III. ASSESSMENT ANALYSIS

The following section provides an overview of the model development process conducted by the IIHR with assistance from the COE. An attempt was first made to develop a general methodology and model formulation capable of identifying areas subject to erosion, regardless of cause. Once this methodology and general formulation had been established, the model was modified in an attempt to single out those locations potentially affected by commercial navigation.

A. Analysis Methods Investigated. Investigations of alternate ways of using the collected data sets were undertaken. A contingency analysis of the data was used to provide a measure of the dependency between pairs of parameters and to show whether the parameters were statistically independent or interrelated. The contingency analysis yielded a series of contingency tables, comparing one parameter against all other selected parameters. To conduct the contingency analysis, a commercial exploratory statistics package, DataDesk (Data Descriptions, Inc., P.O. Box 4555, Ithaca, NY, 14852) was selected. In order to conduct the contingency analysis, the data had to first be divided into discrete categories such as high, medium, and low (each representing 1/3 of the sampling sites).

A sample contingency table is presented in table 2 for explanation. It relates the variable cDist (distance from the bank to the sailing line) and cCwidth (channel top width). These variables are obviously related, since in narrow channel sections the distance that the tow is operating from the bank also tends to be quite small. Both numeric variables were categorized into LOW (L), MEDIUM (M), and HIGH (H) categories and contingency analysis conducted. The correlation between the variables can be seen from the strong diagonal of counts (H-H of 23, M-M of 18, and L-L of 26) and the weak non-diagonal counts. In addition, the Chi-Square value provides a measure of the significance of the variation in the counts that could be expected by chance with independent parameters.

Table 2. A Sample Contingency Table

Rows are levels of cDist
Columns are levels of cCwidth
108 total cases of which only one is missing

		H	*L*	*M*	*Total*
H	Count	23	0	13	36
	Expected Count	11.7757	11.7757	12.4486	36
L	Count	4	26	6	36
	Expected Count	11.7757	11.7757	12.4486	36
M	Count	8	9	18	35
	Expected Count	11.4486	11.4486	12.1028	35
Total	Count	35	35	37	107
	Expected Count	35	35	37	107

Chi-Square = 52.59 with 4 df (degrees of freedom)
p <= 0.0001

Statistics reported by the contingency analysis are:

Count: The number of cases falling into each cell

Chi-Square: The null hypothesis associated with this test for independence states that the two parameters are statistically independent. The probability that a randomly selected case falls in a specified cell depends only upon the probability that the case falls in the specified column and the probability that it falls in the specified row.

Expected value: This is the number of cases expected to be in the given cell were the Chi-Square null hypothesis true. If the null hypothesis is true, then the observed cell counts approximately equal the expected cell counts. If the null hypothesis is false, then the observed cell counts will tend to differ from the expected cell counts.

p: Probability of obtaining a Chi-Square value at least as large as computed, if the two parameters were independent.

1. Analysis No. 1. Since some of the selected erosion sites had data collected at more than one cross section, multiple data sets from the same erosion site were eliminated to avoid bias effects. It was decided to use only the data collected from the midpoint section of each site. Only the UMR site data were considered in this initial analysis, and the list of perceived erosion mechanisms was reduced to the most dominant processes at each site. The parameters considered in this statistical analysis are shown in table 1.

Each quantifiable, numeric parameter was considered individually. A frequency breakdown of the parameter's distribution permitted the continuous numeric parameter to be broken down into a small number of discrete categories. Percentiles were computed for the upper and lower thirds of the distributions and histograms were plotted to verify the computation. Thirty-third and sixty-sixth percentile rankings gave cutoff points by which the original numeric values could be categorized. Values below the thirty-third percentile were categorized as LOW, values above the sixty-sixth percentile were categorized as HIGH, and the remaining values were categorized as MEDIUM.

In order for the model to be implemented on a system wide basis, the model must be limited to those parameters that can be estimated for the approximately 2,000 miles of bankline being considered in this study. Therefore, the number of parameters was reduced to those which were known or which could be readily determined or measured for the entire study area. These remaining parameters were recategorized and the contingency analysis repeated. Data for the forty-three UMR sites were used. Table 3 summarizes numeric ranges that define each of the LOW, MEDIUM, and HIGH categories for each attribute.

Table 3. Categorization of Numeric Variables

Attribute	**LOW value**	**MEDIUM value**	**HIGH value**
Bench width (ft)	< 9 ft	9 ft ~ 17 ft	≥ 17 ft
Channel width (ft)	< 950 m	950 m ~ 1,450 m	≥ 1,450 m
Degree of curvature	< 30°	30° ~ 45°	≥ 45°
Distance to sailing line (ft)	< 500 ft	500 ft ~ 800 ft	≥ 800 ft
Scarp height (ft)	< 1.5 ft	1.5 ft ~ 3.5 ft	≥ 3.5 ft
Scarp slope (V:H)	< 2:1	2:1 ~ 3.5:1	≥ 3.5:1
Subaqueous bench slope (V:H)	< 1:8.7	1:8.7 ~ 1:6.7	≥ 1:6.7

It should be noted that the labels, LOW, MEDIUM, and HIGH, refer only to the relative numerical value of the given parameter at that site, and do *not* refer to the bank erosion risk. For example, a LOW value in the "distance to sailing line" parameter should be seen as a high bank erosion risk. Therefore, a determination was made for each parameter, as to whether the HIGH or LOW values corresponded to a high erosion risk, as shown in table 4.

Table 4. Relationship Between Categorization Value and Risk Value

Measures / Categories	L (Low) High Risk shown in shade	M (Medium)	H (High) High Risk shown in shade
Distance to Sailing Line	L	M	H
Scarp Height	L	M	H
Scarp Slope	L	M	H
Subaqueous Bench Slope	L	M	H
Channel Width	L	M	H
Radius of Curvature	L	M	H
Bench Width	L	M	H

In an attempt to define a relative risk of erosion, a new parameter, Rate of Hit (ROH), was constructed to count the number of parameters (of the seven total per site) that were considered to be in the high erosion risk category. However, the resulting values of ROH failed to provide sufficient resolution between sites or results that were consistent with the field survey observations.

2. Analysis No. 2. A review meeting regarding the initial analysis effort (Analysis No. 1) was held between the IIHR and the COE at the Rock Island District on 25 November 1997. Discussions at the meeting indicated that the general formulation being used in the analytic approach taken by IIHR appeared promising for making limited statements about the relative effects and significance of various parameters on severely eroded sites. It was decided to continue the contingency analysis for the entire UMR and IWW data sets (including the UMR observation sites), as opposed to using just the forty-three UMR sites as in Analysis No. 1.

The analyses continued by investigating a slightly different set of parameters. A new data set with nine parameters (*distance to sailing line, scarp slope, subaqueous bench slope, channel width, radius of curvature of bend, bench width, commercial traffic level, and recreational boat traffic level*) was constructed for the entire UMR and IWW navigation system. Frequency analyses were done and numerical range limits were determined for the LOW, MEDIUM, and HIGH categories for each parameter. Contingency tables for each parameter versus all other parameters were prepared and significant correlations were noted only for parameter pairs related to site geometries, i.e., radius of curvature of bend, degree of curvature of bend, distance to sailing line, and channel width. No significant correlations were observed among other parameters.

Analysis efforts then turned to consideration of the 108 erosion sites observed during the UMR/IWW field surveys. Midpoint sections at each site (forty-three UMR, twenty-nine IWW, and thirty-six UMR observation sites) were extracted for analysis. Frequency analysis resulted in the numeric range limits, and the risk criteria unfavorable to bank-erosion processes were established. The established risk criteria was applied to each site and the numbers of the unfavorable features were counted as before using the Rate of Hit (ROH) measure.

Another approach taken in evaluating the severity of bank-erosion risk factors was to give a numeric value to each of the LOW, MEDIUM, and HIGH values rather than counting the number of occurrences of each erosion risk category. In place of the ROH counting scheme, the categorical weights were increased linearly such as 1, 2, 3, or 1, 3, 5 for the LOW, MEDIUM, and HIGH risk categories. The overall erosion risk measure was then defined as the sum of the resulting weighted-attribute scores. However, simple linear weights did not provide sufficient discrimination among the resulting overall erosion risk categories. Therefore, an exponential categorical weighting scheme, shown in table 5, was devised to provide a better distribution of these categories. A total score from the sum of the weighted values for the nine parameters was then obtained for each site. The resulting frequency distribution of the overall erosion risk scores showed a good distribution; thus, providing the desired discrimination. The histogram of scores is shown in figure 1. The histogram shape approximates a normal distribution, indicating a good discrimination among the erosion site parameters used in this analysis.

Table 5. Exponential Weighting Scheme

Category Value	Weighting Factor
LOW	$2^1 = 2$
MEDIUM	$2^3 = 8$
HIGH	$2^5 = 32$

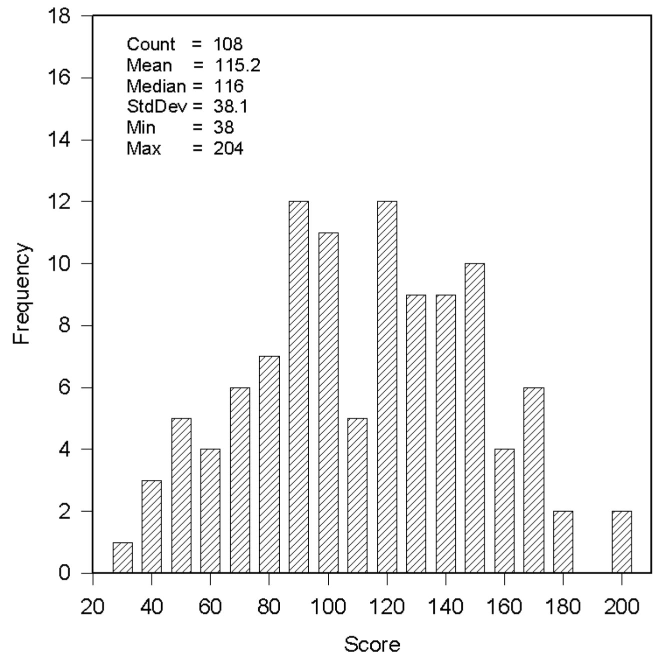

Figure 1. Histogram of overall erosion risk scores using the exponential weighting scheme

It should be noted that all of the sites used in this analysis were diagnosed as severely eroding during the field survey. The risk distribution obtained in this analysis indicated that the proposed exponential weighting scheme could be expanded for further refinement.

3. Analysis No. 3. During discussions between the IIHR and the COE on 31 December 1997, it was decided to continue analyses using the exponential weighting scheme with one adjustment. It was decided to try several different sets of additional weighting factors to be used in conjunction with the exponential weighting used earlier. These weighting factors were to be multiplied by the exponential weights determined according to the erosion risk severity category. The weighting factor represents a combination of the relative importance of the parameter in the overall bank erosion process as well as the interrelated nature of some of the parameters (i.e., if channel width and distance to the sailing line are strongly related, then the weighting factors provide a means to avoid biasing the model result). Hence, the total score for a particular site's attribute would be the product of an attribute-specific weighting factor and a severity-specific exponential value. For example, if "distance to sailing line" had a weighting factor of 8 and the attribute for a particular site was found to be high risk, the resulting attribute score would be: $8 * 2^5 = 256$. The total numeric score for a section of the bank line could then be determined as:

$$Score = w_1 2^{x1} + w_2 2^{x2} + ... + w_n 2^{xn}$$

where: $w_1, w_2, \ldots, w_n$ = parameter weighting factors
x1,x2, … , xn = exponents based on the risk categories
n = the number of parameters used in the analysis

Use of this final score provides a method of quantitatively comparing the relative risk of erosion between different sites based on the set of *n* parameters.

B. Selected Method. Using the general model formulation and methodology developed in Analysis No. 3, the model was adjusted to focus on just those available attributes that are, based on judgement, directly related to the potential for commercial navigation induced erosion. The potential for navigation induced erosion relates directly to the water motions that vessels create and that are capable of attacking banks. These include return currents, water level drawdown, short period and transverse stern waves, and propeller wash. In addition, fleeting activities and temporary mooring associated with tows waiting for lockage could have the potential to produce localized impacts.

The potential for significant drawdown and return currents is highly related to the channel blockage ratio (channel area/vessel area) and is most significant in the IWW and upper reaches of the UMR where channel dimensions are smallest. Since the existing bathymetric data are not sufficient to compute the blockage ratio for all sections of the bank in the system, the channel top width (bank to bank) at low flow conditions was used to represent the potential for vessel drawdown and return current related erosion.

The potential for vessels to produce significant wave heights at the bank line is related to the distance the vessels operate relative to the bank, and the speed, size, direction and draft of the vessel. The Economics Workgroup of the UMR/IWW Navigation Study, has identified little variability in the speed at which tows transit the system. In addition, the most frequently occuring tow size operating on the system pools is 1,200 feet in length (three barges wide by five long) with a maximum draft of 9 to 9.5 feet. Since the speed, draft, and maximum size of the tows operating in the pooled reaches of the UMR and IWW are consistent between pools; the distance from the sailing line to the bank line at low water was used as the significant parameter for the risk of wave attack due to commercial vessel movement.

Propeller wash has the potential to produce erosion in small radius bendways, and in narrow channels sections where the transiting tow is forced to perform additional maneuvering. The potential risk for direct prop wash of the bank is represented in the model by the radius of curvature of the bend, as well as the channel top width and distance to the sailing line at low flow conditions.

The areas currently being used for fleeting and temporary mooring by tows waiting for lockage, have been identified as part of the Navigation Study and are considered high risk areas for the potential for commercial navigation induced bank erosion.

Using these three quantitative (distance to sailing line, channel top width, and radius of curvature) and two qualitative parameters (location of fleeting and mooring areas) the system was screened using the general model formulation presented above, with some minor adjustments. First, the risk ranges were increased from 3 levels to 5, allowing for greater resolution of the high risk areas. The risk ranges and corresponding exponents used in this analysis are listed in table 6. Second, the entire UMR and IWW databases were used to develop the cut-offs for the risk ranges (as opposed to just the 72 sampling sites and 36 observation sites). Therefore, the “HIGH RISK” category represents the five percent on the system most susceptible to erosion for that particular parameter. The UMR and IWW were modeled separately and two sets of risk ranges were computed.

Table 6. Five Level Risk Range Categorization

Range Name	Range	Exponent
HIGH RISK	< 5th Percentile Value	5
HIGH/MEDIUM RISK	5th – 20th Percentile Value	4
MEDIUM RISK	20th - 50th Percentile Value	3
MEDIUM-LOW RISK	50th – 75th Percentile Value	2
LOW RISK	> 75th Percentile Value	1

For all three quantitative parameters, a low value represents a high risk for commercial navigation related bank erosion. Tables 7 and 8 summarize the risk range category limits for the UMR and IWW.

Table 7. Risk Range Category Limits – Upper Mississippi River

Breakpoint Location	Channel Top-Width (m)	Distance to Sailing Line (m)	Radius of Curvature (m)
5th Percentile Value	268	97	1306
20th Percentile Value	419	171	2005
50th Value	607	286	3640
75th Value	754	407	6200

Table 8. Risk Range Category Limits – Illinois Waterway

Breakpoint Location	Channel Top-Width (m)	Distance to Sailing Line (m)	Radius of Curvature (m)
5th Percentile Value	151	68	879
20th Percentile Value	181	87	1300
50th Value	230	113	2548
75th Value	292	148	4450

The new overall erosion risk score was then defined as:

$$\textbf{Score} = \underset{\text{(Dist2Sail)}}{8 * 2^{A}} + \underset{\text{(Channel Width)}}{6 * 2^{B}} + \underset{\text{(Radius of Curvature)}}{4 * 2^{C}}$$

where exponential constants A, B, and C are the values associated with the five risk ranges (Table 6), and 8, 6, and 4 are weighting factors for the distance to the sailing line, channel width, and radius of curvature, respectively. The weighting factors used in this analysis were chosen based on the perceived importance and independence of the parameters, as well as the resulting distribution of model scores (i.e., the selected weighting factors produced good dissemination of model scores).

The model was applied to the GIS database and the resulting scores for each section of the bankline were ranked (the main channel border was divided into approximately 10,000 segments in the GIS database). The resulting score represents the relative potential for commercial navigation related bank erosion at a bank section with respect to other sections. The bank sections with the highest score represent the highest potential, and the bank sections with the lowest scores the lowest potential.

Having ranked each segment of the bank, we then sought to define what score would represent a high, medium, or low potential for commercial navigation related bank erosion. One method would be to simply assign one third of the bank sections a value of "high", one-third a value of "medium", and the remaining third a value of "low". However, this would be inconsistent with the findings of the field survey report (COE, 1998) which concluded that approximately 14% of the banks of the UMR and 20% of the banks of the IWW were actively eroding. Based on the site descriptions and observed erosion mechanisms, it was concluded that approximately 1 in 5 (20%) of the selected erosion sites on the UMR showed signs of navigation induced disturbance. Similarly, approximately 24% of the selected erosion sites along the IWW showed signs of navigation induced disturbance.

Assuming that the sites selected during the field survey and the observed erosion mechanisms are representative of the erosion processes occurring at the other actively eroding sections throughout the system, we can conclude that approximately 2.8% (14% * 20%) and 4.8% (20% * 24%) of the UMR and IWW banks, respectively, are actively eroding in areas where forces generated by commercial navigation is a contributing mechanism. Therefore, the "high" potential areas were defined as those areas most susceptible to commercial navigation related bank erosion which are represented by 2.8% (UMR) and 4.8% (IWW) of the system (i.e., the highest score). In addition, areas used for temporary mooring and fleeting were also defined as having a high potential for commercial navigation related bank erosion. The balance of the actively eroding areas was then divided evenly into the medium and low risk categories. Therefore (14%-2.8%)/2 = 5.6% of the UMR and (20%-4.8%)/2 = 7.6% of the IWW were identified as having a medium potential for navigation related bank erosion.

The high, medium, or low classification of each section of the bank line was generated and loaded into the GIS database for mapping. The model results, by pool, are mapped in Appendix C and summarized in tables 9 and 10 for the UMR and IWW, respectively. The “Total Bank Length” is the bank length of each pool (both banks) upon which the model was applied. The "High Potential Length" and “Medium Potential Length” are the bank lengths of each pool identified by the model as being high and medium risk for commercial navigation related bank erosion. The "Protected Length" is that portion of the high and medium risk areas that were identified as naturally or artificially protected (rock outcrop, revetment, unerodible rocky bluffs, river wall, riprapped, etc.) during the 1995 field survey. Only the high and medium potential areas are identified on the maps, with the balance of the main channel border having a low potential for commercial navigation related bank erosion. Additionally, the locations of temporary mooring locations and barge facilities are indicated on the maps and are considered high potential areas.

C. Limitation of Approach. The method developed in this study attempts to identify sites where there is a possibility that commercial navigation induced forces contribute, to some undeterminable extent, to bank erosion. It can not predict the magnitude of the contribution or to what extent additional traffic would increase the possibility or extent of erosion. The actual rate of erosion at the identified sites is dependent on the nature of the bank materials and subaqueous conditions, the number (or frequencey) of tow events, as well as the other erosion mechanisms affecting the site. Multiple erosion mechanisms were identified as affecting the stability of the bank sections at all sites visited during the field survey. At many locations along the system the natural erosion and deposition of materials would dominate and may completely mask the effects of commercial navigation.

Table 9. Summary of Results For the Upper Mississippi River.

Pool	Total Bank Length (m)	High Potential Length* (m)	% High Potential	Protected Length (m)	% Protected	Medium Potential Length (m)	% Medium Potential	Protected Length (m)	% Protected
4	139,274	21,754	15.6%	6,342	29.2%	14,693	10.6%	2,846	19.4%
5	37,552	4,650	12.4%	2,292	49.3%	7,596	20.2%	680	9.0%
5a	23,231	3,781	16.3%	1,809	47.8%	4,409	19.0%	536	12.2%
6	41,924	4,496	10.7%	1,956	43.5%	7,226	17.2%	3,985	55.2%
7	33,378	4,284	12.8%	3,942	92.0%	4,155	12.5%	260	6.3%
8	57,512	3,089	5.4%	1,165	37.7%	10,137	17.6%	3,904	38.5%
9	79,341	9,489	12.0%	3,564	37.6%	17,387	21.9%	3,564	20.5%
10	96,030	5,511	5.7%	3,304	60.0%	12,274	12.8%	3,852	31.4%
11	87,371	3,163	3.6%	824	26.0%	1,782	2.0%	0	0.0%
12	75,841	3,313	4.4%	2,109	63.7%	2,077	2.7%	1,092	52.6%
13	82,110	3,062	3.7%	1,210	39.5%	5,663	6.9%	1,564	27.6%
14	84,234	9,843	11.7%	2,104	21.4%	1,488	1.8%	0	0.0%
15	32,716	0	0.0%	0	NA	1,016	3.1%	652	64.2%
16	71,903	4,454	6.2%	0	0.0%	1,630	2.3%	272	16.7%
17	65,790	2,804	4.3%	542	19.3%	3,873	5.9%	660	17.0%
18	79,577	1,041	1.3%	0	0.0%	2,962	3.7%	161	5.4%
19	133,567	4,299	3.2%	1,893	44.0%	2,274	1.7%	0	0.0%
20	69,866	5,169	7.4%	368	7.1%	538	0.8%	538	100.0%
21	51,943	1,221	2.4%	0	0.0%	1,047	2.0%	0	0.0%
22	76,244	579	0.8%	0	0.0%	0	0.0%	0	NA
24	90,008	4,008	4.5%	0	0.0%	4,538	5.0%	1,594	35.1%
25	97,078	0	0.0%	0	NA	720	0.7%	0	0.0%
26	135,066	3,831	2.8%	3,758	98.1%	172	0.1%	0	0.0%
open	675,583	67,147	9.9%	45,382	67.6%	5,113	0.8%	4,876	95.4%
Sum	**2,417,140**	**170,989**	**7.1%**	**82,562**	**48.3%**	**112,770**	**4.7%**	**31,035**	**27.5%**

Unprotected High Length: 88,427 (3.7%) **Unprotected Medium Length: 81,735 (3.4%)**

*** Includes Fleeting Areas**

NOTE: Tables 9 and 10 reflect only the three parameter screening and fleeting areas. Temporary mooring locations and barge facilities, which also represent a high potential for commercial navigation related bank erosion, are shown on the maps in Appendix C.

Table 10. Summary of Results For the Illinois Waterway.

Pool	Total Bank Length (m)	High Potential Length* (m)	% High Potential	Protected Length (m)	% Protected	Medium Potential Length (m)	% Medium Potential	Protected Length (m)	% Protected
Alton	249,763	2,181	0.9%	36	1.7%	4,244	1.7%	837	19.7%
LaGrange	240,935	23,443	9.7%	3,680	15.7%	41,088	17.1%	80	0.2%
Peoria	185,149	18,870	10.2%	1,497	7.9%	4,809	2.6%	0	0.0%
Starved Rock	37,480	3,327	8.9%	1,365	41.0%	2,257	6.0%	634	28.1%
Marseilles	85,376	15,879	18.6%	5,676	35.8%	9,821	11.5%	2,765	28.2%
Dresden Island	50,270	8,025	16.0%	1,999	24.9%	6,568	13.1%	2,416	36.8%
Sum	**848,972**	**71,726**	**8.5%**	**14,253**	**19.9%**	**68,786**	**8.1%**	**6,732**	**9.8%**

Unprotected High Length: 57,473 (6.8%) **Unprotected Medium Length: 62,054 (7.3%)**

*** Includes Fleeting Areas**

IV. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations were derived from the present investigation:

A. Conclusions:

1. Because the 1995 field reconnaissance study on bank conditions for the Upper Mississippi River (UMR) and the Illinois Waterway (IWW) (COE, 1998) included only actively eroding sites, the parameters observed in the field were not suitable for developing a model to predict the occurrence vs. non-occurrence of bank erosion on a system wide basis.

2. A contingency analysis, which provides a measure of dependency between pairs of parameters, was found in this case to produce useful information in conducting risk assessment for bank erosion along the UMR and the IWW. An exponential categorical weighting scheme was introduced to rank each parameter into three risk ranges of low, medium, and high category values. The resulting model was applied system wide to screen the system based upon three important parameters (channel top-width, distance to sailing