Estimating Soil and Streambank Erosion in the Great Lakes Watersheds

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Abstract: The study integrates GIS, LANDSAT imagery, aerial photographs and simulation model to estimate soil and streambank erosion in the Cass River Watershed, Saginaw Bay of North America’s Great Lakes basin. Aerial photographs were scanned into GIS for assessing streambank erosion. The Agricultural Nonpoint Source Pollution Model (AGNPS) was used to estimate soil erosion potential in the study watershed. Digital soil data (STATSGO) and vegetation indices which were derived from the LANDSAT TM imagery were used to evaluate soil erosion potential by wind. The results suggest that the Cass River watershed introduce large amounts of nutrients and sediment into the Saginaw River and Bay. The sediment yield was up to 145 tons per acre in the mouth of the watershed near Saginaw after a single 25-year storm event. About 25 percent of the total land area in the Cass River watershed was subject to medium wind erosion. Streambank shifted up to several meters in portions of the watershed between 1937 and 1970. These estimates provide management agencies with information on critical erosion areas for implementing water quality programs.

Key-Words: LANDSAT; GIS; AGNPS; Soil erosion; Streambank erosion; Great Lakes Watersheds.

1 Introduction
Soil erosion is a serious globe problem, affecting 1094 million ha (Mha) by water erosion and 549 Mha by wind erosion, respectively [1]. Annually, over 200 billion tons of top soils are eroded worldwide [1]. In North America’s Great Lakes basin, annual soil erosion is approximately 65 million tons, with agriculture land contributing between 65 to 77 percent of it [2]. Management of the soil erosion requires identifying critical soil erosion areas and estimating soil erosion rates at watershed scale.

While a number of simulation models have been developed to aid in the understanding and management of surface runoff, erosion, sediment, nutrient leaching, and pollutant transport processes such as ANSWERS (Areal Nonpoint Source Watershed Environment Simulation) [3], CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems) [4], AGNPS (Agricultural Nonpoint Source Pollution Model) [5], EPIC (Erosion Productivity Impact Calculator) [6], and SWAT (Soil and Water Assessment Tool) [7], these models are designed to estimate soil erosion by...
water, and cannot estimate soil erosion by wind or streambank erosion. This paper describes procedures for estimating soil erosion by both water and wind erosion and streambank erosion using multiple databases. These estimates will help researchers and managers identify the critical risk areas for implementation of water management programs.

2 Methods
2.1 Study Area

Fig.1: The Cass River watershed and the Saginaw Bay basin boundary.

The study area of this research is the Cass River watershed, a sub-watershed of the Saginaw Bay watersheds in Lake Huron basin. The Cass River watershed runs across Huron, Sanilac, Tuscola, Lapeer, Genesee, and Saginaw counties, and joins the Saginaw River near Saginaw (Fig.1) and has a drainage area of 2,177 km². Agriculture and forests are the two major land uses/covers in the Cass River watershed, accounting for 60 and 21 percent of the total land area, respectively. Soils in the watershed consist mainly of loamy and silty clays and sands, and are poorly drained in much of the area. Major crops in the watershed include corn, soybeans, drybeans, and sugar beets. Over the years, the primary agricultural land use and associated runoff, improper manure management, poor municipal wastewater treatment, irrigation withdrawal, and channel dredging and straightening have led to high nutrients runoff, eutrophication, toxic contamination of fish, restrictions on fish consumption, loss of fish and wildlife habitat, and beach closures in the Cass River watershed [8, 9, 10]. Because of dominant agricultural land use and related high soil loss potential, the Cass River watershed was selected as the study area for estimating the soil erosion potential by both water and wind erosion to assist the management agencies in planning and managing soil erosion activities at the watershed scale.

2.2 Water Erosion Potential

Soil erosion by water includes sheet and rill erosion. Sheet erosion is removal of a thin layer of soil from the surface of the land. Rill erosion is removal of soil from the sides and bottoms of small channels formed where surface runoff becomes concentrated and forms tiny streams. Sheet erosion and rill erosion usually occur together and hence referred to as sheet and rill erosion [11]. This study focuses on the potential of sheet and rill erosion by both water and wind at the watershed scale.

The Universal Soil Loss Equation (USLE) (Eq.1) is one of the most fundamental and widely used methods for estimating soil erosion and sediment loading on an annual basis [12]. A number of simulation models, e.g., ANSWERS, EPIC, AGNPS, and SWAT, use the USLE for erosion and sediment simulation.

\[ Y = R \times K \times L \times S \times C \times P \times \text{SlopeShape} \quad (1) \]

Where \( Y \) is the computed average soil loss per unit area, expressed in ton/acre; \( R \) is the rainfall and runoff factor and is the number of rainfall erosion index (EI) plus a factor for runoff from snowmelt or applied water; \( K \) is the inherent erodibility of a particular soil; \( L \) is the slope-length factor, \( S \) is the slope-steepness factor; \( C \) is the cover and management factor; \( P \) is the support practice factor; and slope shape factor represents the effect of slope shape on soil erosion [5, 12].
Realizing that the USLE is not intended for estimating erosion and sediment yield from a single storm event, we used AGNPS (Young et al. 1989) to simulate runoff, erosion and sediment, and nutrient yields in surface runoff from a single storm event. Basic databases required for the AGNPS model include land use/land cover, topography, water features (lakes, rivers, and drains), soils, and watershed boundary [9,10, 13, 14]. The model output includes estimates of runoff volume (inches), sediment yield (tons), and sediment generated within each cell (tons).

Digital Elevation Model (DEM) of 1:250,000 from the U.S. Geological Survey was used to derive slope and aspect. The STATSGO (State Soil Geographic Data Base) data from the U.S. Department of Agriculture Natural Resources Conservation Service [15] were used to determine dominant texture, hydrologic group, and weighted soil erodibility. The 1979 land use/land cover data from the Michigan Resource Information System (MIRIS) and related hydrography databases were used to derive land use-related parameter values. The storm event chosen was a 24-hour precipitation of 3.7 inches occurring once every 25 years. Fallow, straight row crops, and moldboard plow tillage were assumed in the simulation [9].

The model was applied to the Cass River watershed with a spatial resolution of 125 ha (310 acres) (Note: the cell size was set at 310 acres to ensure the entire watershed was discretized to no more than 1,900 cells – the limit of AGNPS version 3.65) [5,9].

2.3 Wind Erosion Potential
Soil erosion by wind is the removal of soil by strong winds blowing across an unprotected soil surface [16]. Wind erosion results in more than five million tons of the soil erosion, accounting for the 63 percent of the total soil erosion in the Saginaw Bay watersheds[8]. The critical months for wind erosion are April and May in the Saginaw Bay basin. Few methods are available for estimating soil erosion by wind, such as Wind Erosion Equation developed by the USDA-Agricultural Research Service Wind Erosion Laboratory [16, 17,18]. These methods are suitable to estimate wind erosion potential at the field level but difficult to use at the watershed level. As soil erodibility, wind, and quantity of vegetative cover are the main factors affecting wind erosion [18], we used soil association data and vegetation indices to estimate the wind erosion potential for the entire Cass River watershed.

The STATSGO was used to extract six wind erodibility indices for all the soil associations in the Cass River watershed. These groups are: Group 1: 310 ton/acre/year; Group 2:134 ton/acre/year; Group 3: 86 ton/acre/year; Group 4: 56 ton/acre/year.; Group 5: 48 ton/acre/year; and Group 6: 38 ton/acre/year [15]. These indices represent the wind erodibility based on the soil surface texture and percentage of aggregates.

The LANDSAT 5 TM image of June 1, 1992 was used to derive the Normalized Differential Vegetation Indices (NDVI). These indices give a relative quantification of vegetation amount, with vegetated areas yielding high values, and nonvegetated areas yielding low or zero values. The formula for calculating the NDVI is:

$$NDVI = \frac{TM \ Band \ 4 - TM \ Band \ 3}{TM \ Band \ 4 + TM \ Band \ 3}$$

The TM Bands 3 and 4 represent the red and near-infrared spectrum respectively. The differential values between the two help us determine vegetation type, vigor, and biomass content [19].

The wind erodibility group indices from the STATSGO were combined with the NDVI to delineate the potential wind erosion areas. The criteria for classifying the wind erosion based on soil and vegetative factors were shown in Table 1.

2.4 Streambank Erosion
Streambank erosion is the removal of soil materials from the banks of stream by water gushing over the upper part, or scouring the bottom of the stream [21]. It is a natural process of unaltered, dynamic river systems. Human activities can accelerates streambank erosion
through channel modification, reservoir construction, and land use changes [22]. Streambank erosion endangers the bridges, roads, and other infrastructures, causes the loss of the land, results in tremendous amount of economic damage, and alters wildlife and fishery habitat. Factors affecting streambank erosion include basin geology, streamflow and sediment, valley dimensions (slope, width, and depth), vegetation, climate, and channel slope, depth, and form [21].

Methods for determining the streambank erosion include: (1) hydrographic surveys, topographic surveys, or scaled aerial photography over time; (2) interpretation of existing stream map; (3) interviews with locals; and (4) numerical or physical modeling. Out of the four methods, the numerical modeling is the least reliable method to estimating streambank erosion as meandering is a partially random process, and bed bank materials are seldom uniform [21]. Thus, it is impossible at present to reliably model the streambank erosion. The hydrographic surveys or topographic surveys are still the most reliable way in estimating streambank erosion [21]. After an extensive literature search and consultations with relevant research institutions such as the U.S. Army Engineer Waterways Experiment Station, (Vicksburg, Mississippi) and the USDA Agricultural Research Service (ARS) National Sedimentary Laboratory (Oxford, Mississippi) and National Erosion Research Laboratory (West Lafayette, Indiana), we used historic aerial photographs to estimate streambank erosion in the study area. The aerial photographs of 1937, 1955, and 1970 were scanned and saved as GIF images and then imported into Geographic Resource Analysis and Support System (GRASS) [9]. Once in GRASS, these images were rectified based on the transportation and water features base files.

The three geo-referenced raster images of 1937, 1955, and 1970 were digitized to delineate the boundaries of streambanks. The delineated streambanks were then overlaid to depict the changes in the stream channels and banks over the 1937-1970 period.

Table 1. Classification of wind erosion potential based on the soil erodibility and NDVI Values.

<table>
<thead>
<tr>
<th>Wind Erosion Potential</th>
<th>Classification Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NDVI</td>
</tr>
<tr>
<td>No Wind Erosion</td>
<td>&gt;0.60</td>
</tr>
<tr>
<td>Subtle Wind Erosion</td>
<td>0.40-0.60</td>
</tr>
<tr>
<td>Little Wind Erosion</td>
<td>0.40-0.60 or 0.20-0.39</td>
</tr>
<tr>
<td>Medium Wind Erosion</td>
<td>0.20-0.39 or 0.10-0.19</td>
</tr>
<tr>
<td>High Wind Erosion</td>
<td>0.10-0.19 or &lt;0.10</td>
</tr>
<tr>
<td>Severe Wind Erosion</td>
<td>&lt;0.10</td>
</tr>
</tbody>
</table>

3 Results and Discussions

3.1 Water Erosion

The simulated results by AGNPS show that the runoff volume was higher in the agricultural land (Figure 2). The soil erosion rate simulated from the single storm event generally centered around 1 to 1.5 tons per acre, with no or little erosion in the forested areas and greater rate (up to 3.5 tons per acre) in portions of the agricultural land. The sediment yield was highest (up to 45,000 tons in the 310 acre area) near the mouth of the watershed as the flatness of the area and lower peak runoff rate resulted in a higher rate of deposition. These results indicate that agricultural activity was a main nonpoint source pollution contributor under the worst management scenario (fallow, straight row crops, and moldboard plow tillage) [9, 10].
3.2 Wind Erosion
The wind erodibility of the soil groups in the Cass River watershed ranged from 48 to 310 ton/acre/year based on the properties of soil associations from the STATSGO. The normalized NDVI derived from the LANDSAT TM data showed that about 33 percent of the Cass River watershed had NDVI value of between 0.01-0.20, 23 percent of the area with NDVI 0.21-0.40, 39 percent of the land with NDVI value of 0.41-0.60, and about 6 percent of the land with dense vegetation cover (NDVI value of 0.61-1.00). As soil and vegetation are two of the most important factors affecting the wind erosion potential, the wind erodibility and NDVI were combined to produce a wind erosion map for the Cass River watershed. The results indicate that about 25 percent of the Cass River watershed had a medium wind erosion potential (Table 2) and most of the area was in the agricultural land [10].

Table 2: Distribution of Wind Erosion Potential in the Cass River Watershed

<table>
<thead>
<tr>
<th>Wind Erosion Potential</th>
<th>Acres</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Wind Erosion</td>
<td>257,756</td>
<td>44.3</td>
</tr>
<tr>
<td>Subtle Wind Erosion</td>
<td>57,069</td>
<td>9.8</td>
</tr>
<tr>
<td>Little Wind Erosion</td>
<td>120,131</td>
<td>20.7</td>
</tr>
<tr>
<td>Medium Wind Erosion</td>
<td>143,951</td>
<td>24.8</td>
</tr>
<tr>
<td>Severe Wind Erosion</td>
<td>2,155</td>
<td>0.4</td>
</tr>
<tr>
<td>Total</td>
<td>581,063</td>
<td>100.0</td>
</tr>
</tbody>
</table>

3.3 Streambank Erosion
The streambank erosion areas selected was Frankenmuth portion of the Cass River watershed as field inventory showed serious streambank erosions in the area. Measurement of local coordinates of the three aerial photographs using the equal interval sampling was undertaken for both left and right banks of the same area to estimate the relative changes in streambanks over the period of 1937 to 1970. The results show that the river shifted toward right up to 11 to 13 cells between 1937 and 1955 and then changed its course back toward left up to 9-13 cells between 1955 and 1970. These figures, although relative, clearly indicate that streambank erosion is a serious problem in the Frankenmuth portion of the Cass River watershed.

Table 3: Relative Change in Streambank in the Frankenmuth Portion of the Cass River Watershed Width (Distance in Relative Unit-Cell)

<table>
<thead>
<tr>
<th>Year</th>
<th>No. of Sampling Points</th>
<th>Average Width of Left Bank</th>
<th>Average Width of Right Bank</th>
<th>Average Relative Width of the River</th>
</tr>
</thead>
<tbody>
<tr>
<td>1937</td>
<td>44</td>
<td>1952</td>
<td>1970</td>
<td>18</td>
</tr>
<tr>
<td>1955</td>
<td>51</td>
<td>1963</td>
<td>1983</td>
<td>20</td>
</tr>
<tr>
<td>1970</td>
<td>83</td>
<td>1954</td>
<td>1970</td>
<td>16</td>
</tr>
</tbody>
</table>
As the accuracy and scales of the historical aerial photographs were different or unknown, this approach only produced rough estimates of Cass River watershed introduces large amounts of sediment into the Saginaw River and Bay. The sediment yield was up to 145 tons per acre at the outlet of the watershed. About 25 percent of the total land area in the Cass River watershed was subject to medium wind erosion.

Streambank erosion was up to several meters in portions of the watershed between 1937 and 1970. The simulated sediment yield from the AGNPS appears to be greatest in the mouth of the Cass River near Saginaw due to the flatness of the area. The larger amount of sedimentation in the area is likely to have negative impact on streambank meandering and did not provide information on seriousness of erosion at both the upper and lower parts of the banks. If feasible, field hydrologic survey should be employed for estimating streambank erosion.

4 Summary
This paper, through a case study of the Cass River watershed, estimated loading potential of soil erosion by both water and wind as well as streambank erosion. The results suggest that the sediment yield was up to 145 tons per acre at the outlet of the watershed. About 25 percent of the total land area in the Cass River watershed was subject to medium wind erosion. Streambank erosion was up to several meters in portions of the watershed between 1937 and 1970. The simulated sediment yield from the AGNPS appears to be greatest in the mouth of the Cass River near Saginaw due to the flatness of the area. The larger amount of sedimentation in the area is likely to have negative impact on aquatic habitat. It could also lead to elevated streambed and increased flooding frequency and damage in the surrounding areas. These areas could be targeted for future water quality management programs for minimizing nonpoint source contamination potential and protecting critical fisheries and wildlife habitat.

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References


