Effectiveness of Stream Restoration in Reducing Stream Bank Erosion: The Case of Batavia Kill Stream Restoration Projects, New York

Yanwei Chen[1], S. K. Bhatia[2], James Buchanan[3], Doug DeKoskie[4], Rene' VanSchaack[5]

[1]Res. Asst., Dept. of Civil and Environmental Engineering, Syracuse Univ., Syracuse, NY, 13244; PH (315) 443-2313; FAX (315) 443-1243; email: ychen16@syr.edu
[2]Professor, Dept. of Civil and Environmental Engineering, Syracuse Univ., Syracuse, NY, 13244; PH (315) 443-3352; FAX (315) 443-1243; email: skbhatia@syr.edu
[3]Stream Restoration Specialist, Greene County Soil & Water Conservation District, Cairo, NY, 12413; PH (518) 622-3620; FAX (518) 622-0344; jake@gcswcd.com
[4]Stream Program Leader, Greene County Soil & Water Conservation District, Cairo, NY, 12413; PH (518) 622-3620; FAX (518) 622-0344; doug@gcswcd.com
[5]Executive Director, Greene County Soil & Water Conservation District, Cairo, NY, 12413; PH (518) 622-3620; FAX (518) 622-0344; rene@gcswcd.com

ABSTRACT: The number of stream restoration projects has increased dramatically during the last decade, especially in the New York City watershed region, where stream management to improve water quality is a high priority, and where the NYC Department of Environmental Protection and the Greene County Soil and Water Conservation District have partnered to develop a set of restoration demonstration projects. In this paper, the effectiveness of stream restoration projects in reducing stream bank erosion in the Batavia Kill watershed (Greene County, New York) is evaluated. This evaluation is based on a multivariate regression model to relate stream bank erosion rates to various explanatory variables including instruments representing geomorphological characteristics, flow conditions, rainfall conditions, temperature, the vegetation index, soil erodibility, and sediment characteristics. The general to specific approach is used to specify the regression model. A range of statistical tests is applied to check the model accuracy and the validity of the regression model. The results of these tests show that the stepwise regression model accurately predicts stream bank erosion rates on the Batavia Kill stream. The regression model is then applied on the project reaches, assuming there was no stream restoration to predict the stream bank erosion. It is found that the measured erosion on the restored reaches is much smaller than predicted erosion in the "without restoration" case, which means that the effectiveness of stream restoration in reducing bank erosion in the Batavia Kill watershed is significant.

Key Words: Stream restoration, Stream bank erosion, Erosion rates, Multivariate regression model, Model specification, Bank stability, Greene County SWCD, New York City Watershed, NYC Department of Environmental Protection

INTRODUCTION

Stream bank erosion and its associated sediment yield have tremendous negative impacts on water quality. Studies have shown, for instance, that stream bank erosion accounts for the majority of sediment load in some urban watersheds in the United States (Rosgen 1996; Trimble 1997). Sediment loads increase turbidity, alter aquatic habitats, and introduce pollutants, such as trace metals, in surface water. It is reported that an estimated 220,000 kilometers of stream bank are in need of erosion protection in the United States (U.S. Army Corps of Engineers 1983). Therefore, it is important to find out effective ways to minimize bank erosion and improve water quality.

In the 1960's, stream restoration was recognized for the first time as important– an occurrence that resulted from the negative impact of human activities on the watershed system. One can define stream restoration as "returning an ecosystem to a close approximation of its condition prior to disturbance" (Kondolf and Micheli 1995, FISRWG 1998). One primary purpose of the stream restoration is to stabilize stream banks and thus mitigate stream bank erosion. Therefore, the effectiveness of stream restoration in reducing stream bank erosion is critical in evaluating the success of a stream restoration project.

Extensive research has been carried out to analyze and predict stream bank erosion (Hooke 1979; Lawler 1986; Rosgen 1996; Simon and Darby 2002). Most of these studies estimate stream bank erosion rates based on the factors which are likely to control erosion. However, none of these approaches focuses on evaluating the effectiveness of stream restoration in reducing stream bank erosion. This scarcity is partially due to the relative short history of stream restoration projects and the lack of consistent monitoring of pre-project and post-project morphological and hydraulic characteristics, which are considered to be major elements controlling stream erosion. Therefore, a procedure based on stream monitoring data for the purpose of evaluating the effectiveness of stream restoration in reducing stream bank erosion needs to be developed. In this study, pre-project and post-project monitoring data in the Batavia Kill Watershed stream restoration projects have served as the basis of performance evaluation.

BATAVIA KILL WATERSHED STREAM RESTORATION PROJECTS

The Batavia Kill watershed is located in the Catskill Mountains in southeastern New York State (Figure 1). The watershed has an area of 186 km^2 and its mainstream, the Batavia Kill, runs for a distance of 34 km to its confluence with the Schoharie Creek, which is a major water resource for New York City's daily water supply. The New York City Department of Environmental Protection (NYCDEP) had identified the Batavia Kill watershed as having one of the highest turbidity conditions of all the NYC water supply systems. In 1997, the United States Environmental Protection Agency (USEPA) required NYCDEP to either improve the surface water quality to a certain level or to spend $8 billion to build a filtration plant. The NYCDEP has responded by developing a watershed protection program instead of the filtration plant. As part of the watershed protection program, the Greene County Soil & Water Conservation District (GCSWCD) has initiated the use of a geomorphic-based classification, assessment, and restoration strategy for addressing degraded stream reaches in the Batavia Kill watershed.

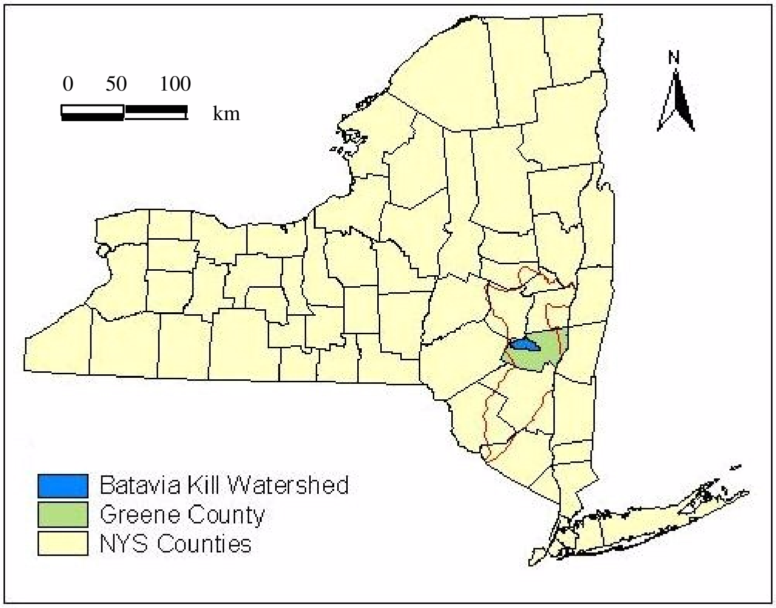

Figure 1: Batavia Kill Watershed Location Map

To date, three stream restoration projects have been accomplished in the Batavia Kill watershed. The first two projects were located in the middle of the stream corridor and are referred to as the Maier Farm project and the Brandywine project. The third project is located at the top of the watershed and is referred to as the Big Hollow project. Figure 2 shows the locations and the restoration periods of each restoration project. The Primary objective of the restoration projects was to mitigate excessive turbidity and the impact of Total Suspended Solids (TSS) on water quality by addressing excessive stream bank erosion (GCSWCD 2003). To achieve this goal, a stable Rosgen C4 stream type (Rosgen 1996) with typical meandering riffle-pool morphology was selected as the restoration strategy for the projects. Channel form and meander pattern were derived from historical aerial photographs, regime equations, and reference reach analyses.

The Batavia Kill watershed monitoring activities have been conducted annually since 1997. The monitoring activities include cross-section and profile survey, pebble counts, and the Bank Erosion Hazard Index (BEHI) measurement. To date, more than 100 cross sections have been established on the Batavia Kill stream. The channel geometry, channel bed materials distribution, and the vegetation information can be derived from the monitoring data.

STREAM BANK EROSION MONITORING AND MEASUREMENT

Sites with apparent erosion on stream banks are selected to conduct erosion monitoring since these sites are likely to show the erosion process more frequently and clearly. These sites are also important from the stream management point of view because they produce considerable amount of sediments, which are the major source of TSS and cause high turbidity. The description of erosion monitoring sites is given in Table 1. In total, eight erosion-monitoring sites were chosen on the Batavia Kill stream: these sites are Head Water, Big Hollow (pre-restoration), Brandywine (pre-restoration), Maier Farm (pre-restoration), Kastanis, Holdens, Red Falls, and Conine. The relative locations of erosion-monitoring sites are given in Figure 2. The drainage area at these sites ranges from 2.8 km^2 to 182.3 km^2. Each site was further divided into several sections based on the morphological characteristics such as sinuosity and the radius of curvature as well as soil erodibility. The subdivision of each monitoring site enables the investigation of the erosion variation under similar climatic and hydrological conditions. Altogether 33 separate sections were obtained by this approach (Table 1).

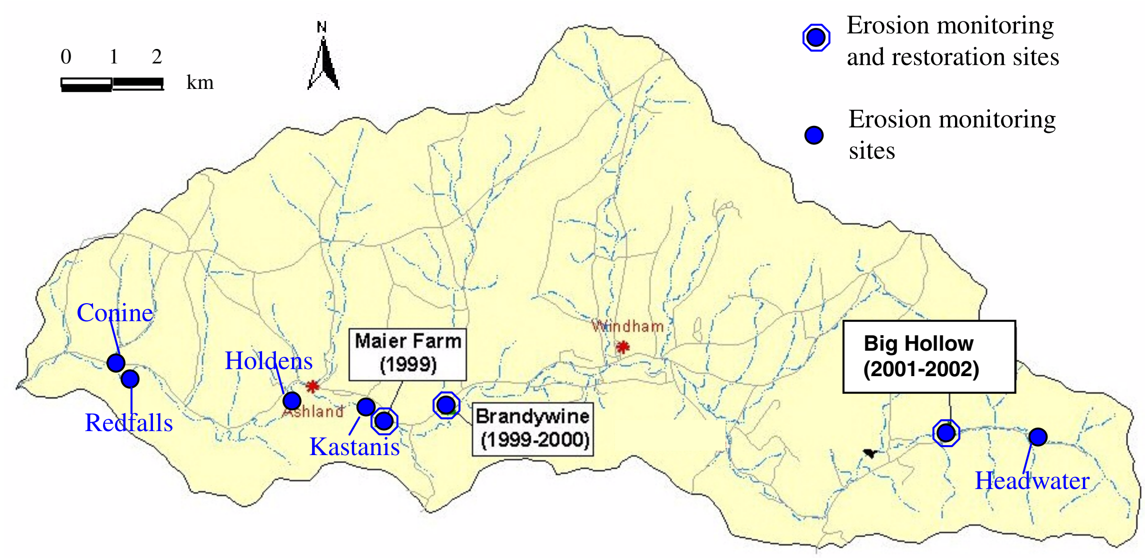

Figure 2: Demonstration Projects and Erosion Monitoring Sites in the Batavia Kill Watershed

The stream bank erosion is determined by overlaying cross-sections surveyed annually over the period from 1997 to 2003 on the Batavia Kill stream, and then measuring the eroded bank area or distance over a monitoring season. This method is believed to have the advantage of minimal disturbance on the stream bank, while covering the erosion measurement on the whole stream cross-section under investigation.

STREAM BANK EROSION PREDICTION

As one of major modeling techniques, multivariate regression is frequently used in the stream bank erosion prediction to establish the relationship between the bank erosion rates and various explanatory variables (Lawler 1986; Rosgen 1996). In this study, the stream bank erosion on the erosion monitoring sections determined from the cross-section surveys is regressed on a set of explanatory variables, and the erosion prediction model derived from the regression has been employed on out of sample data to predict stream bank erosion.

Table 1: Bank Erosion Monitoring Sites

Site	Section	No. of Cross-sections	No. of Observations	Average Drainage Area (km^2)	Description
Head Water	A	2	1	2.8	Upper portion of the reach is relatively stable, but lower portion of the reach exhibits severe erosion. Land cover is dominated by forest. Steep valley slope, narrow channel
	B	2	2	9.3	
	C	1	3	13.8	
Big Hollow	A	2	1	14.1	The reach was restored in 2001 and 2002. Prior to the restoration, the reach was highly unstable with extreme bank erosion. Very little vegetation coverage on the bank. Land use is open space with limited residential usage. Gravel bed channel. Bank materials consist of the mixture of clay/silt, sand and gravel.
	B	1	2	15.0	
	C	5	2	15.1	
	D	1	2	15.5	
	E	2	2	15.5	
	F	2	2	17.0	
	G	1	1	18.2	
	H	1	2	18.3	
Brandywine	A	1	2	108.2	The reach was restored in 1999 and 2000. The reach exhibited extreme bank erosion prior to the restoration.
	B	1	2	108.2	
Maier Farm	A	1	2	133.3	The reach was restored in 1999. The reach was extremely unstable prior to the restoration.
	B	1	2	133.4	
Kastanis	A	1	3	135.2	Experiencing large amount of bank erosion. Some portion of the stream bank has no vegetation cover. Forest and pasture land coverage, low density of residential housing. Gravel bed channel. Bank materials consist of the mixture of clay/silt, sand and gravel.
	B	3	3	136.5	
	C	1	3	136.7	
	D	4	3	136.8	
	E	3	3	137.0	
	F	2	3	137.2	
	G	2	3	137.6	
Holdens	A	2	1	158.5	Average valley slope is 0.3%, broad floodplain. Unstable reach and severe channel migration. Stream bank consists of non-cohesive materials. Farm and pasture land use.
	B	2	1	158.6	
	C	4	1	158.7	
Red Falls	A	2	2	174.7	Average valley slope is 1.2%, steep bank slope. Forest land coverage. Extremely unstable reach and highly negative impacts on water quality. High eroding banks, large clay exposure, active channel lateral migration.
	B	3	2	175.2	
	C	2	2	175.5	
	D	2	2	175.5	
Conine	E	2	2	175.5	Average valley slope is 1.2%, narrow flood plain. Extremely instable, accelerated bank erosion. Poor riparian vegetation.
	A	2	1	181.8	
	B	4	2	182.1	
	C	2	1	182.3	
Sum	33 sections	67	66		

Choices of Explanatory Variables

A number of factors have been identified as having influences on the stream bank erosion rates (Wolman 1959; Knighton 1998). These factors can be categorized into several groups: (1) cross-sectional and longitudinal characteristics; (2) parameters of flow conditions; (3) rainfall conditions; (4) temperature conditions, primarily the influence of frost; (5) vegetation and soil erodibility; and (6) sediment characteristics. Each group of influencing factors contains variables that may affect stream bank erosion rates. These variables have been considered in the regression to test their relationships with the steam bank erosion rates. Table 2 lists the explanatory variables examined in this study.

Table 2: Independent Variables used in the Bank Erosion Prediction

Factor	Variables	Source and method of measurement
(1) Cross-sectional and longitudinal characteristics	Drainage Area	USGS topographic maps measurements
	Cross-section area	Field survey of cross-sections
	Bankfull width	Field survey of cross-sections
	Cross-section maximum depth	Field survey of cross-sections
	Cross-section mean depth	Field survey of cross-sections
	Width/depth ratio	Field survey of cross-sections
	Bank height and Bank angle	Field survey of cross-sections
	Radius of curvature	GIS map measurement
	Radius of curvature/Bankfull depth	GIS map and field survey of cross-sections
	Sinuosity	GIS map measurement
	Channel slope	Field survey of longitudinal profile
(2) Flow conditions	Product of real time stream discharge and flow duration during a monitoring season	United States Geological Survey (USGS) gage stations nearby the bank erosion monitoring sites
(3) Rainfall Condition	Amount of rainfull per season Duration of rainfull per season	National Climatic Data Center (NCDC) station nearby the erosion monitoring sites
(4) Temperature	Froze-thaw circles per season Frozen days per season	NCDC station nearby the bank erosion monitoring sites
(5) Vegetation	Vegetation coverage index	GIS vegetation coverage, field pictures, field surveys, aerial photos, and BEHI.
(6) Bank and Bed Materials	Soil erodibility k, Bed materials size distribution D_{50}	GIS soil coverage, soil survey of Greene County, pebble counts, and bar samples

To quantify the influence of storm events on the stream bank erosion, the hydrograph method (McCuen 1998) is employed to account for the magnitude and duration of stream flows. In this method, volume of flow during a storm event is calculated by integrating the stream discharge with its duration. Since it is the medium to large events that contribute the most to stream bank erosion (Knighton 1998), events with flows higher than the mean peak flow, which is the average of all discharges above the mean annual flow, are taken into consideration. The volume of flows with discharge above the mean peak flow during an erosion-monitoring season at a particular site is selected as an explanatory variable to account for the impact of flows on stream bank erosion. Real time discharge data (recorded every 15 minutes) at each erosion-monitoring site are obtained from the nearby USGS gages in the Batavia Kill watershed to retrieve the flow magnitude and duration. Most erosion-monitoring sties are within several kilometers distance from the nearest USGS gage.

To investigate the influences of vegetation on bank erosion on the Batavia Kill stream, the historical vegetation information on each bank erosion-monitoring site are gathered from BEHI data, field surveys, field pictures, aerial photos as well as the GIS map. The vegetation conditions vary largely from site to site. Some sites have been fully covered by various vegetation, however others are exposed by barren soils. Meanwhile, there are also some banks partially covered by the vegetation. The vegetation condition on each site is categorized into one of these three groups, and is indexed as an explanatory variable in the bank erosion prediction model (full coverage =1, partial coverage =0.5, and barren soil =0).

Multivariate Regression Modeling

The average bank erosion area on cross-sections on an erosion-monitoring section over a monitoring season is selected as the dependent variable. Since the erosion measurement is made only on sections showing apparent bank erosion, whereas restored reaches generally exhibit little or no erosion, the project sites after stream restoration are excluded from the regression model. This strategy results in 66 observations on 33 erosion-monitoring sections. The bank erosion area – the dependent variable – has a mean value of 2.8 m^2 and a standard deviation of 3.3 m^2. There are 20 explanatory variables being considered in the regression analysis. These explanatory variables and their statistics are provided in Table 3.

Table 3: The Statistics of Explanatory Variables

Number	Variables	Abbreviation	Mean	Standard Deviation
1	Drainage area (km^2)	drain.area	107.19	64.65
2	Cross-section area (m^2)	xs.area	19.347	8.815
3	Bankfull width (m)	bkf.width	23.187	8.88
4	Cross-section maximum depth (m)	xs.maxdep	1.443	0.444
5	Cross-section mean depth (m)	xs.meandep	0.824	0.294
6	Width depth ratio	width.dep	32.335	18.837
7	Bank height (m)	bk.ht	3.916	3.248
8	Bank angle (°)	bk.angl	33.913	13.077
9	Radius of curvature	radius.curv	147.462	87.526
10	Radius of curvature/Bankfull width	rc.bkf	2.302	1.912
11	Sinuosity	sinu	1.192	0.288
12	Channel slope	chnl.slop	0.00829	0.00863
13	Erodibility K	erod	0.261	0.045
14	Stream flow ($10^6 m^3$)	streamflow	33.9	33.294
15	Precipitation days	precp.day	129.602	74.967
16	Precipitation (mm)	precp	1252.1	653.7
17	Froze-thaw circles	froze.thaw	134.136	74.300
18	Frozen days	froze.day	175.000	101.091
19	Bed material size (mm)	bed.mat	59.364	26.919
20	Vegetation index	veg	0.379	0.430

An analysis of relationships among explanatory variables shows that a high degree of multicollinearity exists among regressors. This makes it very difficult to interpret the effect of each independent variable on the response. Therefore, a specified model should be derived to best predict the stream bank erosion. The general to specific approach is used to specify the model. This algorithm starts with the full model, which incorporates all explanatory variables, and then deletes one variable from the model at a time. The variable to be removed from the model is the one that makes the smallest contribution. To determine a variable's contribution, the absolute value of that variable's t-ratio is considered. To be removed, the t-value must be less than a critical t-value in absolute value. This algorithm takes into account the joint effect of independent variables. In this study, the t-value corresponding to 95% significance level is used as the critical t-value.

After one variable is removed, the dependent variable is regressed on the rest of the explanatory variables to determine the next variable to be eliminated from the regression model until all variables are statistically significant. The final model selected by this approach has 7 explanatory variables: they are cross-section area, cross-section mean depth, width/depth ratio, bank angle, sinuosity, stream flow, and the vegetation index.

The final model has a R^2 of 0.7553, indicating that more than 75% bank erosion can be explained by the erosion prediction model. The F-statistic is 25.57, which is much higher than the critical F value of 2.172. The explanatory variables are therefore statistically significant in explaining the stream bank erosion. The t-statistic shows that all explanatory variables are statistically significant at a 90% confidence level, except for the bank angle (Table 4). Actually, the bank angle is statistically significant at a 77% confidence level. A variable at this significance level should be retained in the model to avoid screening out variables that may be important (Frees 1996). This choice is motivated by an algebraic result that when a variable enters a model, the standard error of the estimates will decrease if the t-ratio of that variable exceeds one in absolute value (Frees 1996). In addition, from the geotechnical point of view, the bank angle is an important variable contributing to stream bank erosion (Simon and Darby 2002). The level of multicollinearity among the explanatory variables in the final model is checked, and the results show that it is not severe. The stream bank erosion estimated by the final model is plotted against the measured bank erosion in Figure 3.

The final model indicates that bank angle, sinuosity, and stream flow are directly related to stream bank erosion, while the vegetation index has an inverse relationship to bank erosion. Actually, field observations in the Batavia Kill watershed support the above model's interpretation. A large amount of bank erosion is observed at reaches where the banks are steep and the channels are sinuous, such as Kastanis and Red Falls. High flow events generally produce more bank erosion, and this is consistent with observations made by many researchers (Hooke 1979; Knighton 1998). At bank-erosion monitoring sections on the Batavia Kill stream, banks with high vegetation coverage in general have much less erosion than banks with little or no vegetation coverage. Table 4 also shows that bank erosion is directly related to the cross-section area while inversely related to the cross-section mean depth and width depth ratio. However, since width depth ratio can be computed as the cross-section area divided by the square of the cross-section mean depth, the relationship between the bank erosion and the cross-section area, mean depth and width depth ratio becomes intricate. The first order derivative analysis revealed that for most reaches on the Batavia Kill stream, bank erosion is indeed directly related to the cross-section area and inversely related to the cross-section mean depth, which means that wide and shallow reaches have the potential to incur more bank erosion.

Table 4: Summary of the Final Model

	Coefficients	Standard Error	t value	Pr(>|t|)	Significant codes
(Intercept)	-35.029	24.1438	-1.451	0.15221	
xs.area	0.131	0.0693	1.891	0.06367	+
xs.meandep	-18.654	7.672	-2.431	0.01815	*
width.depth	-0.43	0.251	-1.714	0.09185	+
bk.angl	0.241	0.198	1.214	0.22969	
sinu	75.814	9.045	8.382	1.41E-11	***
streamflow	0.00897	0.00265	3.391	0.00126	**
veg	-18.364	6.875	-2.671	0.00979	**

Significant codes: 0 `***' 0.001 `**' 0.01 `*' 0.05 `+' 0.1 ` ' 1

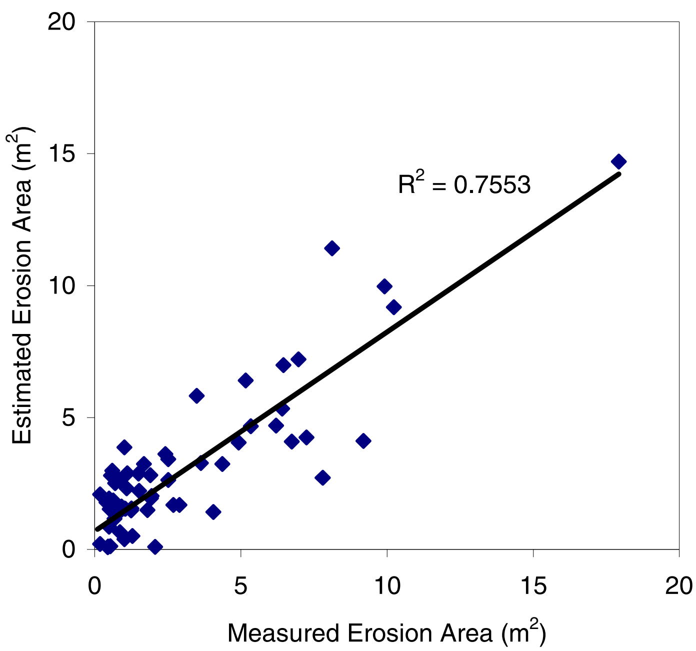

Figure 3: Estimated Bank Erosion by the Final Model vs. Measured Erosion

Model Validation

To validate the methodology being applied to the model specification, the 66 observations are split into two data sets. Each data set consists of 33 observations.

One data set is used to develop a prediction model, and the other data set containing out of sample data is used to validate the prediction model. The same general to specific method is used to specify the prediction model, and the predicted values are compared with the measured erosions (Figure 4). The R^2 between the predicted erosions and the measured erosions is 0.7084, which means that more than 70% of the measured bank erosions could be explained by the regression model. The methodology used in the model specification well predicts the characteristics of stream bank erosion. Notice that the relevant explanatory variables in the regression model generated from the validation process are not necessary the same as those in the final model specified using all observations because those two models are specified using a different number of observations.

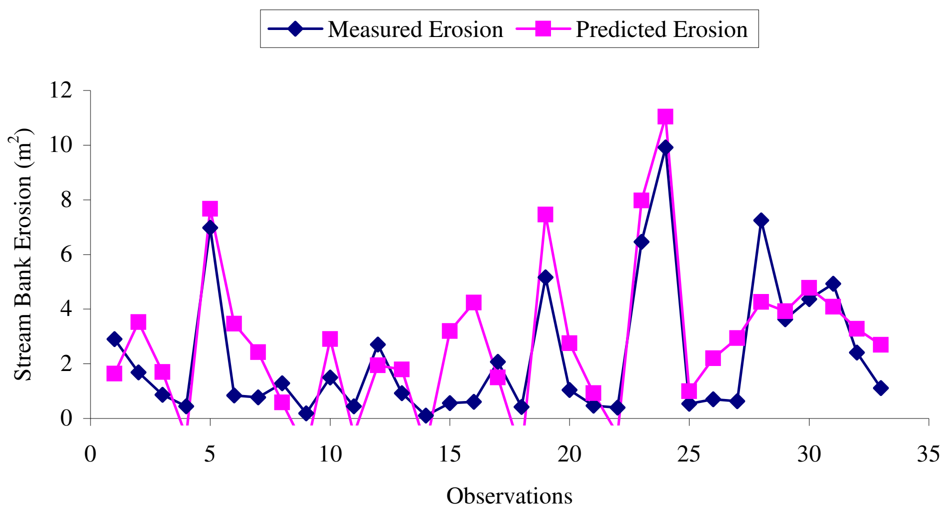

Figure 4: Comparison between the Predicted Erosion and Measured Erosion

Model Comparison

To further evaluate its predictability, the regression model developed in this study is compared with two existing bank erosion prediction models: Rosgen's Streambank Erosion Prediction Model (1996) and the Bank Stability and Toe Erosion Model developed by the United States Department of Agriculture, Agriculture Research Service (http://msa.ars.usda.gov/ms/oxford/nsl/cwp_unit/bank.html). The accuracy of prediction is measured by using three statistics: Mean Square Error (MSE), Mean Error (ME), and Mean Absolute Error (MAE) (Frees 1996). The results show that the regression model predicts the stream bank erosion in the Batavia Kill watershed more accurately than the other two models (Chen 2005). The MSE, ME, and MAE computed from the regression model are always smaller than those calculated from the other two models in absolute value.

EVALUATE STREAM RESTORATION IN REDUCING BANK EROSION

The stream bank erosion prediction model specified using all observations is applied on the Batavia Kill stream to evaluate the effectiveness of stream restoration projects in reducing bank erosion. Suppose there were no stream restoration, the bank erosion at project sites can be estimated using the prediction model given the pre-restoration conditions. The hypothetical bank erosion ("without restoration" case) is compared with the measured bank erosion at restored reaches ("with restoration" case). If the bank erosion estimated in the "without restoration" case is much greater than the erosion measured in the "with restoration" case, the stream restoration is said to be effective in reducing bank erosion. Otherwise, the stream restoration is ineffective in reducing bank erosion.

Table 5 compares the stream bank erosion measured at the restored reaches on the Batavia Kill stream from the completion of each project to the summer of 2003 with the erosion estimated by the prediction model over the same time period assuming no stream restoration. The total volume of measured stream bank erosion at the project sites is 2,685 m^3, and the total volume of bank erosion estimated by the prediction model in the "without restoration" scenario is 10,145 m^3. The "without restoration" case would produce 3.8 times more bank erosion than the "with restoration" case. The volume of reduced bank erosion by stream restoration is 7,460 m^3, which could fill about 1,000 dump trucks. The effectiveness of stream restoration in reducing stream bank erosion is significant.

Table 5: Comparison of Measured Erosion and Predicted Erosion

Project Reaches	Time Period	Reach Length (m)	Measured Erosion Volume at Restored Project Reaches (m^3)	Predicted Erosion Volume Assuming No Stream Restoration (m^3)
Maier Farm	09/99 -06/03	500	1,743	2,465
Brandywine	07/00 -06/03	1,100	226	5,048
Big Hollow	06/02-07/03	1,430	716	2,632
Sum		3,030	**2,685**	**10,145**

CONCLUSION

In this study, multivariate regression is used to relate stream bank erosion to various explanatory variables. These variables include instruments representing geomorphological characteristics, flow conditions, rainfall conditions, temperature, the vegetation index, soil erodibility, and sediment characteristics. The general to specific approach is used to derive a best-fit model to predict the stream bank erosion. The final model selected by this specification procedure shows that the higher the bank angle, sinuosity, and stream flow, the greater the amount of stream bank erosion; contrarily, the higher the vegetation coverage on the stream bank, the less the amount of bank erosion. The first order derivative analysis shows that for most reaches on the Batavia Kill stream, bank erosion is directly related to the cross-section area and inversely related to the cross-section mean depth, which means that wide and shallow reaches on the Batavia Kill stream have the potential to incur more bank erosion.

A set of tests has been applied on the bank erosion prediction model to test the model precision and to validate the methodology used to specify the model. These tests show that the stepwise regression model well predicts the stream bank erosions on the Batavia Kill stream. The regression model is then employed to predict stream bank erosion on the project reaches, assuming there was no stream restoration. The results show that from the completion of each project to the summer of 2003, the restoration projects reduced the stream bank erosion by 7,460 m^3. The effectiveness of stream restoration in reducing stream bank erosion in the Batavia Kill watershed is significant.

ACKNOWLEDGMENT
The first two authors would like to acknowledge support received from the National Science Foundation Award # 3535848. All authors would like to acknowledge data support for this study from GCSWCD, USGS, NYCDEP, and NCDC. We also would also like to thank Dr. Corri Zoli for her editorial help.

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