Mississippi River Levee Failures: June 2008 Flood

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ABSTRACT: *During the spring and summer of 2008, record rainfall in the Midwest United States led to severe flooding as water overtopped the levees bordering the Mississippi River and its tributaries. The erosion associated with the overtopping resulted in levee breaches in many places. After the flooding, a field reconnaissance team was sent to collect time-sensitive data and provide a comprehensive overview of the performance of the levees during the flooding.*

Two locations where levee overtopping occurred are particularly interesting because of their differing site conditions and performance. This paper presents the levee overtopping case histories of the Winfield-Pin Oak site which was overtopped and severe erosion led to failure, and the Brevator site which was also overtopped but did not fail. Included are a hydrological investigation, documented site conditions, geotechnical soil properties, a soil erodibility analysis, and the documented levee vegetative cover. Levee performance is influenced by the flood conditions, the site conditions, and the soil properties. Both sites in this study experienced large levels and durations of overtopping water, but it is proposed that the Brevator site survived because of its vegetative cover and more erosion resistant soils. Erosion is a very complicated phenomenon that cannot be described by any one parameter, but in all cases, dense and consistent native vegetative cover can greatly improve the overall levee performance.

KEYWORDS: Erosion, Erosion Function Apparatus (EFA), Levee, Mississippi River Floods

SITE LOCATION: IJGCH-database.kmz (requires Google Earth)

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INTRODUCTION

After the flooding in the Midwest U.S. during the summer of 2008, a field reconnaissance team was sent to several sites where overtopping had occurred to collect time-sensitive data. The team was comprised of members from Texas A&M University, the University of California at Berkeley, and Missouri University of Science & Technology. The Texas A&M University group documented post-flood field conditions, and collected soil and grass samples for further erosion analyses and geotechnical properties determination. Index and erosion properties for each sample were combined with documented field data as well as a hydrological study to develop an overview of the overtopping erosion issues at each site. The Texas A&M University findings and data analyses are reported in Bernhardt (2009). The final results, showing the collected data and analyses from each of the three universities, are documented in Storesund et al. (2009). For this paper, two sites were selected out of the seven sites investigated because they were valuable examples. The findings at the Winfield-Pin Oak and the Brevator sites during the field reconnaissance along with a hydrological study and an erosion analysis are presented.

U.S. LEVEES AND PREVIOUS FLOODING ALONG THE MISSISSIPPI

In the United States, there are more than 160,000 km of levees (ASCE 2009). Most of these levees were built many years ago in order to protect crops from flooding. What were once low populated and mostly agricultural areas have since been developed and homes and businesses have been located behind the levees, thereby increasing the risk to public health and safety. The Federal Emergency Management Agency (FEMA) estimates that approximately 22% of the nation's 3,147 counties contain levees and that 43% of the US population lives in these counties (ILPRC 2006). The U.S. counties which contain levees are shown in red on Figure 1, with the area of interest for the Midwest Levee reconnaissance outlined in yellow.

The Upper Mississippi River Basin (UMRB) extends across many of the northern states funneling rainwater and melted snow and ice into the lower sections of the Mississippi River (Figure 2). The Upper Mississippi River System, home to the Midwest Levee System, is a set of waterways stretching over 2000 km linking five states to the Lower Mississippi River System and the Gulf Coast export markets (USGS 2007).

For as long as the Mississippi has been in existence, it has flooded the valleys through which it flows. The first recorded flood of the Mississippi was described in 1543 by Garciliaso de la Vega, as severe and prolonged, and after 80 days of flooding the river returned to its banks (USACE 2004). The 1927 flood had the most dramatic impact on the Lower Mississippi River Valley of any flood up to that time, inundating approximately 67,000 km2 and displacing over 600,000 people (USACE 2004). Over 200 lives were lost and property damages reached $1.5 billion in today's prices. The Great Flood of 1993 was disastrous for the Midwestern United States. The months of June, July, and August recorded approximately 200-350 percent above normal cumulative rainfall having recurrence intervals of 75 to 300-years (Stallings 1994). On June 7th 1993, the first levee was overtopped, followed by over 1,000 other locations where levees were either overtopped or failed (Larson 1996). The extreme flooding resulted in the loss of over 48 lives (Interagency Floodplain Management Task Force (IFMTF) 1994). Over 41,000 km^2 in 9 states were flooded, mostly in the UMRB. The damages were estimated at $20 billion (National Oceanic and Atmospheric Administration (NOAA) 1994).

THE 2008 FLOOD

During the spring of 2008, above average rainfall saturated the ground leaving it unable to absorb any more water. In early June, an additional nearly 0.3 m of rain fell on parts of southern Indiana, Ohio, Wisconsin, and Iowa. Thunderstorms producing flash flooding occurred over a large area leading to widespread river flooding in over 58 locations. The large spatial drainage basins dumped record amounts of water into the Mississippi River until the levees bordering it were no longer able to withhold the raging waters. Although very few casualties resulted from the disastrous flood waters, ASCE (2009) estimates almost $600 million in property damages and dead livestock occurred from the breached levees. A precipitation and hydrological flow study was performed to identify the magnitude of the floods the levees were subjected to.

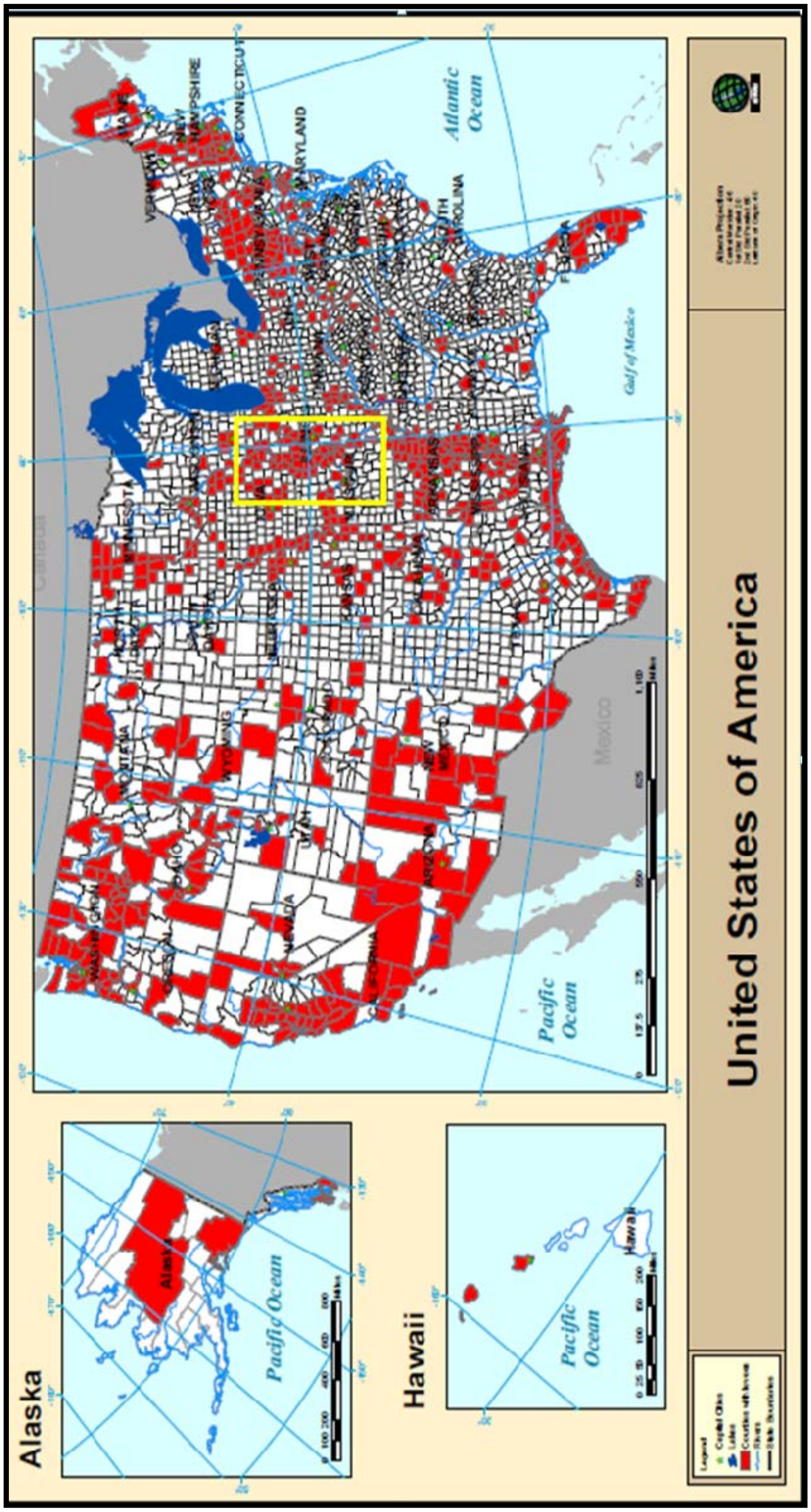


Figure 1. Counties with levees in the U.S. (adapted from Tucker 2009).

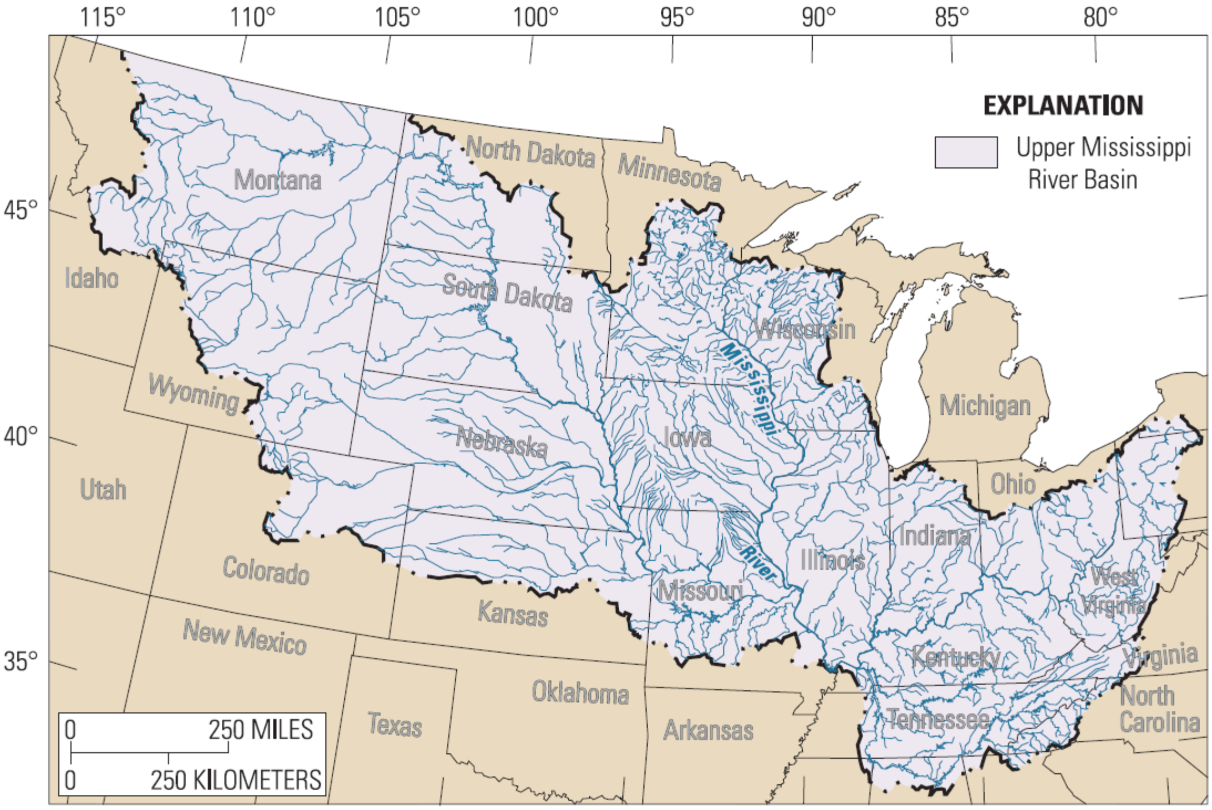


Figure 2. Upper Mississippi River drainage basin (Johnson et. al. 2003).

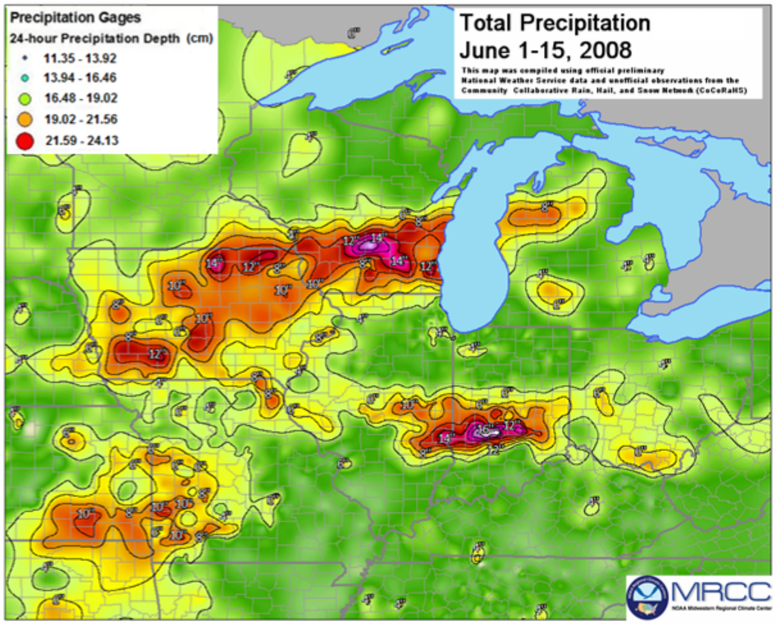


Figure 3. Color contour of the accumulated rainfall during June 2008 (NCDC 2009).

Precipitation

According to the report of the National Climatic Data Center (NCDC), the Upper Mississippi River flood that occurred during June 2008 was caused not only by the extreme precipitation which broke historical records at 15 rain gages across the Midwest (Figure 3), but also by the extremely wet antecedent soil-moisture conditions (Figure 4) which had a recurrence interval of approximately 40-years over a large proportion of the UMRB.

The NCDC report states that the antecedent soil moisture conditions of eastern Iowa and southern Wisconsin had a return period of 25-years. It also indicates that the accumulated depth of precipitation that occurred during the six months prior to the flood (December 2007 to May 2008) is the second highest since the record began in 1895.

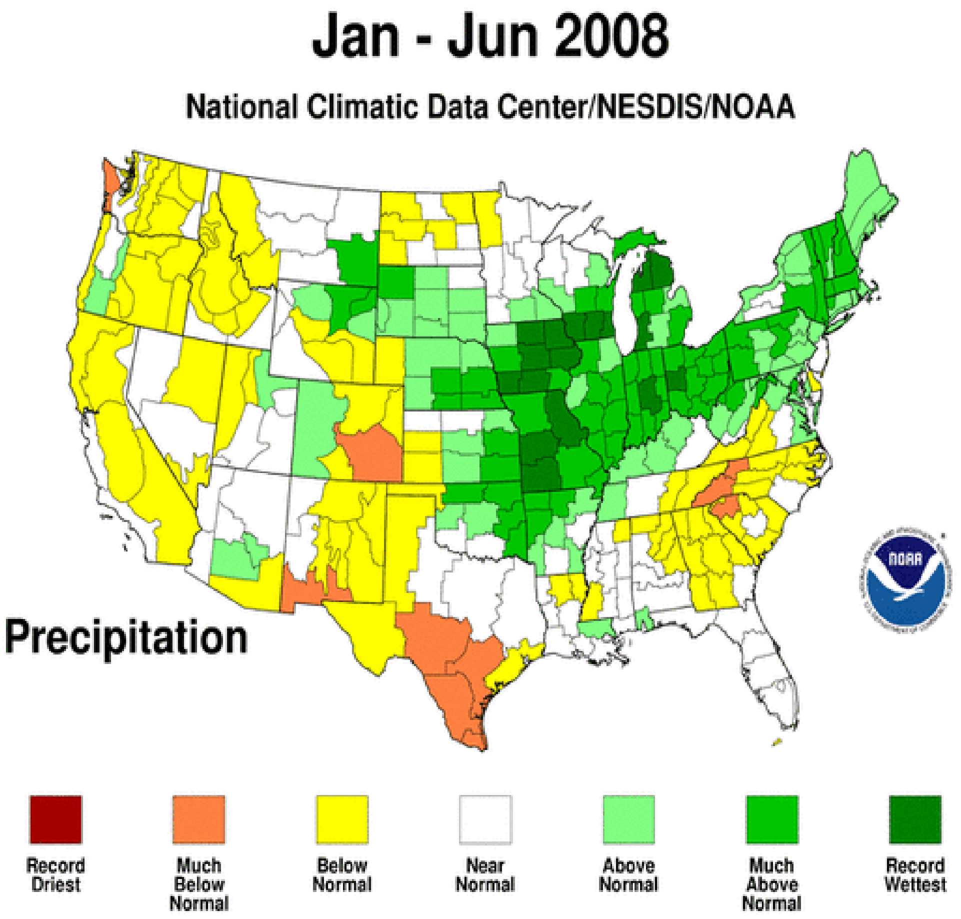


Figure 4. Antecedent soil-moisture conditions (NCDC 2009).

Flow Frequency Analysis

Within the study area, there were six USGS flow gages on the main stream of the Upper Mississippi River where data was available for a flow frequency analysis (Figure 5). The white numbers next to the gage icons represent the USGS gage ID, while the estimated flood recurrence interval for each gage is shown in yellow. The flood recurrence interval represents the probability that a flood of a certain magnitude will occur in any given year and it is estimated by performing a flood frequency analysis as described below. The flood frequency analysis was performed by using the peak flow values. In the cases where the yearly peak flow values were not available or if there were too few data points, the record daily average flow during the flooding event was used.

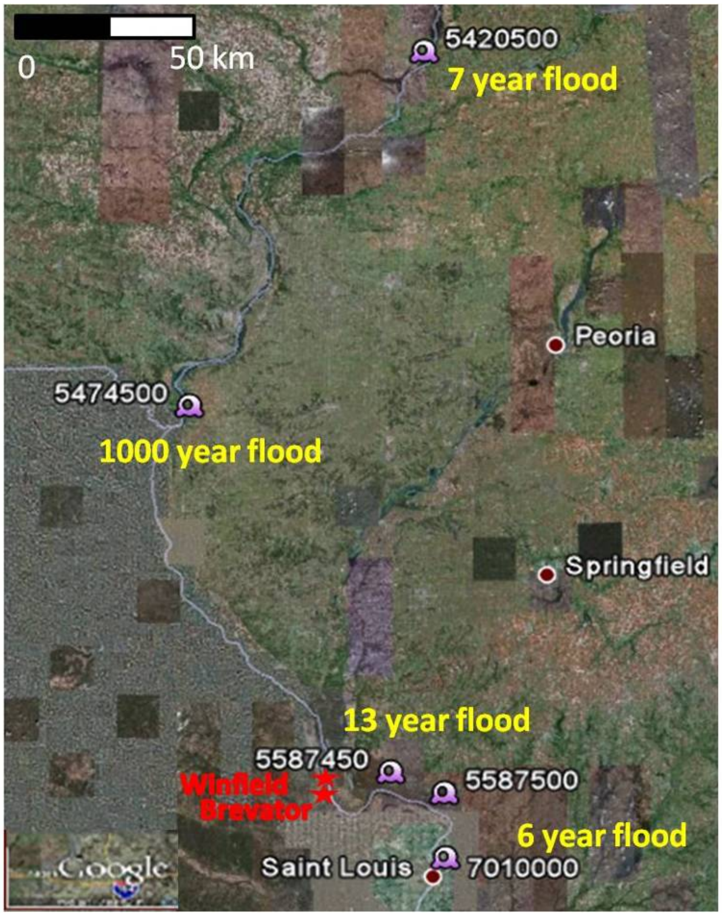


Figure 5. Locations of the USGS flow gages used.

Gage 05587450 is located on the edge of the Mississippi River near Grafton, Illinois. This gage is the closest USGS gage to the Winfield - Pin Oak and Brevator sites (locations indicated by red stars); however, there were only 21 flow peaks available for the gage. This small amount of data can adversely affect the accuracy of the frequency analysis result. Gage 05587500, located in Alton just a short distance downstream of 05587450, has a difference in drainage area of less than 1%. For this reason, the flow peaks observed at 05587500 were combined with the data at 05587450 to increase the data set and enhance the reliability of the flood frequency analysis for Gage 05587450.

The flood frequency analysis consisted of organizing the observed peak flows in ascending order with the corresponding recurrence interval being the ranking of the flood. Then the data points were plotted as flow versus ranking (recurrence interval) (Figure 6). The recurrence interval (R_{2008}) of the June 2008 flood is obtained by fitting the flow versus recurrence data with a chosen distribution and then using that distribution to calculate the recurrence interval (Figure 6). Three commonly used combinations of distribution and parameter estimation methods were selected to fit the data in this study: the generalized extreme value distribution – method of maximum likelihood (GEV-MLE) (Hosking 1985), the generalized extreme value distribution – method of L-moments (GEV-LMOM) (Hosking 1985), and the Bulletin 17B method which uses the Log-Pearson Type III distribution and the method of moments (MOM) for the estimation of the parameters (United States Internal Geological Survey 1982). Note that the Bulletin 17B method is the official method used by USGS and can be regarded as the standard distribution to model flow peak frequency values. Each of these methods has its own advantages and disadvantages.

The recurrence interval of the June 2008 flood based on the three different methods can be read on a fitted curve for the observed value of the flow, such as shown for gage 05474500 in Figure 6. To obtain the estimated recurrence intervals, a horizontal line is drawn from the data point with a flow value of 12,400 m^3/s through the regression lines. Each intersection point represents the recurrence interval for that respective estimation method. The results for the 4 gages of Figure 5 are shown in Table 1. As can be seen from Table 1, the predicted recurrence interval for Gage 05474500 varies significantly among the three methods due to the fact that the data is extrapolated to extreme values. It is clear however, that at this location the flood was very large and in the vicinity of a 1000-year flood.

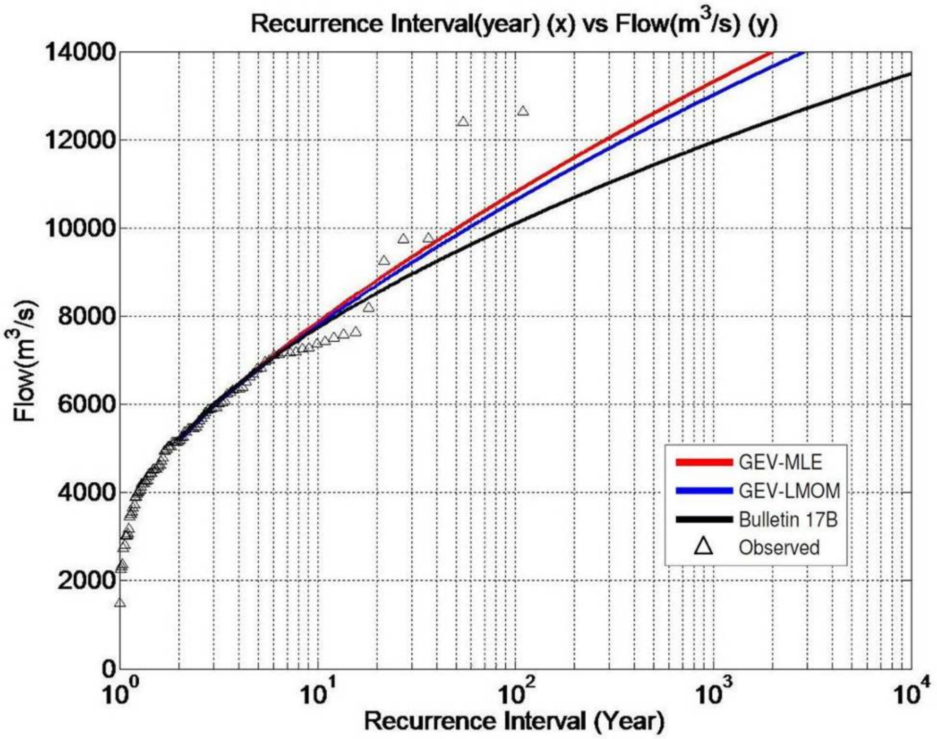


Figure 6. Observed flow peaks versus their recurrence intervals, gage 05474500.

Table 1. Flood frequency analysis results.

USGS ID	Latitude (degree)	Longitude (degree)	Drainage Area (km^2)	Flow Peak June Flood (m^3/s)	Date of Peak	Recurrence Intervals USGS method Bulletin 17B	GEV-MLE	GEV - LMOM
05420500	41.7805	-90.2519	221,700	5,700	6/16/08	8.1	8.2	8.1
05474500	40.3936	-91.3742	308,200	12,400	6/17/08	1900	400	530
05587450	38.9678	-90.4289	444,200	12,400	6/28/08	13	13	12
07010000	38.6306	-90.1175	1,805,200	20,400	6/30/08	5.5	6.1	5.6

The daily flow hydrographs (flow versus time) during the 2008 flood observed at USGS gage 05474500 and USGS gage 05587450 are shown on Figure 7 and Figure 8 along with the reference floods based on the Bulletin 17B flood frequency method. Note that at the location of USGS gage 05474500, the Mississippi River stayed at a stage level equal to or higher than the 100-year flood for approximately 8 days.

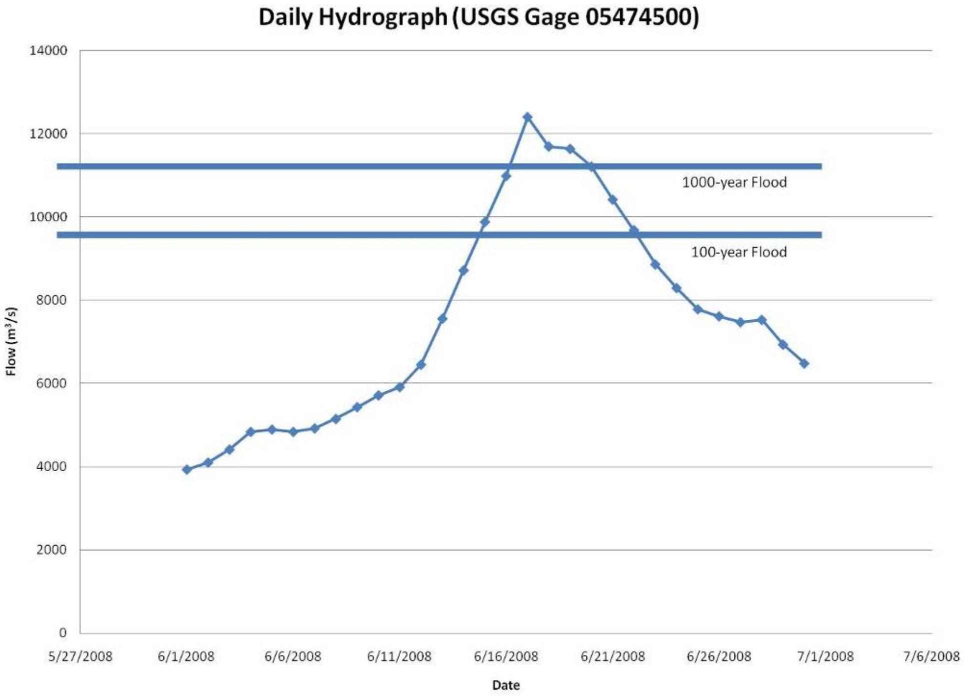


Figure 7. Daily flow hydrograph for USGS gage 05474500.

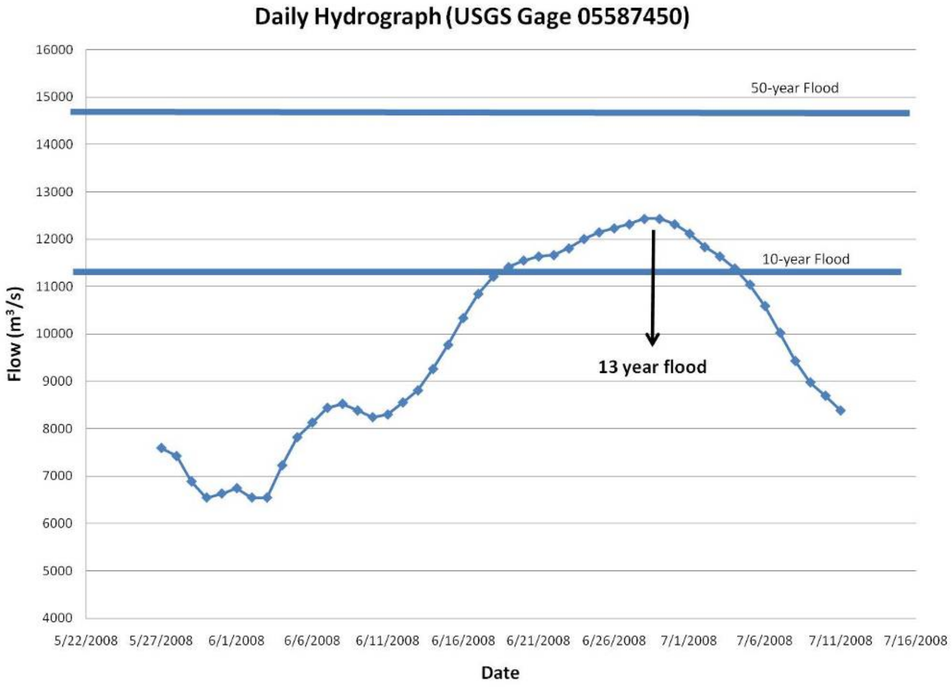


Figure 8. Daily flow hydrograph for USGS gage 05587450.

It was observed that the upstream gage 05420500 experienced a 7-year flood, while gage 05474500 experienced a 1000 plus year flood, and gage 05587450 experienced only a 13-year flood. The large difference in the recurrence intervals determined for the three consecutive gages can be best explained by looking at the drainage areas outlined in white on

Figure 9. The basins were delineated based on stream networks provided by Google Earth. The different colors shown in the background of Figure 9 represent the depths of the precipitation that occurred in the area from June 1 to June 15, 2008.

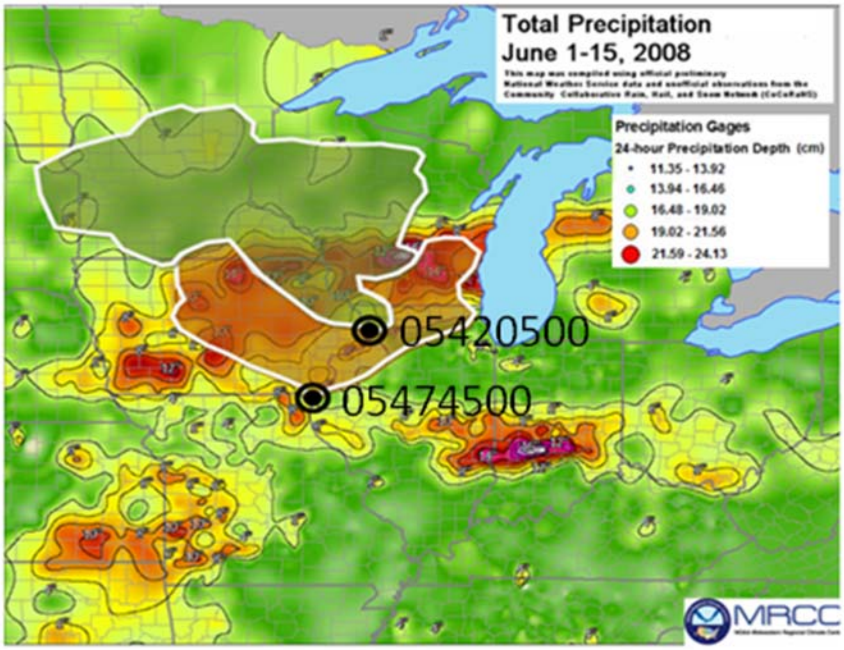


Figure 9. Basin drainage area between two gages (adapted from NCDC 2009).

While the spatial coverage is greater for the northern basin, the southern basin experienced a much larger concentration of rain in which most of the basin saw 24-hour precipitation depths exceeding 190 mm. Also, the northern outlined area drains to gage 05420500 while both the water from the lower basin and the water from the upstream gage contribute to the flood height at gage 05474500. In other words, the lower gage sees the runoff from both drainage areas explaining why the recurrence interval is much higher at this location.

While a 1000-year flood took place at gage 05474500, only a 13-year flood occurred approximately 225 km downstream. The extreme flood caused breaches in several locations between gage 05474500 to the north and gage 05587450 to the south. Because the water in the river drained to the flood plain through the breaches, the flood intensity was reduced at the downstream gage. These natural breaches allowed the city of St. Louis to see only a 6-year flood.

Locations of Overtopping

Figure 10 shows the US Army Corps of Engineers map of each particular levee system along the Upper Mississippi River System and the corresponding overtopping status during the flooding events as reported on 22 June 2008. The areas tagged in red had already been overtopped while the areas tagged in yellow show levee sections that were still in danger of being overtopped at that date.

In general, if a levee is overtopped long enough, the water may cut into the toe of the levee on the “dry” side, erode the “dry” side slope, and then continue to regress to the levee crest creating a breach. The degree of damage is dependent on the depth and duration of the overtopping as well as the soil properties. The duration of the overtopping can be estimated to have taken place for several days based on Figure 8. If the levees were designed to contain a 100-year flood, levees within the area of gage 05474500 could have been overtopped for 8 days. Note that such a long period of overtopping does not mean that the levee is subjected to sheet flow erosion for 8 days. As overtopping takes place, the water level on the “dry” side rises and gets to a point where it reaches the water level on the “wet” side. At that time flow perpendicular to the levee axis stops while flow along the main levee axis continues. The velocity of the flow in the direction of the main axis of the river is usually much lower (around 3 m/s) than the velocity of the overtopping flow perpendicular to the main axis (can reach 10 m/s).

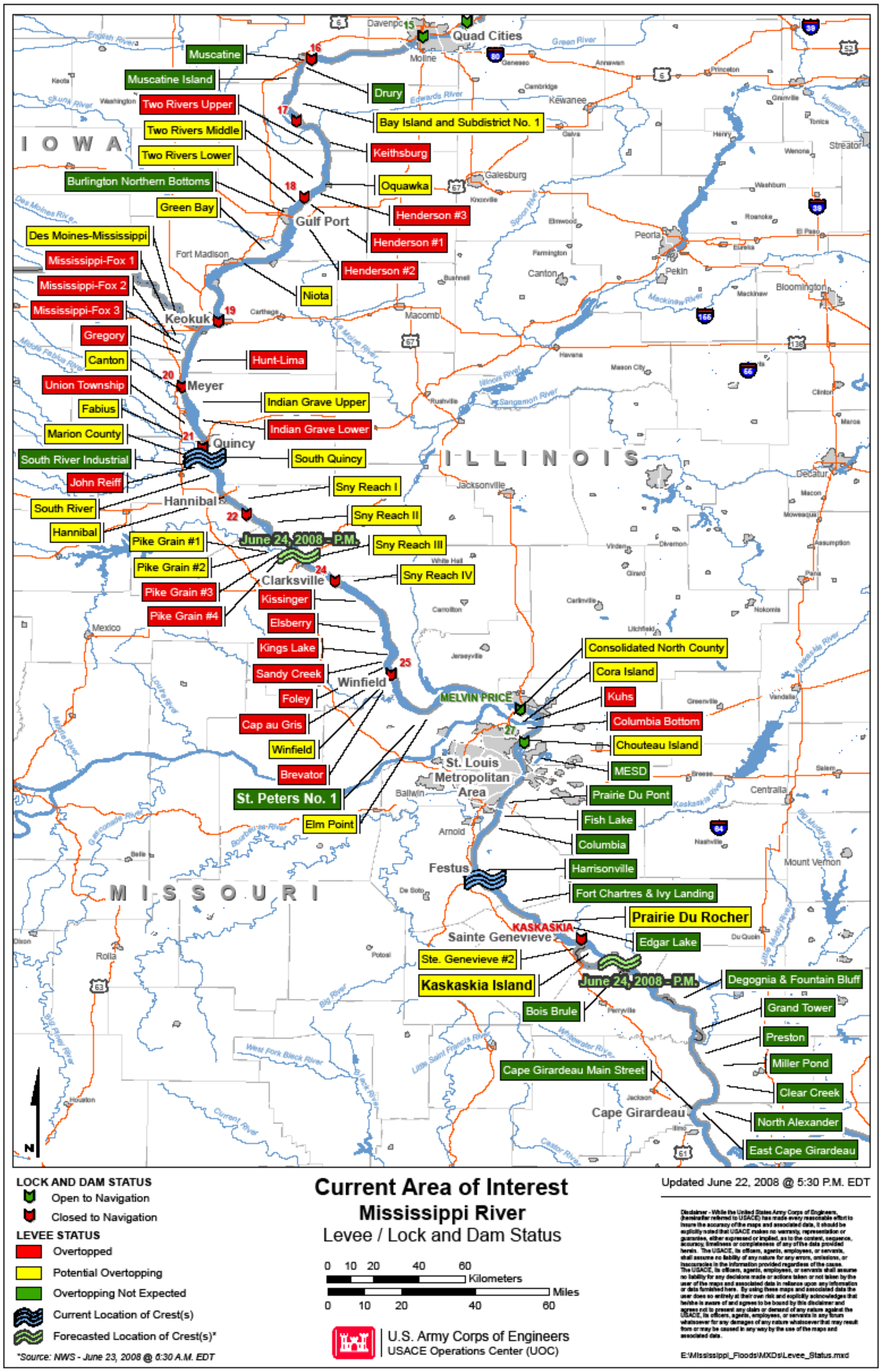


Figure 10. Overtopping status of Upper Mississippi River System (USACE 2008).

2008 Midwest Levee Field Investigation

During the post-flood field reconnaissance, the conditions at seven different sites (Table 2) throughout the Midwest were documented and soil and grass samples were collected so that geotechnical and erosion testing could be conducted in the laboratory. The selected sites were those where the levees had been previously overtopped and failed as well as where the levees sustained overtopping for days without failure. All sites were situated between the USACE St. Louis and Rock Island Districts. Figure 11 shows the study area along with the levee areas that were visited during the investigation (shown in black).

Table 2. Sites investigated during the 2008 Midwest Levee investigation.

Site Name and No.	Latitude*	Longitude*	Levee District
Winfield-Pin Oak – S1	38.9882	-90.6818	Cap au Gris Drainage and Levee District
Bryants Creek – S2	39.2514	-90.7711	Elsberry Drainage District
Brevator – S3	38.9622	-90.7114	Brevator Drainage and Levee District
Kickapoo – S4	39.1850	-90.7427	Elsberry Drainage District
Norton Woods – S5	39.1353	-90.7206	Elsberry Drainage District
Indian Graves – S6	40.0011	-91.4499	Indian Graves Drainage District
Two Rivers – S7	41.0939	-91.0687	Iowa Flint Creek Levee District No. 16

*WGS1984 Geographic Datum

Because the site conditions did not allow for the use of conventional drilling rigs, surficial samples were collected using modified thin walled Shelby Tubes approximately 154 mm long with a diameter of 76 mm and a wall thickness of 2 mm. The area of interest was cleared of any vegetation and the tubes were pushed into the soil. If the tube could not be pushed flush with the ground surface, it was driven by hand the remainder of the way. The borings were designated S_iB_j meaning site i and boring j. The specified sampling depth was estimated relative to the levee crest. Most of the samples were oriented vertically (labeled “V”), however, some locations required samples to be driven horizontally into the side of the breached levees (labeled “H”). A Torvane and a Pocket Penetrometer were also used at each sample location to obtain estimates of the soil strength. Bulk samples were collected at each site to determine the index properties of the soils and to characterize the soils according to the Unified Soil Classification System (USCS).

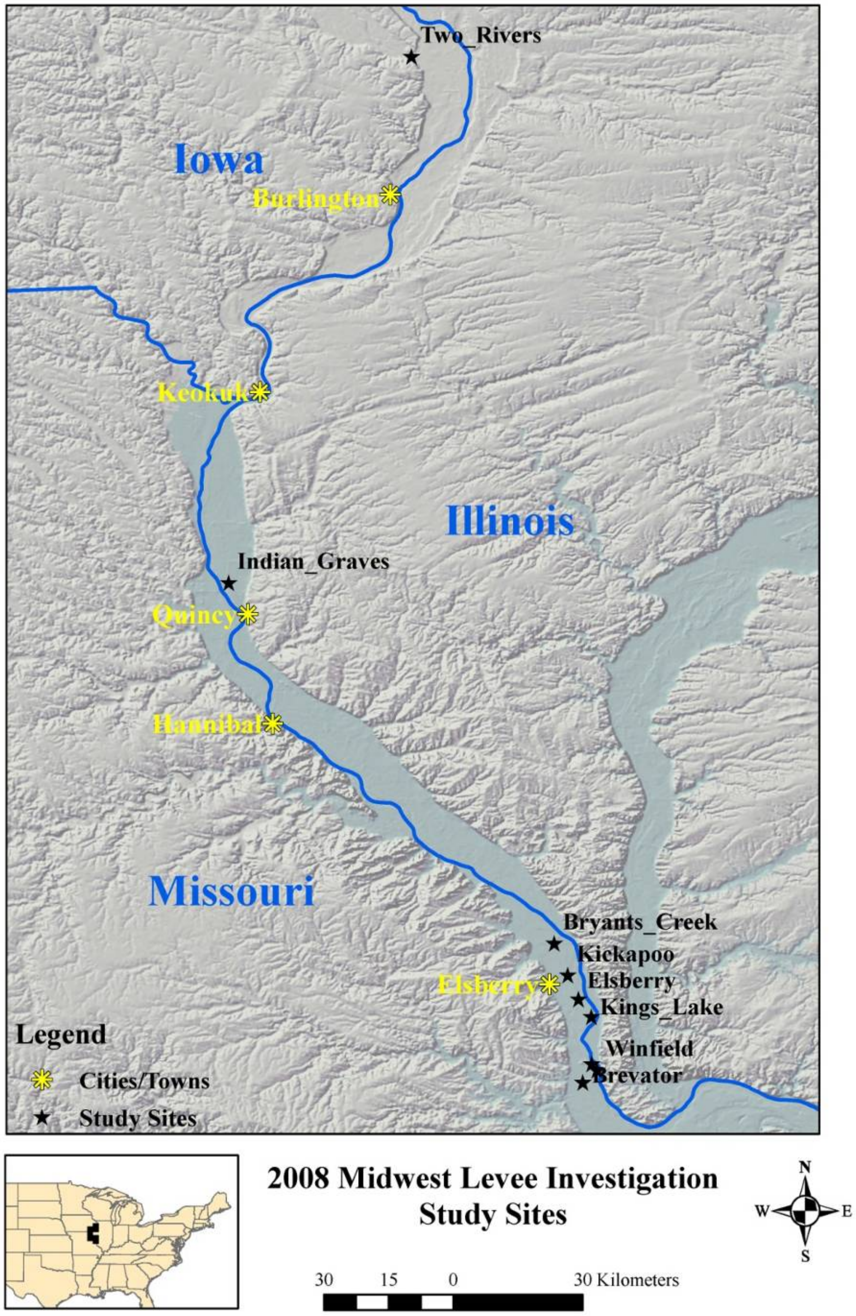


Figure 11. Map of sites visited (Storesund et al. 2009).

Winfield – Pin Oak

The first site visited during the 2008 Midwest Levee reconnaissance was the Winfield-Pin Oak site near Winfield, Missouri. The levee breached on June 18, 2008. A gap approximately 150 m long was created in the levee by the overtopping waters. Figure 12 is a photo taken by the St. Louis District USACE showing an aerial view as two homes were knocked off their foundations by the force of the water. Figure 13 shows the same site on September 29, 2008 during the Midwest Levee reconnaissance. It should be noted that the breach shown in Figure 13 was contained between the blue and white houses shown in Figure 12 even though overtopping was also occurring further down the levee.

Figure 12. Winfield-Pin Oak breach (USACE St. Louis District 2008).

Figure13. Winfield-Pin Oak site, Missouri.

The Winfield-Pin Oak levee is maintained by the Cap Au Gris Drainage and Levee District. This levee system is estimated to reduce the risk of flooding of approximately 493 ha up to a 14-year return period flood event on the Mississippi River (Figure 14). This area failed during the 1993 floods, however, the specific location of the breach (or breaches) was not documented (USGS 2006). This site was overtopped for an extended period beginning on June 18th, 2008.

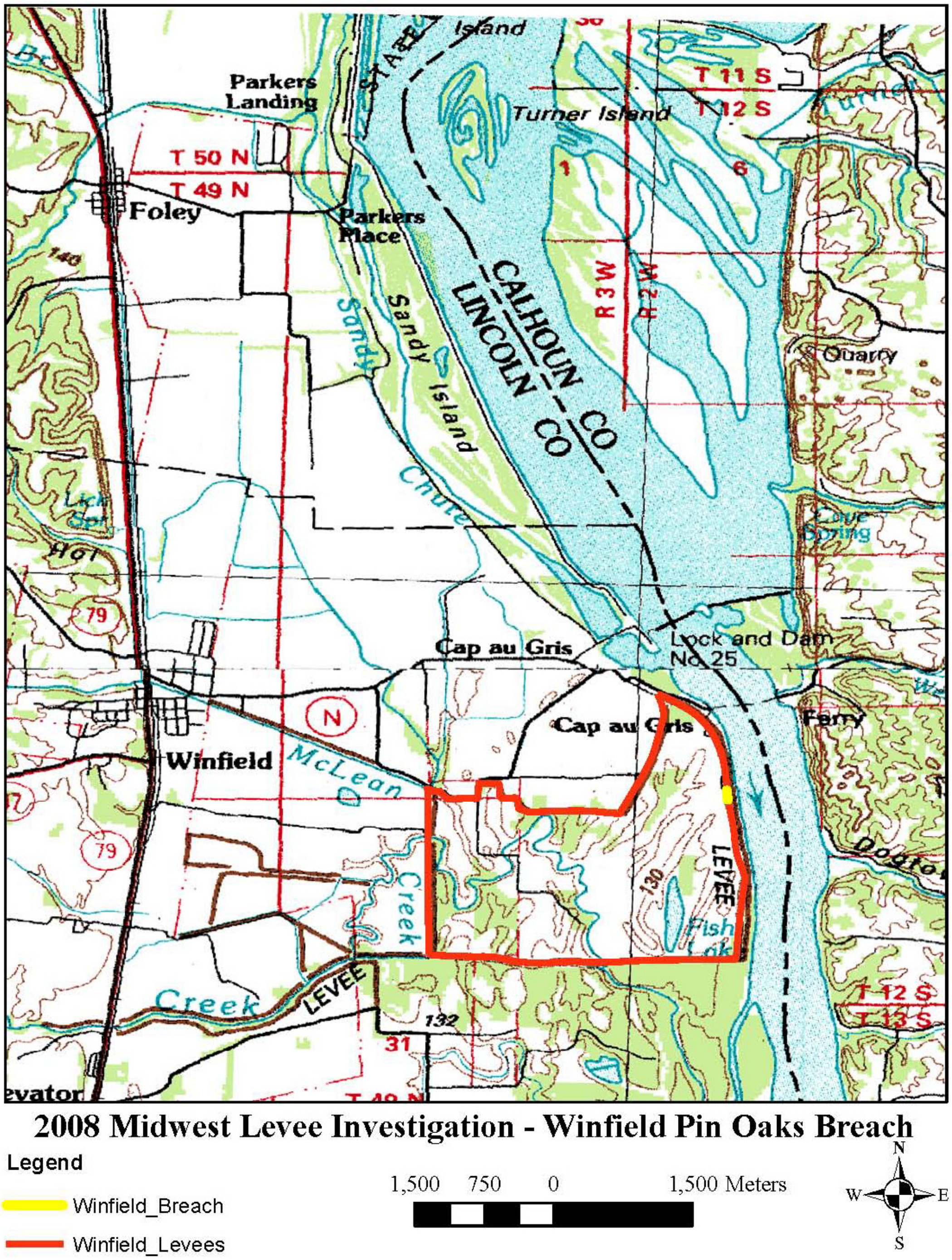


Figure 14. Winfield-Pin Oak levee system and levee breach (Storesund 2009).

Five samples were taken from various locations within the breach (15). Table 3 provides a summary of the sample locations as well as Torvane and Pocket Penetrometer readings. Note that the Pocket Penetrometer gives an estimate of the unconfined compression strength while the Torvane estimate the undrained shear strength directly. Common practice is to take the undrained shear strength equal to 0.3 times the Pocket Penetrometer readings.

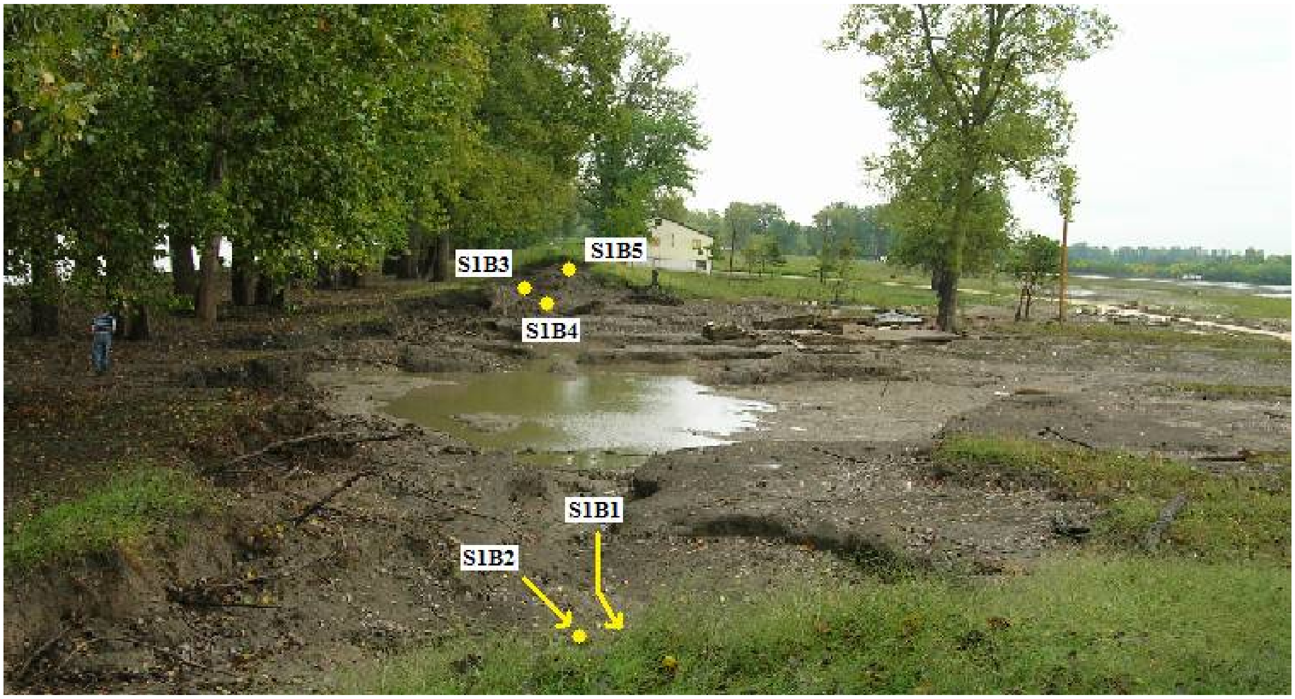


Figure 15. Boring locations Winfield – Pin Oak breach looking south.

Table 3. Winfield – Pin Oak Sample Log.

Sample No.	Direction	Latitude*	Longitude*	Pocket Pen (kg/cm^2)	Torvane (kg/cm^2)	Depth and Location
S1B1	Horizontal	38.98815	90.68191	1.0, 1.1	0.45, 0.47	1.04m, crest centerline
S1B2	Vertical	38.98814	90.68190	0.45, 0.4, 0.35	0.15, 0.14	2.31m, slightly east of center
S1B3	Horizontal	38.98730	90.68179	1.75, 2.1	0.3, 0.29	2.69m, east of center
S1B4	Vertical	38.98731	90.68182	1.2, 1.3	0.21, 0.3	3.96m, slightly east of center
S1B5	Horizontal	N/A	N/A	0.6, 0.7	0.15, 0.2, 0.11	0.86m, crest centerline
S1Bag 1	Bulk					
S1Bag 2	Bulk					

*WGS1984 Geographic Datum

Site Conditions

Figure 15 shows a pond area around the center of the breach. This was the main contraction scour point resulting from the overtopping waters. After returning to the site two days later, the pond was noticed to be almost dry indicating a somewhat sandy or silty material and quick subsurface drainage.

The Mississippi River runs North to South at this location. The levee borders the West river bank while the East bank is bordered by natural cliffs which provide a barrier for the flood waters and force the rising water into the levees. The water line on the trees that border the river side of the levee (Figure 16) was about 1 m higher than the existing levee crests indicating that during peak flow the water was overtopping the levee by almost 1 m. It also shows that the overtopping duration was long enough to leave a water mark or mud line on the trees.

Figure 16. High water marks on trees bordering levees.

Extensive root networks and crayfish tunnels were present throughout the existing levee and breached area (Figure 17). These encroachments often encourage the formation of seepage paths through embankments.

Figure 17. Root networks and crayfish tunnels throughout the levee.

The vegetative cover at the Winfield site (Figure 18) was low to moderate density comprised and mostly of crabgrass and foxtail. While the ground cover looks somewhat established in the Figure, most of the grasses present were annual weeds rather than sod forming grasses. Such weeds are only present for a portion of the year and tend to clump leaving spaces where the soil surface is bare. In several areas there was little or no coverage.

Figure 18. Winfield – Pin Oak vegetative cover.

Foxtail is a "weed-like" summer annual plant which forms in tuft-like groupings and often develops in areas of less dense turf grass (American Lawns 2009). The ground coverage at the site must not have been dense because of the ability of the foxtail to intrude. Crabgrass is an annual grass generally found in the warmer climates. This "weed" is very invasive and can take over an area, but because it is an annual plant it will die out during a freeze. None of the grasses identified at this site are what would be considered "good" protective armoring. These vegetative conditions, however, are based on post flood observations and may not reflect the actual conditions at the time of overtopping.

Geotechnical Soil Properties

The goal of the geotechnical laboratory work was to characterize the gathered levee samples according to the Unified Soil Classification System (USCS). In-situ water content (ASTM D 2216), in-situ density, particle size (ASTM D 422), Atterberg Limits (ASTM D 4318), and maximum dry density based on the Modified Proctor compaction test (ASTM D1557) using a small volume mold were determined for approximately twenty of the samples collected. The results for the Winfield-Pin Oak site are summarized in Tables 4 and 5.

Table 4. Winfield-Pin Oak soil index properties.

Sample No.	w%	In-Situ Density (kg/m^3)	In-Situ Dry Density (kg/m^3)	Max Dry Density (kg/m^3)	Relative Compaction %	LL	PL	PI	USCS
S1Bulk1	--	--	--	--	--	NP	NP	NP	ML
S1Bulk2	--	--	--	1977.6	--	55	25	30	CH
S1B1	16.6	1732.8	1486.3	1977.6*	75.0	55*	25*	30*	CH
S1B2	26.8	1842.4	1453.4	1977.6*	73.3	55*	25*	30*	CH
S1B3	19.7	1946.5	1626.8	1987.8*	82.1	NT	NT	NT	NT
S1B4	24.0	2126.1	1714.0	1987.8	86.2	NT	NT	NT	NT
S1B5	26.0	1894.3	1503.6	1987.8*	75.8	NT	NT	NT	NT

*Used data from similar sample tested at same site.
NP = Not Plastic
NT = Not Tested

Table 5. Winfield-Pin Oak soil properties continued.

Sample No.	d_{50} (mm)	% finer than 75µm	% finer than 2µm	Activity$^+$
S1Bulk1	0.071	55.81	9.91	NA
S1Builk2	0.023	84.15	19.15	1.57
S1B1	NT	82.82*	15.65*	1.92*
S1B2	0.0276	82.82	15.65	1.92
S1B3	NT	NT	NT	NT
S1B4	NT	NT	NT	NT
S1B5	NT	NT	NT	NT

*Used data from similar sample tested at same site.

$^+$Activity = PI / % finer than 2µm

Brevator

The Brevator levee is maintained by the Brevator Drainage and Levee District. The levee system is estimated to reduce the risk of flooding for approximately 745 ha up to a 14-year return period flood event. The levee system is located approximately 2,000 m west of the river bank of the main channel of the Mississippi River (Figure 19). This system also failed during the 1993 flood, however, the specific location of the breach (or breaches) was not documented (USGS 2006).

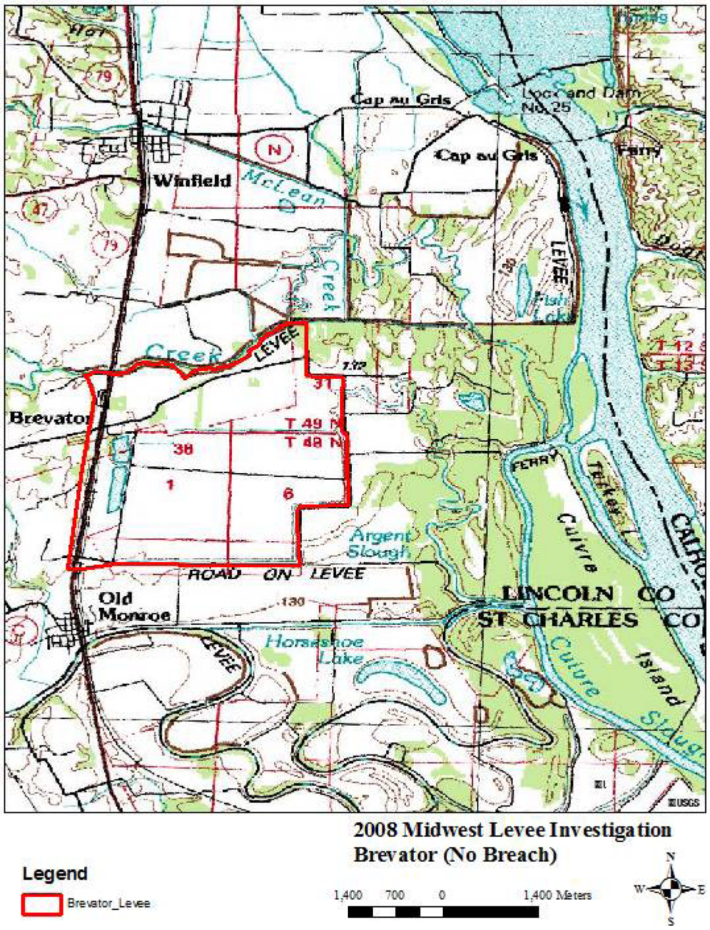


Figure 19. Brevator levee system (Storesund 2009).

This site was unique in the fact that there was no breach in 2008. The only sign of erosion was at a box culvert that was cracked allowing water and soil to seep through. A local resident (Mr. James Pieper) informed the team that the levee was overtopped by nearly 1 m of water for three days and never failed. Four samples were collected from various locations along the levee. Because there was no actual breach, only surficial samples were taken. These samples were much harder to obtain and the soil seemed to be much stiffer than at the previous sites as can be seen by the higher Pocket Penetrometer values (Table 6) obtained at this site compared to the Winfield site. Figure 20 shows the boring locations and Table 6 presents the sample logs for this site.

Figure 20. Brevator boring locations.

Table 6. Brevator sample log.

Sample No.	Direction	Latitude*	Longitude*	Pocket Pen (kg/cm^2)	Torvane (kg/cm^2)	Depth and Location
S3B10	Vertical	38.96272	-90.71165	2.35, 2.6	1.075, 1.025	Surface, crest centerline
S3B11	Vertical	38.96272	-90.71171	1.2, 1.3	0.33, 0.43	3.05m, West toe
S3B12	Vertical	38.95773	-90.71169	1.75, 1.75	0.7, 0.86	Surface, crest centerline
S3B13	Vertical	38.95773	-90.71176	1.1, 1.0	0.56, 0.7	3.05m, West toe
S3Bag 5	Bulk					Taken at S3B10
S3Bag 6	Bulk					Taken at S3B11
S3Bag 7	Bulk					Taken at S3B12
S3Bag 8	Bulk					Taken at S3B13

*WGS1984 Geographic Datum

Site Conditions

While the levees did not breach, there was still a large amount of damage to homes and equipment on the dry side of the levee due to the overtopping waters. The area enclosed by the levees at this site was much smaller compared to the other sites, so the overtopping water began to fill the internal area like a swimming pool. Figure 21 shows the high water marks on a barn located within the area surrounded by the levees. As the water on the dry side of the levee rose, the difference in elevation between the two sides decreased thereby decreasing the erosion potential. Substantial damage occurred within the internal area even though the levee performed well.

Figure 21. High water marks on barn within the Brevator levee system.

At the time of overtopping, there was substantial vegetative cover. Figure 22 shows the vegetative cover present on the levee 3 months after the flooding. It was noted that the grass was Reed Canary grass approximately 1 m tall at the time of flooding. This type of grass survived the continuous flow of water and had a positive impact on preventing erosion. The overtopping waters forced the grass to lay down essentially creating a protective cover or barrier on top of the soil surface and preventing erosion.

Further examination of the grass cover indicated that additional varieties of plants were present at the site including: Switchgrass, Smooth Brome, Reed Canarygrass, and Foxtail. The consistency of the coverage and the root density were much higher at this site than any of the other sites.

Figure 22. Brevator vegetative cover on September 30, 2008.

Because this site performed extremely well under the given conditions, a more in depth investigation of the grasses present was done. *Panicum Virgatum*, commonly known as Switchgrass, is a native summer perennial grass which has very high yields and is resistant to many pests, diseases, and flood or drought conditions (Bransby 2009). Upland types grow up to 2 m and are usually found in well drained areas and low land types can reach up to 4 m high in bottom areas. Switchgrasses have large, permanent root systems that can reach depths of over 3 m. Even though Switchgrass tends to grow in clumps, it is a spreading type grass which tends to develop long rhizomes or underground stems that grow horizontally and interconnect forming a thick dense sod.

Festuca Arundinacea, commonly known as Tall Fescue, is cool season bunch type grass variety which is generally more drought and wear resistant than other cool season grasses (American Lawns 2009). Fescues also tend to have deeper root systems than some of the other similar grasses. Tall Fescues can become very thick and even though the traditional fescues are more bunch forming, there are new turf-type varieties of Tall Fescue that are becoming more popular.

Phalaris arundinacea, commonly known as Reed Canarygrass, is a tall growing perennial grass which is native to many of the northern states (Sheafer 2008; Washington 2008). It is particularly well adapted to saturated or nearly saturated soils, but where standing water does not persist for an extremely long period of time. The ideal conditions for this grass typically occur in ditches or channels, levees, and river dikes. This species of grass spreads by rhizomes forming a solid sod. It is resistant to both flooding and drought and winter freezing, making it excellent for many conditions experienced in the Midwest. The grass creates a dense arrangement of strands that provides excellent erosion protection especially if allowed to grow to a height greater than 0.6 m so that it performs as a protective barrier when it is laid over by the rushing water.

Smooth Brome or *Bromus inermis*, is a cool season perennial grass which spreads by rhizomes and is sod-forming (Bush 2006). It is often used for hay for livestock and is similar to alfalfa or other legumes. The stems can reach over 1 m high. It has a massive root system and is a sod forming grass.

Each of these grasses performs well in the Midwest climates and has root systems that spread to create thick mat-like sods. It was also noted that at this site the trees were located far away from the levee. Trees have root systems that can reach for large distances and penetrate the levee systems leaving paths along which water can seep through. While there was clear evidence of overtopping, there was no evidence that this levee experienced any through seepage or under seepage.

Geotechnical Soil Properties

The results for the Brevator site are summarized in Tables 7 and 8.

Table 7. Brevator soil index properties.

Sample No.	w%	In-Situ Density (kg/m^3)	In-Situ Dry Density (kg/m^3)	Max Dry Density (kg/m^3)	Relative Compaction %	LL	PL	PI	USCS
S3B10	20.43	1832.85	1521.97	1876.6*	81.10	41	20	21	CL
S3B11	28.60	1666.68	1296.02	1876.6*	69.06	50	23	27	CL
S3B12	32.23	1471.52	1112.87	1876.6	59.30	66	26	40	CH
S3B13	31.85	1743.97	1322.66	1876.6*	70.48	64	24	40	CH

*Used max density from other sample tested at same site.

Table 8. Brevator soil properties continued.

Sample No.	d_{50} (mm)	% finer than 75µm	% finer than 2 µm	Activity
S3B10	0.0136	92.9	25.523	0.82
S3B11	0.0162	98.16	22.484	1.20
S3B12	0.0054	95.6	35.6	1.12
S3B13	0.0093	93.55	31.293	1.28

ERODIBILITY OF THE LEVEE SOILS

For cohesive soils, erodibility depends on many factors including: plasticity, water content, grain size, percent clay, compaction, and shear strength. The erosion study consisted of testing the collected tube samples in the Erosion Function Apparatus (EFA) (Briaud 2008) to determine the erosion rate of the material at different velocities. The EFA was developed in the early 1990s to determine the erosion function for a given soil. A more detailed description of the device and method is given in Briaud (2008).

The EFA was used to obtain the erosion functions for 20 Midwest Levee samples. The samples tested were chosen in an effort to encompass a variety of material types, locations within the levee, and erosion performance. In order to compare the erosion functions of the samples, the data points were all plotted on the same graph (Figure 23). This graph also shows the erosion categories developed from previous studies (Briaud 2008). Most of the soils tested show moderate erosion at higher velocity. Please refer to Table 2 for the site identification nomenclature.

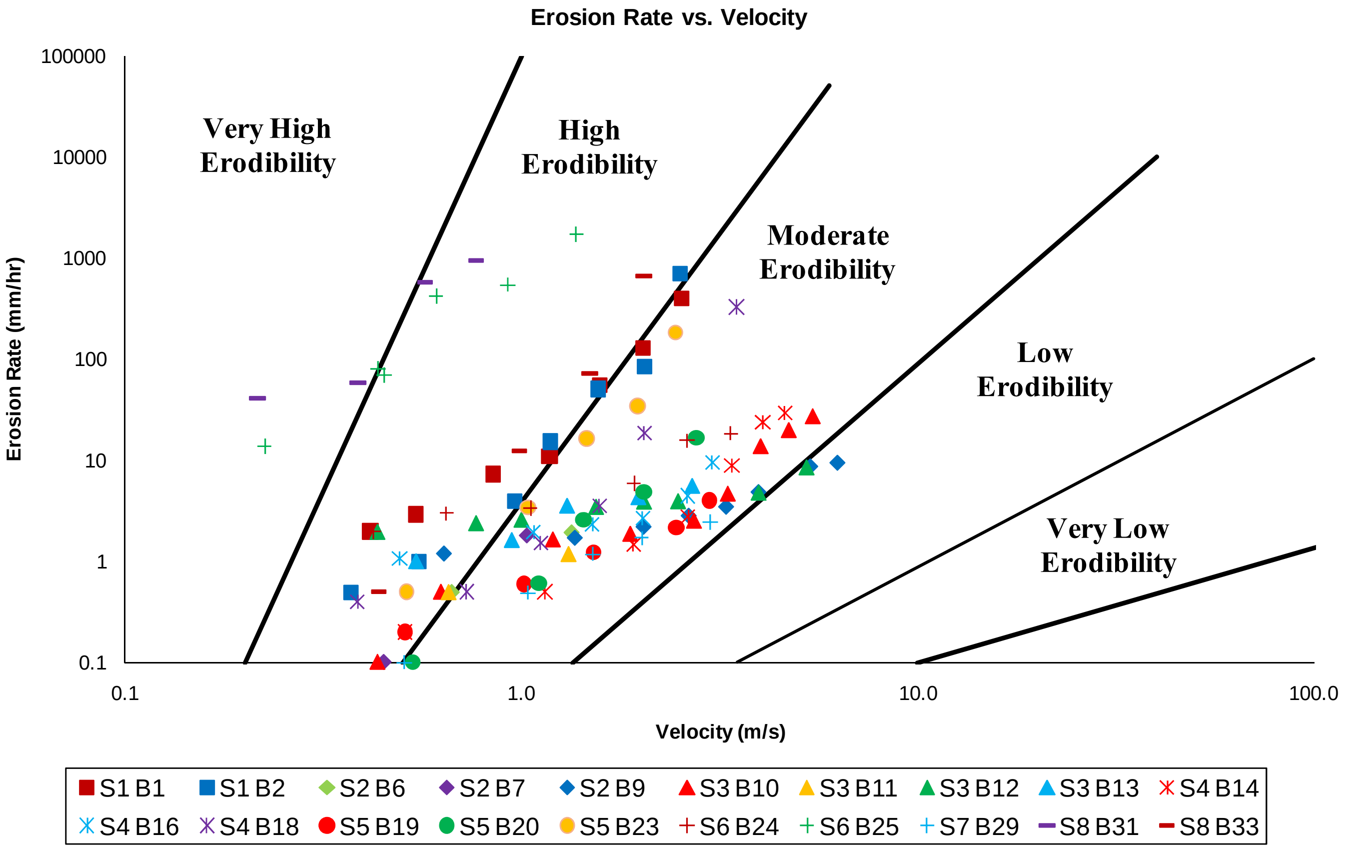
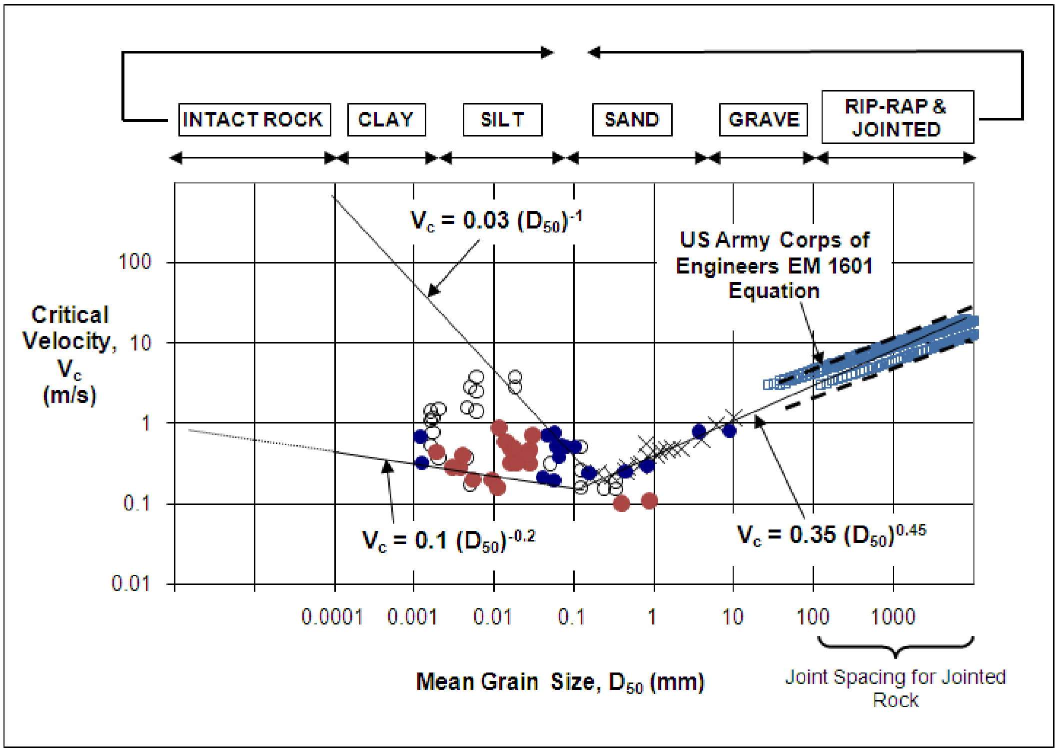


Figure 23. Erosion rate versus velocity for the Midwest Levee samples.

Critical Velocity Threshold

The critical velocity is defined as the maximum velocity that the soil can resist without erosion. This erosion threshold is considered to correspond to an erosion rate of 0.1 mm/hr. Previous comparisons (Briaud 2008) have been made between critical velocity and D_{50} (average particle diameter). Figure 24 shows the Midwest Levee values plotted with values obtained from previous testing. The values follow the trend set by the previous data.



Legend:

- ● TAMU Data as reported by Briaud, J.-L. et. al. (2001). "Erosion Function Apparatus for Scour Rate Predictions." *J. Geotech. and Geoenvir. Engrg.*, ASCE, 127(2), 105-113.
- ○ TAMU Data as reported by Briaud, J.-L. (2006). "Erosion Tests on New Orleans Levee Samples." *Texas A&M University Internal Report.*
- X Data from Shields, Casey, US.WES, Gilbert, White as reported by Vanoni, V.A., ed. (1975). "Sedimentation Engineering." *ASCE manuals and reports on engineering practice*, ASCE, New York.
- □ Data points from simulation using U.S. Army Corps of Engineers EM 1601 Riprap Design Equation (U.S. Army Corps of Engineers 1995).
- ● TAMU Midwest Levee Data

Figure 24. Critical velocity vs. D_{50} combined results.

This plot shows that most of the Midwest levee soils tested have D_{50} values in the silt size range and critical velocities between 0.1 and 1 m/s. Since the levees have heights of 3 to 5 m, the velocity at the bottom of the levee can reach 10 m/s. This can be estimated by equating energies:

$$\frac{1}{2}mv^2 = mgh \rightarrow v = \sqrt{2gh} = \sqrt{2\times 9.81\times 5} = 9.9\frac{m}{s} \qquad (1)$$

Of course this approach does not take into account the energy dissipated in friction on the levee surface, but it does show that the velocity will be much higher than the critical velocity of the barren soil. The plot also confirms that the critical velocity of fine grained soils (soils with $D_{50} < 0.1$ mm) is not proportional to their D_{50} values.

EFA Correlations

An attempt was made to correlate the erosion resistance with the index properties of the soils tested. The difference in erosion resistance between the two selected sites is clearly seen in Figure 25. Soils from the Brevator site are much more erosion resistant that those from the Winfield-Pin Oak site.

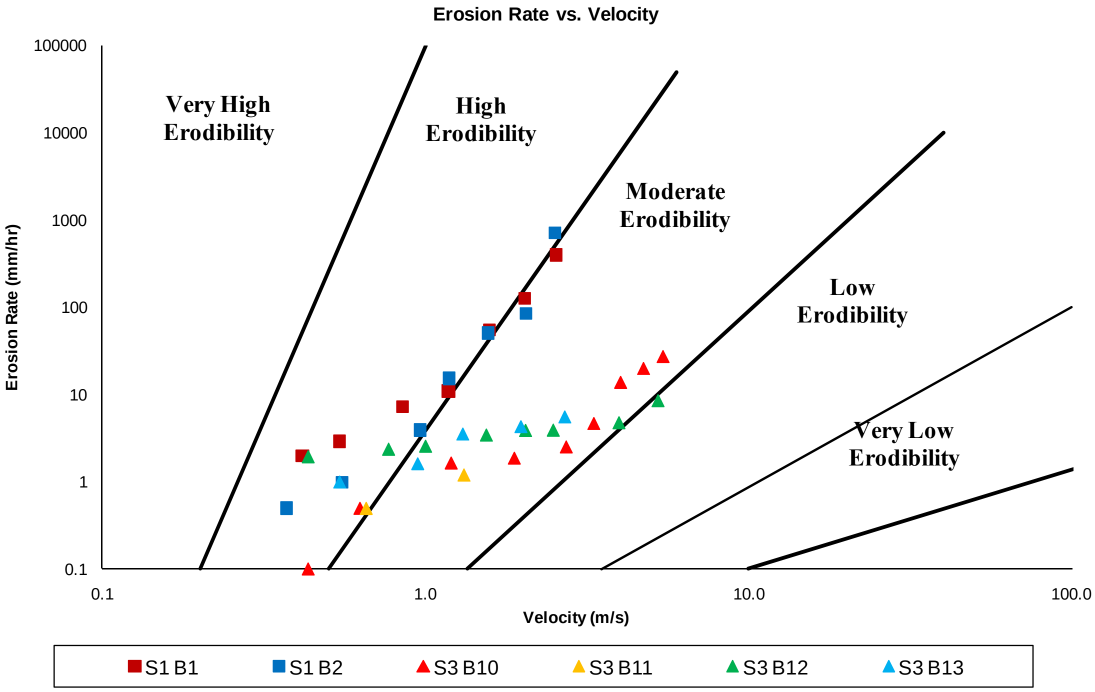


Figure 25. EFA results for Winfield-Pin Oak – S1 and Brevator – S3.

Laboratory tests were performed to obtain the plasticity index (PI), D_{50} , and percent relative compaction. These soil properties were divided into categories and combined with the EFA results to study the influence of these factors on the erosion resistance of a soil. Figure 26 shows the EFA results for the two sites plotted in different colors based on their PIs. Figure 27 shows the same plot for all of the sites studied.

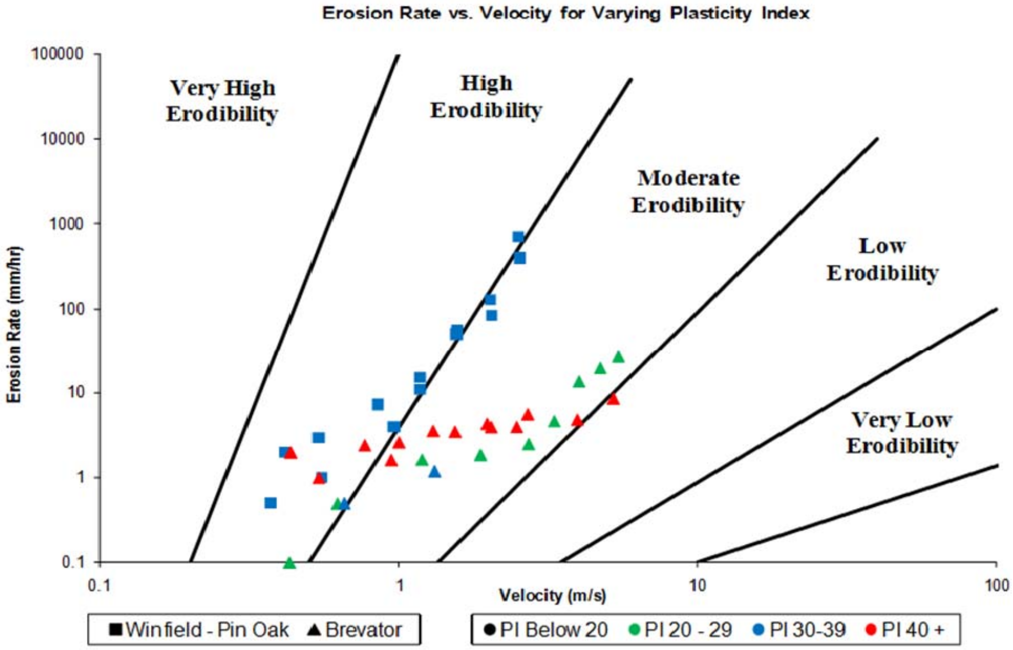


Figure 26. EFA comparison of PI for the Winfield-Pin Oak and Brevator sites.

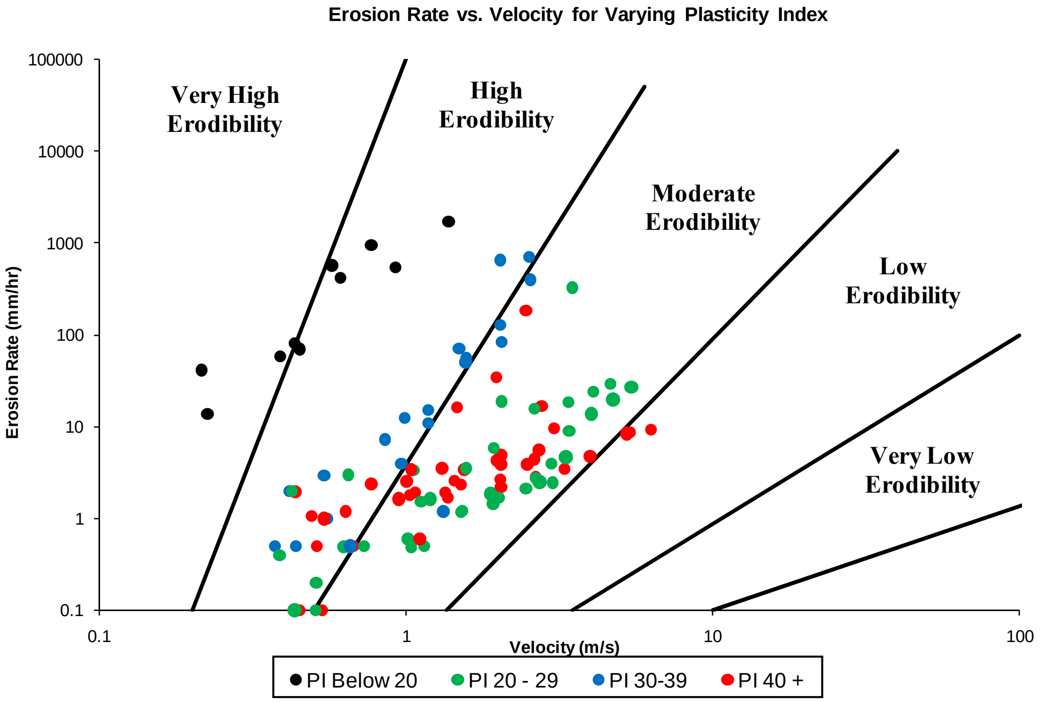


Figure 27. EFA comparison of PI for all sites.

A weak trend seems to exist with the more erosion resistant soils having higher PIs. The trend is not obvious which indicates that plasticity is not the only factor that influences erosion. It should also be noted that other factors varied for the samples plotted and therefore, the influence of plasticity is not singled out by the graphs shown.

Similar charts were constructed for each of the parameters measured. Figure 28 and Figure 29 show the influence of the average particle size, D_{50}, which was obtained from hydrometer and sieve analyses.

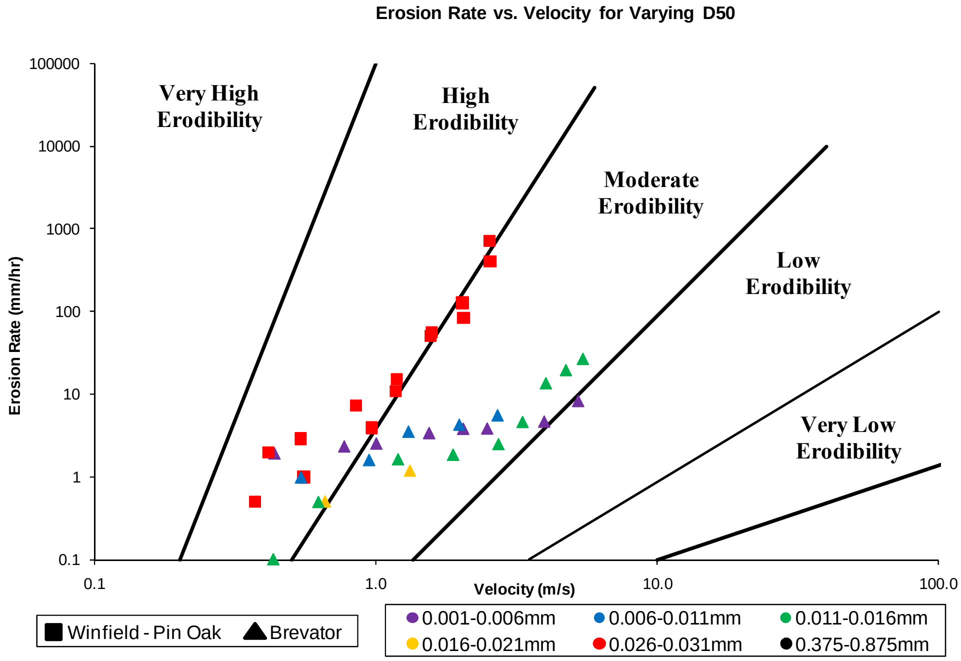


Figure 28. EFA comparison of D_{50} for the Winfield-Pin Oak and Brevator sites.

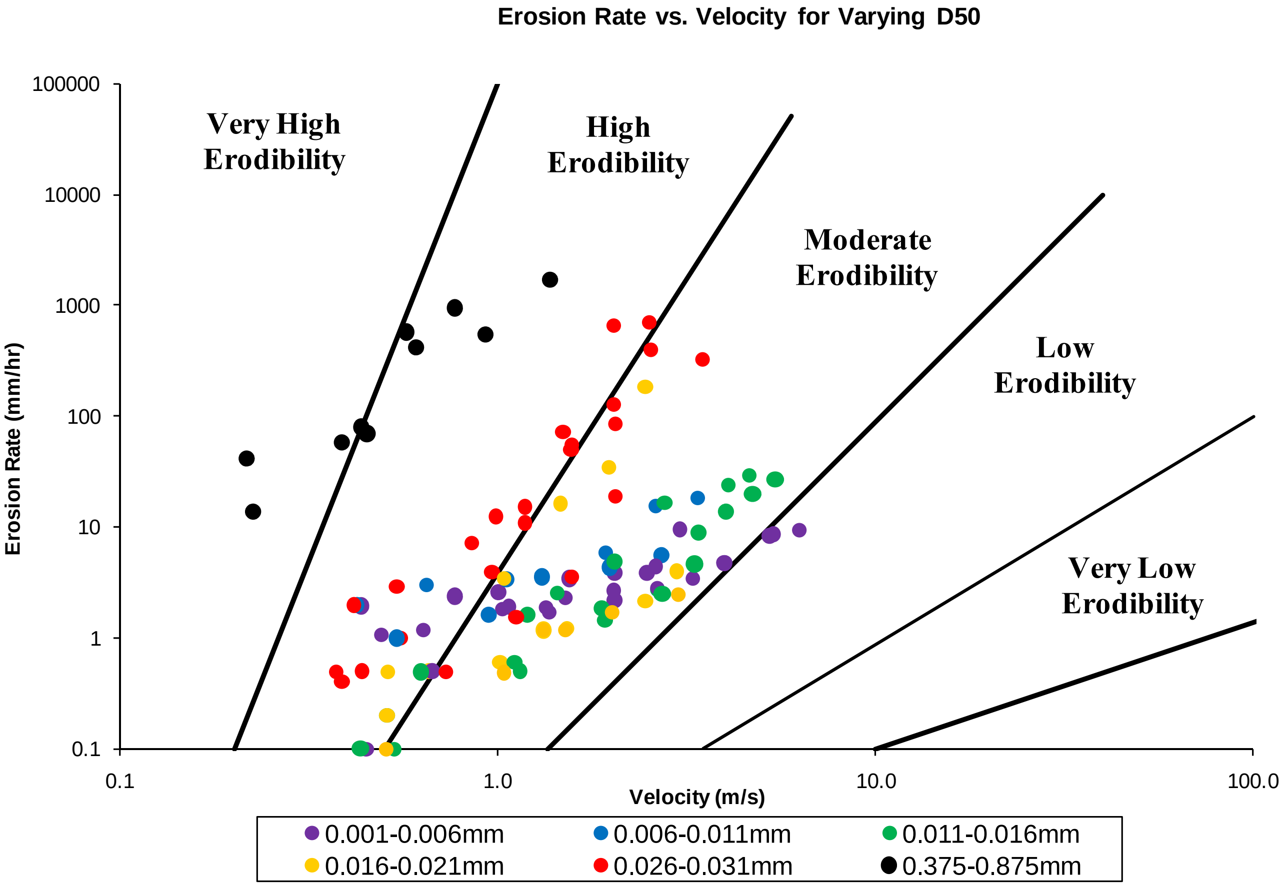


Figure 29. EFA comparison of D_{50} for all sites.

Again some level of correlation is observed indicating that, within the range of D_{50} tested, the soils with the smaller D_{50} are some of the more erosion resistant. It can be seen in Figure 28 that the Brevator site samples are associated with the smallest particle sizes tested while the samples from the Winfield-Pin Oak site were some of the largest. Figure 30 and Figure 31 show the influence of percent relative compaction (% RC) on the erosion resistance of a soil. Because of the small amount of sample available for compaction, a small volume version of the Modified Proctor compaction test was used. Equivalent energies were calculated and applied to the soil contained in a small volume mold per ASTM D-1557. To verify compatibility, compaction curves for a bulk soil sample obtained from the small volume test were compared with those obtained using the full size mold described in the ASTM specifications. The percent relative compaction was calculated by dividing the dry unit weight, γ_d, measured on the intact samples by the $\gamma_{d,max}$ obtained from the small volume Modified Proctor compaction test. Hassan et al. (2004) showed that the erosion resistance of a given soil increased when compacted at higher water contents and higher degrees of compaction. Figure 30 does not show this trend clearly; however, it should be noted that these graphs do not separate out the effects of other factors on erosion. It should also be noted that the trend described by Hassan et al. (2004) only holds for a given soil independently and is not necessarily true for comparing two different soils.

According to USACE design manual EM 1110-2-1911, the minimum acceptable field density for levee design is usually established as 95 percent of the maximum dry density of the soil found using a test procedure utilizing the amount of energy set by the Standard Proctor Test. The values shown in Figure 31 are for Modified Proctor energy. Note that the ratio of compaction energy between the Modified Proctor and Standard Proctor is 4.5 causing the values shown to be lower than they would be if conducted using the Standard amount of energy. Several of the samples were taken at the surface and are expected to be at a lower compaction level so that grasses will root and spread.

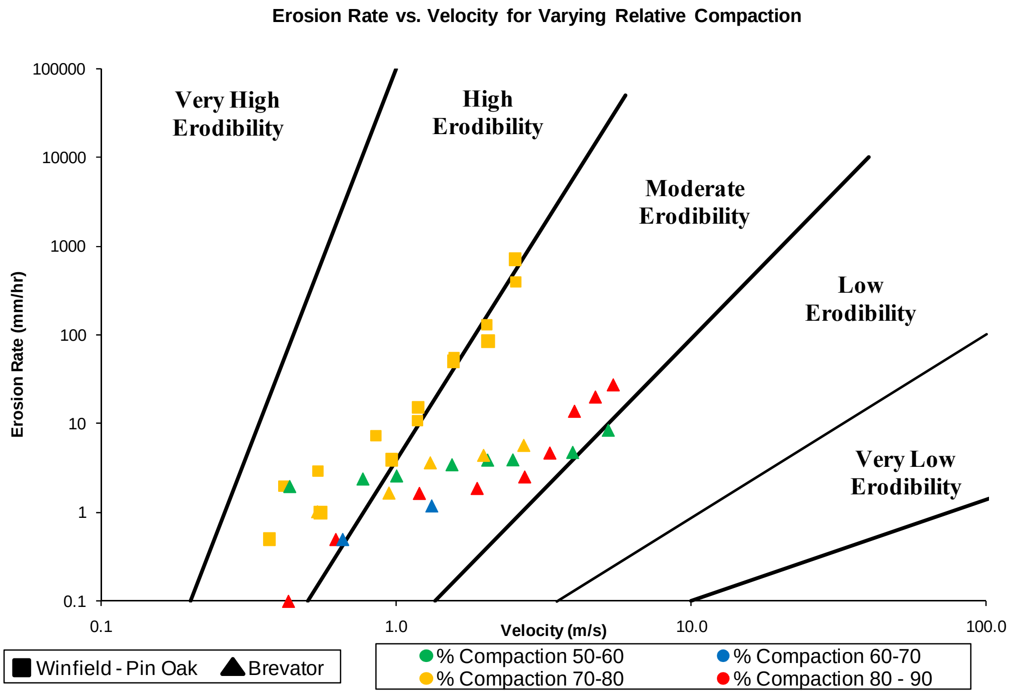


Figure 30. EFA comparison of % RC for the Winfield-Pin Oak and Brevator Sites.

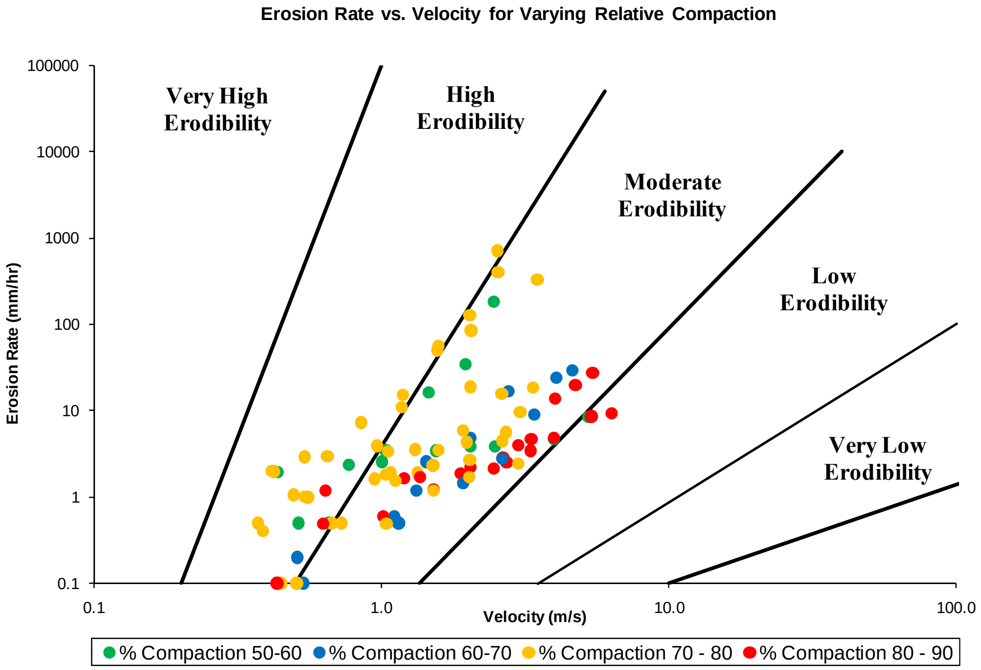


Figure 31. EFA comparison of % RC for all sites.

EFA Erosion Rate at 3m/s Correlations

Because the correlations to individual parameters showed weak trends, another attempt was made to correlate the erosion rate at 3 m/s velocity for each sample to $D_{50,}$ PI, relative compaction, max dry density, in-situ water content, in-situ dry density, % clay, % passing the No. 200 sieve, activity, and Torvane strength. The erosion rate value was extrapolated for those samples that were not tested up to 3 m/s.

While most of the correlations did not exhibit a clear trend, it was noticed that as the clay content increased, the erodibility of the soil decreased. A more noticeable trend appeared in the plot of erosion rate versus activity (Figure 32). As activity increases, so does the erosion rate. Activity is the ratio of the Plasticity Index over the percent finer than 2µm (clay fraction).

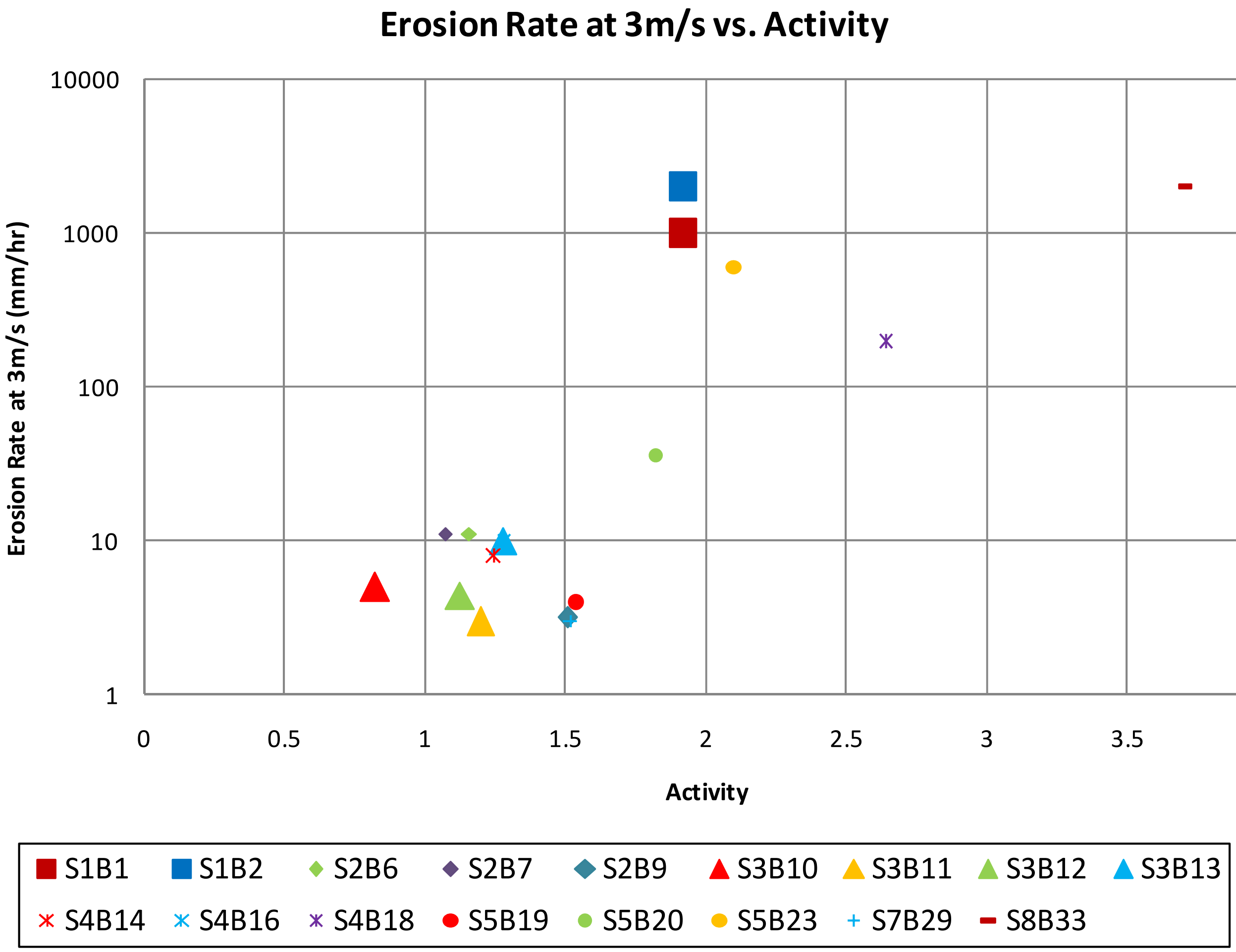


Figure 32. Erosion rate at 3m/s vs. activity.

Figure 33 shows the erosion rate at 3 m/s against the Torvane strength. This graph indicates that as the shear strength increases the erosion rate decreases as may be expected.

Overtopping Pass versus Fail Chart

In an attempt to determine a dividing line between the soils that failed due to overtopping and those that passed, the EFA results were plotted with open circles for samples from levees that did not fail and solid circles for samples from levees that failed (Figure 34). Note that the Brevator site was the only site considered to have not failed.

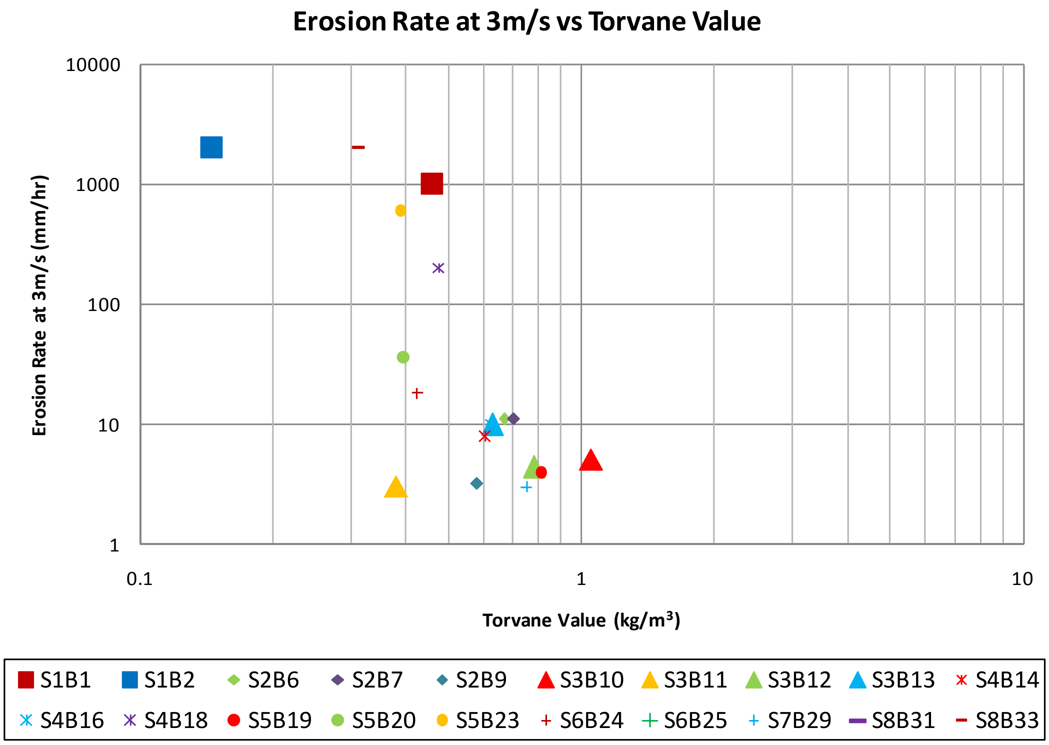


Figure 33. Erosion rate at 3m/s vs. Torvane values.

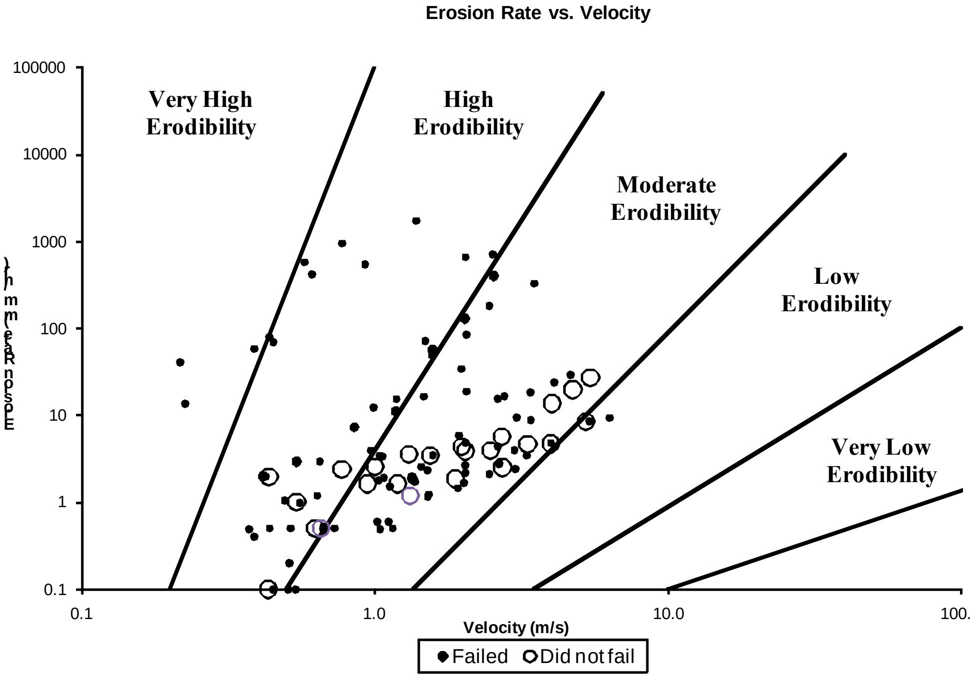


Figure 34. Overtopping comparison of pass vs. fail.

Overall there is no clear division between the two sets of points like what was seen in the Katrina data (Figure 35) given in Briaud et al. (2008). The soils from the Brevator site are among some of the more resistant soils tested; however, there are several sites where the samples are just as resistant yet the sites failed. Comparing the sites that failed to the sites that did not fail based on the plotted points is somewhat deceptive because the EFA tests were limited to the bare soil and did not account for any of the site conditions, such as vegetation or other variables that may have influenced the sites performance. The strong vegetative cover at the Brevator site would increase the resistance and effectively shift the erosion function towards the low to very low erodibility categories.

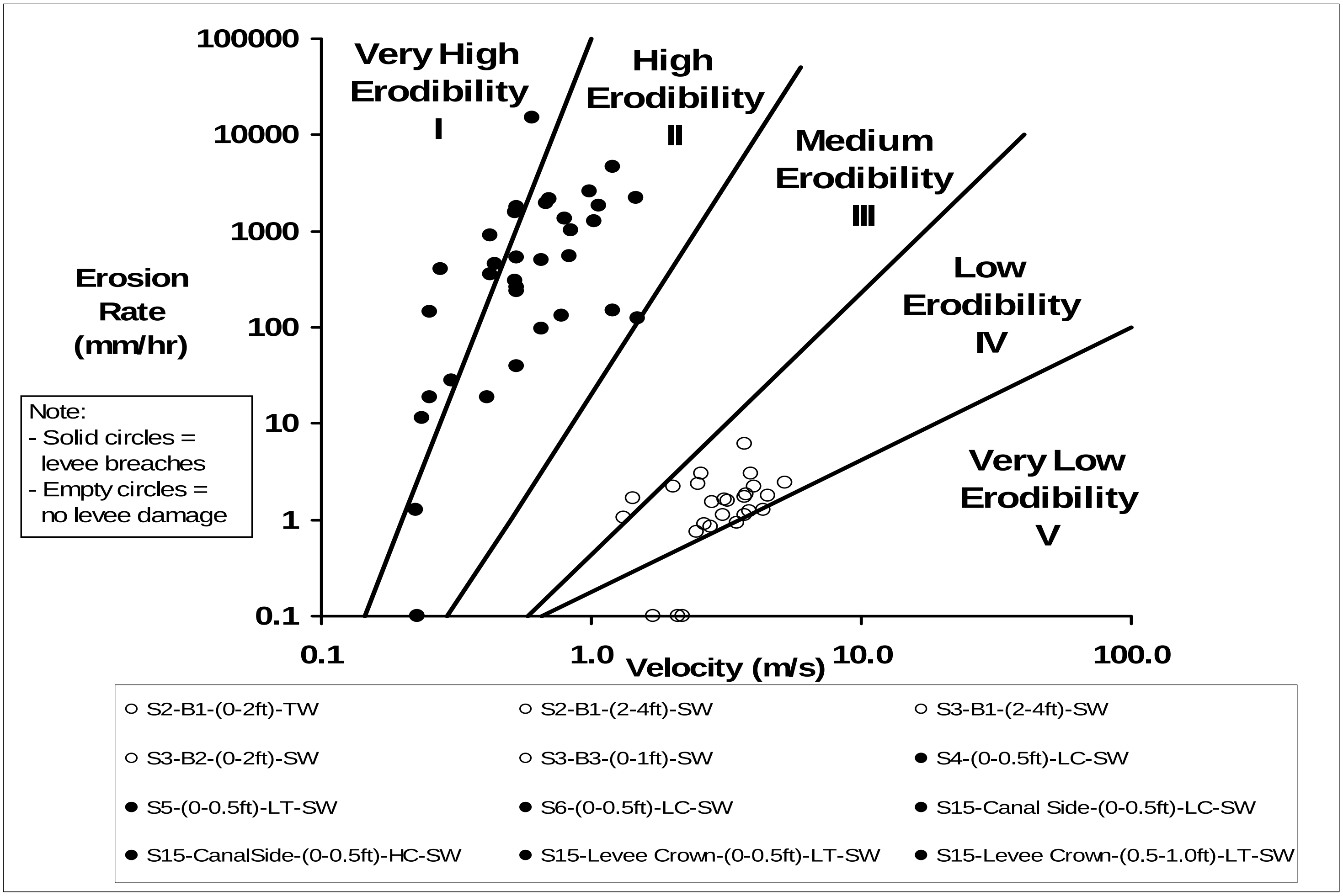


Figure 35. Overtopping comparison - pass vs. fail for Katrina data (Briaud et al. 2008).

The overtopping recommendation chart given in Briaud et al. (2008) was developed for overtopping periods of less than two hours associated with hurricane events. Based on the findings from this study, the chart was expanded to include the longer overtopping periods of 2 days experienced in flood events (Figure 36). The boundary was determined by considering the data of Figure 34 and setting an erosion limit of 0.3 m over two days for a velocity of 10 m/s. This velocity represents an average value for levees at the bottom of the dry side of the levee. To satisfy this criterion, the erosion rate has to be less than 6 mm/hr (red dot and thin red line shown on Figure 36). It is important to note that the EFA tests used to develop this chart were conducted on barren soil and therefore the chart does not account for vegetation present at a site. Also, this chart is based on a limited number of field sites and may not be representative of every field case.

EROSION MATRIX

In an effort to combine the effects of the many different factors influencing erosion at the sites, an erosion matrix was created. The cutoff values were chosen to separate the sites that failed from the Brevator site which did not. The matrix is shown for the two sites of interest (Table 9). The matrix takes into account the soil properties as well as levee vegetative armoring and the presence of tree roots in the levee.

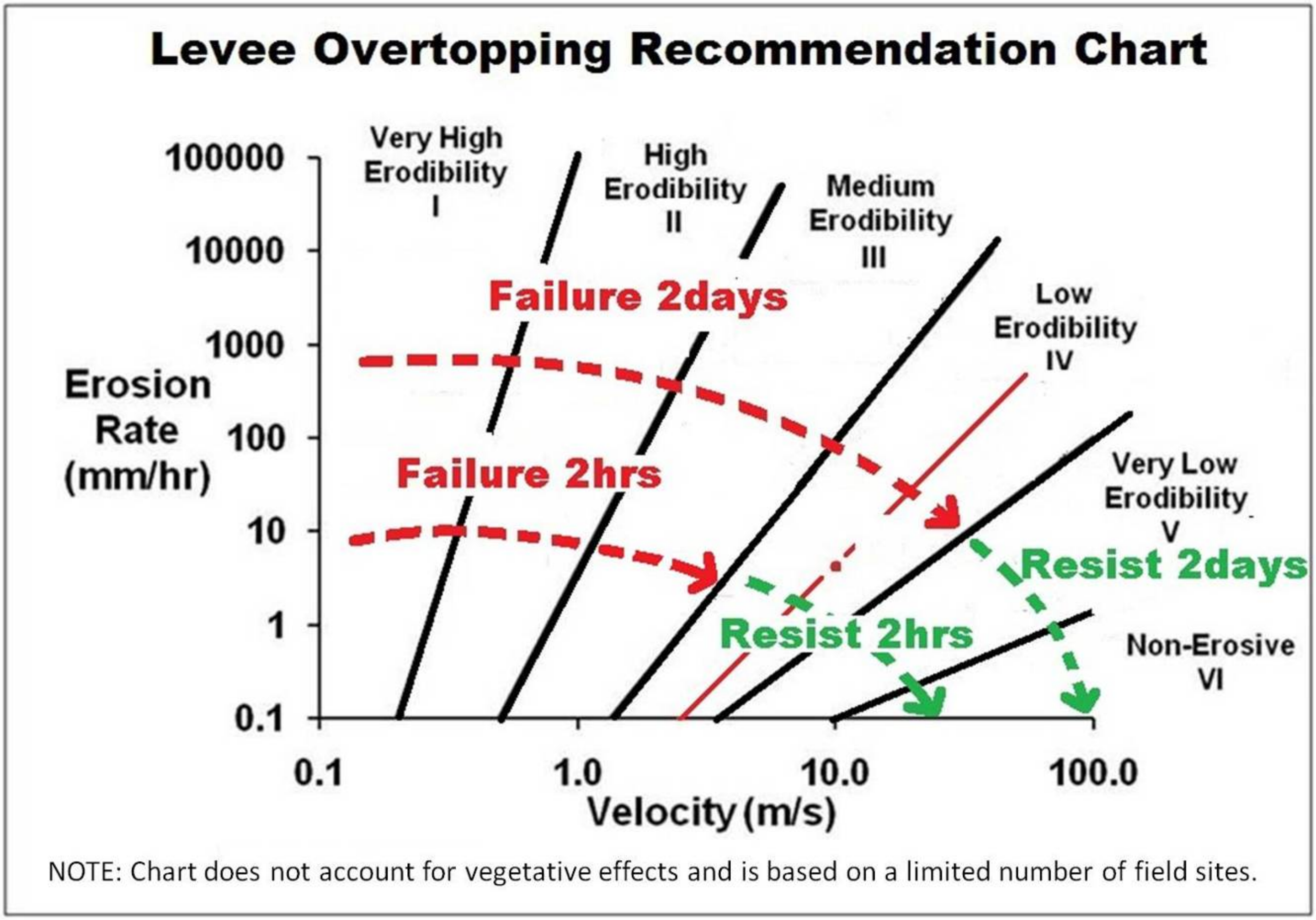


Figure 36. Recommendation chart for overtopping events.

This matrix shows in green the sample parameters and the field conditions that are beneficial in preventing erosion. Red indicates that the sample did not meet the cutoff value. It is clear from the matrix that there is a definite difference between the two sites. It is likely that some variables should be weighted more than others. In the opinion of the authors, vegetative cover is one of the most important factors and one which is easy to control. Because of this, further analysis of the benefits of a good vegetative cover is presented.

VEGETATION ON LEVEES

What constitutes the correct vegetative system for levees is still under much debate. The following paragraphs present some of the existing information followed by recommendations based on current evidence.

Table 9. Midwest Levee erosion matrix

Site Name	Sample	D_{50} less than 0.015mm	Plasticity Index over 25	% Relative Compaction over 80	% Clay over 25	% Passing No. 200 over 90	Activity less than 1.3	Torvane over 50 kPa	Erosion Rate @ 3m/s under 10mm/hr	Tree Roots farther than 20m	Grass Armoring Good/Fair/Poor	PASS/FAIL
Winfield – Pin Oak	S1B 1	NO	YES	NO	NO	NO	NO	NO	NO	NO	FAIR	FAIL
	S1B 2	NO	YES	NO	NO	NO	NO	NO	NO	NO	FAIR	FAIL
Brevator	S3B 10	YES	NO	YES	YES	YES	YES	YES	YES	YES	GOOD	PASS
	S3B 11	NO	YES	NO	NO	YES	YES	NO	YES	YES	GOOD	PASS
	S3B 12	YES	YES	NO	YES	YES	YES	YES	YES	YES	GOOD	PASS
	S3B 13	YES	YES	NO	YES	YES	YES	YES	YES	YES	GOOD	PASS

Current Practice – USACE and NRCS

The USACE encourages vegetation for flood damage reduction projects provided it is limited "to a good growth of sod maintained with grass, from 50 to 300 mm in height, substantially free of weeds and bare spots" (Riley 2007). The main reason the grass height is limited is to ensure proper maintenance and identification of detrimental surface features such as holes made by burrowing animals or seepage evidence.

The USACE Engineering and Design Manual Number 1110-2-301 (USACE 2000) provides the guidelines and criteria for the design of landscape plantings and vegetation maintenance for floodwalls, levees, and embankment dams. This document is a safe design guide rather than a requirement for vegetation near or on levees. The USACE states that any vegetation other than grasses should be kept at least 5 m away from the edge of the levee base. This document also states that the selection of plants is based on prepared lists from the Division and District landscape architects. While the design manual describes the proper way to achieve aesthetically pleasing yet safe vegetative landscaping near the levees, it does not give any specific guidelines on grass types or coverage characteristics.

The National Resources Conservation Service (NRCS) has several specification documents and standards that provide detailed guidelines for the establishment and maintenance of erosion prevention grasses. The Conservation Practice Standard CODE 342 (NRCS 2007) gives the criteria and steps to establish permanent vegetation on sites that may experience high erosion velocities as well as other conditions. This document gives general site investigation criteria and fertilization schemes and should be used simultaneously with the Missouri Agronomy Specification Vegetation Establishment (for the Midwest area), Herbaceous Seeding CODE 723 (NRCS 2008). This particular document provides species selections, site preparation, and seeding specifications. A list of vegetation species for different climate zones is given along with their corresponding ratings in erosion control, wildlife habitat, wet soil tolerance, and drought tolerance. Reed Canarygrass, Smooth Brome, and Tall Fescue are all listed as having excellent erosion control qualities, while Switchgrass is rated as good.

Literature Results

Temple et al. (1987) describe a detailed design of open channels considering grass lining. Three components are responsible for the flow resistance in an open channel: viscous drag on the soil surface, pressure drag in the non vegetal areas due to roughness, and drag on the vegetal elements. Drag on the vegetal components dominates the flow resistance for most grass-lined channels. There are essentially three main flow regions of importance for a given channel. Low flows refer to a flow depth lower than the deflected height of the grass. Intermediate flows refer to a flow depth greater than the deflected height of the grass. Large flows refer to a flow depth much greater than the deflected height of the grass. Most flow situations are concerned with the intermediate flows. At these flow depths, the vegetal elements tend to align themselves with the flow. The vegetal parameters expected to be the most important are the number of stems per unit area and the length of each stem. As the elements align with the flow the leaf structure becomes less important.

Temple et al. (1987) also note that soil particle detachment often begins at low enough stresses to be withstood by the vegetation without significant damage. As the particles of soil are removed, the vegetation is undercut and the weaker vegetation is removed, decreasing the density and uniformity of the cover. This increased roughness leads to higher stresses at the soil/water interface and an increased erosion rate. The vegetative cover should be as dense and uniform as possible to prevent this action.
Levee performance under wave action and overtopping has been a major area of interest in the Netherlands after the disaster of 1953 in which many levees failed from inner slope shearing following overtopping. The primary purpose of the vegetation is to prevent erosion caused by hydraulic forces (Seijffert and Verheij 1998). Normal grass cover can resist velocities up to 2 m/s with little or no erosion; however, higher velocities can become problematic (Figure 37). This chart shows the importance of the duration of the overtopping. As the number of hours of overtopping increases, the benefit gained from having increased vegetative cover decreases. For normal flooding events like those experienced in the Midwest it is not unreasonable to assume that the overtopping lasts 20 hours or more. Velocities at the toe of a levee can reach 10 m/s depending on the levee height. This point (20 hours at 10 m/s) plots much higher than the limiting cases shown in Figure 37. Since the Brevator site survived at least 2 days of overtopping, it is likely that Figure 37 is conservative.

Muijs (1999) notes that the resistance of grass cover to erosion can be controlled by how it is implemented and managed. Sod becomes much more resistant to erosion as the root density increases. The roots connect the small soil particles and prevent them from being washed away. By ensuring a relatively low level of nutrients in the soil, the grasses are forced to invest in their root systems. In a laboratory experiment performed by Muijs (1999), a managed grass cover over a highly erosion resistant clay was found to be resistant to erosion caused by 1.35 m high waves for many hours. This resistance is mainly due to the sod. A structured clay with little root penetration under the sod was eroded 15 to 50 times faster than the well developed sod.

Recommendations

The types of grasses that have proven to be beneficial in preventing erosion have strong mat-like root systems (Li 2008). The roots are the key component in providing strength. Root structures that are adequately deep, but that also spread horizontally to form a firm and intertwined sod are ideal. Also, dense consistent coverage resists the effects of water flow and anchors the soil down. Many native grasses tend to clump in root groups allowing for spots of uncovered and unprotected soil and possible erosion, however, they are generally the easiest grass types to establish. Complete grass coverage needs to be maintained in order to be effective in controlling erosion. Grasses that are not completely dense in nature can also be allowed to grow to taller heights (0.5 to 1 m). As in the Brevator case, the tall grass was pushed over creating a protective barrier between the soil and the water. Examples of good coverage are shown on Figure 20 and Figure 22 and an example of poor coverage is shown in Figure 18.

The blade type may also have an effect on the erosion prevention capabilities of grasses. Wider blade grasses have a slightly better ability to reduce the flow velocities. When taller broad blade grasses are pushed over they create overlapping sheet-like layers forming a protective mat, once again serving as a barrier between the soil and water.

The grasses found at the Brevator site seemed to satisfy all of these criteria. The recommended grasses for the Midwest include: Switchgrass, Tall Fescue, Smooth Brome and Reed Canarygrass. A percent coverage of at least 90 percent is desirable. It is also recommended that the grasses on the levee be allowed to grow to taller heights during the flood season (0.5 to 1 m). While most of the erosion prevention depends on the root system, it is not always adequate for the magnitude and duration of flows experienced during overtopping flood events.

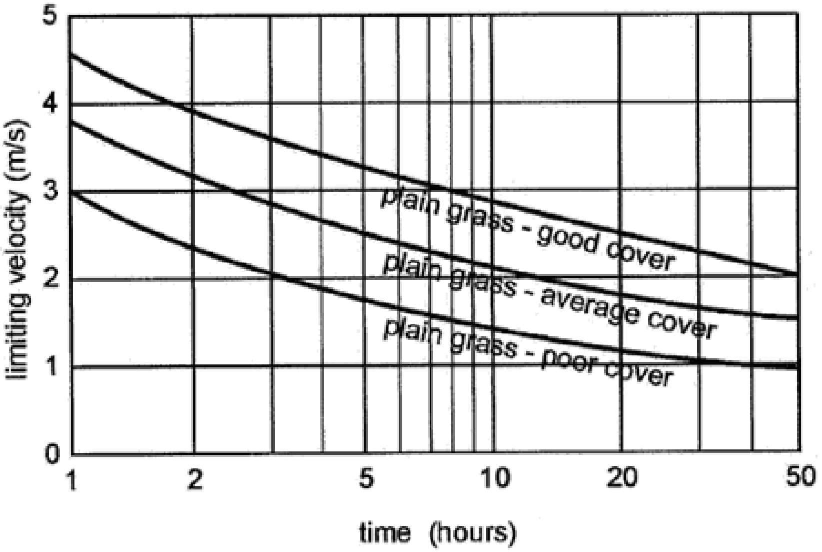


Figure 37. Limiting velocities for plain grass (Seijffert and Verheij 1998).

The presence of trees on levees is a topic of great debate. It is the authors' opinion that trees should be located from the levee toe a distance equal to their mature height. This is based on a combination of maintenance and seepage reasons. Proper regular maintenance is difficult with trees on the levees and in the event of a breach, trees or large shrubs can create additional obstacles which slow down work and impede the recovery and remediation process. Tree roots, as with all other encroachments, can allow the development of seepage paths. These tunnels can weaken the levee structurally, and a combination of seepage and overtopping waters can be detrimental to the dry side slope and toe of the levee. Also, live roots remove existing moisture from the interior of the levee which can cause shrinkage and cracking. In the sites observed during the Midwest Levee investigation, six of the seven main breaches visited had trees on or adjacent to the levees, while the levee site that did not fail had no trees within a considerable distance. Within the breached areas, there were tree roots found in at least half of the sites.

Furthermore, if a tree or large plant is actually on the levee and falls over, the root ball can rip out a large part of the levee. Trees can die and fall over naturally or can be forced over by rushing waters. Also, debris carried by the flood waters can impact the trees causing them to be overturned. Even tree removal as a part of levee maintenance can have detrimental effects on levee performance if not done properly. Low areas, areas not compacted back properly, or channels left by any remaining dying roots can greatly impact a levee's integrity. Whatever the case, the removal of a chunk of the levee material leaves a weakened section of the levee and a possible low area where flood waters can concentrate and ultimately fail the levee.

SUMMARY AND CONCLUSIONS

Many different factors influence the erosion phenomenon. The Winfield-Pin Oak and the Brevator breach sites were analyzed to determine some of the major factors which influence the performance of levees subjected to overtopping flood events. To predict how a site will perform during a particular flood event, there are three main inputs: the flood conditions, the site conditions, and the soil properties. In terms of the flood conditions, both sites presented were overtopped for a long period of time, probably over a day, although the exact depth and duration of the overtopping is still unknown. The soil testing and analysis showed that the erosion resistance of the soils at the two different sites varied tremendously. Also, the vegetative cover on the Brevator levee was dense and consistent, and provided a protective barrier between the water and the soil. The Winfield-Pin Oak levee showed signs of crayfish tunnels and tree roots that could have allowed internal seepage.

By combining the effects of the soil properties and the site conditions, a better estimate of whether a site will fail during a flood event can be made. Low values of activity and high clay contents have shown to be good indicators of an erosion resistant soil. It has also been shown that there is no way of predicting erodibility based on only one of the common soil variables. By obtaining the erosion function using a device such as the EFA, an accurate representation of the bare soil behavior can be determined over a range of velocities and shear stresses.

Recommendations for improvements to the Midwest Levee System include: increased dredging of the Mississippi river, creating sacrificial or emergency breach areas and flood zones along the levee system, repairing any low spots or imperfections along the levee, and raising levee heights in areas where repeated overtopping events have occurred. However, developing a dense vegetative cover is the single most important condition for a levee. Grasses of the proper species, root density, and height can greatly reduce erosion at a site. As seen in the Brevator case, vegetative armor can prevent failure of a levee for long periods of overtopping. Recommended grasses for the Midwest U.S. include: Switchgrass, Smooth Brome, Reed Canarygrass, and Tall Fescue. It is also recommended that these types of grasses be allowed to grow to at least 0.5 m tall during the flood season. Trees and woody rooted shrubs can also be harmful to levees as seen in the Winfield case. It is recommended that all trees and large root plants be removed from levees and that trees are not allowed to grow within a distance equal to their mature height from the levee toe. It is impertinent that any removal processes are done properly and that the levee is fully repaired.

Erosion due to overtopping is a complicated, multi-variable process that is not fully understood. More work is needed to narrow down the relationships between erosion and the other variables considered in this paper. While it still needs further refinement, the proposed erosion matrix provides a useful way to look at erosion and possibly a way to predict future site performance.

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