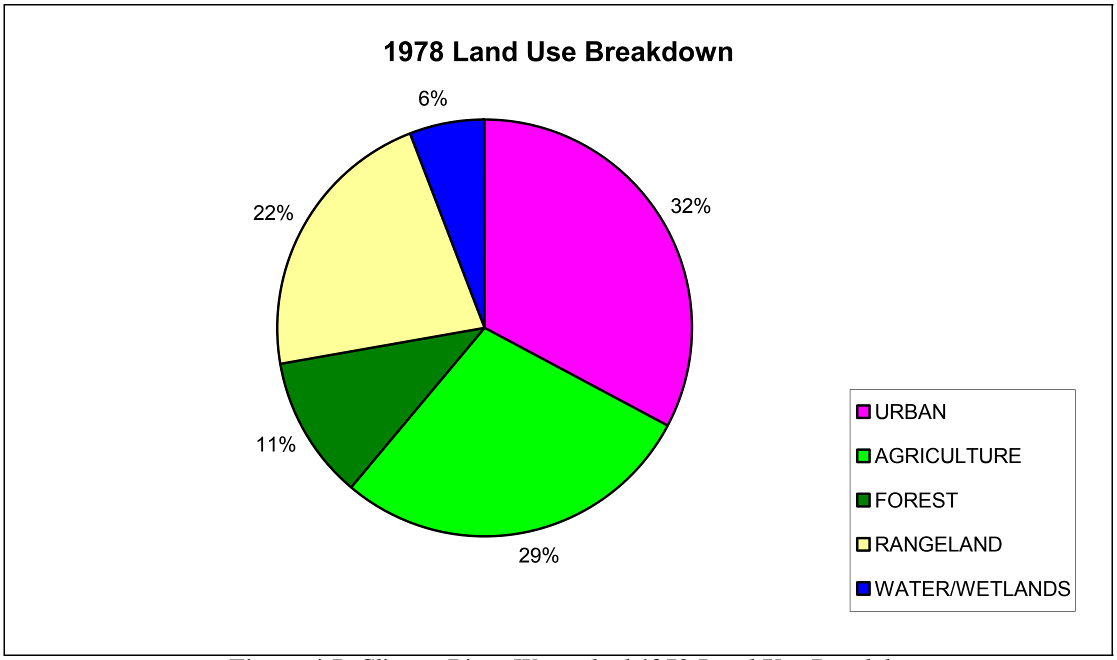

Figure 4.7 Clinton River Watershed 1978 Land Use Breakdown

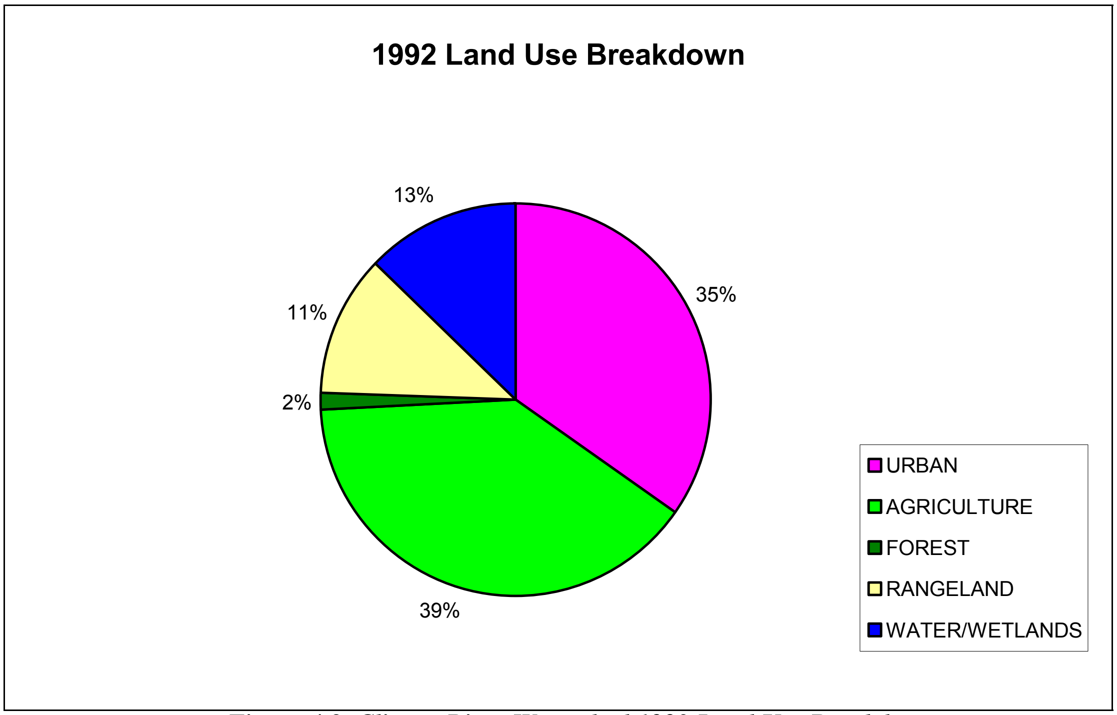

Figure 4.8 Clinton River Watershed 1992 Land Use Breakdown

Results for the average annual net soil erosion per unit area (t/km^2.yr^{-1}) for each land use scenario are shown in Figure 4.9. The yearly values increased by an average of 32 %, which resulted from a 10 % increase in agricultural land area. These results show how the SWAT model can be used to evaluate the impact of different land use scenarios on watershed soil erosion amount.

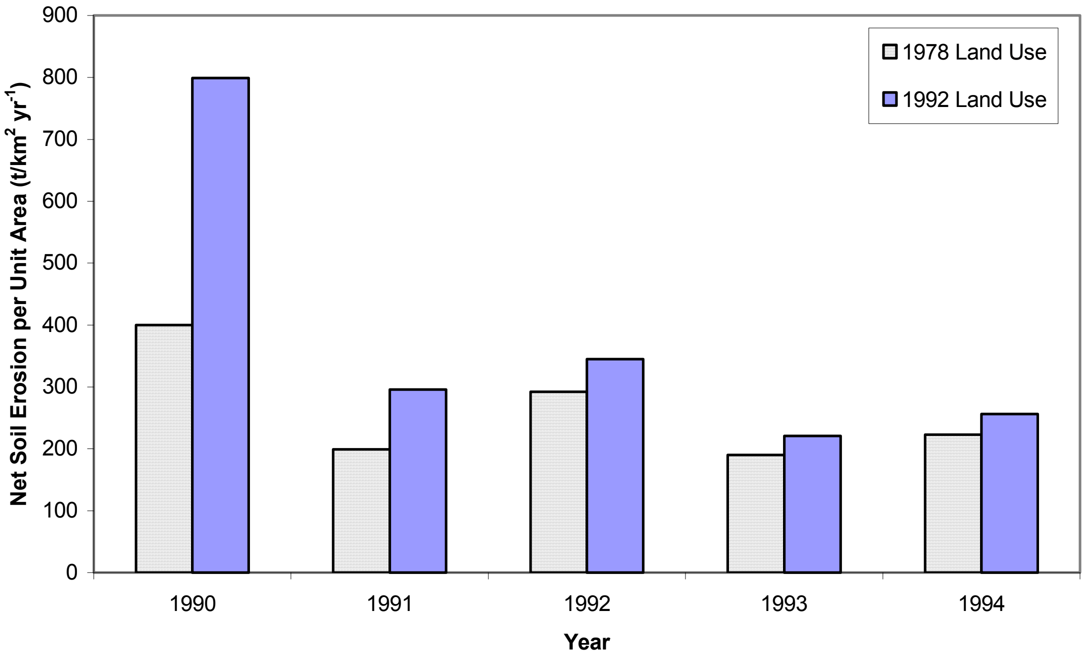

Figure 4.9 SWAT Yearly Net Erosion per Unit Area Results for 1978 and 1992 Land Use Scenarios (with 1990s climate data)

4.3.1 Paint and Galloway Subbasin Results

In addition to the overall Clinton River Watershed SWAT model, two, more detailed models of the Paint Creek and Galloway Creek subbasins were developed. Both these subbasins have USGS gaging stations located at their outlets, which provided calibration data for streamflow. Different time periods were simulated for each subbasin due to the limited availability of streamflow, precipitation and temperature measurements in and near the watersheds.

Daily flow and sediment load results for the Paint Creek watershed are shown in Figures 4.10 and 4.11. Results for Galloway Creek are shown in Figures 4.12 and 4.13. Not all winter and spring snowmelt events are accurately represented due to a lack of local temperature and precipitation data. Due to the lack of measured sediment load data for these subbasins, these SWAT sediment results were not calibrated. However, these same subbasins were modeled using the GSSHA model, and the results are compared in Section 7.

Paint Creek Results

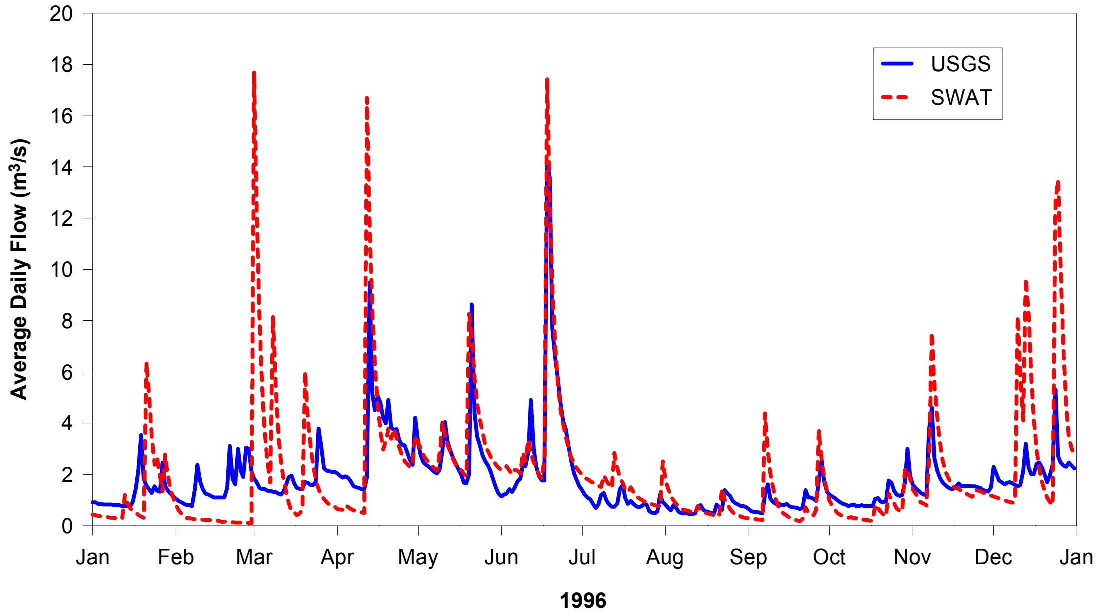

Figure 4.10 Average Daily Flow Comparison of SWAT Results for Paint Creek Watershed and USGS Measurements for 1996

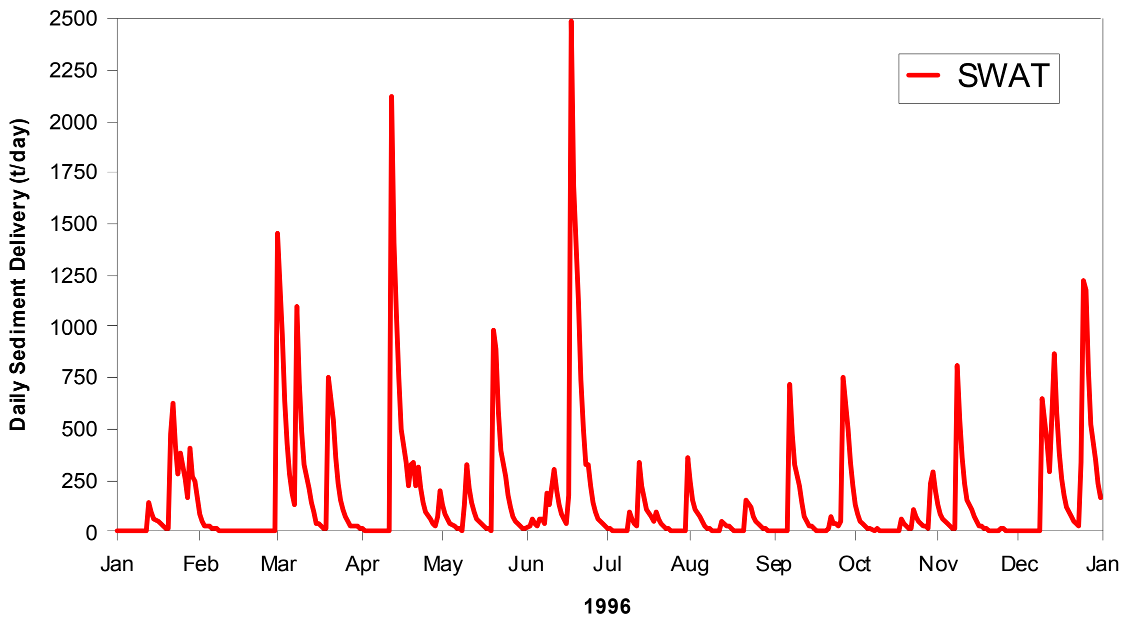

Figure 4.11 Paint Creek Watershed Daily Sediment Delivery SWAT Results for 1996

Galloway Creek Results

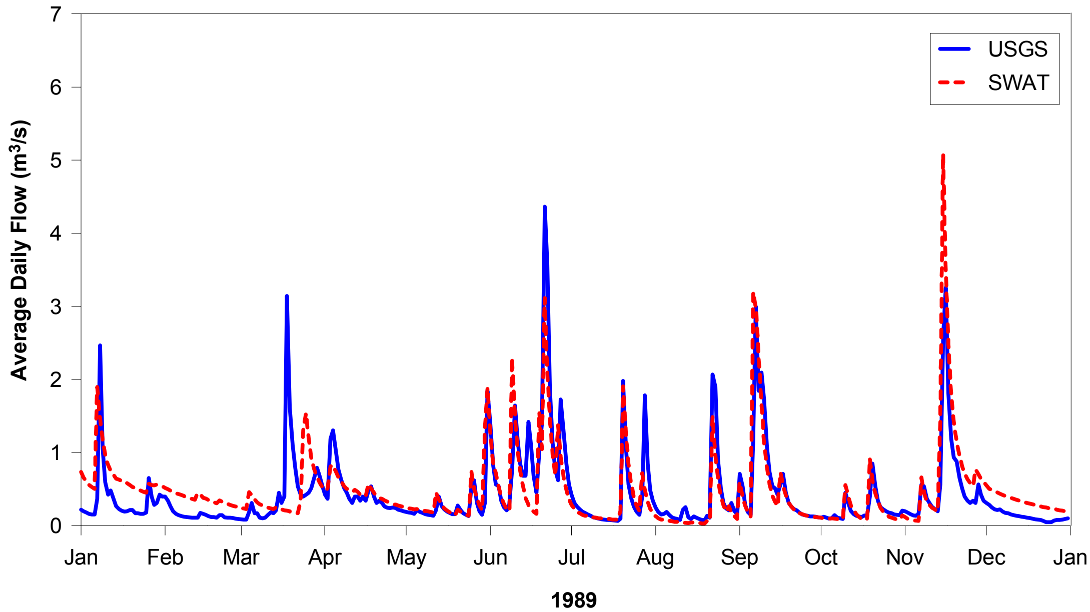

Figure 4.12 Average Daily Flow Comparison of SWAT Results for Galloway Creek Watershed and USGS Measurements for 1989

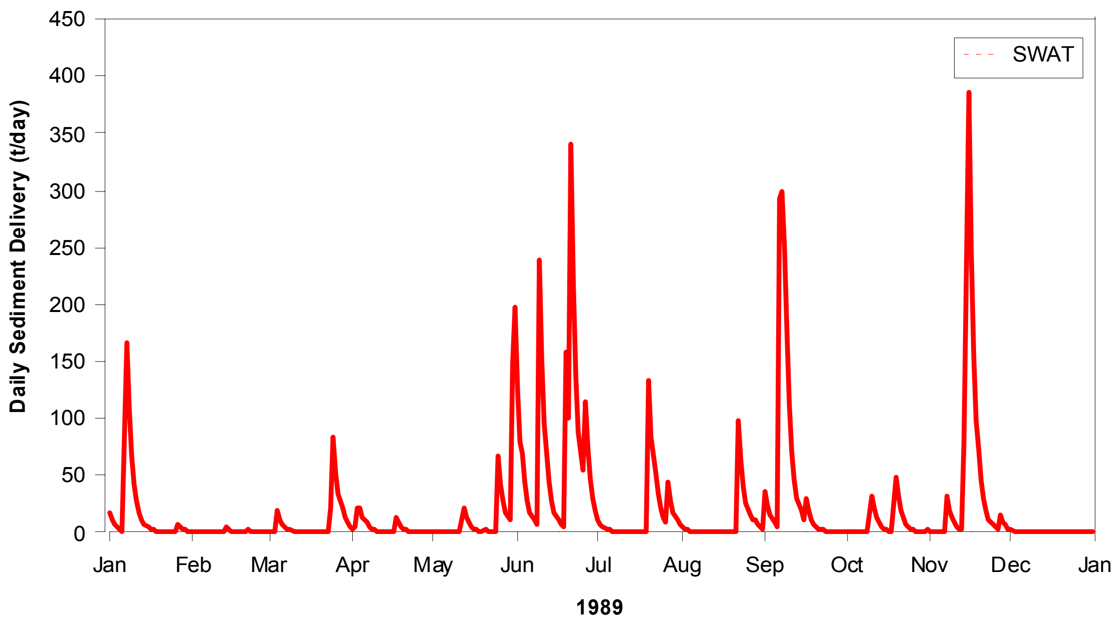

Figure 4.13 Galloway Creek Watershed Daily Sediment Delivery SWAT Results for 1989

4.4 GSSHA Model Description

The GSSHA (Gridded Surface Subsurface Hydrologic Analysis) model was used for the hydrologic and sediment transport numerical analysis. GSSHA is a 2D finite difference model that evolved from CASC2D (Ogden and Julien, 2002). The main difference between these two is the way GSSHA updates the individual processes through time.

GSSHA is a physically-based, distributed-parameter model that simulates the hydraulic response of watersheds to a given hydrometeorological condition. The major components of the model include:

- Precipitation (spatial and temporal variation);
- Precipitation interception;
- Snow fall accumulation and melting;
- Infiltration;
- Evapotranspiration;
- Overland flow routing;
- Groundwater flow;
- Channel routing;
- Overland sediment erosion / deposition;
- In-stream sediment transport.

The following sections describe the general data requirements for a GSSHA subbasin model.

4.4.1 Precipitation

Precipitation can be constant or vary in space. Spatial distribution of rain is specified at different precipitation gages throughout the watershed, which can be constant or change in time (for which a time series must be provided). The precipitation input is then distributed through the domain by application of Thiessen polygons or the inverse distance square weighted method. The former method is a nearest neighbor interpolation routine while the latter method produces a smooth field based on the assumption that the influence of a measured value decreases with the distance from the point of measurement squared (Downer and Ogden, 2002).

4.4.2 Precipitation Interception

Precipitation interception is the process of rain being retained by vegetation before reaching the land surface. GSSHA simulates this process with an empirical relationship that accounts for an initial volume of water that vegetation can retain plus the fraction of precipitation that can be captured by vegetation after the initial volume of water has been satisfied. The amount of intercepted rain is assumed to evaporate. The two-parameter method is further explained by Gray (1970).

4.4.3 Snowfall Accumulation

Snowfall has a large impact on hydrologic fluxes because snowfall is normally stored for a significant period of time before being released as melt water (Downer and Ogden, 2002). In many parts of the world, the effect of snow melting is the single most important yearly event in terms of runoff, and the watershed has a very different hydraulic response to snow melt runoff compared to rain produced runoff.

Within GSSHA, whenever the dry bulb temperature is below 0º C, precipitation will be treated as snowfall. If snow is already present in a cell, the new snow accumulation is added to the existing accumulated snow.

Any accumulation of snowfall is treated as a single layer of snowpack that melts due to heat sources such as non-frozen precipitation *Qv* (Equation 3), net radiation *Q** (Equation 4), heat transfer by sublimation and evaporation *Qe* (Equation 5) and sensible heat transfer due to turbulence *Qh* (Equation 6). For every 80 calories of heat added to the snow pack, $1cm^3$ of melt water is released (Linsey et al., 1982). The effect of frozen soil and changes in surface roughness due to temperature are not taken into account for the simulation of this process nor is complex snowpack behavior such as ripening of the snowpack or refreezing of melt water.

$$Qv = IT_a \tag{3}$$

where I is the precipitation intensity (cm/hr) and T_a is the ambient temperature (Cº).

$$Q^* = 49.56\text{x}10\text{-}10\ (Ta + 273)^4 - 27 \tag{4}$$

$$Qe = \left(f(v) \frac{rh}{100} e_s - 6.11 \right) \tag{5}$$

where *rh* is the relative humidity, *f(v)* = 0.0002, *U* (Km/hr), *U* is the wind speed (m/s) and e_s is the saturated vapor pressure (6.11 mb).

$$Qh = 0.366\ T_a\ P_a\, f(v) \tag{6}$$

where P_a is the atmospheric pressure (mb).

4.4.4 Infiltration

Infiltration is the process whereby rainfall and ponded surface water seep into the soil due to gravity and capillary suction. This process is a function of the soil hydraulic properties and antecedent moisture conditions, which are related to previous rainfall, runoff, soil moisture movement, etc.

GSSHA simulates infiltration in one dimension and can be executed in two main ways: Green and Ampt (GA) method and the Richards equation model. In addition to these two methods, there are two variations of Green and Ampt also available within GSSHA (i.e., Multi-layer Green and Ampt (MLGA) and Green and Ampt with redistribution (GAR)). The full description and implementation of these methods is described in Downer and Ogden (2002). The GA and multi-layer GA methods are more applicable to simulation periods where there is no significant rainfall hiatus and GAR is more applicable to periods where brakes in rainfall are significant.

Green and Ampt (GA)
This method is limited to conditions where Hortonian flow, or infiltration excess, is the dominant streamflow producing mechanism (i.e. where the runoff of water is greater than the possible infiltration rate) and the soils are uniform and infinitely deep. For this method, the water is assumed to infiltrate in a sharp wetting front fashion and precipitation on initially dry soil is quickly infiltrated due to capillary pressure. As precipitation continues and the soil becomes more saturated, the infiltration rate decreases until it approaches the saturated hydraulic conductivity of the soil.

Multi-layer Green and Ampt (MLGA)
The main difference between MLGA and GA is that this method accounts for three different layers of sediment. The changes in hydraulic properties of the soil column cause a reduction in infiltration capacity.

The three layer soil system consists of a top layer composed of loose and highly organic material which produces an increase in porosity and hydraulic conductivity, a middle layer composed of less organic material, reduced biological activity and more compact soil and the bottom layer is even more compact and presents a minimal biological activity.

Green and Ampt with Redistribution (GAR)
With this method, multiple sharp wetting fronts can be simulated, and the water is redistributed in the soil column during no precipitation or low precipitation periods. This allows infiltration capacity to recover for the next precipitation event.

Richards Equation
This is the most complete method to compute water movement and is not limited to Hortonian flows. The partial differential equation describing this method is discretized in a finite difference fashion. Three soil layers are defined, each with independent parameters. Due to the high level of non-linearity, this method can generate a higher computational time throughout a simulation effort. It employs a powerful mass

conservation scheme and has been proven capable of simulating both soil moisture and associated hydrologic fluxes when the proper spatial discretization is employed (Downer, 2002).

4.4.5 Evapotranspiration

Evapotranspiration is the combined effect of evaporation of ponded surface water and water contained in the soil pores and transpiration of water from plants. GSSHA uses this process to keep track of soil moisture during long-term simulations. The simulations can be executed by two methods, the Deardorff (1977) and Penman-Monteith (Monteith, 1965), where the former is used for bare soil simulations and the latter is a more sophisticated method used for vegetated areas.

4.4.6 Overland Flow Routing

When the processes of evaporation and infiltration are no longer active, the water accumulates on the surface. If there is a gradient in surface elevation the water tends to displace from higher elevation to lower elevation cells, which is known as overland flow. This process is simulated with a two-dimensional finite volume explicit scheme of the diffusive wave equation. There are three schemes to compute overland flow in GSSHA: point explicit (PE), alternating direction explicit (ADE) and ADE with prediction-correction (ADE-PC). Downer, et al. (2000) tested the three methods and determined that ADE and ADE-PC could be executed with time steps much larger than PE (up to 240%), but the computational time also increases. ADE-PC provides a more robust and accurate method that can be applied to model domains where terrain is rougher or where the DEMs are not smoothed as much, without being unstable. The negative aspect of ADE-PC is that computational time can increase significantly. More in-depth descriptions of each method and formulations are given in Downer and Ogden (2002).

4.4.7 Groundwater Flow

In areas where base flow discharge is significant, groundwater flow should be included in the modeling process. Saturated groundwater flow is simulated with a two-dimensional finite difference scheme. The grid is mapped from the overland flow grid. The saturated groundwater zone resides below the unsaturated zone, which might be represented with the GAR method or Richards equation model.

Simulation of groundwater flow allows for interaction between stream and groundwater fluxes as well as exfiltration to the overland flow plane based on Darcy’s Law.

4.4.8 Overland Sediment Erosion / Deposition

Surface sediment can be eroded, transported and deposited using a soil erosion model based on the Kilink and Richardson (1973) method with one main difference: this method allows for non uniform flow and considers soil and land use specific factors similar to those described in the Universal Soil Loss Equation (Julien 1995). Cell to cell sediment transport is dependant on the flow, soil and surface characteristics. This model accounts for three different sediment classes (sand, silt and clay). Conservation of sediment mass is used to determine the amount of sediment that is deposited and the amount that stays in suspension. The suspended sediment might be transported along computational cells. If the amount of suspended sediment does not satisfy the erosion demand, then deposited sediment is re-entrained until the demand is met. If the amount of deposited sediment is depleted then surface erosion occurs.

4.4.9 Channel Routing

Although not necessary for the model to run, channel routing can be specified in the model domain. This allows water to flow in a channelized fashion within a watershed. When runoff reaches a stream section, the water flow is routed in a one-dimensional form (similar to the overland flow scheme) until it reaches the watershed outlet. This method, although very simple, has proven to be robust and can be applied to sub-critical, supercritical and trans-critical conditions.

The scheme allows water to remain in the channel after the channel routing process ends and for water to be present in the channel when the process begins. Since groundwater might also discharge water into the stream, channel routing begins anytime there is water in the channel network, but if the routine identifies that there is no flow, then the channel routing process will end. Even at stages where there is no channel flow, the interaction between groundwater flow and streams continues and the volume imported or exported from the channel is accounted for. Flux through the riverbed is calculated based on the difference in elevation between the groundwater surface and the water surface elevation in the stream node (i.e. if the groundwater surface elevation is above the riverbed elevation but below the river water surface elevation the river discharges to the groundwater).

The model stability is not entirely dependent on the Courant number but also on volume changes during each time step. Additional control parameters are included in the channel routing scheme to reduce instability problems associated to groundwater flow and overbank fluxes. The channel routing time step is automatically reduced up to 1/1000 of a second during periods of sharp transition.

Channel cross-sections can be specified with a trapezoidal or dual slope trapezoidal geometry or break point cross-sections. Typically, small streams in the head waters of the watershed are specified as trapezoidal cross-sections, larger streams in the lower watershed reaches are specified as brake-point cross-sections which can be derived from field surveys, detailed topographic maps or high-resolution DEMs.

The hydrodynamic channel routing within GSSHA is much more sensitive to channel cross-section changes than profile changes. To ensure stability and mass conservation, the transitions should be smooth. The Manning's roughness coefficient for this process is used mainly as a calibration parameter.

4.4.10 Instream Sediment Transport

Once the sediment load reaches the stream network GSSHA employs the unit stream power method of Yang (1973) for routing sand size particles. Silt and clay are transported with the flow as wash load (concentration based). In practice this means that once fine sediment enters the stream there is no net erosion or deposition of such particles. The basis for this assumption is that the flow behaves in a turbulent way and the distance a particle travels is relatively small in comparison to the settling velocity of such grain size classes. In order for this scheme to function, the channel cross-sections must be set to a trapezoidal shape.

The channel geometry will only vary in the vertical with erosion and deposition (i.e., no bank erosion is accounted for) until bedrock (specified by the user) is reached.

4.5 Clinton River Subbasin Results With GSSHA

Two basins from Macomb County (Paint Creek and Galloway Creek) and one basin from Oakland County (Middle Branch) were modeled with GSSHA. These basins were chosen based on flow discharge data availability as well as for being significant sources of sediment according to the results obtained from Section 3. There was no measured sediment data available for any of the subbasins thus the sediment loads reported here should not be considered as absolute values but as a comparison basis to determine which basins would produce higher sediment loads within the watershed. The basins were set up according to the procedure described in the GSSHA users manual.

4.5.1 Paint Creek

Paint Creek covers an area of approximately 96 km^2 (37 mi^2) where approximately 23 % is urban/developed, 32 % agricultural, 33 % forested and 11 % wetlands (Figure 4.14) and the soil varies from loamy sand to sandy loam. Paint Creek basin was chosen primarily because there was a long-term flow discharge record at the watershed outlet as well as anecdotal data stating that this basin was a significant sediment source. The model was calibrated against flow discharge from USGS Gage # 04161540 located at Rochester (Figure 4.14), which has a temporal coverage from 1954 to present.

The grid size for this basin was set to 50 m and the time step was set to 20 s. The channels had a constant roughness coefficient of 0.08 and the infiltration processes were simulated using Green-Ampt with redistribution. The groundwater hydraulic conductivity was set to 34 cm/hr., the initial water table elevation was 12 m below the surface and the bedrock elevation was 100 m. Following is a description of the values used for infiltration and erodibility based on soil and land use coverage types.

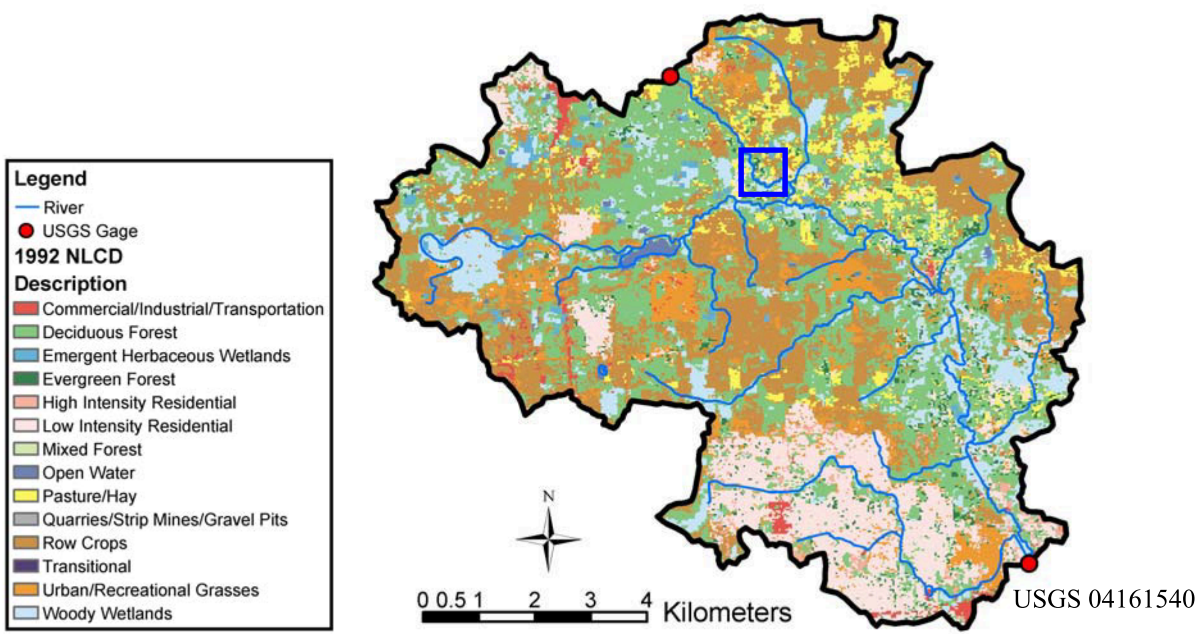

Figure 4.14 Paint Creek Subbasin Land Use, River Network and Gage Location. Blue Frame Represents Small Scale Modeling Area

Infiltration

The hydraulic conductivity and capillary head are the two most sensitive infiltration parameters and thus, are used to calibrate the model output. Capillary head values were set to 11.01 for sandy loam and 6.13 for loamy sand, which were obtained from the GSSHA users manual (Downer and Ogden, 2002).

Different soil types will produce different infiltration rates (e.g. sandy soils will have a higher infiltration rate than finer soil types) and to some degree the land use will also influence the rate (e.g., paved areas will have a very low permeability while bare fields will have a much higher infiltration rate). Hydraulic conductivity (HC) values for this basin were set in a combined land use-soil type approach based on curve number. Table 4.2 shows the final HC values, in cm/hr, applied at Paint Creek.

Table 4.2 Hydraulic Conductivity Values Based on Soil and Land Use Type

Land use type	Soil Type	
	Sandy loam	Loamy sand
Concrete or asphalt	0.076	0.076
Developed/Industrial	0.185	0.836
Range/Forest/ Prairie	0.235	1.068
Crops	1.326	6.004
Lakes / Wetlands	15.00	15.00

Roughness

This parameter, along with the slope, determines how fast overland flow displaces throughout the domain and is a function of the land use type. For example, smooth pavement imposes less resistance to fluid motion while dense vegetated areas impose more resistance to flow displacement. This parameter is also manipulated to calibrate the model. Table 4.3 lists the applied roughness coefficients (Manning's *n*) for the different land use types.

Table 4.3 Manning's Roughness Coefficient for Overland Flow

Land use type	Manning's *n* friction coefficient
Concrete /asphalt	0.011
Developed/ Industrial	0.0137
Bare field	0.050
Range (natural)	0.130
Range (Clipped)	0.100
Small grain	0.150
Row crops	0.100
Short grass prairie	0.150
Forest	0.192
Lakes and wetlands	0.400

Sediment Delivery Parameters

The simulation of soil erosion and sediment delivery to the channel network in GSSHA is controlled by two main sets of parameters. One is related to the soil properties and the other one to land management. These two sets of parameters can be varied to obtain a better calibration. Since there were no sediment delivery data for this basin, the values were obtained from literature (Downer and Ogden, 2002) and NLCD and are listed in Table 4.4.

Table 4.4 Soil Erodibility Values

Land use type	Cropping Management (*C*)	Conservation practice (*P*)
Concrete /asphalt	0.005	1.0
Developed/ Industrial	0.003	1.0
Bare field	0.300	1.0
Range (natural)	0.010	1.0
Range (Clipped)	0.010	1.0
Small grain	0.070	0.5
Row crops	0.120	0.5
Short grass prairie	0.003	1.0
Forest	0.011	1.0
Lakes	0.0001	1.0
Wetlands	0.001	1.0

Baseline Model Results

Flow data from 07/17/1996 to 07/22/1996 was utilized for the basin calibration. This event was chosen firstly because an event within the same time frame of the land use dataset as needed. Within that frame there were some other well-defined events but they occurred in the early spring when the ground may have been frozen and with related uncertainty in the meaning of the data. The other events in the summer months were either smaller or composed of several peaks.

Figure 4.15 shows the measured data along with the simulated data. It can be observed that the receding limb decreases more rapidly than the measured data. This behavior has been observed in other basins simulated with GSSHA even after adjustment of the base flow component. The amount of sediment delivered to the channels is in the order of 30,600 m^3 (12,100 m^3 (31,460 t) of sand and 18,500 m^3 (48,100 t) of fine sediment) from which approximately 23,100 m^3 (4,600 m^3 (11,900 t) of sand and 18,300 m^3 (47,600 t) of silt/clay) makes it out of the system. It should be noted that such high silt/clay sediment loads are questionable and are due to the fact that no deposition of this sediment class takes place in the numerical model. This assumption is based on the idea that most of the sediment yield is composed by the fine sediment fraction, however, since in this watershed there is a significant coverage of wetlands and reservoirs there is the possibility of fine sediment deposition before reaching the watershed outlet.

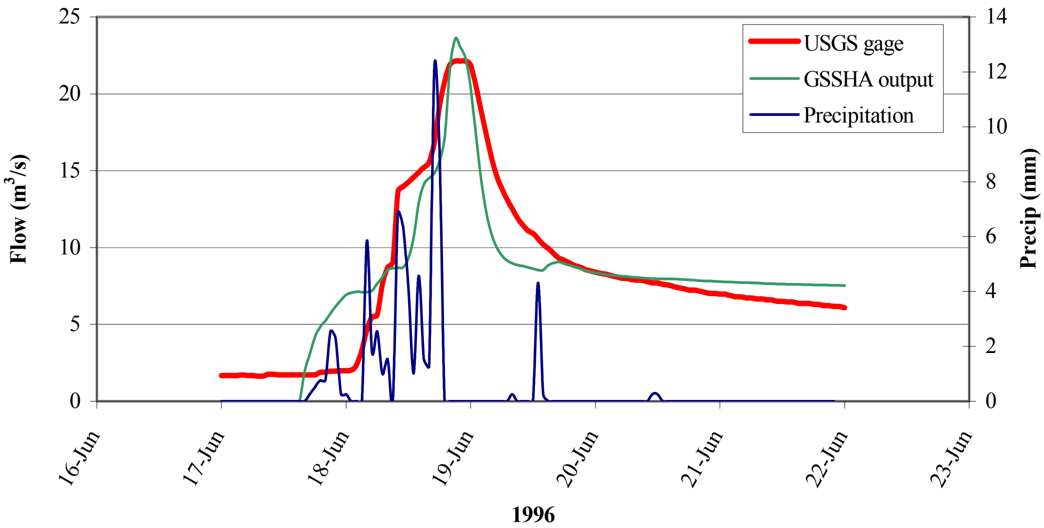

Figure 4.15 Precipitation and Flow Time Series for the June 18th, 1996 Event

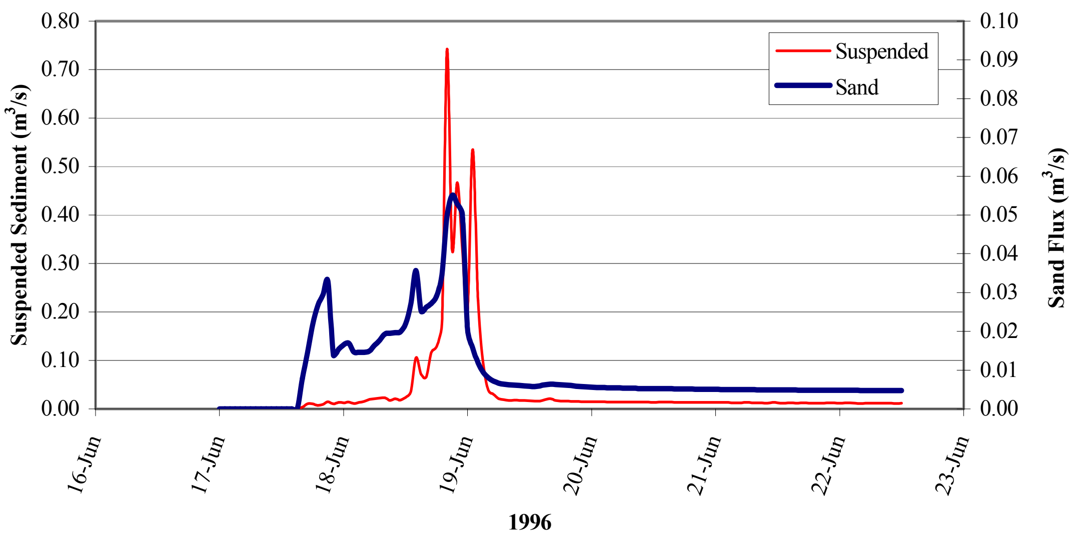

Figure 4.16 Sediment Flux Time Series for the June 18th, 1996 Event

4.5.2 Galloway Creek

The Galloway Creek watershed covers approximately 45 km^2 (17 mi^2). The land use in the watershed was summarized from the 1992 NLCD data and is divided into 44 % urban/developed, 24 % agricultural, 27 % forested and 8 % water and wetlands (Figure 4.17). As of 1992, the basin was less than 50 % developed, but the continued urban growth since then has changed this characterization. The soil types include loamy sands, sandy loams, and loams.

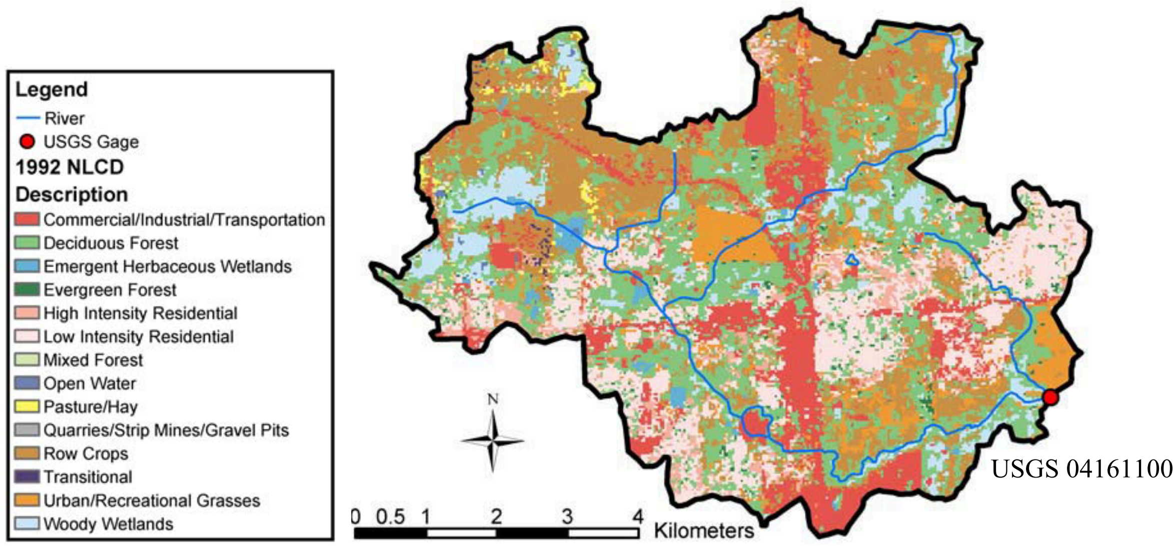

Figure 4.17 Galloway Creek Subbasin Land Use, River Network and Gage Location

The grid size for this basin is 70 m. The surface hydrologic processes had a time step of 15 s, and the subsurface processes was set at 60 s. The channels had a constant roughness coefficient of 0.12. This value is much higher than a typical "*n*" value but was arrived at during the calibration process and produced better results than typical values of 0.025 to 0.045. The infiltration processes were simulated using Green-Ampt with redistribution (GAR), for which the groundwater hydraulic conductivity was set to 15 cm/hr. The initial water table elevation was adjusted for each model run, which was dependent on the antecedent moisture levels in the watershed. These values were in the range of 1 to 2 m below the surface.

Infiltration

The infiltration values used in the GSSHA model originated with published values from the soil survey data, and were adjusted during the model calibration process. The model development process included a spatial analysis of the combination of soil types and land use in the watershed. The infiltration rate for each soil type was adjusted for the land use, by adjusting the infiltration rates to reflect the relative imperviousness of the surface (Table 4.5). During the calibration process, the infiltration values were adjusted to produce the best match between the simulated and observed runoff peaks and total volumes. The resulting values are shown in Table 4.6.

Table 4.5 GSSHA Model Infiltration Adjustment

Land Use Type	Effective Impervious Area (%)	Infiltration Adjustment (%)
Lakes / Wetlands	100	0
Transportation	86	14
Developed/Industrial	86	14
Residential (high density)	48	52
Residential	24	76
Agriculture	5	95
Range/Forest/ Prairie/Crops	0	100

Table 4.6 GSSHA Model Infiltration in cm/hour

Land use type	Soil Association / Type			
	Sandy loam	Loamy sand	Loam-Sandy loam	Loam
Lakes / Wetlands	0.0000	0.0000	0.0000	0.0000
Transportation	0.0168	0.0336	0.0112	0.0084
Developed/Industrial	0.0168	0.0336	0.0112	0.0084
Residential (high density)	0.0624	0.1248	0.0416	0.0312
Residential	0.0912	0.1824	0.0608	0.0456
Agriculture	0.1200	0.2400	0.0800	0.0600
Range/Forest/ Prairie/Crops	0.1200	0.2400	0.0800	0.0600

Roughness

This parameter is adjusted to calibrate the overland flow velocity in the model. Table 4.7 is a list of the roughness coefficients (Manning's *n*) for the different land use types used in the GSSHA model.

Table 4.7 Manning's Friction Coefficient for Overland Flow

Land use type	Manning's *n* friction coefficient
Residential	0.020
Developed/ Industrial	0.013
Bare field	0.050
Range (natural)	0.130
Range (Clipped)	0.100
Small grain	0.150
Row crops	0.100
Short grass prairie	0.150
Forest	0.192
Lakes and wetlands	0.400

Sediment Delivery Parameters
The soil erosion and delivery parameters for Galloway Creek are the same as for Paint Creek, and are listed in Table 4.4.

Baseline Model Results
The model was calibrated against flow values from USGS Gage 04161100, Galloway Creek at Auburn Heights. The gage was in operation from Water Year 1960 through 1991. The precipitation inputs were taken from the SEMCOG database (hourly) and supplemented with data from nearby NOAA gages. A map showing the location of these gages is shown in Figure 2.1. The calibration events were during the months of May through July of 1989. Figure 4.18 shows the measured data along with the simulated data.

The calibration of the baseline model produced results that reasonably replicate actual events. The degree of mismatch is well within the range of what could be defined as normal modeling uncertainty, and the uncertainty in the precipitation quantity and timings.

The amount of sediment delivered to the channels is on the order of hundreds to several thousand cubic meters per event, out of which approximately 93 percent makes it out of the system.

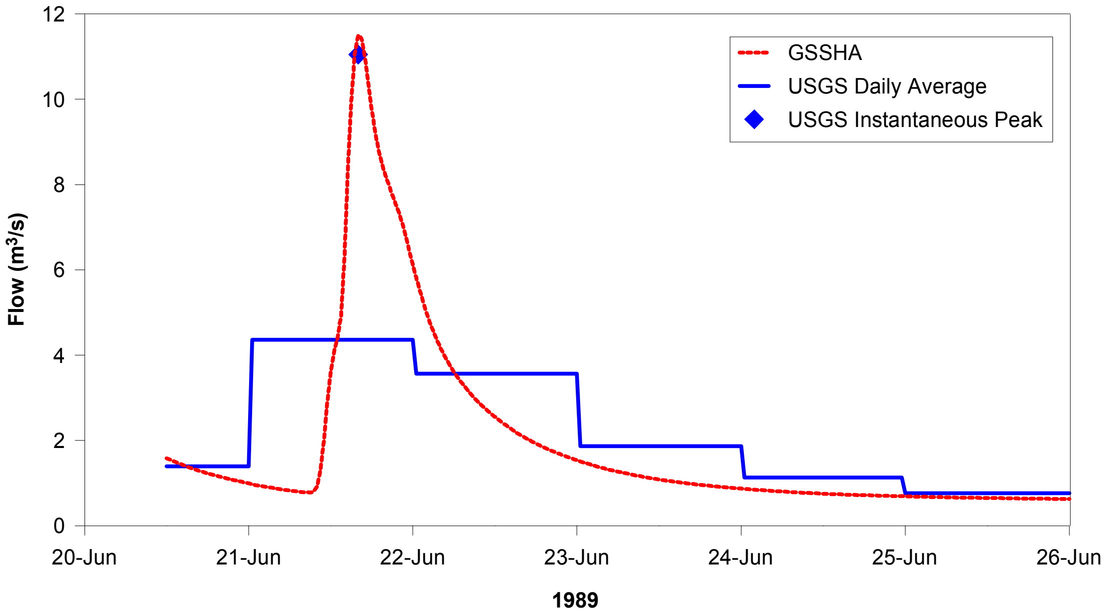

Figure 4.18 Results of Galloway Creek Calibration

4.5.3 Middle Branch Clinton River

The Middle Branch of the Clinton River has a drainage area of approximately 205 km^2 (79 mi^2). The land use in the watershed was summarized from the 1992 NLCD data and is divided into 31 % developed, 24 % forested, 41 % agricultural and 4 % of wetlands and water bodies (Figure 4.19). As of 1992, the basin was less than 50 % developed, but the continued urban growth since then has changed this characterization. The soil types include:

- Clay
- Clay-loam
- Loam
- Loamy Sand
- Sandy Loam
- Fine Sandy Loam

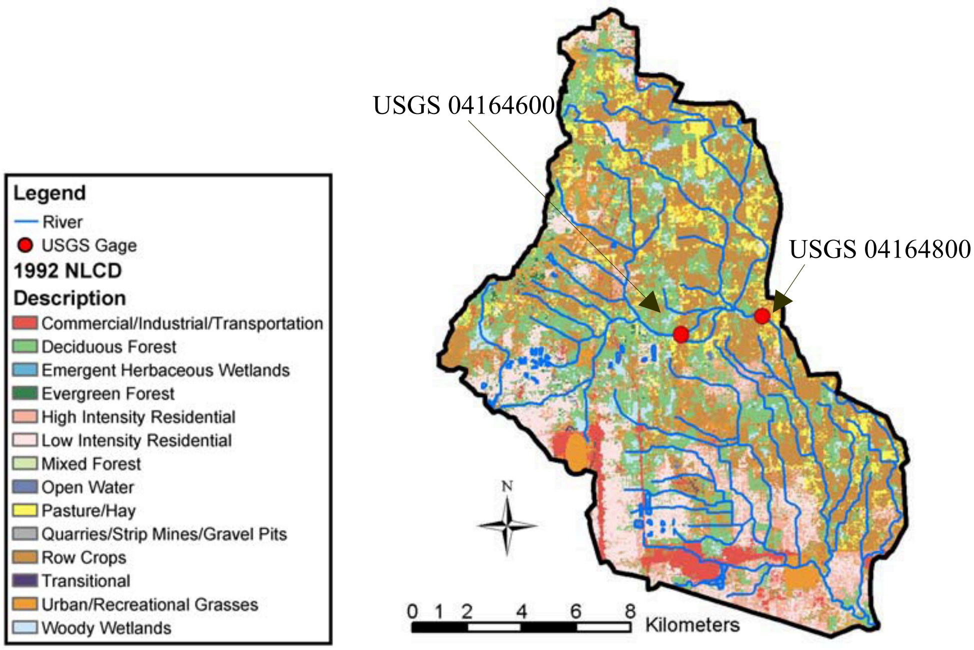

Figure 4.19 Middle Branch Subbasin Land Use, River Network and Gage Location

The grid size for this basin was 100 m. The surface hydrologic processes had a time step of 10 s, and the subsurface processes time step was set to 60 s. The channels had a constant roughness coefficient of 0.10. This value is much higher than a typical "*n*" value, but was arrived at during the calibration process, and produced better results than typical values of 0.025 to 0.045. The infiltration processes were simulated using Green-Ampt with redistribution, for which the groundwater hydraulic conductivity was set to 1 cm/hr. The initial water table elevation was adjusted for each model run, which was dependent on the antecedent moisture levels in the watershed. These values were in the range of 1 to 2 m below the surface.

Infiltration

The infiltration values used for the Middle Branch model were adjusted during the calibration process, in the same manner as used for Galloway Creek. The values used in the GSSHA model are shown in Table 4.8.

Table 4.8 Middle Branch GSSHA Model Infiltration in cm/hour

Land use type	Soil Association / Type					
	Loamy Sand	Fine Sandy Loam	Loam	Sandy Loam	Clay Loam	Clay
Lakes / Wetlands	0.000	0.000	0.000	0.000	0.000	0.000
Transportation	0.034	0.002	0.001	0.001	0.001	0.000
Developed/Industrial	0.034	0.012	0.009	0.007	0.004	0.003
Residential (high density)	0.125	0.084	0.068	0.049	0.030	0.023
Residential	0.182	0.162	0.130	0.094	0.058	0.043
Agriculture	0.228	0.214	0.171	0.124	0.076	0.057
Range/Forest/ Prairie/Crops	0.240	0.225	0.180	0.130	0.080	0.060

Roughness
This parameter is adjusted to calibrate the overland flow velocity in the model. Table 4.9 is a list of the roughness coefficients (Manning's *n*) for the different land use types used in the GSSHA model.

Table 4.9 Manning's Friction Coefficient for Overland Flow

Land use type	Manning's *n* friction coefficient
Residential	0.020
Developed/ Industrial	0.013
Bare field	0.050
Range (natural)	0.130
Range (Clipped)	0.100
Small grain	0.150
Row crops	0.100
Short grass prairie	0.150
Forest	0.192
Lakes and wetlands	0.400

Sediment Delivery Parameters
The soil erosion and delivery parameters for the Middle Branch are the same as for Paint Creek, and are listed in Table 4.4.

Baseline Model Results
The model was calibrated against flow values from USGS Gage #04164600 (Clinton River Middle Branch at Schoenherr Rd. near Macomb, MI) and Gage #04164800 (Middle Branch Clinton River at Macomb, MI). These gages were in operation from water year 1964 to 1969 and 1962 to 1982. The precipitation data source used to

calibrate the model was from the NOAA gage network that was available during the same period as the flow gages. The available flow data for this subwatershed precedes the SEMCOG precipitation gage network. A map showing the location of these gages is shown in Figure 2.1.

The calibration of the baseline model produced results that reasonably replicate actual events. The degree of mismatch is well within the range of what could be defined as normal modeling uncertainty, and the uncertainty in the precipitation quantity and timings. The model calibration involved iterative simulations and comparing the resulting flow hydrographs for peak flow as well as daily average flow. The USGS database includes daily average flows on a continuous basis, and peak flows for each water year. The event chosen for calibration was the peak flow event for 1968. The resulting GSSHA model produces reasonable results both in terms of daily average and peak flow values.

The amount of sediment delivered to the channels is in the order of hundreds to several thousand cubic meters per event, out of which approximately 90 % makes it out of the system.

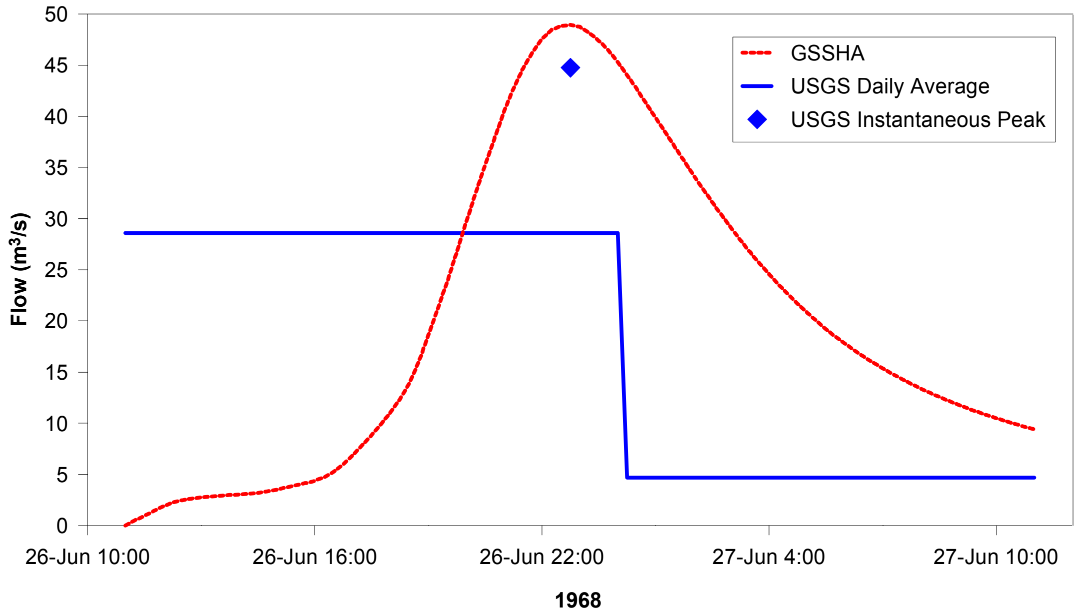

Figure 4.20   GSSHA Model Calibration Results for USGS Gage # 04164800

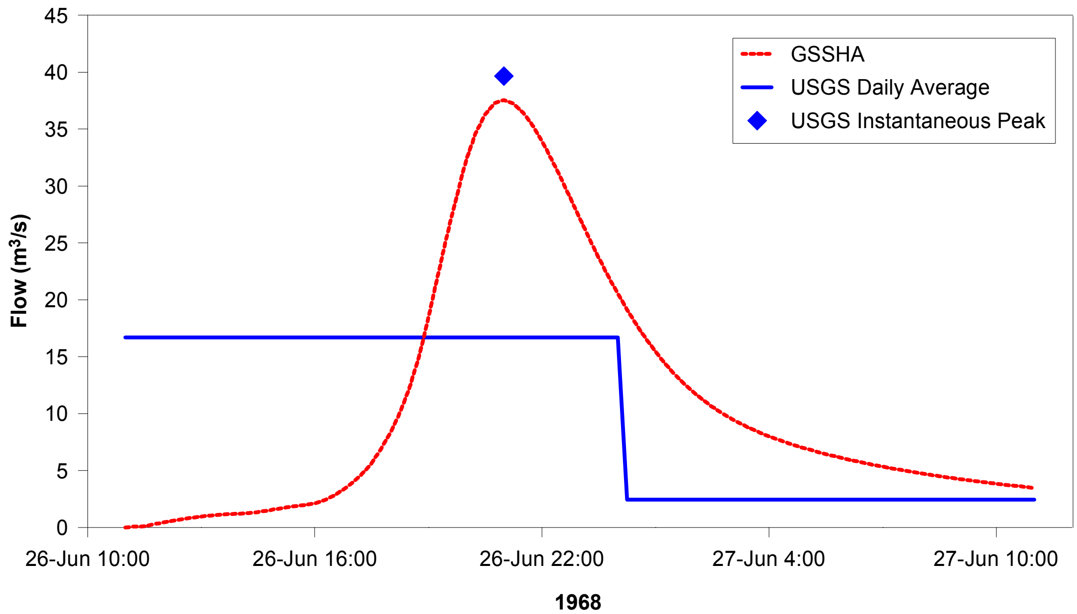

Figure 4.21   GSSHA Model Calibration Results for USGS Gage # 04164600