Modeling Channel Instabilities and Mitigation Strategies in Eastern Nebraska

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Abstract

Little Salt and West Papillion Creeks in eastern Nebraska have incised and widened, and are threatening saline wetlands (Little Salt Creek) and urban infrastructure (West Papillion Creek) adjacent to the channels. Field studies were carried out to determine erodibility of the cohesive streambed-material, shear strength of the cohesive streambank-material, and channel geometry. Channel evolution simulations with the CONCEPTS model indicate that the modeled reach of Little Salt Creek will degrade over its entire length, varying from 1.5 m at its upstream end to 4.0 m at its downstream end, and that the modeled reach of the North Branch West Papillion and West Papillion Creeks will degrade approximately 2.8 m at its upper end. Near the saline wetlands along Little Salt Creek the average widening at the bank top is 0.6 m. Along the North Branch West Papillion Creek the average widening of the bank top near Fort Street is 1.3 m. Controlling the streambed at bridge crossings along Little Salt Creek prevents channel incision near the saline wetlands. Generally, incision is reduced by about 60 percent. Grade control structures along the upper part of North Branch West Papillion Creek only reduce erosion in their upstream vicinity. Grade control structures would reduce average channel incision by approximately 40 percent. However, maximum channel incision is only reduced by 25 percent.

Introduction

Many stream channels in eastern Nebraska were altered in the early 1900's to help alleviate flooding problems. Channel straightening has long been recognized as a cause of channel instability problems (for example, Simon and Rinaldi, 2000), such as downstream deposition, upstream degradation, and widening of the channel, which pose hazards to roads and bridges. In addition the channel banks, which comprise highly erodible soils, were severely eroded by extended periods of saturation following the floods of 1993. Many small county bridges failed or were closed following the floods. Clearing of large tracts of land during settlement of the region prior to and after the Civil War (Brice, 1966) resulted in increased rates of surface runoff, erosion of uplands, and gullying of floodplains and terraces. Removal of woody vegetation from streambanks resulted in decreased hydraulic roughness, increased flow velocities, and contributed to increased peak discharges. Much eroded material was deposited in channels, resulting in loss of channel capacity and frequent and prolonged flooding of agricultural lands (Moore, 1917).

As a result of ubiquitous channel filling, local drainage districts implemented programs to dredge, straighten, and shorten stream channels to reduce flooding and thereby increase agricultural productivity (Moore, 1917). Work was undertaken in southeastern Nebraska around

1910 (Moore, 1917). Dredging and straightening significantly increased bankfull discharge and channel gradient, resulting in a proportionate increase in bed-material discharge and rapid morphologic changes. These changes included upstream degradation, downstream aggradation, and bank instabilities along altered streams and adjacent tributaries. In combination with the low resistance to erosion exhibited by the loess-derived channel materials, it is the increase in the erosional force by channel dredging and straightening near the turn of the 20th century that caused the deep entrenchment, general states of instability, and present day problems in the channel systems in the loess area of the midwestern United States.

The U.S. Geological Survey-Nebraska District (USGS), Papio-Missouri River and Lower Platte South Natural Resources Districts, Nebraska Department of Roads, Federal Highway Administration, University of Nebraska, Lincoln, U.S. Army Corps of Engineers (USACE), and U.S. Department of Agriculture-Agricultural Research Service-National Sedimentation Laboratory (NSL) are examining the effects of channel instabilities on bridge structures and floodplain resources in a 23-county area of eastern Nebraska. One aspect of NSL's role includes numerical channel-response modeling of parts of Little Salt Creek (LSC) near Lincoln (Figure 1), and West Papillion Creek (WPC) near Omaha (Figure 2). The numerical model study reaches were located on: (1) Little Salt Creek, reach extending from 0.4 km upstream of Raymond Road to Bluff Road, Lancaster County; and (2) North Branch West Papillion Creek (NBWPC) and WPC, a reach extending from 0.7 km upstream of Fort Street to West Center Street, Douglas County. The purposes of the modeling efforts are: (1) evaluate the ability of alternative types and placements of mitigation measures to enhance channel stability (Papillion Creek and Little Salt Creek Basins), and (2) evaluate the effects of urbanization on channel stability (Papillion Creek Basin).

LSC is a tributary of Salt Creek and drains approximately 119 km^2. The average channel slope along the modeling reach is 0.0015. Saline wetlands in the Salt Creek basin have diminished from 6,500 ha originally to approximately 500 ha (Lower Platte South Natural Resources District, 1999). They hold a diversity of wildlife and contain rare plant communities. Channel incision is endangering a saline wetland north of Raymond Road, which may lead to draining of the wetland. Channel incision may also lead to additional streambank failures and loss of wetland area. WPC is a tributary of the Big Papillion Creek and drains approximately 163 km^2 just upstream of the confluence with South Papillion Creek and Hell Creek. The average channel slope along the modeling reach is 0.0023. WPC has been severely impacted by urbanization. The channel has incised and widened significantly. Urbanization in WPC watershed is continuing north of Blondo and Maple Streets. It is expected that runoff will increase, leading to continuing incision and streambank failures along NBWPC.

CONCEPTS Model Overview

The CONCEPTS (CONservational Channel Evolution and Pollutant Transport System) model is being developed to evaluate stream-corridor restoration designs (Langendoen, 2000). The basic components of the model are channel hydraulics and morphology. CONCEPTS simulates unsteady, one-dimensional flow, graded-sediment transport, and streambank-erosion processes. Sediment loads are calculated using a mass-conservation equation with erosion and deposition rates that depend on the type of bed material. The streambeds of the modeling reaches are cohesive. The erosion rate (E) of a cohesive streambed can be defined as:

$$E = K(\tau - \tau_c) \tag{1}$$

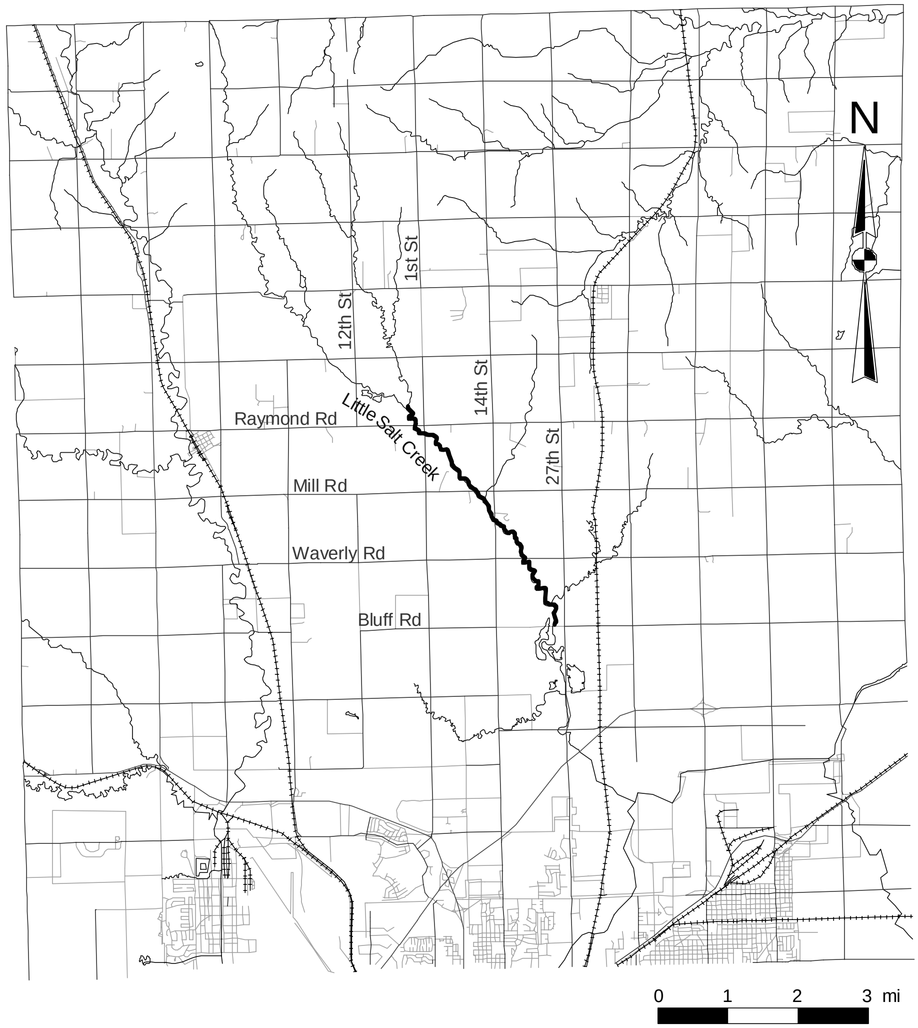

Figure 1 Map of Little Salt Creek, Lancaster County, Nebraska.

where K is an erodibility coefficient, τ is the shear stress exerted by the flow on the streambed and τ_c is a critical shear stress at which bed material will be entrained.

In the study reaches streambank erosion has occurred by channel-bed lowering followed by mass failure. Erosion of cohesive streambanks is a combination of lateral erosion of the bank toe by fluvial entrainment of bank-material particles and mass failure of the bank. We use Osman and Thorne's (1988) method based on excess shear stress (similar to Eq. (1)) to calculate lateral erosion. Streambank failure occurs when gravitational forces that tend to move soil downslope exceed the forces of friction and cohesion that resist movement. The risk of failure is expressed by a factor of safety defined as the ratio of resisting to driving forces. CONCEPTS computes factor of safety for unsaturated streambanks taking into account the effects of positive and negative pore-water pressures, and confining pressures (Simon *et al*., 1999).

Characterization of Study Sites

Discharge. A USGS gaging station is located downstream of the modeling reach at Arbor Road on LSC. Daily discharges are available for water years 1969-1998 and semi-hourly

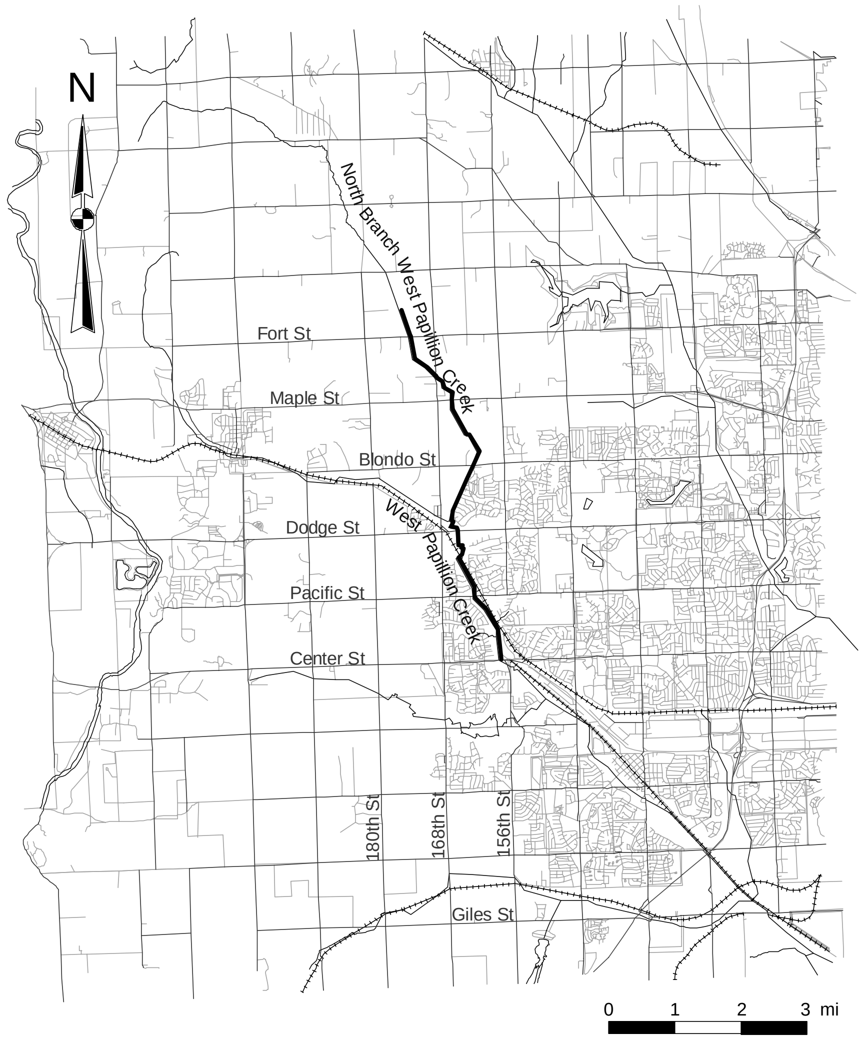

Figure 2 Map of North Branch West Papillion and West Papillion Creeks, Douglas and Sarpy Counties, Nebraska.

instantaneous discharges for water years 1991-1994 and 1996-1998. A USACE gaging station is located near Giles Road on WPC. Daily discharges are available for water years 1965-1977 and hourly instantaneous discharges for calendar years 1997-1999. We converted the daily discharges to unsteady flow hydrographs (Langendoen and Simon, 2000). Using drainage-area analysis, we converted the discharges at the gaging stations to discharges at the upstream boundary of the modeling reaches.

Bed-material properties. We performed in situ field experiments using a submersible jet device (Hanson, 1990) to measure the erodibility coefficient (*K*) and critical shear stress (τ_c) of the cohesive streambed material of LSC and WPC. The apparatus consists of a submerged jet with a nozzle diameter of 13 mm, set at a height of 0.22 m above the initial soil surface. Monitoring the depth of scour during a test yields the erodibility coefficient and critical shear stress. Bed-sediment samples were collected to determine particle size distributions.

Critical shear stress is fairly constant along the modeling reach on LSC (Langendoen and Simon, 2000). The average critical shear stress is 7.7 Pa. The average erodibility is

0.28×10^{-6} m/Pa s. The critical shear stress varies significantly along the modeling reach on NBWPC and WPC. The critical shear stress increases from 2.5 Pa near Fort Street ($K = 0.36$ m/Pa s) to 10 Pa near 168th Street ($K = 0.14$ m/Pa s), to 55 Pa downstream of Blondo Street ($K = 0.008$ m/Pa s), and to 118 Pa near Dodge Street ($K = 0.015$ m/Pa s).

The streambed material of LSC and WPC is a silt loam. The clay content on WPC (22%) is slightly larger than that on LSC (14%).

Bank-material properties. We performed a series of in situ field experiments using a borehole shear test (BST) device (Luttenegger and Hallberg, 1981) to determine the shear strength of the cohesive streambank material of LSC and WPC. The shear-strength parameters determined by the BST device are apparent cohesion and angle of internal friction. On LSC, the average effective cohesion is 4.3 kPa and average angle of internal friction is 30.9 degrees. On WPC, the average effective cohesion is 4.75 kPa and average angle of internal friction is 29 degrees.

Bank material samples were collected at the BST locations to determine bank material composition and unit weight. The average bulk density along LSC is 1.58 g/cm^3. The average bulk density along NBWPC and WPC is 1.45 g/cm^3. The bank-material composition is similar to that of the bed.

Little Salt Creek Study Results

Setup of simulations. We used CONCEPTS to study the long-term stability of LSC between Raymond and Bluff Roads. We performed model runs to determine the sensitivity of the modeling results to bed roughness and discharge. Langendoen and Simon (2000) report the results of all simulations. Here, we only present the significant outcomes. Manning's *n* of streambanks and floodplains are 0.06 and 0.15, respectively, except for the streambanks upstream of Raymond Road that have *n* values of 0.08 because of the level of vegetation overgrowth. Values of bed and bank-material parameters are given in the previous section. Data on the critical shear stress to entrain bank-material particles are unavailable. Therefore, we assume it to be equal to that of bed-material particles, that is 7.7 Pa.

In the following sections we refer to the distance downstream of the upstream boundary of the modeling reach as "model kilometer."

Channel evolution. Figure 3 shows the predicted thalweg profiles of the modeling reach at various points of time using the historic 30-year discharge data. We did not fix the elevation of the channel bed at the downstream boundary of the modeling reach during the simulation. The downstream end of the modeling reach is degrading. In reality, processes occurring further downstream, for example at the confluence of LSC with Salt Creek, control the downstream boundary of the reach. However, the bed protection at the drop (model kilometer 7.3) prevents any disturbance (incision) at the downstream boundary from propagating upstream.

The figure shows that the modeling reach is degrading. Channel incision varies from about 4.3 m near the downstream end of the channel (model kilometer 7.1) to 1.5 m at the upstream end of the channel. The increase in bank height associated with incision leads to a series of bank failures along the entire channel. The average widening is 0.6 m upstream of Raymond Road, 1.5 m upstream of Mill Road, 0.4 m upstream of North 14th Street and Waverly Road, and 1.2 m near Bluff Road.

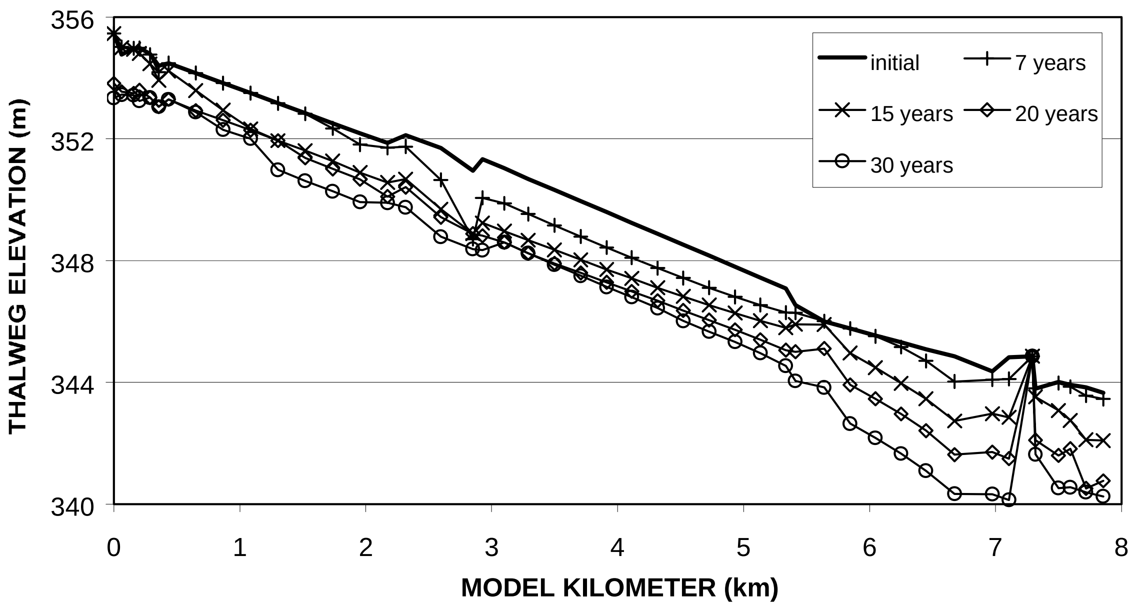

Figure 3 Simulated evolution of the thalweg profile, Little Salt Creek, for a 30-year period.

Stabilization alternative. Given the observed erodibility of the surface of the streambed and types of flows occurring between 1969 and 1998, LSC will incise further. Figure 3 shows that incision progresses from the middle and downstream end of the modeling reach to its upstream end. Hence, controlling channel grade at selected locations may deter incision.

We performed a simulation in which we controlled the grade of all bridge crossings along the modeling reach. Figure 4 shows the resulting simulated evolution of the thalweg profile. With the addition of the simulated grade-control structures at the bridges there is no or only minor channel incision upstream of Mill Road. Incision has been reduced between Mill and Bluff Roads. Figure 4 also shows that the second grade-control structure, bridge crossing at North 1st Street, may be omitted.

West Papillion Creek Study Results

Setup of simulations. We used CONCEPTS to study the long-term stability of NBWPC and WPC between Fort and West Center Streets. We performed model runs to determine the sensitivity of the modeling results to discharge, Manning *n* of the streambed, and critical shear stress of the bank material. Langendoen and Simon (2000) report the results of all simulations. Here, we only present the significant outcomes.

Using the measured erodibility and critical shear stress for the streambed resulted in excessive scour of the streambed at the upstream end of the modeling reach, upstream and downstream of Fort Street. Even the smallest flow events (those slightly larger than the base-flow discharge of 0.2 m^3/s) exerted shear stresses at the bed exceeding 2.6 Pa. Therefore, we doubled critical shear stresses between Fort and 168th Streets, which now vary from 5.0 Pa to 10.0 Pa. Measured data on critical shear stress to entrain bank material are not available. We may assume that it is similar to that of bed material. However, the latter is as large as 100 Pa along the modeling reach. This is an unreasonable value for moist bank-material. Hence, we used a critical shear stress similar to that in the LSC study, 8 Pa. In addition, we carried out

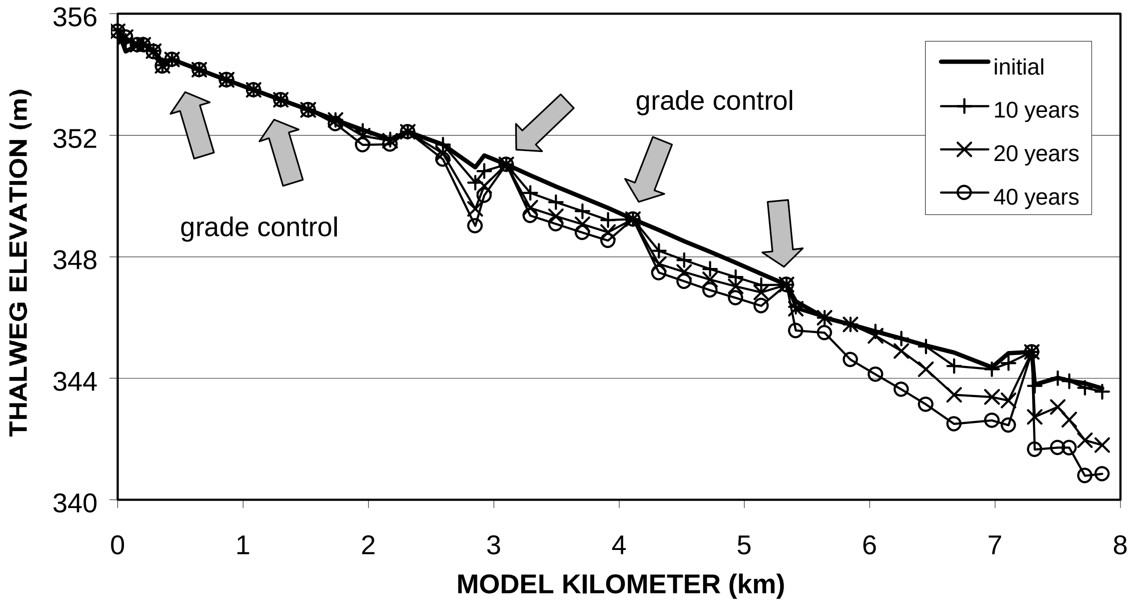

Figure 4 Simulated evolution of the thalweg profile, Little Salt Creek, for a 60-year period and the streambed controlled at each bridge crossing.

simulations with critical shear stresses for bank material of 6 Pa and 16 Pa. Manning's *n* of streambanks and floodplains are 0.04 and 0.15, respectively. Values of bank-material parameters are those measured.

In the following sections we refer to the distance downstream of the upstream boundary of the modeling reach as "model kilometer."

Channel evolution. Figure 5 shows the predicted thalweg profiles of the modeling reach at various points of time using the historic 16-year discharge data. The figure shows that the streambed is degrading from the inlet of the modeling reach to model kilometer 3.91, which is halfway between Maple and Blondo Streets. Further downstream, the streambed is stable because the shear stresses exerted by the flow are smaller than the critical shear stress to entrain the bed material. The maximum simulated channel-incision is approximately 3.5 m near Fort Street.

Incision leads to a series of bank failures upstream and downstream of Fort Street. Also, several streambanks failed downstream of Blondo Street. As in the LSC study, incision prevails over bank retreat at the bank toe (Langendoen and Simon, 2000), because the erodibility coefficient computed by Osman and Thorne's (1988) method is much smaller than that measured of the streambed. For example, lowering the critical shear stress by 25 percent causes the lateral erosion to increase from 0.4 m to 3.7 m for cross section 1 upstream of Fort Street (model kilometer 0) and from 0.1 m to 2.3 m for cross section 7 downstream of Fort Street (model kilometer 1.01) after 10 years. As a consequence, the widening rate at the top of the bank also increases. The average widening rates are 1.3 m for $\tau_c = 8$ Pa, and 1.8 m for $\tau_c = 6$ Pa. Failure of both banks of a cross section ($\tau_c = 6$ Pa) as opposed to only one of the banks of a cross section ($\tau_c = 8$ Pa) causes this.

Stabilization alternative. The above simulations show that the NBWPC will incise upstream of Maple Street using the historic 16-year discharge record and the observed erodibility of the

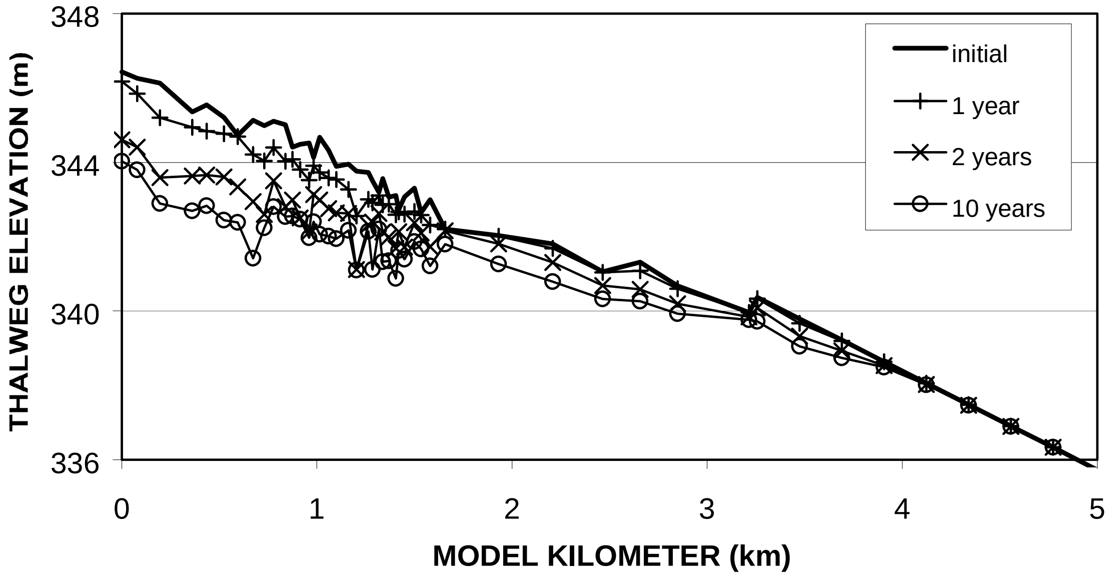

Figure 5 Simulated evolution of the thalweg profile, North Branch West Papillion and West Papillion Creeks, for a 16-year period.

surface of the streambed. We evaluated the following stream-channel stabilization alternative: the grade at the bridge crossings at Fort, 168th, and Maple Streets are controlled and control structures are added halfway between the upstream boundary and Fort Street, and halfway between Fort and 168th Streets.

Figure 6 shows the simulated evolution of the thalweg profile. Although, the control structures reduce incision in their upstream vicinity, the magnitude of erosion further upstream of the structures is the same as without control structures (cf. Figure 5). The average amount of incision upstream of Fort Street reduces from 2.8 m to 1.3 m. The average incision between Fort Street and model kilometer 1.6 reduces from 2.0 m to 1.4 m. The maximum amount of incision upstream of Fort Street reduces from 3.9 m to 2.5 m. The maximum amount of incision between Fort Street and model kilometer 1.6 reduces from 3.2 m to 2.9 m. It appears that the erodibility of the streambed mainly determines incision, and therefore, the structures cannot sufficiently control incision along the entire section between Fort and 168th Streets.

These stabilization measures, however, significantly reduce the number of streambank failures. Twenty-five simulated streambank failures were recorded over a 16-year simulation period without any stabilization measures, whereas only 5 streambanks failed with the stabilization measures.

Summary and Interpretation

Little Salt Creek. The erodibility of the streambed material governs the morphology of the modeling reach. In situ field experiments with a jet-test device suggest that erodibility of the streambed material is similar along the modeling reach. In the model simulations, we therefore assumed constant erodibility coefficient and critical shear stress to entrain bed material. As a result, channel incision increases along the modeling reach (Figure 3). The resulting increase in bank height leads to bank failures along the entire modeling reach. Because incision at the downstream end of the modeling reach is larger than that at the upstream end, the thalweg profile

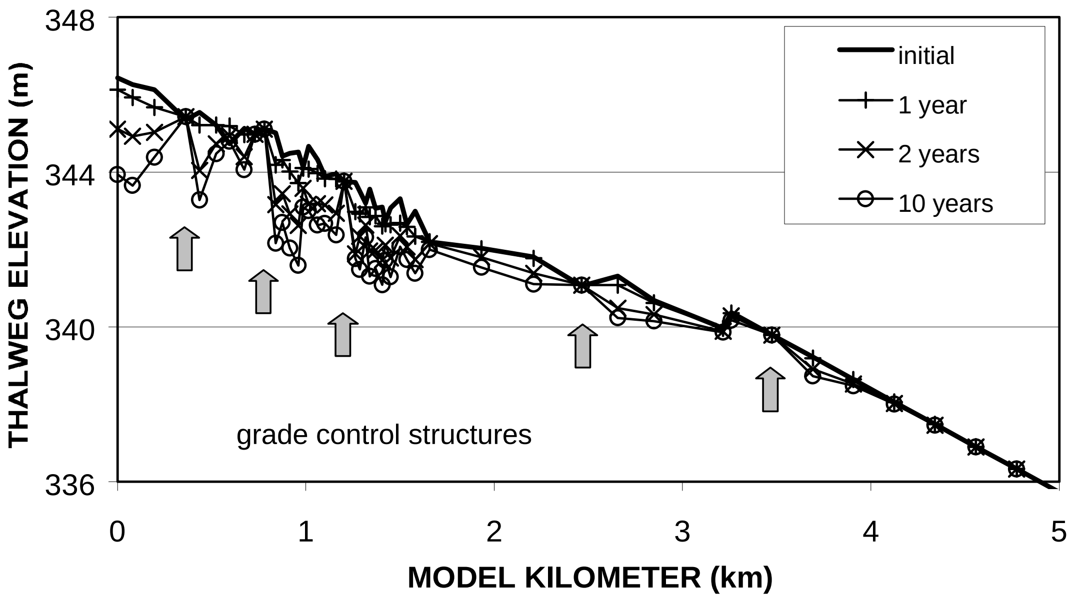

Figure 6 Simulated evolution of the thalweg profile, North Branch West Papillion and West Papillion Creeks, for a 16-year period and grade control structures at model kilometers 0.4, 0.8, 1.2, 2.5, and 3.5.

steepens, causing incision to progress from downstream to upstream. Therefore, we can deter incision by controlling channel grade at selected locations. Figure 4 shows that grade control structures at either Raymond Road or North 1st Street, Mill Road, North 14th Street, and Waverly Road prevent channel incision at the saline wetlands upstream of Raymond Road. Channel incision between Mill and Waverly Roads is reduced by approximately 60 percent.

North Branch West Papillion and West Papillion Creeks. The erodibility of the streambed material governs the morphology of the modeling reach. Along the section between Fort and 168th Streets, the shear stresses exerted by the flow on the channel bed are larger than the critical shear stress necessary to entrain bed material measured by the jet-test device. As a result, NBWPC incises upstream of 168th Street (Figure 5). The resulting increase in bank heights leads to a series of bank failures upstream and downstream of Fort Street. Grade control structures may partially alleviate the incision of the streambed (Figure 6). They reduce average channel incision by approximately 40%, but maximum channel incision upstream of the various grade control structures only by approximately 25%. The grade control structures are more effective in reducing the number of streambank failures; there is a reduction of 80%. Figure 6 also shows that the grade control structures at 168th and Maple Streets may not be needed for the spectrum of flow events that occurred during the period 1965-1977 and 1997-1999. However, the expected increase in discharge due to ongoing urbanization upstream of Maple Street will result in increased shear stresses exerted on the channel bed. Langendoen and Simon (2000) show that larger discharges produce greater shear stresses on the streambed, causing greater incision and extending the incision from model kilometer 3.91 to model kilometer 5.21.

The results should be interpreted with care. The main parameters determining future evolution of the modeling reaches are the erodibility of the streambed material and the critical shear stress at which erosion commences. We measured these parameters at the surface of the streambed and assumed them constant across the depth of the streambed. Commonly the bed becomes firmer and more resistant to erosion away from its surface. Cores collected upstream of Raymond Road along LSC show that the bed becomes firm to very firm at a depth of 0.3 m. Also, the lower end of the modeling reach along WPC has previously incised exposing soils much more resistant to erosion ($\tau_c \approx 100$ Pa versus $\tau_c \approx 5$ Pa). The incision of LSC and NBWPC may, therefore, be regarded as upper limits of expected incisions.

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