COMPARISON OF SUBMERGED JET TESTING TO FIELD EROSION RATES IN CLAY AND SAND CHANNELS, BLACKLAND PRAIRIE ECOSYSTEM, TEXAS

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Abstract Streambank erosion rates were monitored with erosion pins and water level recorders at 12 sites in North Texas for a period of one year. The sites were all located on unvegetated cutbanks of streams with drainage areas ranging from 3 to 241 sq. km. Cumulative and event based storm erosion were monitored and compared to submerged jet tests done on representative samples taken from the same sites. The 12 watersheds were about equally divided between clay and sand dominated alluvial systems. Cumulative annual erosion ranged from 30-572 mm in the clay channels and from 27-150 mm in the sand watersheds. The clay channels showed erodibility rates of 0.0027-0.0049 cm^3/N-s; the sand channels ranged from 0.0052-0.03cm^3/N-s computed with ASTM D5852-95 method. Computed erosion rates using the cumulative tractive force and the submerged jet values underestimated monitored field erosion in the lower bank by 11% and underestimated upper bank erosion by 84%. Differences in erodibility and erosion processes in lower and upper bank positions in both clay and sand channels and were attributed to antecedent conditions related to wetting and drying and surficial processes. A new sampling device was created to retrieve large undisturbed samples from the field for jet testing.

INTRODUCTION

Channel erosion is a natural process occurring when the tractive force or turbulence of the water exceeds the strength of the bank or bed materials resulting in entrainment of the material. Changes in basin land use, river slope, and climate can effect the rates of erosion. The US Army Corps of Engineers estimates that there are currently over 575,000 bank miles of erosion in the United States with cost of repair exceeding a billion dollars. Similarly, annual bridge repair due to channel incision could approach 50 million dollars.
Historically, channel erosion has been studied in the field using three methods: (1) by superposition of historic maps or photographs to ascertain change in the top of banks, (2) by detailed engineering stability analysis of bank profiles along stream reaches, and (3) by monitoring of the time rate of bank retreat using repeat bank surveys or erosion pins, (Lawler, 1992; Couper et. al. 2002; Zaimes, et. al. 2005). While these procedures can give local rates they are time consuming and costly. Another approach has been to assess erosion rates by subjecting channel materials to hydraulic shear utilizing specially designed flumes (Jepsen, et.al. 1997), rotating cylinders (Ariathurai and Arunlanandan, 1978), or more recently submerged jets (Hanson, 1991; Allen et al, 1999; Hanson and Cook, 2004;Wynn, et. al. 2008). In addition to the hydraulic tests, the alluvial materials are also subjected to a wide variety of laboratory tests in an attempt to cultivate predictive equations for erosion (Grissinger, 1965; 1982, Winterwerp, et. al.1990). To date, both the field and the testing have shown that sediments can basically be classified into non

cohesive and cohesive with a rather arbitrary boundary at 10 percent clay (Raudkivi, 1990). Below 10 percent clay, the erodibilty of the material is a function of gradation and grain size. Above the 10 percent clay threshold, no comprehensive method has been shown to determine soil erodibilty based only on measurable material properties.

Recent research has shown that along with the lab based erodibility tests of hydraulic erosion, long term channel erosion must be seen as occurring in stages based on periods of quiescence, material weathering and preparation followed by fluvial entrainment (Wolman, 1959; Lawler, 1992; Prosser, et. al., 2000; Couper and Maddock, 2001; Wynn and Mostaghimi, 2006; Wynn et. al, 2008). This approach also must take into account the presence of vegetation types (I-IV), (Thorne, 1992; Abernathy and Rutherford, 1998), the stratification of the bank, bank height, and the changes in material properties of bulk density, cohesive forces, and particle aggregation related to clay mineralogy, temperature, and chemistry of the pore fluids and eroding water (Grissinger, 1965, 1982; Thorne, 1992; Simon et. al. 2000).

With this degree of complexity, erosion must be measured in the field as well as the laboratory and results compared. While many cited studies have reported lab measurements or results of extensive field monitoring, few have compared the two. While extensive monitoring gives perhaps the best overall data, it is very time consuming and costly and site specific. This research attempts to compare lab and field measurements within an ecoregion in order to illustrate the applicability of insitu and lab testing for erosion rate prediction in the field after similar work in the Loess region of the US by Hanson and Simon (2001).

LOCATION

The study area is located within the Blackland Prairie Ecoregion (Simon, et. al., 2001) and Blackland Prairie and Cross Timbers Physiographic Provinces, Texas. This area is about 400 kilometers from the Gulf of Mexico. The altitude ranges from about 150 to 210 meters above mean sea level. The area is underlain by Cretaceous aged limestones, sandstones and shales which dip gently to the southeast 5.7 meters/km.. The overlying soils range from highly expansive clays and silty clays over the limestones and shales to sandy clay loams over the sandstones. The climate of the area is temperate with hot summers (mean 30 C) and mild winters (mean 7.2 C). The most common storms that occur in the spring and summer are thunderstorms while long duration low intensity storms occur in the fall and winter. Mean annual rainfall is 88.6 cm.

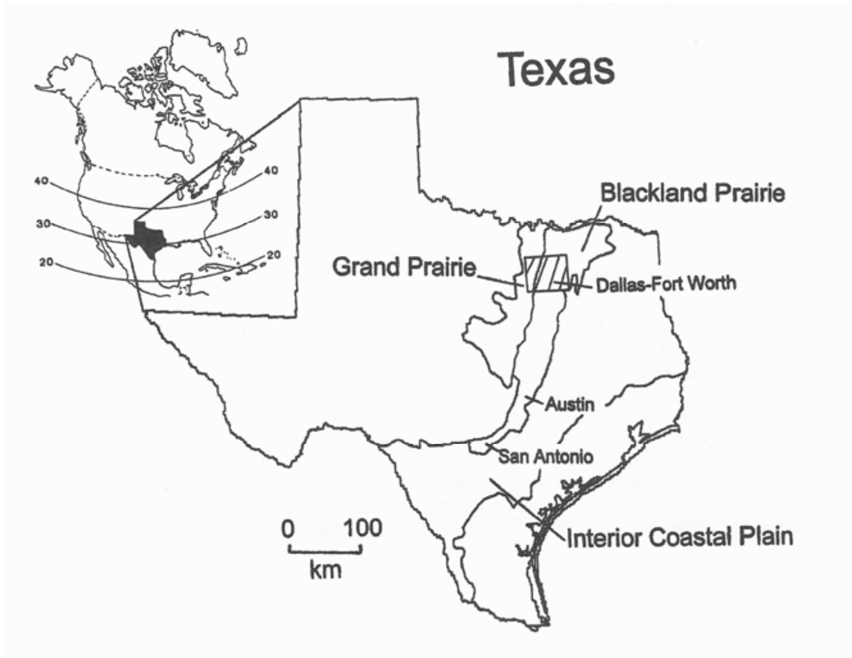

Figure 1 Location of the study area.

METHODS

Nine sites were chosen based on drainage area (5-239 sq. kms), basin land use, and access: five sites in the sandy terrain, and four sites in the clay terrain, Table 1. At each site, the channel cross section and planform was surveyed. In order to test the maximum erosion rates, erosion pins (6.35mm X 610 mm) were placed in a grid formation of five columns with one meter spacing between pins on the outside of meanders in areas of no vegetation. The pins were placed in two rows at one third and two thirds the stream bank height. The pins were monitored for a period of a year. Pin erosion was measured using venier calipers after each storm event.

A water level data logger was employed at each site to record water level in 15 minute increments during the study period. Soil samples were collected from identical areas as the pins using a specially designed large core sampling device. Samples were brought back to the lab for material testing (grain size, bulk density, atterberg tests) and erodibility measurements. Erodibility measurements were performed utilizing submerged jet test procedures after Hanson and Cook (1990) and ASTM, (1999). The jet tests were run under dry and saturated conditions to test for the influence of antecedent bank conditions. Bank shear was assessed utilizing methods by Wynn et. al. (2008) as well as results from the submerged jet testing. Channel shear was calculated based on water height taking into account bend curvature.

RESULTS

Three events were recorded for the clay sites and 4-5 events recorded for the sand sites over the monitoring period. The recurrence intervals of the storms ranged from 0.5 year to over 100 years. In general, the storm recurrence interval decreased with watershed area as most of the recorded storms were thunderstorms with little areal coverage.

Pin loss rates were related to bank position and storm duration. Hourly loss rates for the clay were 12.6 times greater in the upper bank than lower bank position. Hourly loss rates in the sand upper bank loss rates were 4.7 times the lower bank loss rates, Tables 2 and 3.

Table 1 Results of pin erosion in monitored basins.

Bank Type	Drainage Area	Lower Bank Wetting Duration (hrs)	Loss (mm)	Upper Bank Wetting Duration (hrs.)	Loss (mm)
clay	5	157	30.53	42	41.38
	32	351	75.94	102	54.15
	90	267	38.3	120	54.23
	239	247	162.11	68	571.54
sand	3	50	41	20	40
	6	115	40	24	48
	12	229	27	21	49
	22	209	150	42	61
	41	49	144	7	133

Submerged jets test results for each site are shown along with index properties of the bank materials, Tables 2 and 3. Results indicate that clay jet values under estimate lower pin erosion loss rates by 1 percent and under estimates upper bank values by 87 percent. Sand jet values underestimated the lower bank loss rates by 21 percent and underestimated upper bank rates by 81 percent. Overall, including both lithologies, the lower bank jet average underestimates the measured erosion rates by 11 percent; the upper bank underestimates the measured erosion by an average of 84 percent.

Table 2 Lower Bank results. Lab refers to submerged jet tests and Field-LB refers to measured rates on the lower bank position.

	Area (Sq. km.)	% clay	pb dry (gms/cc)	cm3/N-s (Lab)	cm3/N-s (Field-LB)
clay	5	10.97	1.5	0.0032	0.0032
	32	24.44	1.42	0.0042	0.0042
	90	20.34	1.36	0.0027	0.0027
	239	23.44	1.34	0.0049	0.0049
sand	3	0.61	1.34	0.0072	0.0069
	6	1.31	2.32	0.023	0.0059
	12	5.41	2.2	0.0081	0.0050
	22	2.92	2.4	0.0052	0.015
	41	2.58	2.58	0.0083	0.033

Table 3 Upper Bank results. Lab refers to the submerged jet test results and Field UB refers to measured rates on the upper bank position.

	Area (Sq. km.)	% clay	pb dry (gms/cc)	cm3/N-s (Lab)	cm3/N-s (Field-UB)
clay	5	17.32	1.57	0.0036	0.0249
	32	10.54	1.4	0.0039	0.0066
	90	17.58	1.4	0.0042	0.0062
	239	13.77	1.38	0.0036	0.0787
sand	3	1.9	1.32	0.0072	0.0119
	6	2.16	2.21	0.0239	0.0574
	12	5.16	2.33	0.0292	0.0393
	22	3.5	2.42	0.0169	0.04195
	41	2.83	2.64	0.0125	0.3278

Comparison of submerged jet test values to monitored field loss values in cm/sec is shown in Figure 2. The regression coefficient of correlation is 0.27 and standard error of estimate 0.00218. The Nash Sutcliffe efficiency is -.1 indicating that the observed mean of the observed erosion is a better predictor than the Jet values.

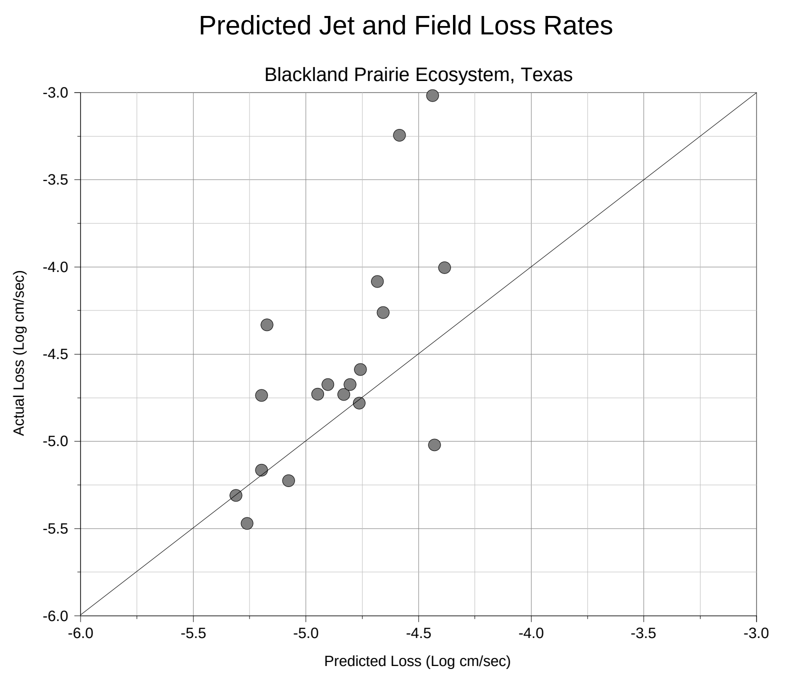

Figure 2 Comparison Submerged Jet loss rates versus measured loss rates for clay and sand watersheds, Texas

Based on the Jet results, another analysis was made based on work by Jepsen ,et.al.(1997) and is shown in Figure 3. Here the loss rate recorded is shown to be well correlated to sediment bulk density and tractive force. The coefficient of correlation is 0.62 and the mean absolute error is 0.34. This demonstrates that the erosion rate is a unique function of the bulk density and shear stress where Tc (Pa) and pb is the bulk density (gms/cc) and the coefficients are dependent upon the type of sediment. This equation is designed for high shear stress, where Tcr<Tc. Under these conditions, the critical shear stress term becomes less important in the equation. In the current study, the Tcr was an order of magnitude less than the calculated shear at the pins.

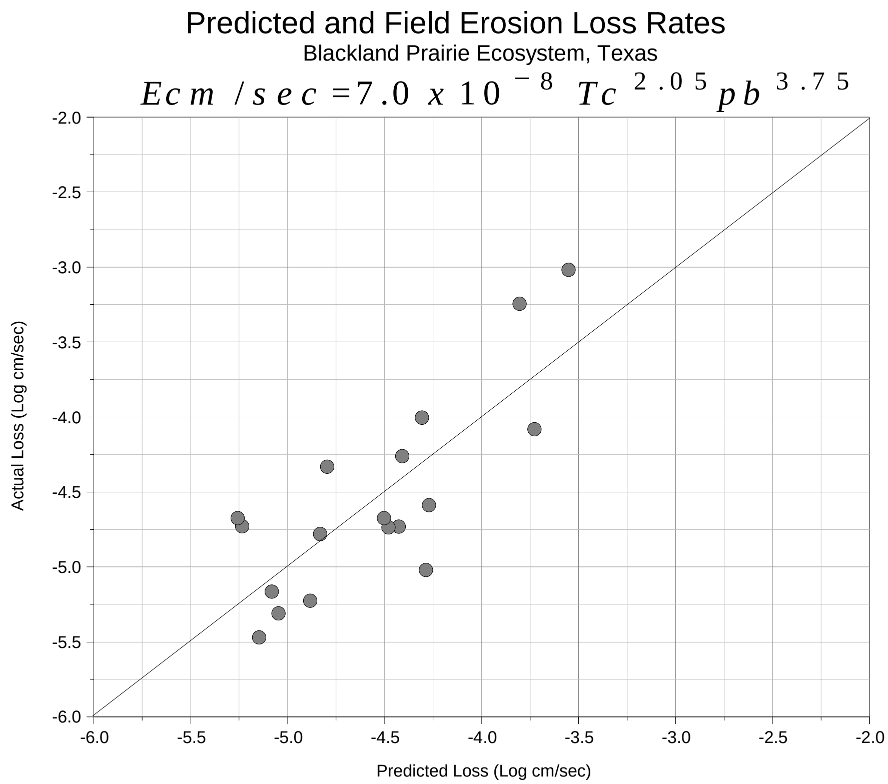

Figure 3 Predicted and Observed loss rates in clay and sand basins, Texas.

DISCUSSION OF RESULTS AND CONCLUSIONS

This study used the results of two year long monitoring projects to assess the erodibility and applicability of the submerged jet test to quantify stream channel erosion within the Blackland Prairie Ecosystem. Erosion rates measured during this study ranged from 30-162 mm/yr in the lower bank and from 40-571 mm/yr in the upper bank. These results are comparable to those reported by Hooke, 1980; Prosser, et al, 2000 among others.

In general, loss rates per flood duration were greater in the upper bank positions for both lithologies. The increase in loss rates for the upper banks is attributed to greater subaerial preparation of the bank material coupled with upper bank slope failures.

Erosion rates were in the same order of magnitude downstream in the basins until a threshold was reached as shown by Lawler (1995); Lawler et. al. (1999); it appears in the clay basins at approximately 90 sq. km. and in the sand basins at about 22 km. These thresholds relate to the upper bank processes and reach hydrology and hydraulics.(The sand basins were urban and the clay basins were predominantly rural which may account for some of the discrepancy).

While the second equation (Figure 3) allows for better predictive potential for measured streams, it still requires expensive long term monitoring in order to establish such relationships. This study demonstrates that even with the inherent complexity of the erosion process, the jet device can give reasonable rates of erosion. For example, for the study areas, for the lower and upper bank positions, using average jet values, duration of flow, and tractive force, the jet loss rates for the lower bank sites is within 8 mm of the annual erosion; it predicts upper bank erosion within about 40mm. These would be maximum erosion rates for the area as the pins were placed to achieve maximum erosion. Given the complexity of erosion in the field, these results indicate that the submerged jet can be used to estimate field erosion rates in this area within an acceptable range. More work needs to be done to ascertain the effect of subaerial processes on erosion. Upper bank preparation in this area is related to wetting and drying, Preliminary work by the authors have shown that submerged jet values can change by up to 140 percent with drying in some clays; this factor would be more pronounced on the upper bank. Further north, Wynn e.t. al. has shown frost to be the principal factor in lowering erosion thresholds.

REFERENCES

Ariathurai, R. and K. Arulanandan, 1978. erosion rates of cohesive soils. J. Hyd. Div. ASCE, vol. 104, no. HY2, Feb. pp. 279-283.

Abernathy, D. and I.D. Rutherford, 1998. Where along a river's length will vegetation most effectively stabilize stream banks?. Geomorphology, v. 23, n.1, p. 55-75.

Allen, P.M., J. Arnold, and E. Jakubowski, 1997. Design and testing of a simple submerged-jet device for field determination of soil erodibility: Environmental and Engineering Geoscience, v.3, n. 4, p. 579-584.

ASTM, 1999, Standard Test Method for Erodibility Determination of Soil in the Field or in the Laboratory by the Jet Index Method, No. D5852-95:ASTM, West Conshohocken, PA, 04.08:686-690.

Clark, L.A. and T.M. Wynn, 2007. Methods for determining stream bank critical shear stress and soil erodibility: Implications for erosion rate predictions: Transactions of the ASABE, v. 50, n.1, p. 95-106.

Couper, P.R., and Maddock, 2001. Subaerial river bank erosion processes and their interaction with other bank erosion mechanisms on the River Arrow, Warwickshire, UK: Earth Surface Processes and Landforms, v. 26, p. 631-646.

Couper, P. T. Scott, and I. Maddock, 2002, Insights into river bank erosion processes derived from analysis of negative erosion pin-recordings: observations from three recent UK studies: Earth Surface Processes and Landforms, v. 27, n. 1, p 59-79.

Grissinger, E.H., 1966.Resistance of selected clay systems to erosion by water. Water Resources Research, v. 2, n. 1, p. 131-138.

Grissinger, J.H. 1982. Bank erosion of cohesive materials. In: Hey, R.D., J.C. Bathurst, and C.R. Thorne, eds.:Gravel Bed Rivers, John Wiley and Sons, Chichester, UK, p. 273-287.

Hanson, G.J. 1991. Development of a jet index to characterize erosion resistance of soils in earthen spillways: Transactions of the ASCE, v. 34, n.5, p. 2015-2020.

Hanson G.J., and K.R. Cook. 2004. Apparatus, test procedures, and analytical methods to measure soil erodibility in situ. Applied Eng. In Agric. Vo. 20, no. 4, p. 455-462.

Hanson, G.J., and A. Simon, 2001. Erodibility of cohesive streambeds in the loess area of the Midwestern USA. Hydrological Processes, v. 15. p. 23-38.

Hooke, J.M., 1980. Magnitude and distribution of rates of river bank erosion. Earth Surface Processes . v. 5, p. 143-157.

Jepsen, R., J.Roberts, and W. Lick, 1997. Effects of bulk density on sediment erosion rates. Water, Air, and Soil Pollution, v. 99, p. 21-31.

Lawler, D.M., 1992, Process dominance in bank erosion systems. In: Carling, P. and G.E. Petts, Eds. Lowland Floodplain Rivers, Wiley:Chichester, p. 117-113.

Lawler, D.M., 1995. The impact of scale on the processes of channel side sediment supply: a conceptual model. In: Effects of scale on interpretation and management of sediment and water quality (Proceedings of a Bouder Symposium, July 1995) IAHS Publ. no. 226, p. 175-184.

Lawler, D.M., J.R., Grove, J.S. Couperthwaite, and G.J.L. Leeks, 1999, Downstream change in riverbank erosion rates in the Swale-Ouse system, northern England: Hydrological Processes, v. 13, n. 7. p. 977-992.

Partheniades, E. 1965. Erosion and deposition of cohesive sediment. Journal of the Hydraulics Division, ASCE, vol 101, no. 1, p. 65-80.

Pizzuto, J., 2009. An empirical model of event scale cohesive bank profile evolution. Earth Surface Processes and Landforms, vol 34, p. 1234-1244.

Prosser, I.P., A.O. Hughes, and I.D. Rutherford, 2000. Bank erosion of an upland channel by subaerial processes: Tasmania, Australia: earth Surface Processes and Landforms, v.25, n.10, p. 1085-1101.

Raudkivi, A.J., 1990. Losse boundary hydraulics. Pergamon Press., N.Y., 538p.

Simon, A., A. Curini, S. Darby, and E.J. Langendoen, 200. Bank and near bank processes in an incised channel: Geomorphology, v. 35, n. 3-4, p. 193-217.

Simon A., W. Dickerson, and A. Heins, 2004. Suspended sediment transport rates at the 1.5 year recurrence interval for ecoregions of the US; transport conditions at the bankfull and effective discharge. Geomorphology, vol. 58, p. 243-262.

Thorne, C.R., 1992. Processes and mechanisms of river bank erosion. In Hey, R.D., J.C. Bathurst, and C.R. Thorne Eds. Gravel Bed Rivers, John Wiley and Sons, Chichester, UK, p. 125-144.

Thorne, C.R., 1990. Effects of vegetation on riverbank erosion and stability. In: Thornes, J.B., ed: Vegetation and Erosion: Processes and Environments, John Wiley and Sons, Chichester, UK, p. 125-144.

Trimble, S.W., 1997. Contribution of stream channel erosion to sediment yield from an urbanizing watershed. Science, vol 278(5342)p. 1442-1444.

Winterwerp, J.C., J.M. Cornelisse, and C. Kuijper, 1990. Parameters to characterize natural muds, in Abstract Volume, Int. Workshop on Cohesive sediments, Brussels, KBIN, Brussels, p. 103-105.

Wolman, M.G., 1959. Factors influencing erosion of a cohesive river bank. American Journal of Science, v. 257,p. 204-216.

Wynn, T.M. and S. Mostaghimi, 2006. The effects of vegetation and soil type on streambank erosion, southwestern Virginia, USA:Journal of the American Water resources Association, Paper Number 04154.

Wynn, T.M., M.B. Henderson, and D.H. Vaughan, 2008. Changes in streambank erodibility and critical shear stress due to subaerial processes along a headwater stream, southwestern Virginia, USA. Geomorphology, v. 97, p. 260-273.

Zaimes, G.N., R.C. Schultz, T.M. Isenhart, S.K. Mickleson, J.L. Kovar, J.R. Russell, and W.P. Powers, 2005. Stream bank erosion under different riparian land-use practices in northeast Iowa. AFTA 2005 Conference Proceedings, p. 1-10.