6-1-2007

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An ASABE Meeting Presentation
Paper Number: 072088

Modeling Beaver Dam Effects on Ecohydraulics and Sedimentation in an Agricultural Watershed

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Written for presentation at the
2007 ASABE Annual International Meeting
Sponsored by ASABE
Minneapolis Convention Center
Minneapolis, Minnesota
17 - 20 June 2007

Abstract. *Populations of North American beaver (Castor canadensis) have increased in recent decades throughout the agricultural Midwestern U.S., leading to an increase in the frequency of beaver dams in small streams. The impact of beaver dams on channel structure in this region is not known. Our field observations indicate that beaver dams are too dynamic and their affects on channel structure occur over longer time frames than is practical to study with field measurements. Modeling is therefore needed to determine if beaver dams will help stabilize and aggrade incised streams. The objective of this paper is to determine how a channel evolution model (CONCEPTS) might be used to predict the impact of beaver dams on channel structure.*

The study area, Little Muddy Creek watershed in southeastern Nebraska, is predominantly in agricultural land use. The main reach of the third –order watershed was surveyed for beaver dams from 2003 to 2005. Dam locations were mapped, integrity of dam structure was noted, and water surface elevations were measured. Failure of dam structure was documented following runoff-producing storms. While some dams were repaired within weeks, others were abandoned and left to *degrade, causing a significant and transient change in the water surface profile of the stream. Field observations showed that the spatial arrangement and hydraulic condition of beaver dams were temporally dynamic in both short and long term scales.*

Laboratory tests were conducted to determine if beaver dams could be modeled as broad-crested weirs. Discharge-rating curves were developed for a simulated beaver dam and a conventional weir. The roughness caused by the sticks on the surface of the dam significantly altered the stage-discharge relationship, but did not violate the broad-crested weir model.

Accounting for the temporal dynamics of spatial and hydraulic characteristics of beaver dams represents the greatest challenge to modeling the impact of beaver dams on stream channel morphology. TheCONCEPTS model, however, enables manually inserting the appropriate temporal patterns of structural change into model simulations and, thus, allows prediction of dynamic, long-term effects.

Keywords. beaver dams, sedimentation, ecohydraulics, failures, rating curve, modeling

Introduction

In southeastern Nebraska, the majority of land has been converted from tallgrass prairie to agricultural land use with 75% of land currently used for row crops. Between 1904 and 1915, many stream channels in southeastern Nebraska were dredged and straightened (Wahl and Weiss 1988), resulting in shorter and steeper channels. These changes have resulted in severe channel incision and stream bank instability, a problem that is repeated throughout the deep loess regions of the central United States (Lohnes 1997). This trend towards continued channel degradation continues to this day (Zellars and Hotchkiss 1997), creating numerous environmental and economic concerns related to land loss and water pollution.

Beaver can affect geomorphology of streams in ways that may counteract the channel degrading processes. Beaver dams reduce stream velocities, causing increased sediment deposition behind the dam (Naiman 1986) and giving the channel gradient a stair-step profile (Naiman 1988). In a forested ecosystem, Naiman et al. (1986) studied beaver dams in fourth order and smaller streams and found that ponds behind individual dams held between 2000 – 6500 m^3 of sediment. There was an average of 10.6 beaver dams/km of stream. They calculated that approximately 10,000 m^3 sediment/km of channel were retained by beaver dams in two forest watersheds in Quebec, Canada.

The influence of beaver dams on channel morphology and stability in developed agricultural areas is not known. Our field observations indicate that beaver dams are too dynamic and their affects occur over longer time frames than is practical to study with field measurements alone. Modeling is therefore needed to determine if beaver dams will help stabilize and aggrade incised streams. The objective of this study is to determine how a channel evolution model (CONCEPTS) might be used to predict the long term impact of beaver dams on channel structure in our study watershed.

Methods

Channel Evolution Model - CONCEPTS

The CONCEPTS model is a watershed-scale, mechanistic, stream channel evolution model that is based on the hydraulics of flow and of erosion and sediment transport and deposition (Langendoen 2000). The model enables the placement of in-stream structures and estimates the long-term response of channel dimensions. To model beaver dams using CONCEPTS, field measurements and laboratory data must be collected to properly describe the spatial, temporal, and hydraulic characteristics of beaver dams as in-stream structures. The next step is to develop a strategy for inputting these data, particularly the temporal data, into CONCEPTS in order to describe the effects of beaver dams on channel morphology over decades-long periods of time.

Study Site

The study was conducted on Little Muddy Creek, Otoe County, in southeast Nebraska. The study stream reach was 8810 m long from the uppermost first-order tributaries (Strahler 1957) to the furthest downstream third-order reach that was surveyed. The first- through second-order portion of the survey has 430 hectares of upland watershed. The total contributing watershed area to the end of third –order reach is approximately 1813 hectares. Land use in the watershed is mainly agricultural, with approximately 75% of the land in cropland and 25% in pasture or Conservation Reserve Program (CRP). The predominant soils in the uplands are eroded, fine-textured loess and glacial till soils with slopes from 2 – 7 %. In the drainages, soils are clay and silt loams and silty clays.

Little Muddy Creek is a tributary to the Little Nemaha River, which drains into the Missouri River. Land clearing until the 1930's increased surface runoff, soil erosion from the uplands, and sedimentation in the streams, which lead to increased flooding (Soenksen 2003). To reduce flooding, the Little Nemaha River and its tributaries were dredged, straightened and cleared of vegetation starting in the early 1900’s. This disturbance is regarded as the main cause of present channel incision throughout the basin (Rus 2003). In the upper reaches of the basin, Muddy Creek was straightened between 1947 and 1953. Knickpoints from channel straightening migrated upstream and most effects on streambeds have already occurred (Rus 2003). In our study area, knickpoints are still evident, working up the first order portions of the streams. It is estimated that in the Little Nemaha River Basin, streambed degradation since settlement averaged 1.9 meters for 21 bridge locations throughout the basin (Rus 2003).

Study I. Field Spatial and Temporal Characteristics of Beaver Dams

Field Methods

Surveys were conducted on seven different dates from 2003 – 2005. The surveys were conducted on the first-order through third-order reaches of the stream. On each date, locations of beaver dams were recorded using a mapping grade GPS unit. At each beaver dam, the drop in the water surface upstream to downstream was measured with a hand level and survey rod. Dams were classified as either “intact” or “damaged” based on whether or not they were in good repair or had breached. A breach in the dam allowed water levels to drop behind the dam; however some breached dams still ponded water and had a localized water level drop. Photographs and field notes were used to record the condition of the dams and evidence of the presence of beaver, such as recent gnawing on trees by beaver, active dam building, and evidence of den locations such as the lodge itself or a food cache.

Surveys conducted in 2003 and 2004 were done on first- through second-order reaches of Little Muddy Creek, where the total stream length was 670 m with 270 m of first-order and 400 m of second-order reaches. In 2005, the survey area was extended 6610 m downstream to the confluence with Muddy Creek with 2680 m of second-order and 3930 m of third-order streams. Total stream length surveyed along the Little Muddy was 7280 m along the main channel.

Surveys were conducted during late winter, spring and summer, allowing for comparison of beaver dam structures during these seasons. One survey was conducted to document damage to beaver dams following a large storm runoff event. The May 21, 2005 survey of late spring conditions was repeated one week later on May 28, 2005 following a 25-year storm during which increased stream flows from storm runoff resulted in structural damage to beaver dams.

Field Results

Surveys conducted during 2003 and 2004 showed variation in the number of intact dams along Little Muddy Creek (Table 1). A comparison of April 2003 and April 2004 showed that the number of intact dams decreased from 10 dams to 0. Many of the dams labeled as damaged still had water ponded and therefore showed a localized drop in water surface elevation. Compared to the April 15, 2003 survey, where the total water drop from all dams (intact and damaged) was 4.5 m, the water drop from all dams had been reduced to 2.2 m by April 4, 2004. By May 21, 2004, the same surveyed area had evidence of 5 intact dams.

Table 1. Summary of beaver dam surveys on Little Muddy Creek, Otoe County, Nebraska.

	Number of intact dams*	Number of damaged dams	Channel Distance (km)	Total water drop from all dams (m)	Average water drop at intact* dams (m)	Intact* dams/km	Water drop from all dams/km (m/km)
April 15, 2003	10	4	0.67	4.5	0.4	14.9	6.7
April 4, 2004	0	18	0.67	2.2	0	0	3
May 21, 2004**	5	17	0.67	4.5	0.6	7.5	6.7
May 28, 2004***	1	22	0.67	3.6	1.0	1.5	5.4
August 29, 2004	8	16	0.67	3.2	0.3	11.9	4.8
February 2-March 16, 2005	13	6	6.61	6.6	0.5	2.0	1.0

Note: Surveys done between April 15, 2003 and August 29, 2004 were on 1st- and 2nd-order reaches on a total length of 270 m of 1st-order and 400 m of 2nd-order reaches. The February/March 2005 survey was done downstream from 2nd - 3rd order reaches along 6610 m of the main channel with 2680 m of 2nd order and 3930 m of 3rd order streams.

*Not included were dams that were degraded or damaged by storm runoff.
**Survey following a 2-year storm
***Survey following a 25-year storm

Comparison of the May 21, 2004 and May 28, 2004 surveys indicate the changes following a 25-year storm in the watershed with associated storm flows. The number of dams that were intact decreased from 5 to 1 over the surveyed area. The 25-year storm damaged all of the beaver dams except for one in a 1st-order tributary. The remaining beaver dam had a drop of 1 m. Damage to beaver dams from this storm is indicated by the reduction in the total water drop from all dams in the survey from 4.5 to 3.6 m. As indicated by the May 28th survey, the increase in average water drop of individual dams was caused by the one intact dam. Two months later, in August 2004, the total drop of all dams (3.2 m) had not yet reached the pre-25-year storm level of May 21, 2004 (4.5 m) and the average drop at individual dams also decreased from 0.6 m to 0.3 m from May 21, 2004 to August 2004.

Surveys done in Feb/March 2005 extended 6610 m further downstream along Little Muddy Creek, covering second- through third-order reaches of the main channel. Since the 2005 surveys were done earlier in the year, beaver activity was expected to be less evident than during the late spring and summer surveys. There was no significant difference between the average water level drop at intact dams or the number of intact dams per km when comparing the first- through second-order to the downstream second- through third-order surveys.

The field surveys of beaver dams showed substantial variation in physical condition of individual dams over the period from 2003 to 2005. Dam integrity was seen to be compromised by storm runoff and general decline due to abandonment of the area by beavers. Dams that were damaged by increased storm runoff were not consistently repaired by beavers and repair may vary seasonally, however data is limited in making an assessment of seasonal beaver activity. The total water level drop per stream kilometer tended to correlate with the number of intact dams with the exception of the August 29, 2004 survey, when the number of intact dams increased while the total drop/km decreased. This data suggests that although the number of dams that were repaired had increased, they had not rebuilt to previous heights. This may be due to beavers abandoning the area or decreased dam building activity during the summer months.

The spatial arrangement of the dams also varied with time, with new dams being built and old dams left to degrade (Figure 1). There was a noticeable grouping of beaver dams where several dams would be clustered around a zone of beaver activity. Zones were noted by long gaps between groups of intact dams. In addition, evidence of recent beaver presence such as recently gnawed trees and beaver dens correlated strongly to clusters of intact dams. Field observations indicate that locations of intact dams have a positive spatial correlation to the beaver den.

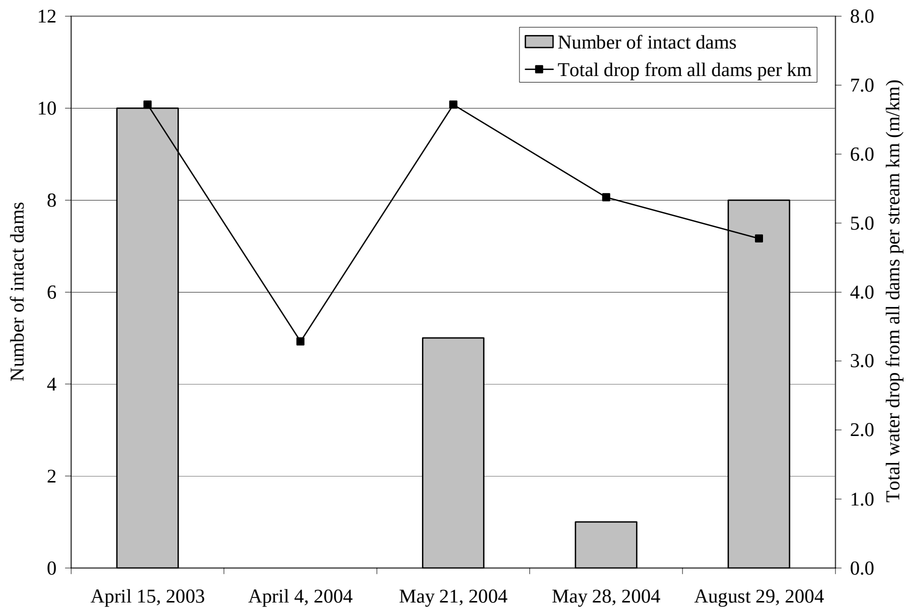

Figure 1. Number of intact beaver dams over the survey period and impacts of the beaver dams on water drop.

Study II - Laboratory Tests of Hydraulic Characteristics of a Beaver Dam

Laboratory Methods

A laboratory study was conducted in the hydraulics laboratory at the Biological Systems Engineering Department at the University of Nebraska-Lincoln to determine if a beaver dam could be reasonably modeled as a broad-crested weir. A replica beaver dam was constructed and installed in the open channel of the lab to examine the effects of roughness (sticks) on the surface on the rating curve as though it was a broad-crested weir.

A replica beaver dam was constructed in the laboratory based on the survey of a beaver dam on Little Muddy Creek (Figure 2). Actual dimensions of the beaver dam were replicated in the laboratory, with the exception of the actual dam width. The laboratory channel was 0.91 m wide, while the actual beaver dam surveyed was 3.7 m wide. The replica beaver dam consisted of a pressure-treated plywood structure installed into the laboratory channel. The smooth plywood simulates the smooth mud surfaces on the upstream slope of beaver dams that we observed. Sticks from actual beaver dams in the field were collected and attached to the plywood replica dam to mimic roughness observed in the field. They were fastened to the dam with small wire.

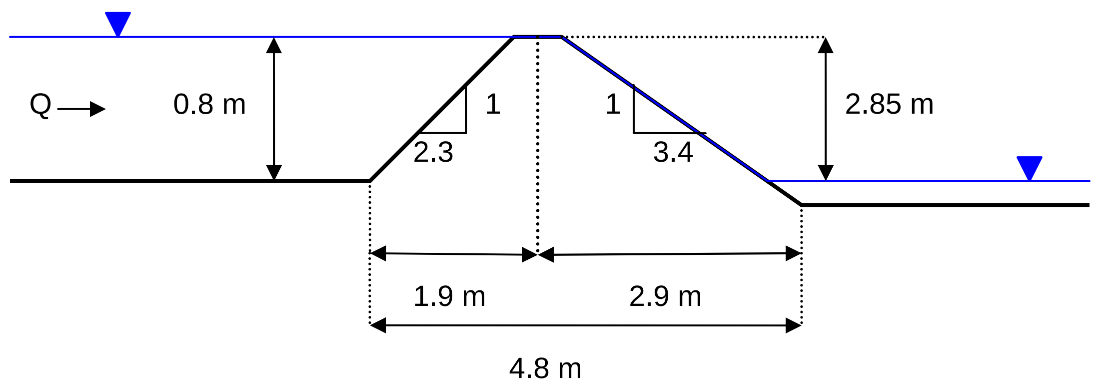

Figure 2. Representation of the side profile of a beaver dam on Little Muddy Creek. Drawing is not to scale.

Field observations and photos were used to help construct the structure of the sticks on the simulated beaver dam. Larger diameter sticks were first attached to the bottom of the downstream face of the dam with gradually smaller diameter sticks being attached while working up the downstream dam face. The pattern of stick attachment was similar to shingling a roof, with the sticks on the top of the dam covering the sticks further down the dam on the downstream face. No sticks were attached to the upstream face of the dam, replicating the smooth mud surface of the beaver dams observed in our watershed.

Two phases of tests were conducted on the replica dam. First, a series of control tests were run on the smooth plywood shell of the dam. Second, beaver dam sticks were attached to the top and downstream face of the replica dam and the series of tests was repeated. Four flow rates were used for both control and experimental tests: 0.014, 0.042, 0.071 and 0.11 m^3/s. Flow was measured using a 15.24 cm venturi for the two lowest flow rates and a 25.4 cm venturi for the two largest flow rates.

Once each flow rate was established, 10 minutes was allowed for water levels to stabilize in the channel. A point gage was then used to measure water surface elevation at 10 points along the centerline of the channel, from the top of the dam to 4.6 m upstream of the dam. A reference height was established at the top of the dam's front edge centerline and was the same for both the smooth dam and replica beaver dam. Two replications were done for each flow rate tested for both the control and replica dam.

From the water surface elevation data collected, rating curves were developed for both control and replica beaver dam tests. In developing the rating curves, the water surface elevations at 1.5 meters upstream of the dam were used, as at this distance, the water profile was relatively level compared to close to the dam. Rating curves were developed using Sigma Plot using a form of the power equation. For the smooth dam rating curve a power equation was used in the form: $Q = a * H^b$, where Q is the flow rate, H is height of the water surface above the reference sill height, and a and b are fitting parameters with b set to equal1.5. For the replica beaver dam a rating curve was fit using a modified version of the power equation of the form: $Q = a * (H-H_o)^b$, where Q is the flow rate, H is the height of the water surface above the reference sill height, H_o represents an average height of the sticks above the reference sill, and a and b are fitting parameters with b set to equal 1.5. Both rating curves were then translated into the engineering form of the wier equation of the form: $Q = CLH^{3/2}$, where L is the width of the dam (0.91 m). Terms embedded in the C term are as follows: $C=C_d*C_v*(2/3)^{3/2}*g^{1/2}$. C_d is the discharge coefficient which corrects for energy losses, velocity distributions and streamline curvature. C_v is the approach velocity coefficient and g is gravity (Clemmens 2001).

Laboratory Results

When compared to the smooth dam, the replica beaver dam showed an increase in water surface elevation for each of the four flow rates (Figure 3). This increased water surface elevation was approximately 30 cm for the lowest flow rate and 60 cm for the highest flow rate. The rating curve fitted for the control dam was: $Q = CLH^{3/2}$, where $C = 1.69 m^{1/2}/s$. The rating curve for the replica beaver dam was $Q = CL(H-H_o)^{3/2}$, where $C = 1.61\ m^{1/2}/s$ and $H_o = 0.033$ m.

The laboratory tests showed an expected result, that the roughness of the sticks led to increased water height upstream of the dam compared to a smooth dam of equal base dimensions. While the replica beaver dam was constructed to be as realistic as possible, we were restricted from using mud on the dam, which may result in a smoother surface at the sill of actual beaver dams. Field surveys showed that beaver dams had exposed sticks on the top and backside of dams, with mud typically pushed up along the upstream edge of the dam sill. However, given this laboratory restriction, the generated rating curves give a starting point from which to model a beaver dam as a broad-crested weir, adjusting the C coefficient for roughness of the sticks compared to a broad-crested weir of a homogeneous material (earthen, plywood, etc).

Discussion

A Strategy for Modeling Long-Term Impacts of Beaver Dams

Channel evolution models typically require input of a structure that remains constant with time. However, our results clearly show that modeling beaver dams requires that dams change temporally in both dimension and spatial arrangement in ways that may substantially influence how they affect stream channel morphology.

The results of laboratory testing of a beaver dam replica indicate that it is reasonable to model these structures as broad-crested weirs, but it appears that it may be necessary to adjust the crest elevation of the dam with an offset. In the lab test, this offset was about 3 cm, but the offset likely depends on other geometric characteristics of the dam.

Hydraulic characteristics of beaver dams vary temporally over both long and short time periods. For example, some dams are damaged by storm runoff and only some of them are repaired after a period of weeks, while others were never repaired and their structure disintegrates over a longer period of time.

The spatial arrangement of beaver dams along the stream also varies with time. Locations of intact dams along the second-order reaches of Little Muddy Creek shifted generally downstream with dams in the uppermost parts of the second-order reach being abandoned over the course of our study. Surveys in the lower portion of the watershed (second- through third-order reaches) indicated fewer dams (intact and damaged) existed than in the upper portion of the watershed (first- through second-order).

In order to model the dynamic nature of beaver dams (e.g. dam failures, rebuilding) using CONCEPTS, the structures will be need to be added or removed from the modeled stream channel and the dimensions of individual dams will need to be altered to reflect structural changes. To do this, temporal and spatial patterns of the hydraulic characteristics beaver dams must be manually adjusted at defined time points during model simulations. The patterns that were observed at the field site will help to define both the nature of the adjustments that are required and the timing of them over a long time-period simulation.

Some aspects of the dynamic character of beaver dams (e.g. failures, abandonment) cannot be modeled precisely by CONCEPTS. Field observations show that beaver dam failures often occurred as a small breach in the dam, leaving much of the structure intact. To model beaver dam failure in CONCEPTS, the entire height of the structure must be reduced rather than just a portion of it. It is not clear how sensitive modeled results might be to this inaccuracy.

Future work will involve calibrating and validating the model for the study site and then using the model to predict the impact of beaver dams on channel structure in incised streams in eastern Nebraska. Model scenarios will be run to compare channel dimensions in the presence of beaver dams over a multi-decade period with that in the absence of beaver dams.

Conclusion

This study confirmed that beaver dams may be reasonably modeled as broad-crested weirs for predicting their long term impact on stream channel morphology. However, field observations also determined that hydraulic characteristics of individual dams and the spatial arrangement of multiple beaver dams along stream reaches varies temporally over both long and short time periods. These characteristics of beaver dams represent challenges for modeling their long-term effects on stream channels. The challenges are not insurmountable since it appears possible to manually insert the appropriate temporal patterns of structural changes into the CONCEPTS model in order simulate long term effects.

Acknowledgements

Special thanks go to Alan Boldt for his help on this project, including surveying stream cross sections, and managing and analyzing Total Station and GPS data. Thanks also to Jodi Harper, whose honors thesis in 2003 was the initial study from which this paper has built upon. Many student workers spent time with me in the field, collecting data about beaver dams, including Paulo Luchiari, Brian Twombly, and Carrie McMurray. Thanks also to Eddy Langendoen at the USDA-ARS-National Sedimentation Lab for his ideas about how to simulate a beaver dam in CONCEPTS as well as help in setting up and running the model.

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