TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA/TX-05/0-4695-2	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Bed Load Mobility: Interim Report		5. Report Date August 2004 6. Performing Organization Code
7. Author(s) David Thompson		8. Performing Organization Report 0-4695-2
9. Performing Organization Name and Address Texas Tech University Department of Civil Engineering Box 41023 Lubbock, Texas 79409-1023		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 0-4695
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, TX 78763-5080		13. Type of Report and Period Cover Technical Report, Aug. 11, 2003 through Aug. 31, 2004 14. Sponsoring Agency Code

15. Supplementary Notes
Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

16. Abstract: Significant work was undertaken during the first year of the bed-mobility research project (TxDOT 0-4695). A literature review was completed, from which the most significant finding was that no literature treating the design of low-water stream crossings was found. However, much research has been invested in gravel-bottomed streams. The dynamics of sediment transport, while a difficult subject, has a rich literature.

Results of the field trip from July 2004 are still being digested. It appears that a number of methods for characterizing bed composition are available and will produce similar results.

A single run of the physical model was made. The researchers can produce behaviors in the flume that are similar to what was observed in the field. More work is necessary in this area.

The conclusion is that it is still early in the research project. Current lines of research need to be completed before an assessment of the benefits of project continuation past the two-year mark can be made. It is suggested that a project meeting be held during the first part of calendar year 2005 (before the semi-annual reports are due) and that a determination of the fate of continued research be made at that time.

17. Key Words Hydraulics, Bedload, Sediment Transport.		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161, www.ntis.gov	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 20	22. Price

Form DOT F 1700.7 (8-72)

Bed Load Mobility: Interim Report

by

David Thompson
Associate Professor
Department of Civil Engineering
Texas Tech University

Report 0-4695-2

Project Number 0-4695
Research Project Title: Guidance for Design in Areas of Extreme Bed-Load Mobility

Sponsored by the
Texas Department of Transportation

August 2004

Center for Multidisciplinary Research in Transportation
Department of Civil Engineering
Texas Tech University
P.O. Box 41023
Lubbock, TX 79409-1023

AUTHOR'S DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation. The United States government and the State of Texas do not endorse products or manufacturers. Trade or manufacturer's names appear herein solely because they are considered essential to the object of this report. The researcher in charge of this project was David Thompson.

PATENT DISCLAIMER

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

ENGINEERING DISCLAIMER

Not intended for construction, bidding, or permit purposes.

TRADE NAMES AND MANUFACTURERS' NAMES

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

Prepared in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

TABLE OF CONTENTS

LIST OF FIGURES

TxDOT Project 0-4695 - Bed Load Mobility

Interim Report

Background

Low-water crossings are commonly used on low-volume stream crossings in the hill country of Texas. Low-water crossings are periodically overtopped. However, the crossings are perceived as an economic alternative to more substantial culverts and bridges for drainage structures where flooding is relatively rare. The flow of water and concomitant movement of bed material over the crossing has caused numerous failures, some structural, some from the deposition of gravel to boulder-sized material on the roadway, and all from submergence.

Because of structural and depositional failure modes, TxDOT seeks guidance on design of low-water structures (although significant progress has been made here) and on mitigation of depositional processes. As a result, a two-year research project was initiated to review the literature, reconnoiter several sites that exhibited problem behaviors, and determine if further research would be fruitful.

What We Have Learned

The literature dealing with gravel-bed streams, the motion of gravel bed loads, and the formation of and mitigation of debris flows has been reviewed and presented in literature review as a separate report (Heitmuller and others, 2004).

Through a review of TxDOT MMIS records, the costs associated with repairs and replacement of low-water crossings in Edwards, Kimble, and Real Counties were estimated. Over a four-year period, from 1998-2002, total repair expenditures in the three counties were about $672K.

All County 1998 Total	193843.81
All County 2000 Total	80,173.96
All County 2001 Total	200224.82
All County 2002 Total	197444.69
	All County Total
	671,687.28

During the course of the cost review, it became clear that the MMIS system does not serve the needs of TxDOT to determine the *long-term* costs associated with bed-load mobility. Details of task costs are lost after three years, limiting the ability to review historical flood damages. Furthermore, because of the breakdown of tasks, it is possible that each event may have some costs associated with flood-damage repairs that are not accounted for.

The spatial extent of bed-mobility problems extends to at least 11 other counties, and perhaps as many as 17 counties or more. By extrapolation from the economic data from three counties, the four-year cost associated with bed-mobility is at least $2.4M (assuming an 11 county spatial extent).

We have completed a limited characterization of three crossings of Johnson Fork Creek and the Nueces River ("Ben Williams" crossing. An example from Guzman crossing of Johnson Fork Creek is shown on figure 1 below.

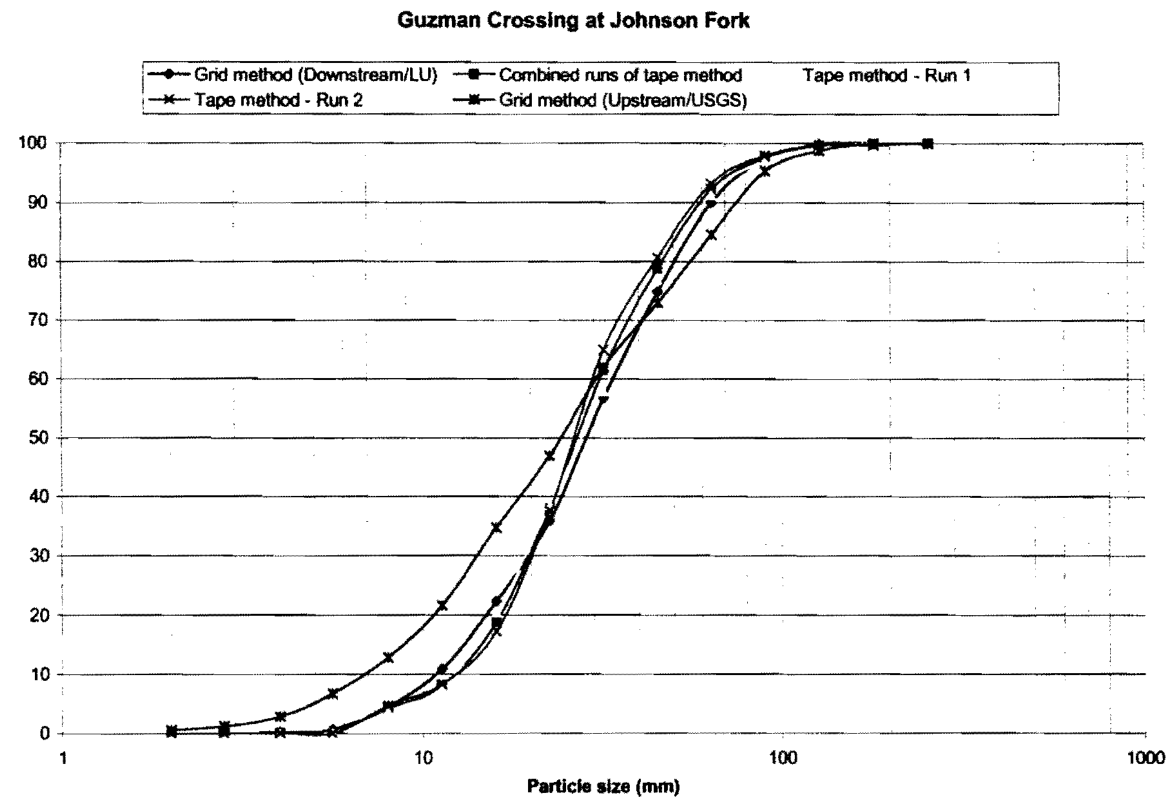

Figure 1. Particle size distributions at Guzman crossing of Johnson Fork Creek.

In the case of the Guzman crossing, D50 upstream is greater than the D50 downstream from the crossing. However, the distribution of particles downstream is more uniform than that of the particles upstream.

Furthermore, tests of different methods run on downstream sediments were consistent, meaning that any of the field methods used would yield about the same result. This is important, because some of the methods for determining surface distribution of particles require substantially less effort to apply than the gravelometer method, which is laborious.

Results from the gravelometer and tape methods for Johnson Fork Creek are shown on figure 2. It was observed that particle sizes at the upstream of a low-water crossing were generally larger than ones at the downstream. Some large-size particles existed at the upstream of Paks crossing, but did not exist at Guzman crossing (upstream of Paks) and Lowlands crossing (downstream of Paks)

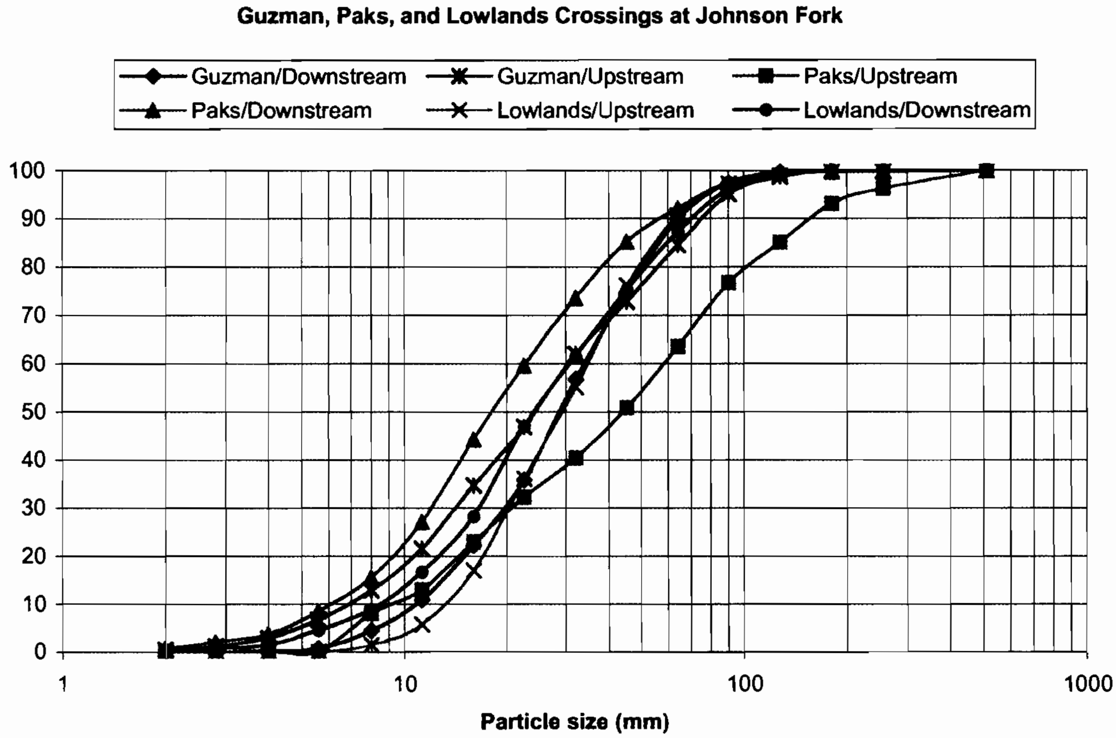

Figure 2. Particle size distributions of bed gravels for Johnson Fork Creek.

In addition to the data presented in figures 1 and 2, similar figures were produced for a size characterization based on screening samples collected at the indicated locations. In these characterizations a volume taken from a 60 cm x 60 cm area was passed through large screens and the cumulative weight retained and passing was recorded. These results include both surficial characterization, and material below the surface (at Johnson creek about 6 – inches below grade) and at Ben Williams up to six feet below grade.

Figures 3 through 6 present the results of these analyses. In the figures the measured values are displayed as markers, while the curves on the plots are log-normal distributions passed through these markers – principally to guide the eye. The lognormal mean and variance were determined by a one-dimensional root solver method. The results compare favorably with classical granular analysis techniques and allow some extrapolation beyond the measured data.

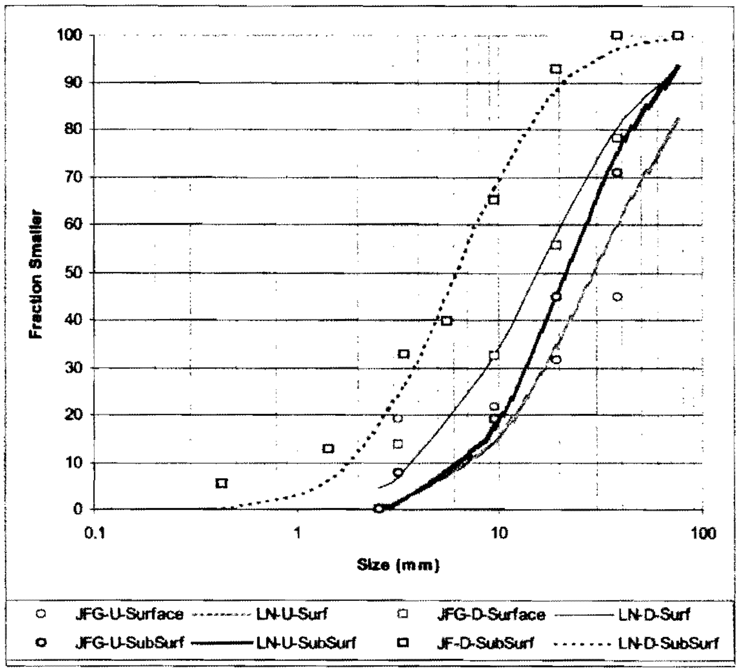

Figure 3. Johnson Fork - Gooseman Crossing - Size Distributions of Surface and Shallow Subsurface Samples.

In Figure 3 the mean grain diameter (size) is larger upstream of the crossing, and the surface samples are larger than respective subsurface samples. The mean size at this location is about 20 mm.

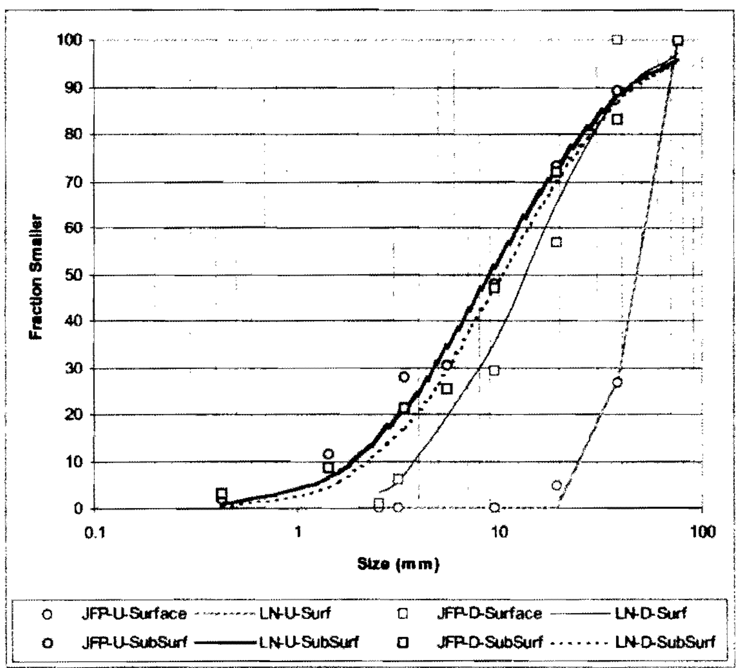

Figure 4. Johnson Fork - Paks Crossing. Size Distributions of Surface and Subsurface Samples.

In Figure 4 the mean grain diameter (size) is difficult to interpret. Excluding the upstream surface sample, the mean size at this location is about 10 mm.

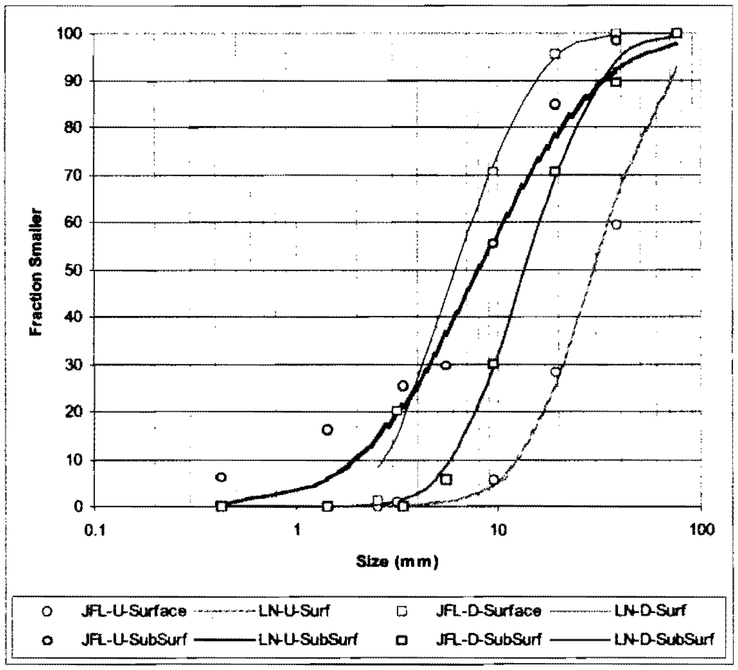

Figure 5. Johnson Fork - Lowlands Crossing. Size Distributions of Surface and Subsurface Samples.

In Figure 5 the surface samples mean diameter is larger upstream of the crossing, while the opposite is displayed for the subsurface sample. At this location the mean size is difficult to establish, but 15 mm is probably a good estimate.

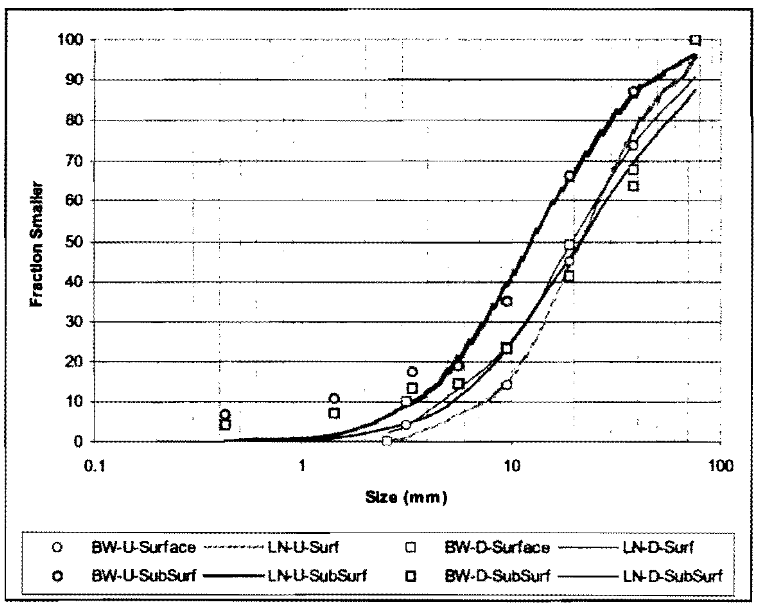

Figure 6. Ben Williams Crossing. Size Distributions of Surface and Subsurface Samples.

Figure 6 shows the Ben Williams results. This location was treated differently because an excavator was available for collecting the samples. Apparent in the plot is less variability both upstream and downstream and with regards to depth. The mean size at this location is about 20mm, but there were several large stones uncovered during the field trip, one measuring over a meter in its long dimension and weighing 140 pounds.

From these initial characterizations we conclude that we are dealing with solids in the 20 mm. range (about 1 inch), but there are significant masses larger than this size. In terms of existing literature, these sizes are on the larger end of the scale of prior work.

The term "failure" for low-water crossings is a loose term. Failure modes for low-water structures comprise:

- Loss of service because of submersion during relatively extreme events,
- Loss of service because of structural failure, and
- Loss of service because of overflow of gravel/cobble bars.

All three modes cause loss of service for varying amounts of time. Loss of service defines failure of the structure from a use perspective. The list is in order of increasing length of time of loss of service. The failure mode of a low-water crossing is a difficult cost to quantify in comparative terms to more substantial stream-crossing structures.

Hydrostatic "blowout" of the downstream apron of low-water crossings can be prevented by use of weep holes to reduce pressures during flood events. This conclusion is based on observation of existing structures and on recent TxDOT engineering experience.

Historical information of flood occurrence in the study area is useful to establish context of recent low-water crossing maintenance operations by TxDOT. Two long-term stations were selected as "index" streamflow-gaging stations for flood occurrence: 08150000 Llano River at Junction, Texas and 08190000 Nueces River near Laguna, Texas. The measure of flood occurrence is the nonexceedance probability of the annual peak streamflows.

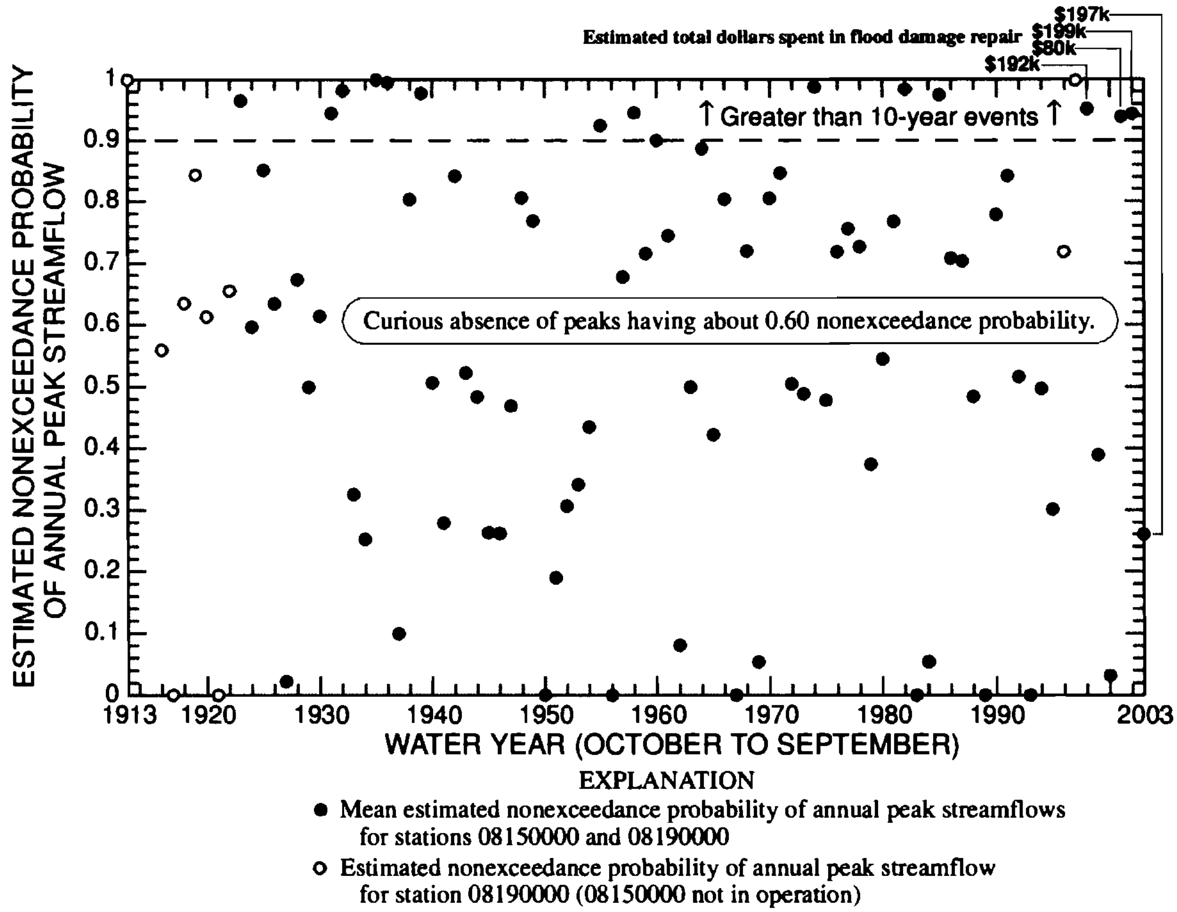

Figure 7. Nonexceedance probabilities of flows from 1913 to 2003.

Asquith (1999) provides regional regression equations to estimate the L-moments of annual peak streamflow applicable for the stations using drainage area, basin shape factor, and main channel slope as predictor variables. Asquith and Slade (1997) lists these basin characteristics for the stations. The L-moments (mean, L-scale, L-skew, and L-kurtosis) were estimated, and for each station a four-parameter kappa distribution fit to the L-moments. The kappa distribution provides a continuous function representing the "flood-frequency curve" for the stations. Subsequently, the annual peak streamflows were successively substituted into the distribution, and the nonexceedance probability for each year at each station was calculated. To simplify analysis, the mean of the two estimated nonexceedance probabilities for each year was computed—This mean is a more reliable flood occurrence measure. (Station 08150000 does not have corresponding record for each year of record at station 08190000.) The kappa distribution is not restricted to positive values of peak streamflow for the smallest annual peak streamflow values; a nonexceedance probability could not be completed. When a negative value occurs, a nonexceedance probability of zero was assumed for plotting purposes only. The time series of the estimated nonexceedance probability by water year is shown in figure XX. The symbols on the plot distinguish between years having both stations in operation and years having one station in operation. The nonexceedance probability associated with the 10-year recurrence interval event is shown. Also, the total dollars for each water year are superimposed on the figure.

Several important observations about flood occurrence information depicted in the figure are made. First, a wide range in nonexceedance probability is evident, which is expected from hydrologic statistical theory. Second, there is a curious lack of 0.60 nonexceedance probability values from about 1930 to the present. Third, there appears to be two clusters events having large nonexceedance probabilities spanning a half decade or more: 1930s and late 1990s to early 2000s. The clustering of historically significant flood events in the 1930s in the study area is widely known, and it is known that from about 1997 to at least the present (2004) that substantial floods have occurred throughout the study area. Fourth, TxDOT does not report significant damage repair costs in 1999 and 2000—These are years lacking significant flooding (at least on upper Nueces and Llano River main stems). Finally, the substantial 2003 damage costs are not associated with large nonexceedance probability; this is illustrative of the limited spatial representation of the two index stations. A logical conclusion from the data depicted in the figure could be that TxDOT has experienced historically unusually large flood damage costs in recent years because of historically unusual, but not unprecedented floods.

A single physical model experiment was conducted in late August. The purpose of this experiment was to demonstrate that the laboratory flume could be operated in a fashion to simulate flash-flooding and consequent bed mobility without damaging the flume and pumping system. Cinder blocks were used as models for a box culvert, and road bed. Samples from the July 2004 field trip were used as the bed material. The culvert is placed, and then the material is spread on the upstream side of the culvert. The next series of images are documentation of the experiment. In our discussions the research team assumed that interesting behavior would occur at critical and super-critical flow. While that indeed was true, we discovered that visible bed motion occurred even with relatively stable sub-critical flows.

Figure 8 is an image of the model during a simulated flooding event. In this image the upstream and downstream Froude numbers are about 0.30. In the laboratory smaller particles can be observed to be moving, but most of the bed appears stable. In Figures 1 and 2 the water depth above the gravel bed is about 0.72 feet. The measured discharge is 0.94 cfs. The calculated section velocity is 1.3 ft/sec. Prior to this image the model was run for about ½ hour with the depth of flow below the invert elevation of the model box (that is the road bed was not flooded).

Figure 8. Upstream portion of model looking towards culvert. Entire "road bed" is submerged.

Figure 9 is an image during the same flow regime. The "hole" in front of the culvert is a consequence of the flow. When the experiment was started, the gravel bed was essentially parallel with the culvert entry, but higher than the bottom of the culvert. The hole material deposited on the downstream side of the culvert (not pictured). The hole grew in the upstream direction (slowly) as if it were a head cutting stream.

Figure 9. Upstream of culvert. Note "hole" in gravel bed that eroded when the flow regime was changed from open flow to submerged flow.

The next images are the result of larger flows forced through the test section. The forces in these materials are probably quite large, if not enormous, were this were a real channel. The point of this particular set of flows was to determine if we could cause deposition on top of the culvert model. The flow rate and water depths in the following pictures were not measured.

Figure 10 displays the gravel bed filling the culvert. When the culvert became full of gravel the flow was essentially vertically upward which carried the solids materials up onto the road bed. Figure 11 is an image of deposition during this flow.

Figure 10. Gravel bed filling culvert.

Figure 11. Deposition on top of culvert.

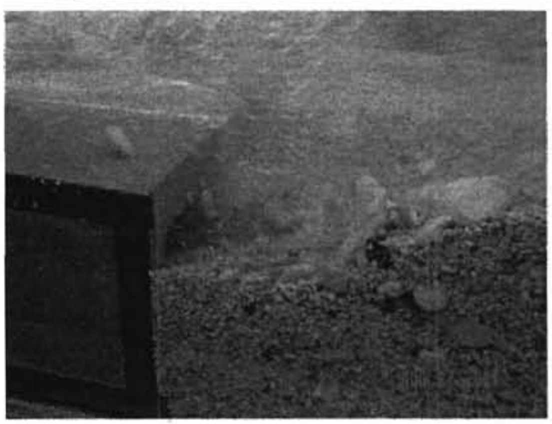

Figure 12. Downstream side during "flash flood."

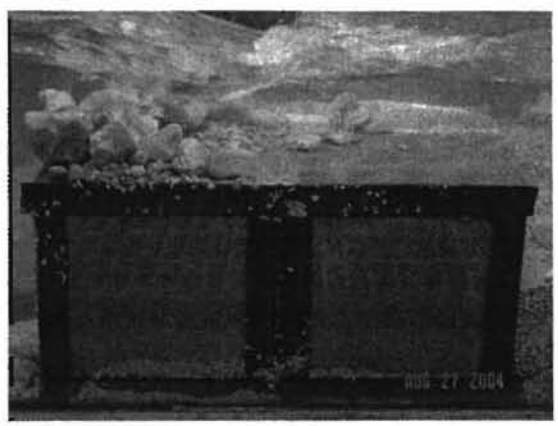

Figure 13. Side view during "flash flood."

Figure 12 is an image on the downstream side of the model during high flow. The hole being formed on the downstream side is from water cascading over the structure (significant vertical flow component and visible hydraulic jump in the erosion region). In this image there is little flow through the culvert as it is completely clogged by gravel on the upstream side.

Figure 13 is an image of the model during receding part of the flood wave. Note the gradation of the deposition (large material on the leading edge, smaller as one moves downstream). Forensic field-work should verify if such gradation occurs in natural flows.

Figure 14 is an image of the model after the flood event. Again note the gradation moving downstream from the structure.

Figure 14. Model deposition after flood waters have receded.

Not included in this report are some images of the transitional flows. For example, as the culvert goes from open flow to submerged, there is a rapid erosion event until the culvert is fully surcharged, then the solids motion returns to relatively stable beds. Again, this phenomenon should be field verifiable in smaller real events.

What We Want to Know

It is important to the project and to TxDOT to define the costs of loss of service for these structures over a longer period of time and over a wider geographic area. It is likely that substantial amounts of money are expended in repair and rebuilding of these structures, but the costs are not recoverable from accounting records.

There are several directions of knowledge or information development that are needed to more adequately address the effects of extreme bed load mobility on low-water crossings before potential financial or design mitigation strategies can be developed. These directions in little significant order are enumerated below.

1. Long-Term Costs--Does data exists to predict long-term recurring maintenance costs? A detailed forensic analysis of the TxDOT MMIS showed that there is a lack of fiduciary infrastructure to predict long term costs associated with maintenance of low-water crossings associated with flooding caused by substantial precipitation. Therefore, if TxDOT desires to increase the reliability of maintenance budget projections, then an improved cost tracking system would be needed.

2. Structural Design--Does low-water crossing design influence failure mode type or frequency? TxDOT information is helpful for survivability, but less so for deposition. TxDOT staff has indicated through several conversations with research personnel that there has been a historical tendency to mitigate gravel deposition by raising the road profile or elevation--that is, making low-water crossings higher. Furthermore, TxDOT reports or is aware that raising of the road profile could be compounding the problem of gravel deposition. TxDOT is now attempting, on an *ad-hoc* basis, to lower the hydraulic grade line at selected stream crossings. More information concerning hydraulic characteristics near the crossings is needed.

3. Hydraulic Regime--Little is currently known about the hydraulic regimes (subcritical, critical, or supercritical flow) produced by flooding on many stream courses in the study area. Enhanced specification of hydraulic regime in the study area and in particular proximal to TxDOT low-water crossings greatly influences how future research might proceed and how design changes might be made. For example, if gravel deposition is the principle failure mode for a structure and if the Froude number (a measure of the hydraulic regime) decreases from upstream to downstream of the structure, then gravel deposition is likely on the structure. A mitigation strategy might be then to proceed with design changes that increase Froude number in a downstream direction. Data collection and modeling strategies could be developed to improve understanding of hydraulic regime in the study area.

4. Peak Discharge--Peak discharge or the maximum instantaneous rate of streamflow during substantial flood events is unquestionably an important contributor to gravel transport in the study area. Little is currently known about the magnitudes of peak discharge to cause gravel movement. The peak discharge for a particular site that causes problems is unknown; related is the peak discharge associated with the loss of service. More information concerning the peak discharge magnitude and frequency near the crossings is needed.

5. Other Factors Influencing Failure Probability--Stream Power, time base of runoff, particle size distribution, and others seem likely to have significant influence on failure probability.

Where Do We Go From Here?

Reliable predictions of necessary research direction(s) from this point in the project are difficult to make. As a case in point, it is not even know whether the low-water crossing structures as built contribute to (or even mitigate) failure potential. However, several juxtaposed lines of inquiry in a loose order of execution are envisioned: field research and documentation, physical modeling, and numerical modeling. Field research is needed to further document the hydraulic regimes experienced by streams and crossings.

Field Research

Additional field research is beneficial. This research must, as a principle objective, provide further guidance as to the flow regime, as measured by at least Froude number, in the study area. The Froude number for the peak discharge for substantial flood events can be estimated through indirect measurement of peak discharge methods.

Inclusive to field research is the use of commercially available remote sensing instruments. Multi-spectral analysis of pre- and post-flood channels in the desert southwest has proved promising (Mayer and Pearthree, 2002). Furthermore, an exciting line of research into documenting channel hydraulics could be the evaluation of the feasibility of using high resolution (0.6m) imagery for peak discharge estimation (see Zhang and others, 2004). Both imagery and field surveying would provide the basis for the feasibility study.

In addition to planned field work, any documentation of deposition grading across a structure would be beneficial. Specifically, after event photographs similar to those of the hydraulic model will help establish the nature of the flows that created the deposition and confirm if the model deposition pattern (large to small looking downstream) is indeed reproduced in nature.

Physical Modeling

The results of on going, but generalized small scale, physical modeling are not yet available. However, physical modeling is beneficial. It is necessary that the model be able to reproduce certain morphological forms such that a reproduction of field observations is produced. The single experiment established that models can be run in the laboratory flume and we can create deposition events. To date we have not made any attempts at proper force scaling.

Numerical Modeling

Certainly numerical modeling is a useful tool. Application of numerical modeling at this time is limited to examination of general cases. It might be possible to reproduce bedforms and gravel movement for typical cases, such as what is being attempted with the physical modeling. If this were the case, then an attempt at measuring the relative impact of crossing relative elevation (to the bed) could be made.

Bottom Line

It is too early in the research project life to predict the outcome of the research. Current open lines of research, as expressed in the above paragraphs, need to be finished before recommendations as to project continuation and project workplan can be made. It is recommended by the researchers that an assessment of results and plans be done again, in a project meeting to be held in the first quarter of calendar year 2005. At that *time, a decision of whether to continue the project, and the workplan for such a continuation, can be made with the Project Director and the Project Advisory Committee.*

References

Asquith, W.H., 1997, Effects of regulation on L-moments of annual peak streamflow in Texas: U.S. Geological Survey Water-Resources Investigations Report 01-4243, 66 p.

Asquith, W.H., and Slade, R.M., 1997, Regional equations for estimation of peak-streamflow frequency for natural basins in Texas: U.S. Geological Survey Water-Resources Investigations Report 96-4307, 68 p.

Heitmuller, F.T., Asquith, W.H., Fang, X., Thompson, D.B., and Wang, K.H., 2004, Guidance for Design in Areas of Extreme Bed-Load Mobility: Literature Review for Texas Department of Transportation Research Project 0–4695: U.S. Geological Survey Open-File Report, in review

Mayer, L., and Pearthree, P.A., 2002, Mapping flood inundation in Southwestern Arizona using Landsat TM data—A method for rapid regional flood assessment following large storms: Ancient Floods Modern Hazard, House, P.K., Webb, R.H., Baker, V.R., and Levish, D.R., editors, American Geophysical Union, Washington D.C., pp. 61–76.

Zhang, J., Xu, K. Watanabe, M., Yang, Y. and Chen, X., 2004, Estimation of river discharge from non-trapezoidal open channel using QuickBird-2 satelite imagery: Hydrological Sciences, vol. 2, no. 2., pp. 247-260.