NEMADJI RIVER BASIN SEDIMENT TRANSPORT MODELING FOR TWO SUBWATERSHEDS

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TABLE OF CONTENTS

1. INTRODUCTION

1.1 Background

Per authority granted in Section 516(e) of the Water Resources Development Act of 1996, the Corps of Engineering was directed to develop sediment transport models for tributaries to the Great Lakes that discharge into Federal navigation channels or Areas of Concern. This report describes the development of sediment transport models for the Nemadji River Basin.

The Nemadji River comprises a 433 square mile watershed. The river flows to Superior Bay at Superior, Wisconsin. The watershed covers three counties (Carleton, Pine and Douglas) in the states of Minnesota and Wisconsin. The region is comprised of roughly 69% forested areas, 18% cropland and pastures, and 11% wetlands and lakes. Roughly one third of the Nemadji River Basin is comprised of glacial till, and glacial lake-laid clay soils commonly known as Red Clay. This Red Clay is considered to be highly erodible, and is prone to extensive mass wasting and bank slumping. Due to high turbidity and sediment loads, an estimated 33,000 tonnes of Nemadji River sediments are dredged annually by USACE. A comprehensive sediment budget completed as part of the Nemadji River Basin Project (1998) determined that 98% of the sediment yield from the Nemadji Basin is derived from the erosion of the valley walls. In addition, the sediment delivery ratio (SDR) was found to be almost 98% – indicating almost all of the sediment that is eroded along the Nemadji Basin tributaries is transported to the mouth of the river. Forestry and timber harvesting practices may have had an impact upon this erosion. The turbidity in the river and dredging in the mouth have an impact on fishing and other recreational uses. A tool to assess the implication of land use planning and the merits of remedial measures is required. This report describes the development of a watershed based sediment transport model and addresses this requirement. It consists of hydrologic, hydrodynamic, erosion and sediment delivery models.

1.2 Scope of This Study

This report presents the results of Phase II. This study encompasses the following four parts.

- **Model system development**: a model system to assess the impacts of land use change on the sediment loading has been developed. The model system consists of the database preparation, hydrologic model, hydrodynamic model and sediment transport model. The system has been applied and calibrated in two sub-watersheds --- Skunk Creek and Deer Creek.

- **Training and user manual preparation**: a workshop was held in Duluth on April 11-12, 2000. The detailed capabilities of the model and how its results can be used were presented to the local agencies and organizations in attendance at the workshop. A detailed user's manual has been prepared that provides step-by-step instructions to run additional scenarios.
- **Land use assessment**: The system has been applied to assess the effects of forestry practices upon hydrodynamic and sedimentary response systems. As a part of the forestry practices research, the effect of 65% open space (65% open space was identified as a critical value in a paper by E.S. Verry – 1993) has been assessed by the system. The effects of increased precipitation have also been assessed.
- **Necessity of the application to the whole watershed**: The necessity of the application of the developed system to the whole watershed has been assessed.

1.3 Organization of This Report

This report is organized into the following components:

- General description of the Nemadji Sediment Transport Modeling (NSTM) system;
- Spatial database preparation within a GIS environment;
- Development of hydrologic and hydrodynamic models in the two sub-watersheds, Skunk Creek and Deer Creek;
- Sediment transport model development;
- Assessment of effects of land use change on the hydrodynamics and sediment transport; and
- Assessment of necessity to apply the system to the entire watershed.

1.4 Acknowledgments

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- Mr. David White of Wade-Trim, the prime contractor on this project. Wade-Trim provided assistance in the hydrological modeling and the model selections.
- Mr. Paul Sandstrom, NRCS, provided representation of local interests in addition to local knowledge of the Nemadji River Basin;
- Mr. Tony Kroska, (GIS specialist) who provided the GIS data from Carlton County; and
- Dr. Mark Riedel (at the time with University of Minnesota) who provided insight into erosion processes in addition to data for the Skunk Creek subwatershed.

2. NEMADJI SEDIMENT TRANSPORT MODELING SYSTEM

In order to assess the effects of the land use change on the hydrodynamics and sediment transport in the Nemadji River, a hydrologic model, a hydrodynamic model and a sediment transport model are employed and linked together. To identify challenges in developing a modeling system, an approach was taken to obtain, restore, and convert models and archived historic databases to current computer and software platforms. This allows a clear assessment of the required level of effort in developing a modeling system based on available low cost applications. A greater portion of this effort would be devoted to the development and engineering of custom software utilities to link the different modeling components. In this project, a model system has been developed to account for the hydrology, hydrodynamics and sediment transport in the Nemadji River Basin, collectively called Nemadji Sediment Transport Model (NSTM) system.

The NSTM system consists of GIS-database components, a hydrologic model, a river hydrodynamic model and a sediment transport model as shown in Fig. 2.1. ArcView GIS is used to create geographic data, analyze the data, and prepare the data for input to the hydrologic model and the hydrodynamic model. The hydrologic model generates time-series runoff for input to the river hydrodynamic model. The hydrodynamic model provided the hydrodynamic parameters such as water velocity, depth and discharge to the sediment transport model. Lastly, the sediment transport model predicts sediment erosion and deposition in the river.

Based on the review of the modeling options in Phase I of this project, the Danish Hydraulic Institute (DHI) MIKE system was chosen for the hydrological model and hydrodynamic model for the NSTM system. A sediment transport model in the NSTM system was developed in this project because the DHI MIKE sediment transport module cannot account for the river cutting and bank slumping, the source of almost all the sediment yield.

Details for these components are described in the following sections.

3. DATABASE PREPARATION

3.1 Watershed Delineation using GIS

A watershed defines the catchment area of a surface drainage feature such as a creek or river. A specific catchment area includes all the land that contributes (drains) to a central point. This overland drainage pattern is based on the topography of an area.

This drainage behaviour can be modeled within a GIS environment using a combination of datasets and analysis tools. The process described here will use Digital Elevation Model (DEM) datasets from the United States Geological Survey (U.S.G.S.). DEMs consist of a sampled array of elevations for a number of ground positions at regularly spaced intervals. The software used is ArcView GIS 3.2, from Environmental Systems Research Institute (ESRI), Redlands, California.

The watershed delineation process is described step-by-step in the accompanying User Manual, using the Nemadji River tributary Deer Creek as an example. The process is detailed using ArcView GIS.

3.1.1 The ArcView Environment and Extensions

To delineate watersheds, two ArcView extensions developed by ESRI are used: Spatial Analyst v.1.1 which must be purchased separately; and Hydrologic Modeling v1.1, which is included with ArcView v3.1 and v3.2. The use of these extensions is detailed within the accompanying User Manual.

3.2 Subwatershed-Based Curve Number Valuation

3.2.1 Curve Numbers

Curve numbers provide a way of describing how quickly and to what extent storm rainfall becomes runoff for a particular area. Major contributing factors include land use cover and soil type.

Curve numbers have been developed by the Soil Conservation Service to describe the characteristic land use, treatment or practice, hydrologic condition, hydrologic soil group present within a watershed, and antecedent moisture condition. Land use defines whether the area is agricultural, suburban or urban land. Treatment refers to agricultural practices such as straight row, terraced or contoured farming. The hydrologic condition (poor, fair, good) refers to a number of factors that tend to increase or decrease runoff (i.e. density of vegetative canopy or degree of surface roughness). The hydrologic soil group refers to the general nature of the underlying soil.

Curve numbers for various conditions were developed by the SCS from studies of gaged watersheds. The CN value takes into consideration the initial abstraction which consists of interception, infiltration, and depression storage.

3.2.2 Creating Unique Areas for Curve Number Valuation

The land use and soil type dataset themes are readily available in GIS data formats. Each theme separately describes features as shapes with attributes. Combining these two data sets will provide unique areas for curve number valuation. This process is undertaken completely within the ArcView GIS environment. This process is described in detail in the accompanying User Manual, section 3.3 Integrating Multiple Source Data Sets for CN Valuation.

Once the unique areas of CN valuation have been determined, they must be aggregated to drainage catchment areas to provide area-weighted curve numbers. Again, this process is undertaken completely within the ArcView GIS environment, and is described in detail in the accompanying User Manual, section 3.4 Calculating Area-Weighted Curve Number Values.

4. RAINFALL-RUNOFF AND HYDRODYNAMIC MODELING

The Nemadji River sediment transport model system includes the MIKE11 model package. Two modules of the MIKE11 model, Rainfall-Runoff (RR) and Hydrodynamics (HD), are licensed at this time and available for modeling the Nemadji River. This section describes the model set-up and calibrations of the Rainfall-Runoff and Hydrodynamic modeling in detail. The MIKE11 system links internally both the RR and the HD modules. For this reason, the detailed configurations for these two models are presented together.

4.1 Model Set-up

Two sub-watersheds of the Nemadji River basin have been modeled: Skunk Creek and Deer Creek. Due to changes in data availability along with improvements in creating links within the NSTM model components, slightly different approaches have been taken in setting up both Skunk and Deer Creek. The work performed to set both up is presented here.

In general, the RR and HD model set-up for each of these sub-watersheds consist of the following steps:

- Data Collection;
- Preparation of river network and cross-sections;
- Preparation of catchments;
- Selection of model input parameters; and
- Development of boundary conditions.

4.1.1 Data Collection

Data collection efforts were performed under the Phase I work for use in the modeling of the sub-watersheds. In general, topographic maps, soil type data, land use coverages, stream lines, precipitation data, stream discharge and stage data, photographs, surveyed cross-sections, and historical flood studies were utilized. This information was converted to a consistent data format within a GIS framework. The GIS tools were then used to convert the GIS-formatted data to model inputs. Details on the GIS work are presented in Section 3.

Precipitation records in the period from 1976 to 1978 were collected from the Holyoke meteorological station, which is the nearest station to the modeling area. The hourly stage recorded within five selected storm events from 1977 and 1978 were collected at the U.S.G.S. Deer Creek Gage near Holyoke, MN (U.S.G.S. Gage Number: 04024098). The hourly discharges for these five storms are calculated from the discharge table provided by the

U.S.G.S.. Continuous daily discharges from 1976 to 1998 are available to identify storm periods during these years.

4.1.2 River network, Cross-sections and Catchments

Skunk Creek

The model domain is the entire watershed of Skunk Creek and its branches, Duesler and Elim Creeks (see Figure 4.1). The river network prepared for the HD model consists of Skunk Creek and its main branches as Duesler Creek and Elim Creek as shown in Figure 4.1. Multiple control points are selected in the creek in order to obtain a representative river chainage. The grids of the Skunk Creek network are shown in Figure 4.2. All other smaller streams are neglected and dealt with as lateral inflows in the hydrodynamic model because a reasonable representation can be obtained using lateral inflows.

Cross section shapes were surveyed at different locations of Skunk Creek as shown in Figures 4.3 to 4.9. The cross-sections used in the model were obtained from a field survey performed in the spring of 1998. The longitudinal profiles of Skunk Creek are shown on Figures 4.10 to 4.12. The entire watershed is divided into 31 catchments as shown in Figure 4.1. Each catchment is uniquely identified with a letter-number combination. The letter suffix identifies the main branch that the catchment is based upon: '**S**' identifies the main Skunk Creek branch, '**D**' identifies Duesler Creek, and '**E**' identifies Elim Creek.

Deer Creek

The model domain is the entire watershed of Deer Creek and its branches (see Figure 4.13). The river network prepared for the HD model consists of only the Creek and a main branch identified as Branch 1 in Figure 4.13. Multiple control points are selected in the creek in order to obtain a representative river chainage. The grids of the Deer Creek network are shown in Figure 4.14. All other smaller streams are neglected and dealt with as lateral inflows in the hydrodynamic model because a reasonable representation can be obtained using lateral inflows.

Cross section shapes were surveyed at different locations of Deer Creek as shown in Figures 4.15 to 4.20. The cross-sections used in the model were obtained from the topographic map and adjusted with the measured cross-section parameters obtained from a field survey performed April 10, 2000. The typical cross-sections are shown in Figure 4.21. The longitudinal profile of Deer Creek determined by cross-sections is shown in Figure 4.22.

The entire watershed is divided into 29 catchments for small streams as shown in Figure 4.23. Runoff of each catchment is generated using the RR model. These runoffs are inputted into the hydrodynamic model as lateral inflows of the neglected streams.

4.2 Rainfall-Runoff Model Parameters

Within the Nemadji River Model MIKE11 modeling framework, two hydrology modules are available for use in modeling the rainfall-runoff process. The UHM model, which is suitable for the simulations of runoff from a single storm event, was selected and applied to Skunk Creek and Deer Creek. The SCS loss method is used to calculate the excessive rainfall and the dimensionless hydrograph method is used to generate the time series runoff.

NAM

The NAM module is a Danish Precipitation-Runoff model developed at the Institute of Hydrodynamics and Hydraulic Engineering at the Technical University in Denmark (1973). NAM features 10 distinct parameters for use in describing overland flow, interflow, and groundwater baseflow components. It requires the input of precipitation, potential evapotranspiration, storage capacities of the soils, overland flow runoff coefficients, time constants for interflow, baseflow parameters, capillary flux and water logging data, a series of threshhold values, and time constants for overland flow routing.

Determination of each of these parameters requires calibration to actual gaged data. While the NAM has been applied to watersheds all over the world, its application in the U.S. and availability of typical parameters is limited. Since one goal of this project is to provide a modeling system that could be directly used by local users, it was decided that this model, while available for detailed modeling, would not be used as a part of the Phase II efforts. However, future users that were interested in considering the use of a more complex and data intensive method would have the option of using NAM within the overall modeling system.

UHM (Unit Hydrograph Model)

The UHM Module within MIKE11 provides for several options for hydrologic modeling including the use of the SCS Method to determine runoff volume and hydrograph shape. It was felt that the use of the SCS Method would be a good starting point for the development of a hydrologic model. Similar work was performed on Deer Creek by the U.S.G.S. using the SCS methods. This work helped to define SCS runoff curve numbers as a function of tree type and age. It was proposed to build upon both of these resources for use in developing a consistent system for developing Nemadji River watershed hydrology.

The SCS Loss method within the UHM module allows for the calculation of runoff based on Curve Number as a function of land use and soil type. The SCS method within the UHM module allows for the following unit hydrograph options:

- Triangular
- SCS Dimensionless

- User Defined
- Lag Time (SCS)
- Lag Time (User Defined)

The Lag Time (SCS) method was selected for use on this project.

4.2.1 Model Input Parameters

Rainfall-runoff calculations are performed in all catchments independently. The modeling parameters for each catchment can be set differently. In general, the RR Model Input Parameters for each catchment in the UHM Model are:

- Area adjustment factor
- Base flow
- Dimensionless Curve Number (CN)
- Antecedent moisture condition (AMC)
- Lag time (tL)

Details of the Nemadji River work for each input are presented below.

Area Adjustment Factor

Area adjustment factor accounts for the spatial variation in the rainfall intensity within a catchment. There does not exist any information about the rainfall spatial variations. Only one rainfall gaging station (Holyoke Station) is available near Skunk Creek and Deer Creek watersheds. Therefore, the assumption was that rainfall intensity is uniform for all model areas and the factor is set as one for all catchments in both sub-watersheds.

Base Flow

Base flow represents the constant flow during periods without rainfall. It was found that the base flows in these two creeks are so small and are therefore neglected. No base flow is applied in the two hydrological models.

Curve Number

Curve Number (CN) is the most important parameter in the UHM model, which is used to calculate the excess rainfall for a single storm event. The CNs are calculated according to soil type and land coverage for each catchment using the GIS procedure as described in Section 3.

Land Use

For the Skunk Creek work, only four land classes (Wetlands, Open, Conifer, and Deciduous) were defined in the available GIS data layer for the watershed. For the Deer Creek work, 10 original land use classes were available (Mixedwood forest, Coniferous forest, Deciduous forest, Farmsteads and rural residences, cultivated land, shrubby grassland, grassland, open water, wetlands – bogs, and wetlands – marsh and fens). The CNs for the Skunk Creek catchments are listed in Table 4.1. The CNs for the Deer Creek catchments are listed in Table 4.2.

Soil Types

Major soil classifications in the GIS data layers for the Skunk and Deer Creek watersheds identified three major categories:

Red Clay Areas (MN 300)
Non-Red Clay Areas (MN 255)
Non-Red Clay Areas (MN 254)

The SCS Soil Survey for Carlton County was obtained to review some of the detail from aerial maps to better define the composition of each of these land classes. The Soil Survey was reviewed to understand better the detailed hydrologic nature of the soil in terms of hydrologic soil type. The soil type does not consider slope or vegetative cover type.

A: Soils with high infiltration rates (0.30 to 0.45 inches per hour)
B: Soils having moderate infiltration rates (0.15 to 0.30 inches per hour)
C: Soils having slow infiltration rates (0.05 to 0.15 inches per hour)
D: Soils having very slow infiltration rates (0 to 0.05 inches per hour)

Typical Nemadji Soil Types can be classified as follows:

Soil Name	**Type**
Allendale	B
Bergland	D
Beseman	A/D
Blackhoof	D
Campia	B
Dawson	A/D
Duluth	B
Dusler	C
Greenwood	A/D
Nemadji	B
Newson	A/D
Omega	A
Ontonagon	D
Spooner	C/D
Udorthents	B

(/ - designates a drained vs. undrained conditon)

In the future, it is anticipated that detailed soil layer data based on the SCS Surveys will be converted to a GIS compatible format. This information could be readily used in future within the Nemadji modeling framework.

Antecedant Moisture Conditions (AMC)

There are three types settings for the initial antecedent moisture condition that can be set in the UHM model - dry, normal and wet conditions are available to present the moisture condition at the beginning of simulations. Antecedant moisture conditions are defined as:

Condition	**Description**	**5-Day Antecedant Rainfall (mm)**	
		DORMANT	**GROWING**
I	Optimum soil condition	<13	<36
II	Average value for annual floods	13-28	36-53
III	Heavy rainfall or light rainfall/low temperatures within 5 days prior to a storm	>28	>53

(from U.S. Department of Agriculture, Soil Conservation Service, SCS National Engineering Handbook, 1972)

Initial AMC is set in the hydrological model according to the previous five day rainfall records. Initial AMC used in an individual storm is described below.

Lag Time

Skunk Creek

For the Skunk Creek work, it was proposed to use the SCS method to determine lag time as presented in the Minnesota Hydrology (MH) Handbook. The MH handbook outlines the application of the SCS method specifically to Minnesota. However, after performing initial calibration comparisons between the Skunk Creek modeled versus gaged flows, it was found that the Minnesota SCS method tended to overpredict the flow rates from the watershed. Based on this, the lag times were manually adjusted based on comparisons between metered and modeled flows for several storm events. In most cases, this resulted in lag times that were two to four times greater than the originally calculated times. For the Deer Creek work, this issue was revisited and a refined method was developed to address this issue. It is recommended that any further work be conducted using the method developed for the Deer Creek work.

The hydraulic lengths and averaged slopes are listed in Table 4.1.

Catchment ID	Loss Curve Number	Original Lag Time (hr.)	Adjusted Lag Time (hr.)
D2	80	4.6	24
S9	85	1.7	8
E2	83	1.7	8
S8	86	2.2	8
E1	83	8.8	24
E1-E2	80	1.0	8
E3	86	1.6	8
S8-S9	82	0.6	8
S7-S8	83	0.5	4
E2-E3	86	1.4	8
S10-S11	84	.4	4
E3-S7	83	.4	4
D4	82	1.5	8
S6	87	1.8	8
S10	84	2.7	8
S9-S10	84	1.0	4
D1	76	3.2	24
D1-D2	81	0.7	8
D3-D4	83	0.6	4
D4-D5	83	0.5	4
S5-S6	84	1.0	4

S6-S7	83	1.3	4
D2-D3	80	1.1	4
S4-S5	84	1.6	4
D3	85	6.3	8
S4	86	7.3	24
S3-S4	87	.8	4
S2	88	7.5	8
S1	83	4.0	24
S2-S3	85	0.7	4
S1-S2	84	1.6	8
S3	85	16.6	24

Deer Creek

The other important parameter in the UHM model is lag time, which distributes the excess rainfall through time series. The lag time can be determined by hydraulic length and average slope which are measured from the topographic map. The hydraulic length for a catchment is measured as the average distance along streams from catchment to the inflow point in the hydrodynamic river. The averaged slope is measured as the division of the maximum elevation difference and hydraulic lengths. The hydraulic lengths and averaged slopes are listed in Table 4.2.

Table 4.1 UHM Parameters using the Rainfall-Runoff Model

Catchment	Hydraulic Length (km)	Loss Curve Number	Lag Curve Number	Slope(%)	Lag Time (hr.)	Adjusted Loss CN
DCC_01	0.55	80	20	4.4	1.36	63
DCC_02	1.39	78	20	2.4	3.93	61
DCC_03	0.51	79	20	6.0	1.11	62
DCC_04	0.67	79	20	3.3	1.86	62
DCC_05	1.22	79	20	1.7	4.17	62
DCC_06	0.24	79	20	3.5	0.79	62
DCC_07	1.82	79	20	1.5	6.11	62
DCC_08	0.17	80	20	7.0	0.42	63
DCC_09	1.44	81	20	1.5	4.98	64
DCC_10	0.46	79	20	1.6	1.97	62
DCC_11	1.87	76	19	1.4	6.69	58
DCC_12	0.47	76	19	1.9	1.91	58
DCC_13	2.00	79	20	1.4	6.87	61
DCC_14	0.63	75	19	1.4	2.84	57

DCC_15	1.45	75	19	1.4	5.56	56
DCC_16	0.22	77	19	6.0	0.58	59
DCC_17	1.73	78	19	1.2	6.69	60
DCC_18	1.50	79	20	1.2	5.90	61
DCC_19	2.60	71	18	1.1	10.41	52
DCC_20	2.17	79	20	1.6	6.81	62
DCC_21	2.05	79	20	2.0	5.81	62
DCC_22	0.11	79	20	1.2	0.73	62
DCC_23	4.28	77	19	0.8	16.99	59
DCC_24	0.56	78	20	2.2	1.99	61
DCC_25	2.58	76	19	1.1	9.73	58
DCC_26	0.70	81	20	1.2	3.14	64
DCC_27	1.33	81	20	2.1	3.94	64
DCC_28	2.95	69	17	1.1	11.77	50
DCC_29	0.07	82	20	3.0	0.31	66

4.3 Hydrodynamic Model Parameters

Hydrodynamic parameters consist of the bottom friction, initial water level and discharge, and parameters relating to the numerical scheme. Manning's roughness coefficient is used to represent the bed resistance.

Skunk Creek

Manning's coefficient is used to account for bed resistance in the hydrodynamic model. The constant Manning's coefficient (0.05) is applied in all points in the Skunk Creek.

Deer Creek

Since there is no Manning's coefficient measured in Deer Creek, Manning's coefficient is set from 0.03 at the mouth of the creek to 0.05 at the furthest point upstream. The reason to increase Manning's coefficient from the mouth to upstream is that more vegetation, beaver dams and large cobbles are found upstream. Initial discharge is set at zero and water level is set at bed elevation plus minimum water depth. The default values are used for the parameters relating to the numerical scheme.

4.4 Boundary Conditions

Skunk Creek

Boundary conditions in the Skunk Creek model are given as discharge at the upstream limit of each creek and the discharge/waterdepth (Q/H) relationship is given downstream of Skunk Creek. Since the flows at the upstream of the creeks are generated by the Rainfall-Runoff model, zero discharges are set for all upstream boundary condition. All lateral inflow boundary condition are provided by the Rainfall-Runoff model which are automatically input to the MIKE 11 model.

Deer Creek

Boundary conditions should be given as the downstream and upstream limits of the creek and the lateral inlet points of its branches. The discharge boundary conditions are applied for all upstream boundaries while the water level boundary conditions are used at the downstream boundary. The boundary condition of runoff is calculated by the RR model. The downstream water level is obtained from the observations at the Gage. In this process, it is simply assumed that the water depth at the Gage is the same as at the downstream boundary. Thus, the water level at the downstream boundary can be calculated as the water depth plus the bottom elevation.

4.5 Calibrations

4.5.1 Calibration/Verification Data

Precipitation, discharge, and stage (water level) data are needed for model calibration and verification. The principal input to the model is precipitation data. Precipitation is defined as the sum of rainfall plus snowmelt. Precipitation data was found to be available from two stations, Holyoke and Croquet, located near the Skunk Creek and Deer Creek watersheds. Hourly precipitation data was available from Holoyoke, while only daily totals were available from the Cloquet station. Data from the Holyoke gage was input to the model for calibrations.

Over the years, the U.S.G.S. has maintained numerous stream gages in the Nemadji River watershed. Stream gage data was available for Elim Creek, a portion of Skunk Creek, and a portion of Deer Creek.

Drainage Basin	Area (km^2)	Gage No.	County	Period of Record
Skunk Creek	22.97	04024093	Carlton	1976 to 1978
Skunk Creek	23.1*			
Elim Creek	2.79	04024090	Carlton	1976 to 1978
Deer Creek	17.33**	04024098	Carlton	1976 to 1978

* Total Skunk Creek drainage area
** Effective drainage area

The hourly stage in the five selected storm periods from 1977 and 1978 were collected at the Deer Creek Gage near Holyoke, MN (U.S.G.S Gage Number: 04024098). The hourly discharges for these five storms are calculated from the discharge table provided by the U.S.G.S.. Continuous daily discharges from 1976 to 1998 are available to find storm periods during these years.

4.5.2 Skunk Creek Calibrations

The calibration of the model included comparing model results from actual storm events to gage data on Elim and Skunk Creek.

The rainfall and gaged data were reviewed and screened to select three storm events for use in the calibration process. The focus of this modeling effort was on large flow events that typically produced sediment transport. For this reason, storm events from 1978 were selected for use in the calibration. Both 1976 and part of 1977 were subject to drought conditions in the Nemadji River basin and did not produce events with significant peak flows. The following three events were selected for the calibration:

Storm on April 1978

The initial AMC used in this storm is a wet condition (AMC = III). The comparison of modeled discharge at the Skunk Creek Gage and the Elim Creek Gage with the U.S.G.S. hourly gage discharge is shown in Figure 4.23. The computed discharge agrees well with the observed discharge. The runoffs calculated in the catchments are shown in Figure 4.24, which was used in the hydrodynamic model.

Hydrodynamic modeling of two other storms, May, 1978 and August 1978 was also completed, but there is no hourly gage discharge available to compare to the model results.

4.5.3 Deer Creek Calibrations

The RR model calibrations are carried out to verify the Curve Number calculated in the GIS component and the estimated lag time. The CN value is a main parameter influencing the excess rainfall which should be equal to total runoff in a single storm event. The lag time is another key parameter that distributes the excess rainfall in time and influences the duration of the runoff period. Both parameters are adjusted according to calibration results. Table 4.2 lists the final CN values and lag times used in the model.

The purpose of hydrodynamic model calibration is to check whether the model parameters such as bottom friction are correct. This bottom friction controls the flow velocity and water level. Since there is no velocity data available, the calibration is performed by the comparison of gaged water levels.

The five storms were originally selected for the purpose of model calibration are listed in Table 4.3. These storms were chosen according to the correlation of the discharge and suspended sediment concentration observed at the U.S.G.S. Gage at Deer Creek, as shown in Fig. 4.26. The storm with the highest concentration observed in April, 1978 may not be representative because the high concentration might be caused by other factors besides the hydrodynamics. Unfortunately, the precipitation data is available only for Storms 2 and Storm 4. Thus, only the calibrations for these two storms were carried out.

Table 4.3 Storm Selections for Deer Creek Model

	Start	End	Peak Time	Peak Discharge (m^3/s)	Peak Sediment Concentration (mg/l)
Storm 1	04-May-79	20-May-79	10-May-79	5.49	1840
Storm 2	20-Aug-78	26-Aug-78	23-Aug-78	4.02	1480
Storm 3	21-Sep-77	06-Oct-77	24-Sep-77	3.43	2370
Storm 4	06-Jul-78	11-Jul-78	7-Jul-78	3.37	1680
Storm 5	10-Apr-79	04-May-79	17-May-70	3.4	943

Storm in August 1978

Figure 4.27 shows the input rainfall and runoff computed by the RR model in the selected catchments for the Storm 2. These calculated runoffs are input into the HD model as lateral inflows. The discharge computed by the HD model at the Gage is compared with the observed discharge, as shown in Figure 4.28. The computed water level at the Gage is also compared with observations (see Figure 4.29). It can be seen that the peak values of the computed water level and discharge are in agreement with the observations. The peak times, however, of both water level and discharge are delayed by about four hours. Figures 4.30 and 4.31 show the comparison of the observed water level and discharge with the computed ones that have been moved about four hours in advance. It is clear that the development and decay of a storm is simulated well by the model.

Storm on July 1978

Another storm for which the precipitation data is available occurred on July 1978 and has been simulated by the system. The initial AMC is set as III for all catchments referred to as historic rainfall. Figure 4.32 shows the runoff calculated by the model in the selected catchments. The comparisons of the modeled water level and discharge with the observed levels at the gage are shown in Figure 4.33 and 4.34. The calculated results match well with the recorded data and there is no peak time delay in this case.

5. SEDIMENT LOADING MODEL

This chapter describes the ArcView 3.x extension that processes MIKE 11 output files, and calculates valley wall erosion based on Creek valley segments as defined by the user. For each valley segment, calculations of erosion volume, vertical erosion, cumulative vertical erosion, and cumulative spatial erosion volume are tabulated. For more detailed, step-by-step instructions on using the ArcView-based sediment transport model, refer to the accompanying document “User Manual – Nemadji River Sediment Transport Modeling.”

5.1 Model Development

The simple sediment transport model has been developed based on the MIKE 11 hydrodynamic model results and bathymetry of the Creek. The model takes into account downcutting and bank slumping in rivers. In order to estimate non-uniform sediment erosion along the river, the entire river is divided into a number of calculation river segments. Each segment includes the river and its corresponding river valley, which can be delineated by ArcView (see Fig. 5.1). The MIKE hydrodynamic model provides the velocity and water depth in the calculation segments. The shear stress can be calculated by the following equations:

$$t = r u_*^{2} = r\left(\frac{kU}{\ln\left(2.5d/n\right)}\right)^{2}$$

where t is shear stress (N/m^2); r is water density (=1000kg/m^3); k is von Karman’s coefficient (= 0.4); U is velocity (m/s); d is water depth or hydraulic radius (m), and n is roughness. Based on the physical experiments of glacial sediment (completed by Baird in several other studies), the erosion rate can be calculated by

$$E = a\left(t - t_{cr}\right)$$

where E is erosion rate (mm/hr), a is factor relating to shear stress; and t_{cr} is critical shear stress (N/m^2). Thus the erosion volume in a certain period can be calculated by

$$V = b \cdot E \cdot A \cdot \Delta t$$

where b is bluff slumping factor; which represents the possibility of bluff slumping during the period of interest; A is area of the computational river segment including river valley; and Dt is time period.

All calculations are developed in an ArcView extension file. All the functionality of this extension is encapsulated in one Extension File. To load the extension, copy the extension file (MIKE11POSTPRO.AVX) to the ArcView extensions folder (\ARCVIEW\EXT32\). Start ArcView and using the command **File > Extensions**, add **MIKE11 POSTPRO**.

5.2 INPUTS

This extension combines information from three different sources: data from MIKE11, data from ArcView shapefiles, and inputs from the user.

This extension provides post processing of Mike11 Velocity and Depth output files. The structure of the Mike11 output files is quite simple: tab delimited with columns representing different points (cells) along the stream network, and rows representing different time periods. These files must be manually created by the user by simply copying the raw data from within MIKE11 and pasting into an Excel spreadsheet.

In Excel, use the SAVE_DATA_GIS macro as described in step 4.5n of chapter 4 of the manual. This macro will convert the data into a GIS compatible format as follows: columns represent spatial variations, rows represent temporal variation; the first column indicates the time step; the second column indicates the elapsed time; and the first row identifies the river chainage or valley segment identification. This first row should contain the ‘key’ identifier for each cell that corresponds to values in an attribute field in a polygon theme.

Inspect the output text files and ensure that they do not contain any trailing blank lines at the end of the file. These lines must be deleted in order for the ArcView extension to function properly.

This extension also requires a polygon shapefile corresponding to the MIKE11 calculation points along the stream network. For each point, a polygon is delineated that extends to the top of the stream valley walls. These polygons will form the basis for calculating erosion volumes. Each polygon should be uniquely identified with an attribute field identifying a corresponding MIKE11 calculation point. This polygon shapefile should also have its area geometry calculated in square meters and stored in an attribute field called “AREA”.

The user will also need to identify values for Roughness, Critical Shear Stress, and Factor Relating Erosion to Shear Stress. Default values for each will be suggested.

5.3 USING THE EXTENSION

Once loaded, the extension is launched from a button on the View button bar. For the button to be available, the view must contain a polygon coverage representing stream valley polygons corresponding to the MIKE11 calculation points.

This extension also calculates the spatial (downstream) cumulative erosion volume (the total volume of sediment that will pass by any point along the stream). For this function to work, the stream valley polygon theme must contain an attribute field that identifies the polygon's corresponding ' DRAINS_TO ' polygon. One special polygon is the river mouth polygon which identifies ITSELF as the 'drains to' polygon. All other polygons will drain to another polygon as identified in the 'DRAINS_TO' field.

In the view window, with the valley polygon theme selected, click on the PostPro button on the button bar on the top of the ArcView screen. ArcView will display an information box, and then prompt the user to enter values for three variables: Roughness, Critical Shear Stress, Factor Relation Erosion to Shear Stress, and Bluff Slumping Factor. Default values are presented for each: 0.0025, 4, 0.1, and 0.002, respectively.

Roughness describes how the unevenness of the bed slows the flow of water above the bed.

Critical Shear Stress is the shear stress at which erosion of sediment is just initiated. It has been determined through an in-house Baird database from experimental tests and calibration.

Factor Relating Erosion to Shear Stress describes how the rate of erosion changes with shear stress. This parameter has also been determined through an in-house Baird database from experimental tests and calibration.

Bluff Slumping Factor relates the erosion forces of the stream to the area of the valley polygons defined by the user. This parameter represents the ratio of stream erosion area to the total area of the valley polygon and has been calibrated for the Deer Creek subwatershed. Effectively this factor accounts for the fact that the contribution to sediment load from bluff slumping is an internittent process that depends on factors other than erosion of the creek or river bed.

Next, the user is presented with a list of all the attribute fields for the valley polygon theme, and asked to select the 'KEY' field. The KEY field uniquely identifies each polygon and corresponds to the MIKE11 calculation points identified in the MIKE11 output files for depth and velocity.

Next, the user is prompted to select the MIKE11 depth table file and the velocity table file. These files should be tab delimited.

The user is then prompted to select a base name for the output tables that will be generated. These five tables are: Shear Stress; Erosion Volume; Cumulative Erosion Volume; Vertical Erosion; and Cumulative Vertical Erosion.

Lastly, spatial (downstream) cumulative erosion for each cell (polygon) is calculated. To provide this functionality, the user is prompted to identify two attribute fields within the valley polygon theme: the cumulative vertical erosion field, and the "**Drains To**" field.

5.4 Calibrations

The calibrations of sediment load calculations were carried out by adjusting the model parameters and comparing the calculated erosion volume with daily sediment concentration observed at the Deer Creek Gage. The critical shear stress and factor relating erosion to shear stress were primarily determined from an in-house database of experimental test results on cohesive sediment erodibility. The bluff slumping factor was adjusted to relate measured to predicted sediment load. Figure 5.2 and Figure 5.3 show the time series sediment concentrations computed by the model as well as the observation in the storms of July, 1978 and August, 1978. The calculated sediment concentration agrees quite well with the observation. The parameters used in the calculations are listed in Table 5.1.

Parameters	Values
Rougness	0.0025
Critical Shear Stress	1
Factor Relating Erosion To Shear Stress	0.1
Bluff Slumping Factor	0.003

Figure 5.4 illustrates the (downstream) cumulative spatial erosion volume over time shown as extruded areas, based on valley polygon boundaries.

6. APPLICATIONS

Three different scenarios have been examined by the calibrated system. The results of these different alternatives are compared with the values computed in the existing scenario (obtained in the model calibrations). The model of Deer Creek in the storm of July, 1978 is selected for these examinations because a good calibration was obtained in this case. Details for each scenario are provided here.

6.1 Effect of Harvesting Forest Land

Harvesting forestry lands will decrease rainfall abstractions and increase soil loss. An assessment of harvesting 500 acres of the existing forested land is carried out to account for the effect that harvesting has on changing the hydrodynamics and sediment transport. In this assessment, the forest land around the branch of Deer Creek is changed to the harvested land (see Figure 6.1). The new CN values are obtained using the GIS component of the NSTM system. These changed CN values are inputted into the RR model and Hydrodynamic model to obtain the discharge. The hydrodynamic results are used for the sediment transport calculation. To account for the impact of this change on hydrodynamics and sediment transport in the river, the model results computed for this change are compared with ones computed in the existing condition, as shown in Figures 6.2 and 6.3. The total runoff, peak runoff and sediment load for the storm are listed in Table 6.1. It is seen that this land use change has no significant impact on the hydrodynamics and sediment transport in the Creek. The peak discharge at the gage is increased by about 1.6% and the peak sediment concentration is increased about 12.3%. The increase of total discharge and total sediment load for the entire event are almost the same (about 1%, see Table 6.1).

Table 6.1 Impacts of Harvesting Forest Land on Hydrodynamics and Sediment Load

	Peak Discharge (m^3/s)	Total Water Volume (m^3)	Peak Concentration (mg/l)	Total Sediment Load (Ton)
Existing	10.364	431802	1869	403
Harvested	10.528	438580	2099	407
Increase	1.6%	1.6%	12.3%	1%

6.2 Effect of Having 65% Open Land

Open lands are defined as meadow, pasture or 0-15 year old timber growth. An open land coverage of 65% was identified as a critical value in a paper by E.S. Verry (1983). The open lands in the Deer Creek basin currently cover about 36% of the total watershed. To investigate the effect of altering this value to a critical level on the hydrodynamics and sediment transport, the forest lands around the upstream of the Deer Creek are changed into “open lands” resulting in the 65% open land for the sub-basin (see Figure 6.4).

As mentioned in the previous examination, the Curve Numbers are updated to reflect this change and input into the MIKE 11 model and the sediment transport model calculates total sediment load. Figure 6.5 and 6.6 shows the comparison of the modeled discharge and sediment loads in this examination with the existing conditions. The scenarios of 65% open land area will increase the peak discharge by 6% and the total runoff by 9%. However the peak sediment concentration is increased only by about 2.3% while total sediment load increases 6.5% (see Table 6.2).

Table 6.2 Impacts of 65% Open Land on Hydrodynamics and Sediment Load

	Peak Discharge (m^3/s)	Total Water Volume (m^3)	Peak Concentration (mg/l)	Total Sediment Load (tons)
Existing	10.364	431802	1869	403
65% Open Land	11.019	472381	1913	431
Percentage	6.3%	9.4%	2.3%	6.5%

6.3 Effect of Increased Precipitation

To investigate the effect of increasing the precipitation on the hydrodynamics and sediment transport in the river, the recorded precipitation in the storm of July, 1978 was amplified by 50% and 100% and then run through the model, respectively. The 100% amplified hourly precipitation is a little larger than the historic maximum precipitation (23mm/hr). Figure 6.7 and 6.8 shows the comparison of the computed water level and discharge at the gage for this scenario with the existing conditions. The increase of computed discharge varying with the precipitation increase is shown in Figure 6.9. For a given percentage increase in precipitation, the discharge will increase by twice that amount The computed sediment concentrations for these two precipitation increases is compared with the existing conditions (see Fig. 6.10). Increasing precipitation will erode more sediment from the river basin. However, it was interesting to find that the sediment load computed in the scenarios of 100% precipitation increase is lower than that computed in the scenarios of 50% precipitation increase. This may result from the flooding that occurs in such a large rainfall event that effectively reduces the averaged velocity in a cross-section.

Table 6.3 Impacts of increased precipitation on Hydrodynamics and Sediment Load

	Peak Discharge (m^3/s)	Total Water Volume (m^3)	Peak Concentration (mg/l)	Total Sediment Load (tons)
Existing	10.364	431802	1869	403
50% increase	19.525	826578	2489	574
Percentage	88%	91%	33%	42%
100% increase	29.247	1265641	2164	541
Percentage	182%	193%	16%	34%

7. NECESSITY OF APPLYING THE SYSTEM TO THE ENTIRE BASIN

The NSTM system has been applied and calibrated in the Skunk Creek and Deer Creek sub-watersheds. The system is ready to be applied to other tributaries within the Nemadji River Watershed. The sediment from these two watersheds is also a small part of the total sediment deposited at the mouth and delivered to Lake Superior. To accurately assess sediment loading to the Nemadji River Basin, hydrologic and hydrodynamic models for the entire watershed should be developed. The reasons for this are:

- An individual model of a sub-watershed cannot account for total sediment transport deposit in the mouth and delivered to Lake Superior. As tested in this report, an isolated forest harvest of a small area in a sub basin may not have a significant effect on the sediment transport in the River. However, it is likely that on the Nemadji River watershed scale, cumulatively these forestry practices might have significant impacts on the sediment transport.
- As found in this study, it is difficult to control the downstream boundary of each individual model in a sub-watershed. Generally, the water level used as the model boundary condition at the downstream limit should be provided by a model of the entire basin. It is relatively easy and accurate to set the downstream boundary condition of the entire basin model as the water level of Lake Superior because detailed water levels of the lake are available as measured data and relatively steady.
- An entire basin model could provide the sediment deposition in the mouth of Nemadji River in addition to sediment delivered to the Lake. These model results would be useful for land use planning to manage the sediment load in the Nemadji River Basin.

Though a detailed model in each sub-basin is required in order to accurately assess the impact of the land use change on the sediment transport in the River, it is not necessary to develop the detailed models for all sub-basin in the initial stage. It is suggested that the whole project be divided into three levels based on the level of detail required:

Level I A sediment transport model system is developed for the entire Nemadji basin. In this model, only the main rivers in the basin are included and all creeks, which are directly tributaries of the River, are regarded as lateral inflows. This model is called a 'River-Level Model'. The sub-watershed of each creek is regarded as a hydrologic unit in which a hydrologic model is developed to provide the runoff of this sub-watershed. The sediment yielded from a sub-watershed is temporarily estimated using the relationship of sediment load and discharge and input into the model. This model may not be used to describe detailed land use practice in each watershed but could determine which sub-watersheds have the most impact on sediment transport in the River. This would focus the direction of the next study level.

Level II In this level, an individual model is developed for each sub-watershed in which the land use change has been determined to have significant impacts on the sediment transport. In the model, main creeks in the sub-basin are included and smaller catchments in the sub-basin are regarded as hydrologic units. This model could be called 'Creek-Level Model'. The downstream portion of the model is linked to the River-Level Model developed in Level I. Detailed land use practice assessments could be performed with the model. The discharge and sediment load for the sub-basin is automatically outputted to the River-Level Model to assess the effects of the land use practice on the sediment loads in the River. The NSTM system applied to the Skunk Creek and Deer Creek in this report is a good example of a Creek-Level Model. The Creek-Level Model also identifies whether or not a more detail model should be developed for the streams in the next level. It may not be necessary to develop the Creek-Level Models for all sub-watersheds, depending on budget constraints and the level of detail required for a given sub-watershed.

Level III Similar to Level II, an individual model may be developed for a catchment in which more detail land use plan is required. This model is directly linked to the Creek-Level Model. Therefore, all changes in this catchment automatically affect the sediment load in the River.

The model development procedures depend on the required level of detail necessary to perform meaningful land use planning and on budget constraints. Roughly estimating the impacts of land use change on sediment transport could be done in the River-Level Model. Detail forestry practice and land use planning require the use of a detailed Level III model.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The following summarizes the efforts of this study:

- The developed NSTM system integrates ArcView GIS, MIKE 11 hydrological model and hydrodynamic model and a customized sediment transport model. The system has been calibrated and tested in the Skunk Creek and Deer Creek subwatershed. It is ready to be applied to other subbasins.
- The system can assess the impacts of different land use scenarios on hydrology, hydrodynamics and sediment load in watersheds. It can be used to model land use change as a result of forest harvesting and other land use plan changes, flooding prediction for a storm event, and provide a tool to assess schemes to reduce the sediment load to the lake.
- An assessment of harvesting forestry lands has been carried out using the system. Harvesting forested land will increase runoff and sediment transport slightly but the sediment concentration at peak time increases more than the increase of total sediment load for the entire event.
- Increasing open land area more than 65% has a significant effect on the hydrodynamics and total sediment loads in the sub-basin. The total sediment load in a storm increases more than the peak concentration increase.
- For a given percentage increase in precipitation the discharge increases by twice this factor and the sediment load increases by half this factor.

8.2 Recommendations

Curve Number valuation is an important aspect of the NSTM system. The Curve Number values used in this system are calculated from the land use information, vegetation coverage and soil type and adjusted according to the model calibrations in these two sub-watersheds. Although Curve Number valuation was well verified in the system development, it could be refined and adjusted in the future. More detailed land use data, hourly precipitation data, and hourly gage data are required to update the Curve Numbers.

The sediment transport model has been developed on the basis of previous surveys and studies. Key parameters, such as the critical shear stress for erosion, and the factors relating shear stress to erosion might be updated if more suspended sediment data are available and more surveys are carried out.

In the system, the components work independently. The internal links between components is manual, requiring the user to cut and paste information from one software application into another. A good understanding and working knowledge of both ArcView and MIKE 11 is required for end users to operate this system. These manual links in the current system might reduce the operational efficiency and could cause errors in data transfer from one component to another. Basin wide application would benefit from improvements to data interchange between modules.

A low-detail Level I model of the entire Nemadji River Basin should be developed. The model would only include the main rivers in the Basin and treat all creek sub-basins as catchments for hydrologic modeling. This entire model can provide the general information of hydrodynamics and sediment load in the Nemadji River. The model would be a basic model of the Nemadji River model system because the model also provides boundary conditions for higher-detail-level models.

Multi-level model procedures are suggested in the model development. The higher-detail level model may be developed for a creek sub-basin according to the needs of forestry practices in that area, complexity of vegetation coverage, contribution to the whole basin, and budget constraints. The higher-detail-level model can be automatically linked to the entire model such that any change in the creek model could reflect the entire model automatically. This model procedure is easily controlled and flexible.

The higher-detail level model or Creek-Level model could be developed basin by basin. Since Creek-Level models in sub-basins are independent, the models can be developed at the same time.

9. REFERENCES

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