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An evaluation of the impacts of land voiding caused by degrading waterways: an engineering economic approach

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by

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I. INTRODUCTION

Much of western Iowa is covered by Wisconsin Age loess (wind blown soil) that was deposited from 29,000 to 14,000 years ago (Ruhe, 1969). Loess, a geological term of German origin meaning loose or crumbly, consists primarily of silt and clay sized particles which have a low resistance to erosion. In the northermost portion of the region (Sioux and Plymouth counties and a portion of Ida county), loess deposits range from 5 to 20 feet thick. In the southern counties, loess deposits range from 100 feet thick along the Missouri River bluff line to 15 feet to the east and north (Dirks, 1981).

Until the early part of this century, streams in western Iowa's leoss region were naturally meandering rivers which frequently flooded their valleys (Massoudi, 1981). Beginning around 1900 and continuing until approximately 1960, many streams and rivers in the region were channelized (straightened) for land reclamation and flood control purposes. The channel improvement programs were successful in converting flood-prone wetlands to fertile land for cultivation and other agricultural uses, however; the programs resulted in severe stream channel degradation and widening.

Stream degradation has been responsible for the entrenchment of many of these streams and rivers from 1.5 to 5 times their original channelized depths. This vertical degradation has been accompanied by width increases of 2 to 5 times the original channelized stream widths. As a result, much of western Iowa's loess region has experienced considerable land erosion, or voiding.

The deepening and widening stream channels have imposed substantial costs on public and private infrastructure in western Iowa's loess region (Morris et al., 1994). Degradation of main channels as well as tributaries has jeprodized the structural integrity of rural roads and bridges. State and county governments have been forced to close or add approach spans to county and local roadway bridges (Lohnes et al., 1980). As bridges are abandoned or repaired, rural residents in western Iowa incur increased travel time and costs. For example, a Pottawattamie county farm dissected by Walnut Creek, a degrading stream, suffered a bridge closure due to degradation. The farm owner was forced to traverse an additional six miles for each trip to the "other side" of his farm property. The farm livestock operation located there has since been discontinued due in part to the closing of the bridge (Western Iowa Degrading Streams Task Force, 1991).

Buried natural gas, petroleum, anhydrous ammonia, rural water, and telephone lines have also been exposed and damaged from stream degradation, resulting in increased costs and risk of service interruption. In addition, hundreds of miles of riparian wildlife habitat have been damaged or destroyed by degrading streams. Biologically diverse ecosystems have been replaced by barren stream banks and sediment-congested waters.

Problem Statement and Research Objectives

Problem Statement

The loss of irreplaceable land being voided is a major consequence of stream degradation in western Iowa. Loess is among the most productive soils in the world (Baumel et al., 1994). Land voided due to stream degradation and its embodied productivity are lost forever. Additionally, this erosion of bed and bank material within western Iowa stream channels is responsible for much of the damage to rural infrastructure investments caused by degradation. Methods are needed to estimate the impacts of stream degradation on land and rural infrastructure investments in western Iowa. In addition, methods are needed to facilitate efficient decision making with regard to the allocation of limited funds to control stream degradation. The following objectives of this research attempt to address these needs.

Research Objective One

The first objective is to develop and clarify methods by which the impacts of stream degradation can be estimated. The first objective includes historical as well as predictive analyses of stream degradation. The historical analysis considers the channelized reaches of two degrading western Iowa streams. The analysis utilizes historical data and information to estimate the economic impacts of stream degradation with respect to land voiding and rural infrastructure investments. A model of stream widening over time is developed and used to estimate annual stream widening from the dates of channelization through 1991. Based on the annual stream widening, cost estimates to land and rural infrastructure investments are made. Estimates of the costs of traffic re-routing to circumvent bridges under repair due to degradation are also made. A present value model of asset prices is developed to estimate the economic costs associated with stream degradation.

In order to predict stream degradation, a two stage engineering analysis is employed. First, a tractive force model of stream degradation is used to predict vertical degradation on various segments of two degrading western Iowa streams (Levich, 1994). An estimate of the time for degradation to occur is generated with a rational model of the rate of stream degradation over time (Lohnes, 1980). Second, a computer simulation of a planar slope failure model of stream widening is developed to predict stream widening and land voiding based on the predicted vertical degradation of the tractive force model (Lohnes, 1991). The two stage analysis provides estimates of the maximum stream widening and land voiding for the stream segments considered.

Research Objective Two

The second objective is to develop information, systems, and methods for use in making resource allocation decisions for the protection of land and rural infrastructure investments from the impacts of stream degradation. The second objective considers measures to control stream degradation under the budget constraints of local governmental agencies. An economic model is developed to determine if and where grade stabilization structures should be constructed. The model examines the benefits and costs of placing stream stabilization structures at various locations on two actively degrading western Iowa streams. The optimal mix of project locations is determined by maximizing the net benefit of stream stabilization subject to the budget constraint for the construction of stream stabilization structures.

II. LITERATURE REVIEW

Much has been written within the engineering and geological science disciplines in regard to stream degradation. Daniels (1960) and Daniels and Jordan (1966) studied degradation on Willow Creek. Lohnes, Massoudi, and Dirks have also researched the problem in western Iowa. Lohnes et al. (1980) developed a predictive model for the rate of stream degradation and studied alternative methods for stabilizing degrading streams in western Iowa. Massoudi (1981) studied Willow Creek in an effort to develop a predictive model of stream degradation. Dirks (1980) took a geomorphic approach to predicting stream degradation. Lohnes (1991) developed a model for estimating land loss due to stream degradation.

Morris et al. (1994) measured the historic economic impacts of degrading streams on transportation and utility infrastructure costs. Levich (1994) utilized a tractive force model to predict stream degradation. Yang (1994) estimated the impacts of stream degradation on highway bridges and rural travel patterns. In addition, numerous Iowa Department of Transportation reports have been written on the problem of scour and related structural damage to highway bridges.

Daniels (1960) studied the entrenchment of the Willow Creek channel. In his paper "Entrenchment of the Willow Drainage Ditch, Harrison County, Iowa," Daniels discussed the characteristics of Willow Creek prior to, during, and after its channelization. The author provides a detailed description of the constructed drainage ditch and the subsequent changes it underwent during the period 1919-1958. Included in Daniels' documentation are changes in the width, shape, and longitudinal profile of Willow Creek. Daniels also discusses the mechanism of stream entrenchment (degradation), its effects, and its influence on tributaries. Daniels argues that the change in the stream gradient during the construction of the drainage ditch was a probable reason for the entrenchment of Willow Creek. The author also argues that the entrenchment of Willow Creek was responsible for much of the deep entrenchment of its tributaries.

Daniels and Jordan (1966) studied Willow Creek in an effort to determine the cause and effect relationships that exist in the process of stream degradation. Included in the analysis is a detailed discussion of the entrenchment of Willow Creek and its tributaries during the period 1916-1958.

Lohnes et al. (1980) developed the following rational model for determining the rate of vertical degradation:

$$\frac{dh}{dt} = -k' h , \qquad (2.1)$$

where:

- dh/dt = the rate of vertical degradation,
- h = elevation of a given reach along the stream above base level, and
- k' = a constant describing the rate of degradation.

The theory underlying the model implies that there is a systematic decrease in the rate of vertical degradation over time. It further theorized that the degradational constant, k', should be a function of discharge through the reach of stream under consideration. The following assumptions were made in developing this model:

- the most recent cycle of stream degradation is the result of stream channelization.

- the average discharge of a given reach of stream has been constant since channelization.

- the streams were in equilibrium with respect to vertical degradation before channelization began.

- the channel components that were effected by channelization were width, depth, and channel slope.

By separating the variables and setting the boundary conditions that h_0 exists at $t = 0$ and h_1 occurs at $t = 1$, the model is written as:

$$\ln\left[\frac{h_1}{h_0}\right] = -k' \, (t_1 - t_0) \, , \qquad (2.2)$$

and, if t_0 is the time of channelization, then

$$\ln\left[\frac{h_1}{h_0}\right] = -k' \, (t) \, ,$$

where:

t = the time since channelization in years,

h_0 = the original elevation after channelization, and

h_1 = the elevation at some time after channelization, t_1.

According to Lohnes et al. (1980), the logic for this relationship is that if a stream in equilibrium is disturbed (e.g. channelization) the stream will adjust to a new equilibrium with the rate of adjustment decreasing as the new equilibrium is approached. The authors note, however, an obvious limitation of the rate equation; theoretically, the channel would never reach equilibrium, but would approach an equilibrium depth at an ever decreasing rate.

Dirks (1981) utilized historic and geomorphic evidence to define and clarify the mechanisms which control degradation. Based on data from Daniels (1960), Dirks plotted Willow Creek elevations through time on semilog paper and found a linear trend. From this result Dirks concluded that a standard rate decay equation could be used to describe the rate of vertical degradation for a given reach of stream.

Massoudi (1981) developed an equilibrium stream profile model for Willow Creek considering both vertical degradation and stream widening. Massoudi's model considers streambed elevation changes and estimates subsequent changes in the channel cross section. The model follows an iterative routine until equilibrium is achieved in the channel. The model was used to predict the final equilibrium profile and channel dimensions of degrading streams.

The Federal Highway Administration and the Iowa Department of Transportation have also researched the problem of stream degradation. Various reports include a discussion of degradational damages to bridges and suggestions for stabilization methods to impede the degradational process. In his paper "Prediction of Channel Bed Grade Changes at Highway Stream Crossings", Brown (1982) studied the problem of degradation and its effects on highway bridges. In 1981, The Federal Highway Administration published "Methods for Assessment of Stream-Related Hazards to Highways and Bridges" in which the problem of stream degradation is defined and discussed with respect to damage to highways and bridges.

Lohnes (1991) developed a model for estimating the land loss associated with stream degradation. The model can be used to predict the amount of land lost for a specific reach of stream given the characteristics of its longitudinal profile. The model is based on a theoretic planar surface failure model of stream widening.

Morris et al. (1994) estimated the impact of stream degradation on private and public infrastructure investments in the deep loess soil region of western Iowa. The study consisted of a detailed analysis of five actively degrading streams in western Iowa's deep loess soil region. The results of the analysis were generalized to other similarly degrading streams in the region. The study considered damage to highway bridges, railroad bridges and right-of-ways, pipelines, telephone lines, electric lines, and rural water lines. In addition, estimates were made of the traffic re-routing costs due to bridge closure for repair due to degradation. The costs were compiled on a time neutral and time value basis. Time neutral costs were a simple 1992 unit cost per infrastructure multiplied by a change in stream width. Time value costs were compounded at a four percent interest rate since the dates the losses were incurred. Table 2.1 summarizes the total costs incurred by public and private infrastructure due to stream degradation in western Iowa's deep loess soil region.

Yang (1994) studied the problem of stream degradation and its impacts on highway bridges and rural travel patterns. The author utilized a benefit-costs analysis to evaluate alternative investment strategies on bridges affected by stream degradation in western Iowa. Investment decisions were based on a comparison of the net societal benefit from keeping bridges open to the public and the costs of providing the bridges. The author's conclusions from the analysis indicated the possibility of abandoning some rural highway bridges with a net gain to society.

Table 2.1 Estimated time neutral and time value costs of degradation on transportation and utility infrastructure in western Iowa's deep loess soil region.

Type of infrastructure	Time neutral costs	Time value costs
Highway bridges	$101,606,900	$723,416,100
Railroad bridges and right-of - ways	30,109,300	205,762,400
County bridge traffic re-routing	8,079,800	23,825,200
Pipelines	1,484,000	3,248,600
Telephone lines	329,800	2,165,800
Electric lines	131,900	400,600
Rural water lines	6,600	10,800
Total	$141,748,300	$958,829,500

Source: Morris et al. 1994

Levich (1994) utilized tractive force models to predict stream degradation in western Iowa's loess region. The analysis considered two models of stream degradation based on the longitudinal profile of a stream. The Hack model was applied to short reaches of degrading streams were the geological characteristics of the stream were constant. A tractive force model was applied to longer stream segments and predicted the final, stable streambed elevations.

III. STREAM CHANNELIZATION IN WESTERN IOWA

Prior to 1900, much of the bottomland in the loess region of western Iowa could not be cultivated due to the frequency and severity of flooding by naturally meandering streams and rivers. Consequently, in 1850 the federal government donated much of the untillable land to the state of Iowa. In 1853, the Fourth General Assembly of Iowa ceded the "swamp land" to the respective counties with the declaration that all proceeds from their sale be used to reclaim the land by the construction of levees, roads, and bridges (Dirks, 1981). The area designated as swamp land in Harrison County alone totaled more than 120,000 acres, however; the $150,795 collected by the county for the land was never used for reclamation purposes. (Smith, 1888).

Beginning around 1900, channel improvement programs were undertaken in many western Iowa counties to reclaim the land for cultivation and other agricultural purposes, as well as to control flooding in the region. The demand for consistently productive floodplain cropland initiated the construction of drainage ditches, levees, and dikes. According to Dirks (1981), the programs began on a small scale as early as 1870 in Monona county; however, most of the major channelization projects in the region were undertaken during the period 1890 to 1920, with some as late as 1960.

Daniels (1960), Lohnes et al. (1980), Massoudi (1981), Dirks (1981), and Levich (1994) have identified the channelization of these streams and rivers as a possible major cause of stream degradation. The construction of drainage ditches, or channelization, created artificial stream channels which were shorter than the natural channels, had steeper channel gradients, and had much smoother perimeters than the natural channels (Massoudi, 1981). The shortened channels, combined with steeper gradients, increased the flow velocity of the streams. Thus, the erosion of stream bed and bank material proceeded at a higher rate. The smooth perimeters of the channelized streams reduced the surface friction factor and further increased the flow velocity (Massoudi, 1981).

As time progressed it became apparent that many streambeds in western Iowa's loess region were unstable at higher flow velocities. Channel degradation resulted and continues today. Active degradation in western Iowa has been documented on 57 streams and rivers with a combined length of approximately 1,480 miles (Adkins, 1992). On many of these degrading streams and rivers, the incidence of degradation has not been limited only to those channelized segments of the streams, but rather entire stream systems.

Method of Channelization

Contracts for channelizing a stream were advertised and awarded to the lowest bidder and paid by the county, usually through bond issuance. Various counties established drainage districts to legislate the channelization programs. Under the direction of the county board of supervisors, the contractor followed channel specifications determined by a drainage engineer. The specifications included the length, depth, width, side slopes, and gradient of the new channel. The drainage ditch was mapped out and right of ways were established for the length of the ditch.

In a report to the Board of Supervisors of Shelby County, Iowa in 1913, the drainage engineer discussed Indian Creek:"... the following lands in Clay Town Township, Shelby

County, Iowa, ... , are all adjacent to the stream known as Indian Creek, are subject to overflow and too wet for cultivation, and that the public health, welfare, convenience and public benefit and utility, will be promoted by ditching, draining, the construction of levees thereon, and by the straightening of the said Indian Creek and other water courses therein" (Board of Supervisors, Shelby County, Iowa, 1913, p. 75).

In a similar report to the Shelby County, Iowa, Board of Supervisors in 1915, the drainage engineer described the local condition of Mosquito Creek as follows: "... I have made an inspection of the lands in the district and found that the valley is subject to overflow and at times too wet for successful cultivation... that the Mosquito Creek is crooked and more or less obstructed and its present condition has not sufficient capacity to carry the storm waters which reach the valley... To relieve this condition and to drain and reclaim this valley, I would recommend the construction of a ditch and drainage system..." (Board of Supervisors, Shelby County, Iowa, 1915, p. 1).

Under the proposal of the drainage engineer, the county board of supervisors awarded the project to a drainage ditch contractor. Construction of drainage ditches was completed using gasoline or steam powered mechanical dredges. The dredges were equipped with drag lines and excavation buckets. A drag line excavator was capable of dredging 16 feet in one minute in any direction and had an excavation capacity of 2 cubic yards. This type of excavator moved across the ditch ahead of excavation and was capable of constructing stream bank levees. Some mechanical dredges were revolving shovels, equipped with a boom and excavation bucket. Other devices used in the channelization of streams were steam shovels and trench machines, both capable of the required work for a drainage ditch. Larger channelization projects required the use of a floating dredge, which constructed the drainage ditch while floating in the channel. Floating dredges were commonly used for the channelization of large streams and rivers in western Iowa.

Channelized Stream Dimensions

There are few published data on the original dimensions of channelized streams. Moreover, many of the original records have been discarded by the drainage districts and county recorders. During the data collection for this research, a number of historical records of stream channelization projects were collected. These records include drainage district reports, reports of various county boards of supervisors, and drainage engineer reports. The information provided in these records, although incomplete, helps clarify the process of stream channelization in western Iowa.

The historical records provide information on the size of the constructed channel as well as the project location and date. Information was gathered on the channelization of Willow Creek, Keg Creek, Mosquito Creek, Walnut Creek, Indian Creek, Silver Creek, and Pony Creek. The data collected on the constructed channels of these streams establishes a point of reference for measuring the amount of degradation since their channelization.

Willow Creek

The channelization of Willow Creek began in 1906 and took 14 years to complete. The constructed drainage ditch was 26.9 miles long and was accomplished in three stages; Harrison/Pottawattamie Drainage Ditch, Upper Willow Drainage Ditch No.1, and Upper

Willow Drainage Ditch No. 2. The Harrison/Pottawattamie Drainage Ditch was 7.72 miles long and located entirely in Harrison County, Iowa. Willow Creek drains an area of approximately 110 to 140 square miles at this location. The ditch dimensions were an 18 foot bottom width and a depth of 15 feet from the top of a constructed flood berm. Side slopes of the ditch were 1:1 with a corresponding width of 42 feet.

The Upper Willow Drainage Ditch No. 1 underwent construction beginning in 1916 and was finished in 1919. The ditch began in township 80N of Harrison County, Iowa and proceeded south for 10.25 miles to Monona County, Iowa. Willow Creek drains approximately 80 to 108 square miles at this location.The ditch dimensions in this region included a bottom width of 12 feet and an average depth of 15 feet. The side slopes were specified at 1:1, corresponding to an average top width of 42 feet.

Construction of Upper Willow Drainage Ditch No. 2 began in 1919 and was finished in 1920. The ditch began in township 82N of Monona County and proceeded south for 11.63 miles. The drainage area of Willow Creek in this region is approximately 50 to 70 square miles. The dimensions of the ditch were a 12 foot bottom width for the first 3.37 miles, a 10 foot bottom width for the next 7.75 miles upstream, and a bottom width of 8 feet for the last 0.68 miles of the upstream reach. The depth of the ditch averaged 11 feet throughout Upper Willow Drainage Ditch No.2, with side slopes of 1:1. This corresponds to an average top width of 34 feet in the lower reaches of Upper Willow Drainage Ditch No. 2. The average top width for the upper reaches of Upper Willow Drainage Ditch No. 2 was approximately 40 feet (Daniels, 1960).

Keg Creek

Historical records document the channelization of Keg Creek in the 1920s. The drainage ditch was constructed in southern Pottawattamie and northern Mills counties where Keg Creek drains approximately 145 to 165 square miles. The depth of the ditch varied from 8.1 feet in the upper reach to 11.3 feet in the lower reach. The side slopes were specified at 1.5:1. The top width varied from 34 to 40 feet.

Keg Creek was also channelized further south in Mills County, Iowa during the late 1920s. Keg Creek drains approximately 170 to 190 square miles tn this region. The lower reach of the stream in Mills County was channelized with a width of 50 feet at the sub-grade level with a total ditch width of 80 feet. Construction of the drainage ditch also included flood berms or levees along the channel. The flood berms increased the total drainage ditch width to 150 feet (Board of Supervisors, Mills County, Iowa, 1927).

Mosquito Creek

The channelization of Mosquito Creek took place in township 80N of Shelby County, in 1915. Mosquito Creek drains approximately 35 to 80 square miles in this region. The dimensions of the ditch included a bottom width of 10 feet and side slopes of 1:1. The width of the ditch ranged from 26 to 42 feet (Mayne, 1915).

Walnut Creek

Channelization began on Walnut Creek in 1922 in township 70N in Fremont County, Iowa. Walnut Creek drains approximately 140 to 160 square miles at this location. The dimensions of the ditch included a bottom width of 8 feet, side slopes of 0.5:1, and an average depth of 11 feet. The width of the ditch was approximately 30 feet (Board of Supervisors, Fremont county, Iowa, 1921).

Indian Creek

The Indian Creek drainage ditch began in 1913 in the northern section of township 78N in Shelby County, Iowa. Indian Creek drains approximately 70 square miles at this location. The dimensions of the ditch included a bottom width of 14 feet, side slopes of 1:1, and an average depth of 10 feet. This corresponds to a width of 34 feet (Board of Supervisors, Shelby County, Iowa, 1913)

Silver Creek

Silver Creek was channelized in township 73N of Mills County, Iowa in the 1920s. The drainage area of Silver Creek at this location is approximately 192-230 square miles. This segment of Silver Creek was channelized with a bottom width of 16 feet and slopes of 1:1. The width was documented at 36 feet (Board of Supervisors, Mills County, Iowa, 1927).

Pony Creek

Pony Creek was channelized in the late 1920s in township 72N of Mills County, Iowa. Pony Creek has a drainage area of approximately 20 square miles at this location. No depth measure was recorded, however, the width of the ditch was 20 feet with side slopes of 1:1 (Board of Supervisors, Mills County, Iowa, 1927).

The records indicate that the size of the drainage ditch varied with the drainage area of the reach of stream being channelized. A comparison of the dimensions listed above with current dimensions provides a measure of stream degradation with regard to width and depth of the channels. The historical records collected during this research were used as a gauge of stream degradation in western Iowa's loess region. Data collection on the current dimensions of these streams was limited to only those of research interest. In 1992, width measures were made on Willow Creek and Keg Creek. The difference in the original and 1992 widths of these streams is the subject of the historical analysis in this thesis and is discussed in Chapter V.

IV. STUDY AREA AND DESIGNATION OF STREAM SEGMENTS

This analysis considers the impacts of stream degradation with respect to land voiding and rural infrastructure investments on Willow Creek and Keg Creek in western Iowa's loess region. Both streams include segments that were channelized during the early part of this century which have subsequently degraded both vertically and laterally, making them representative of the many degrading streams in the region.

Willow Creek flows within an area where loess deposits are between 50 and 75 feet deep and drains approximately 146 square miles. Keg Creek flows in loess deposits between 35 and 50 feet deep and drains approximately 190 square miles (Dirks, 1981). Figure 4.1 indicates the location of Willow Creek and Keg Creek in western Iowa.

Both streams contain channelized segments, segments that have stabilized and are no longer degrading, segments that are currently degrading, and segments that are expected to degrade. Therefore, the status of each segment was determined and each was examined categorically. Table 4.1 describes the stream segment categories used in this analysis.

Table 4.1 Stream segment categories followed in this analysis.

Category	Description
Channelized	Modified channel, usually straightened and shortened.
Stable	No longer degrading, no evidence of future degradation.
Currently degrading	Has previously degraded and continues to degrade.
Expected to degrade	Newly degrading segments, beginning to show evidence of degradation.

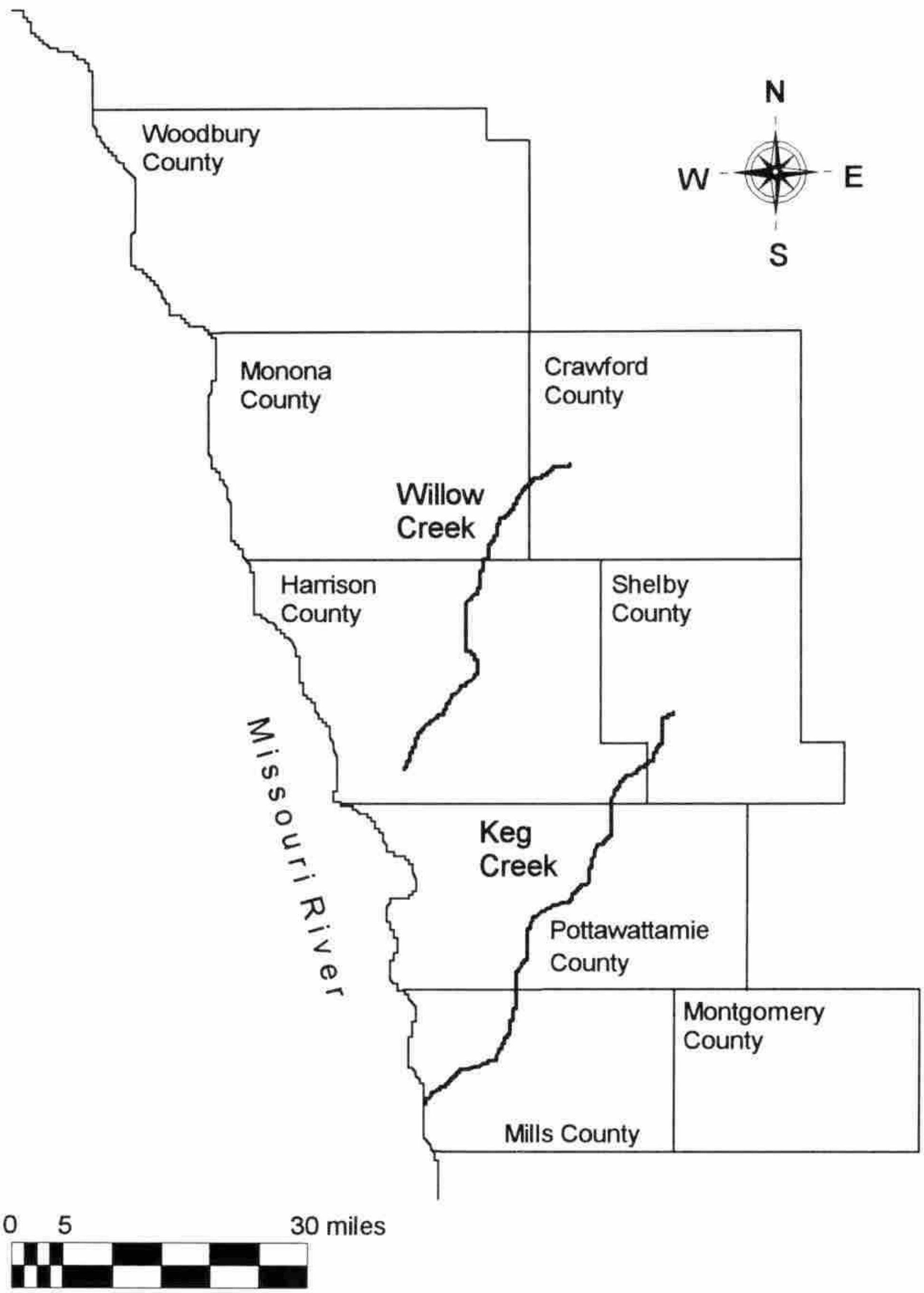


Figure 4.1 Keg Creek and Willow Creek in western Iowa's loess region.

The segments of Willow Creek and Keg Creek were defined in terms of drainage area. The total drainage area of each study stream was divided into drainage area intervals after Larimer's *Drainage Areas of Iowa Streams*. Each drainage area interval measures the cumulative drainage area served by specific points along a stream in square miles. The specific points measuring drainage area intervals include county borders, stream confluences, and Iowa Geologic Survey Gauging Stations. Table 4.2 lists the drainage area intervals of Willow Creek and Keg Creek and their assigned status followed in this analysis. The status of each stream segment was determined from a combination of historical records, previous engineering studies, discussions with conservation officials, and low altitude aerial videos.

The analysis of the segments of Willow Creek and Keg Creek listed in Table 4.2 consists of three main sections. The first section, Chapter V, considers the historical impacts of stream degradation based on an analysis of the channelized segments of Willow and Keg Creek. The historical analysis considers each drainage area interval of the study streams that was channelized and is now stable.

The second section, Chapter VI, develops a method to predict future stream degradation based on an analysis of those segments categorized as currently degrading or expected to degrade. For the predictive analysis, each drainage area interval listed in Table 4.2 was subdivided into smaller segments for modelling purposes.

The third section, Chapter VII, develops an economic model for the placement of stream stabilization structures based on the predictive results of Chapter VI. The model maximizes the total discounted benefit of stream stabilization subject to a budget constraint for the construction of stabilization structures.

Table 4.2 Drainage area intervals of Willow Creek and Keg Creek in square miles and their assumed status followed in this analysis.

Willow Creek		Keg Creek	
Drainage area interval	Status	Drainage area interval	Status
0 - 7.11	Expected to degrade	0 - 10.4	Expected to degrade
7.11 - 22.1	Expected to degrade	10.4 - 20.2	Expected to degrade
22.1 - 29.1	Expected to degrade	20.2 - 29.4	Expected to degrade
29.1 - 53.9[s]	Currently degrading	29.4 - 50.4	Expected to degrade
53.9 - 60.7	Currently degrading	50.4 - 59.6	Expected to degrade
60.7 - 69.3	Currently degrading	59.6 - 70.5	No information
69.3 - 146.0[s]	Stable	70.5 - 81.0	No information
		81.0 - 91.4	Currently degrading
		91.4 - 111.0[s]	Currently degrading
		111.0 - 190.0	Stable

V. HISTORICAL ANALYSIS OF STREAM DEGRADATION

Method of Analysis

The historical analysis includes segments of Willow Creek and Keg Creek that were channelized and have stabilized. The channelized segment of Willow Creek is located in Harrison County. Channelization was completed on Willow Creek in 1920. Two drainage area intervals included in the channelized segment of Willow Creek were designated as currently degrading and are analyzed in Chapter VI. The channelized segment of Keg Creek is located in Mills County. Channelization of Keg Creek was completed in 1927.

The channelized portions of the study streams were identified from the records documented in Chapter III. The historical analysis considers the impact of stream degradation from the initial channelization of Willow Creek and Keg Creek through 1991. The channelized drainage area intervals of Willow Creek and Keg Creek included in the historical analysis are listed in Table 5.1.

Table 5.1 Channelized drainage area intervals of Willow Creek and Keg Creek included in the historical analysis, in square miles.

Willow Creek	Keg Creek
69.3 - 87.2	137.0 - 149.0
87.2 - 108.0	149.0 - 163.0
108.0 - 118.0	163.0 - 181.0
118.0 - 129.0	181.0 - 190.0

Changes in Stream Width Since Channelization

Estimation of the impacts of stream degradation with respect to land voiding and rural infrastructure investments on Willow Creek and Keg Creek was based on the change in stream width from the date of initial channelization through 1991 for each drainage area interval listed in Table 5.1. The original channelized stream widths were provided in the documented records in Chapter III.

The 1992 stream widths were estimated using Soil Conservation Service 1:24,000 scale aerial photographs and remote sensing work stations. The scale of the photographs, combined with vegetation cover, prohibited the accurate measurement of the top-of-bank stream widths in many cases. Therefore, stream width measurements were made within the channels of Willow Creek and Keg Creek were stream banks were visible. Personnel from the Soil Conservation Service, U. S. Department of Agriculture made the stream width measurements using a Model 1280-24 Lasico digitizer.

The measurements made by the Soil Conservation Service personnel were adjusted to account for the difference between the top-of-stream widths and the widths within the channel. The adjustments were made using recent Iowa Department of Transportation bridge inspection reports for bridges crossing both Willow and Keg Creek. Channel surveys included in the 1992 bridge inspection reports provided estimates of top-of-stream widths at each bridge location. A regression analysis indicated a relationship existed between the estimated top-of-bank stream widths and the SCS measurements. The resulting regression coefficients were used to adjust the SCS measurements to an estimated 1992 top-of-bank stream width.

The resulting measurements for each drainage area interval provided an estimate of the 1992 stream widths of Willow and Keg Creek. A weighted average top width for each drainage area interval was calculated using the adjusted SCS measurements. The weighted average top widths obtained from equation 5.1 were compared to the original channelized widths for each drainage area interval included in the analysis.

$$W_{dai} = \sum_{1}^{N} \left[\frac{L_i}{L_t} \right] W_i \;, \tag{5.1}$$

where:

W_{dai} = the weighted average top width for the drainage area interval,

N = the number of SCS measurements within each drainage area interval,

L_i = the distance between each SCS measurement within each drainage area interval in feet,

L_t = the total length of the drainage area interval in feet, and

W_i = the adjusted SCS stream width measurement.

Equation 5.1 provided an estimate of the 1992 top width for each degrading drainage area interval included on Keg Creek and Willow Creek. The 1992 weighted average top width was compared to the initial channelized top width for each drainage area interval on the study streams and a total width change was obtained. The total width change was an estimate of the amount of stream widening from initial channelization through 1991. Stream widening was defined as the major component of stream degradation in the historical analysis and a model of stream widening over time was developed.

Model of Stream Widening Over Time

Equation 5.2 was used to determine the rate at which stream widening has occurred from the date of initial stream channelization through 1991 for each drainage area interval (Baumel et al., 1994).

$$SW(t) = IW + (FW - IW)\left[\frac{(t - t_0)}{(t_f - t_0)}\right]^{\beta} , \qquad (5.2)$$

where:

SW = stream width at time t,

IW = initial channelized stream width estimated from historical records,

FW = 1992 adjusted SCS weighted average stream width,

t = year corresponding to stream width being estimated,

t_0 = year corresponding to initial channelization of stream,

t_f = year corresponding to the final stream width in 1992.

The model of stream degradation specified in equation 5.2 estimated the rate of degradation with respect to stream widening from initial channelization through 1991. The model was constrained through two end data points for each drainage area interval included in the analysis. The first point, the original channelized stream width, was the beginning point at the time of channelization, t_0. The second point, the 1992 weighted average top width, was the final point at t_f. Equation 5.2 was based on the theory proposed by Lohnes et al., 1980 which states that there is a decrease in the rate of degradation over time. The theory was developed with respect to vertical degradation and was assumed valid for lateral degradation, or widening. The model of stream widening assumes that Willow Creek and Keg Creek have widened at the same rate as a result of channelization. The model also assumes that the rate of stream widening on Willow Creek and Keg Creek has not been constant over time.

Rate of Stream Widening

Degradation is defined as the rate of change in the stream width with respect to time:

$$\delta = \frac{dSW}{d(t - t_0)} = \beta(FW - IW)\left[\frac{(t - t_0)}{(t_f - t_0)}\right]^{\beta - 1}\left[\frac{1}{(t_f - t_0)}\right]. \tag{5.3}$$

The change in the rate of degradation with respect to time can be defined as follows:

$$\frac{d\delta}{d(t - t_0)} = \frac{d^2SW}{d(t - t_0)^2} = \beta(\beta - 1)(FW - IW)\left[\frac{(t - t_0)}{(t_f - t_0)}\right]^{\beta - 2}\left[\frac{1}{(t_f - t_0)}\right]^2. \tag{5.4}$$

Taking the ratio of equations 5.3 and 5.4 yields the following:

$$\left[\frac{d\delta}{(t - t_0)}\right]\left[\frac{1}{\delta}\right] = \frac{\beta(\beta - 1)(FW - IW)\left[\frac{(t - t_0)}{(t_f - t_0)}\right]^{\beta - 2}\left[\frac{1}{(t_f - t_0)}\right]^2}{\beta(FW - IW)\left[\frac{(t - t_0)}{(t_f - t_0)}\right]^{\beta - 1}\left[\frac{1}{(t_f - t_0)}\right]}, \tag{5.5}$$

Simplifying equation 5.5:

$$\left[\frac{d\delta}{d(t - t_0)}\right]\left[\frac{1}{\delta}\right] = \frac{\beta - 1}{(t - t_0)} . \tag{5.6}$$

By multiplying each side of equation 5.6 by (t - t_0), a time elasticity of degradation was derived. Equation (5.7) shows the elasticity:

$$\varepsilon_{\delta t} = \left[\frac{d\delta}{d(t - t_0)}\right]\left[\frac{(t - t_0)}{\delta}\right] = \beta - 1 , \tag{5.7}$$

which can be written as equation (5.8),

$$\varepsilon_{\delta t} = \beta - 1 . \tag{5.8}$$

Equation 5.8 is a time elasticity of degradation where $\varepsilon_{\delta t}$ = the percent change in the rate of degradation divided by the percent change in the time period under consideration, (t - t_0). The time elasticity of degradation derived in equation 5.8 illustrates the sensitivity of the rate of degradation over time. A positive value would indicate that the rate of degradation is increasing with time, while a negative value would indicate that the rate of degradation is decreasing with time. An estimate of β is presented in the data section of this chapter, resulting in a time elasticity of degradation equal to -0.27.

Equation 5.2 was estimated as an inherently linear regression model in natural log form. The specification of the model was one with no constant term. The regression equation is shown in equation 5.9 (Baumel et al., 1994).

$$\ln(SW_t - IW) - \ln(FW - IW) = \beta \ln\left[\frac{(t - t_0)}{(t_f - t_0)}\right] . \tag{5.9}$$

The model was estimated using previously published data on the Willow Creek channel over time (Daniels, 1960). Once an estimate for the parameter β was obtained, the model was run for each drainage area interval included in the analysis. Setting the conditions that IW exists at t_0 and FW exists at t_f, the model provided an estimate for the stream width in each year from initial channelization through 1991.

Physical Land Voided over Time

The land voided each year from initial channelization through was calculated from the annual difference in the stream width and was converted to acres by equation 5.10 (Baumel et al., 1994).

$$LV_{it} = [(SW_t - SW_{t-1})\ L_i\ ][43,560]^{-1} , \tag{5.10}$$

where:

LV_{it}= acres of land voided in drainage area interval i in year t,

L_i = length of drainage area interval i in feet, and

SW_t = the stream width in drainage area interval i in year t.

The acres lost in each year for each drainage area interval included in the analysis were calculated and valuated over time to estimate the economic impact of stream degradation resulting from land voiding.

Estimation of the Historic Economic Impact of Land Voiding

In order to calculate the annual cost of land voiding from channelization through 1991, the following present value model of asset prices was developed.

Let the value of one acre of land in year t be represented by V_t. The present value of one acre of land voided in year t is equal to:

$$PV_t = \left[V_t (1 + r)^{(1992 - t)} \right] , \qquad (5.11)$$

where:

PV_t = the present value of one acre of land voided in year t in current dollars,

V_t = the value of one acre of land in year t, and

r = a long run real interest rate.

The total cost of the land voided from channelization through 1991 for each drainage area interval in 1992 dollars can be written as equation 5.12 (Baumel et al., 1994).

$$LC_i = \sum_{t = y*}^{1991} (P_t)(V_t)(LV_{it})(F|P\ r,\ 1992 - t) , \qquad (5.12)$$

where:

LC_i = the total cost of land voided from channelization through 1991 i n drainage area interval i in 1992 dollars,

y* = the date that stream widening began,

P_t = an index to account for inflation.

V_t = the value of one acre of land in year t,

LV_{it} = the acres of land voided in drainage area interval i in year t,

F|P = a future value given a present value in year t, and

r = a long run real interest rate of four percent.

County land values for the period 1920-1982 were taken from Banard and Jones. The data for this period were adjusted for the inclusion of buildings using the fraction of the total land value attributable only to land. The county land values for the period 1982-1992 were taken from Duffy et al., (1992). Duffy et al., (1994) reported the value of high grade, medium grade, and low grade farmland. The low grade values were spliced with the values reported by Banard and Jones to make the series as consistent as possible. Discount rates were taken from White, Agee, and Case (1989). The relative change in the consumer price index was used as an approximation of the inflation rate. These values were taken from the Statistical Abstract of the United States.

Equation 5.12 provided an estimate of the total cost of the land voided from initial channelization through 1991 for each drainage area interval of Willow Creek and Keg Creek included in the historical analysis. Summing these costs provided an estimate of the total cost of land voiding for the period under consideration (Baumel et al., 1994).

Estimation of Historic Economic Impacts to Rural Infrastructure Investments

In addition to the impacts of land voiding , stream degradation has imposed substantial costs on public and private infrastructure costs in western Iowa's loess region. Baumel et al., 1994 reported an estimated 1.1 billion dollars in damage to public and private infrastructure as a result from stream degradation since the majority of streams in the region were channelized. This section was developed to estimate the impacts of stream degradation on rural infrastructure investments on the channelized segments of Willow Creek and Keg Creek .

Rural infrastructure considered in the analysis included state and county highway bridges, railroad bridges, and pipeline, electric, telephone, and rural water line crossings. Impacts of stream degradation were calculated based on the change in stream width from initial channelization through 1991 for each drainage area interval included in the analysis.

Estimates of the impacts to rural infrastructure investments were obtained by multiplying the annual change in stream width by the current per unit cost of constructing highway and railroad bridge, pipeline, electric line, telephone line, and rural waterline crossings. Per unit costs were obtained from the Iowa Department of Transportation, the Burlington Norhtern Railroad Company, Murphy Brothers, Inc. Pipeline Company, AT&T, and Vista Telephone Company. The impacts incurred by electric line crossings were obtained directly from rural electric companies with lines crossing the study streams.

The location of the rural infrastructure investments were obtained from the Iowa Department of Transportation, various county engineering offices, and from railroad, pipeline, electric, telephone and rural water industries operating in the region.

Equation 5.2 was used to estimate the stream width in each year for each drainage area interval. Equation 5.13 was used to estimate the total cost of stream degradation on rural infrastructure investments for each drainage area interval on Willow Creek and Keg Creek (Baumel et al., 1994). Equation 5.13 estimated the costs of stream degradation based on the change in stream width in each year.

$$TC = \sum_{t=y^*}^{1991} (P_t)(C_t * \Delta SW_t)(F|P\ r,\ 1992 - t) \tag{5.13}$$

where:

TC = the total cost to rural infrastructure investments from stream degradation in drainage area interval i from initial channelization through 1991 in 1992 dollars,

y^* = the date that stream widening began,

ΔSW_t = the change in stream width in year y in drainage area interval i,

C_t = the per unit cost of the infrastructure in year y,

P_t = an index to account for inflation,

y = the year corresponding to the change in the stream width, and

r = a long run real interest rate of four percent.

Equation 5.13 provided an estimate of the total cost of stream degradation for each channelized drainage area interval from the date of channelization through 1991. Summing the total cost for each drainage area interval provided an estimate of the total cost over the channelized segments of Willow Creek and Keg Creek.

Estimation of Increased Travel Costs

Many county bridges in western Iowa have suffered closure for repair due to stream degradation. As a result private and commercial vehicle traffic in western Iowa incur increased travel time and distance. According to Lohnes et al., 1980, 18% of the highway bridges in a 13 county region in western Iowa had one or more approach spans added as a result of stream degradation. Lohnes et al., (1980) reported the following percentages for the counties included in the current study: Shelby 28.3%, Crawford 25.4%, Harrison 19.5%, Monona 15.9%, Pottawattamie 12.8%.

Based on discussions with Iowa Department of Transportation bridge engineers, each bridge in the study area was assumed to have been closed for 60 days for repairs and extensions. Thus travelers incurred additional costs while circumventing bridges under repair.

Traffic re-routing over county bridges was simulated with TRANSCAD, a transportation geographic information system (GIS) program. First, a cost minimizing base solution was simulated to estimate travel costs with each bridge open. Assumed destinations were the county seat town for household traffic and the nearest town for farm, school bus, and post office traffic. Then, a minimum cost solution was simulated with each bridge closed for a 60 day period. The difference between each solution was the estimated cost of traffic re-routing due to the bridge closure. This cost was a direct result of stream degradation. Equation 5.14 estimated the travel cost for each simulation (Baumel et al., 1994).

$$TC = \sum_{d}^{2} \sum_{v}^{5} \sum_{r}^{3} (V_{rvd})\,(M_{rd})\,(TP_{vd}) \tag{5.14}$$

where:

TC = the total travel cost,

VC = the variable vehicle operating cost for vehicle type v, road type r, to destination d,

M = miles traveled on road type r to destination d, and

TP = total trips for vehicle v to destination d.

Equation 5.14 provided an estimate of the total increased travel cost as a result of stream degradation from initial channelization through 1991 for Willow Creek and Keg Creek

The Data

Estimated Initial Channelized Stream Widths

The estimated initial channelized stream widths for each drainage area interval are shown in Table 5.2. The estimated initial channelized stream widths for each drainage area interval were based on the information gathered from historical drainage district records. As indicated in Chapter III., the size of the drainage ditch varied with the drainage area.

Table 5.2 Estimated initial channelized stream width as a function of drainage area for Willow Creek and Keg Creek, in feet.

Willow Creek		Keg Creek	
Drainage area interval	Estimated initial channelized stream width	Drainage area interval	Estimated initial channelized stream width
53.9 - 60.7	34.0	137.0 - 149.0	42.0
60.7 - 69.3	34.0	149.0 - 163.0	42.0
69.3 - 87.2	42.0	163.0 - 181.0	42.0
87.2 - 108.0	42.0	181.0 - 190.0	42.0
108.0 - 118.0	42.0		
118.0 - 129.0	42.0		
129.0 - 146.0	42.0		

Estimated 1992 Stream Widths

The 1992 stream widths were estimated using Soil Conservation Service 1;24,000 scale aerial photographs of the study streams. These measurements were made within the stream channel were the stream banks were visible. Current Iowa Department of Transportation and county bridge inspection reports for bridges crossing Willow Creek and Keg Creek were used to adjust the SCS measurements to a corrected estimate of the stream top widths. Channel surveys included in the inspection reports provided estimates of the stream top widths at bridge locations crossing the study streams. The estimated stream top widths obtained from the inspection reports were regressed on the SCS measurements to obtain an estimate of the stream top widths. The regression equation used to adjust the SCS measurements is shown in equation 5.15 (Baumel et al., 1994).

$$TW = \alpha + \beta \ SCS_w \ , \tag{5.15}$$

where:

TW = estimated 1992 stream top width,

SCS_w = estimated SCS stream width,

α = a constant, and

β = the adjustment coefficient.

The constant term, α, was not statistically significant. Table 5.3 shows the regression results for the model and the value of the adjustment coefficient used to adjust the SCS measurements for Willow Creek and Keg Creek. The adjusted SCS measurements used to calculate a weighted average top width for each drainage area interval using equation 5.1.

Table 5.3 Regression results and adjustment coefficients for estimating the 1992 stream top widths of Willow Creek and Keg Creek.

Stream	Adjustment coefficient	Standard error	R^2	t ratio
Willow	3.13	.325	.61	9.6
Keg	2.47	.133	.53	18.5

Model of Stream Degradation over Time

The model of stream degradation with respect to stream widening presented in equation 5.2 was estimated as an inherently linear econometric model using the data presented in Table 5.4. The width measurements indicate the change in stream width from channelization through 1958. The data provided by Daniels (1960) were the only available time series data on degrading stream widths in western Iowa.

The initial width was the estimated channelized width and the final, 1992 width, was the 1992 SCS adjusted weighted average top width. The data from Daniels (1960) reported the stream width of Willow Creek from 1919 to 1958. Combining the data from Daniels (1960) with the data collected on the initial channelized widths and the 1992 widths provided a time series data set which spanned the entire historical period under consideration. The model of stream widening over time was run in standard OLS regression analysis in natural log form. The model of stream widening provided an estimate of the rate of widening over time for Willow Creek. Keg Creek was assumed to have widened at the same rate as Willow Creek in the historical analysis.

Table 5.4 Top widths of Willow Creek over time, in feet.

	Upper Willow Drainage District No. 1.		Upper Willow Drainage District No. 2.	
Year	T79N R43W	T80N R43W	T81N R43W	T81N R42W
1919[i]	42	42	-	-
1920[i]	-	-	34	34
1929	-	-	50	-
1931	-	57	-	-
1933	72	-	-	-
1936	80	-	-	-
1942	-	-	80	-
1950	-	-	-	100
1952	-	-	-	110
1958	110	100	96	120
1992[f]	139	123	128	128

Source: Daniels, 1960.

i Estimated initial channelized top width

f Adjusted 1992 SCS weighted average measurements.

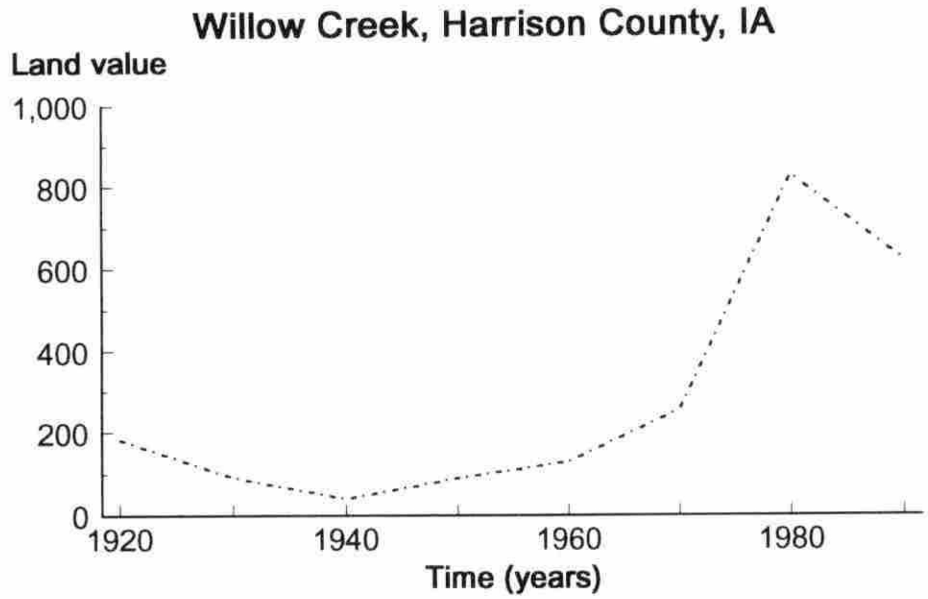
The estimated coefficient for the parameter β was 0.73251 with a standard error of 0.054. The coefficient of determination, or R^2, was 0.8409. The estimated parameter had a calculated t-value of 13.55. Solving equation 5.8 indicated that the time elasticity of degradation based on the estimation was equal to -.27. The result indicated that the rate of stream widening was decreasing with time.

County Land Values

County land values for the period 1920-1991 used to estimate the impact of stream degradation with respect to land voiding are shown in Figure 5.1. The channelized segment of Willow Creek included land values for Harrison County. The channelized segment of Keg Creek included land values for Mills County. The series was compiled based on two time series data sets of county land values in western Iowa.

Per Unit Infrastructure Costs

Table 5.5 shows the per unit costs used to estimate the impacts of stream degradation on rural infrastructure investments. The per unit costs included highway bridges, railroad bridges, pipelines, rural water lines, and telephone lines. The per unit cost for both pipelines and rural water lines were a function of the diameter of the pipe. Per unit costs for telephone lines were a function of the manner in which they spanned the degrading streams. Cost estimates for electric lines crossing Willow Creek and Keg Creek were obtained directly from rural electric companies operating western Iowa. Actual costs may vary depending upon the conditions at each specific site.



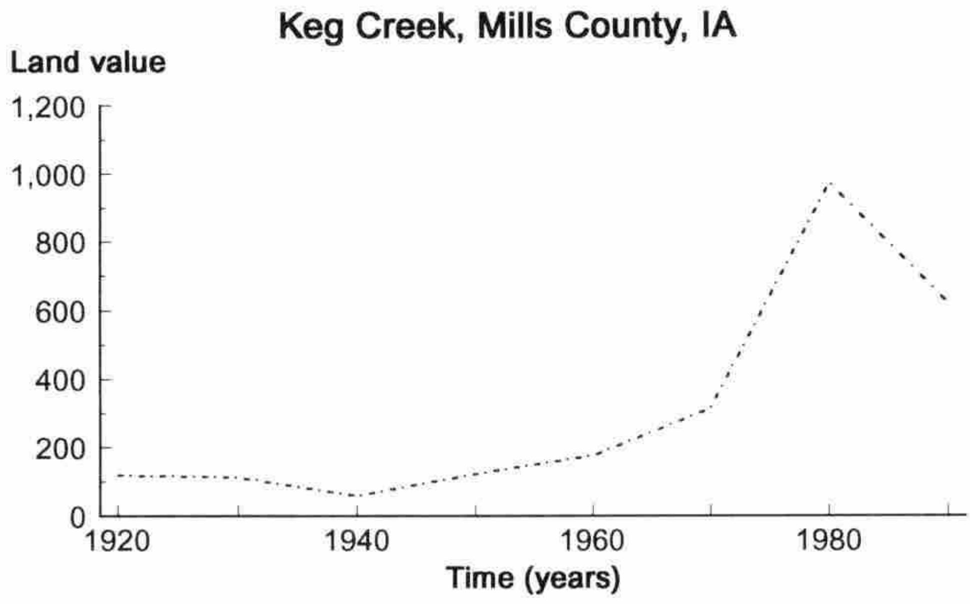


Figure 5.1 County land values used to estimate the economic impact of stream degradation with respect to land voiding on Willow Creek and Keg Creek.

Table 5.5 Per unit costs used to estimate impacts of stream degradation on rural infrastructure investments.

Infrastructure investment	Per unit measurement	Cost per unit (1993 real dollars)
Highway bridges	Square foot	$40.00
Railroad bridges	Linear foot	1300.00
Pipelines	Linear foot	
2 inch		27.00
6 inch		83.00
8 inch		111.00
10 inch		138.00
16 inch		221.00
20 inch		276.00
24 inch		331.00
36 inch		497.00
42 inch		597.00
Waterlines	Linear foot	
2 inch		27.00
3 inch		40.00
4 inch		53.00
5 inch		68.00
6 inch		83.00
Telephone	Linear foot	
Bridge attached		9.25
Buried		10.75
Fiber optic		625.00
Coaxial		625.00
Electric Lines	Actual cost	Varied

Source: Baumel et al., 1994.

Increased Travel Costs

Table 5.6 shows the estimated variable vehicle operating costs on gravel, paved, and state roads used to estimate the increased travel costs.

Table 5.6 Estimated variable cost per vehicle mile and road type in cents per mile.

	Road type		
Vehicle type	State	Paved county	Gravel
Auto/pickup	20.2	21.6	28.1
Single axle truck	42.8	44.9	62.5
Tandem axle truck	58.7	61.6	85.7
Semi-tractor-trailer	66.9	70.3	97.7
Tractor-wagon	113.0	118.7	165.0

Source: Baumel, et al., 1991.

Table 5.7 shows the distribution of types of trips assumed in the analysis of increased travel costs as a result of stream degradation. The data in Table 5.8 were obtained from a survey of travel patterns in a 100 square mile area of Shelby County, Iowa. Traffic volumes for each bridge were taken from the most recent Iowa Department of Transportation bridge inspection reports. The distribution of rural traffic in western Iowa was defined as household, farm, and other. Household traffic provided the largest percentage of rural traffic, accounting for 68 percent of the total. Farm traffic accounted for almost 30 percent of total rural traffic. School bus and post office traffic accounted for a combined total of 2 percent.

Table 5.7 Percentage of travel by vehicle type.

Type of vehicle		Percent of total
Household		
	Auto	58.9
	Pickup	7.5
	Truck (single axle)	2.0
Subtotal		68.4
Farm		
	Auto	0.6
	Pickup	23.4
	Truck (single axle)	1.93
	Truck (tandem axle)	0.75
	Truck (semi)	0.22
	Tractor-wagon	0.28
Subtotal		29.7
Other		
	School bus	0.8
	Post office	1.1
Subtotal		1.9
Total		100.0

Source: Baumel et al., 1989.

Results

Table 5.8 shows the estimated historical costs of land voiding due to stream degradation on the channelized segments of Willow Creek and Keg Creek. Willow Creek had an estimated $913,100 in land voiding costs on four channelized drainage area intervals. The cost on Willow Creek was nearly 60% of the total land voiding costs. The drainage area furthest upstream had the highest land voiding costs on Willow Creek. The average land voided on the channelized segments of Willow Creek was 41.5 acres.

Table 5.8 Estimated historical costs of land voiding due to stream degradation on the channelized segments of Willow Creek and Keg Creek in 1992 dollars.

Stream	Drainage area interval	County	Land Voided (acres)	Total cost of land voided
Willow	69.3 - 87.2	Harrison	45.48	$250,400
Willow	87.2 - 108.0	Harrison	42.72	235,200
Willow	108.0 - 118.0	Harrison	35.80	197,100
Willow	118.0 - 129.0	Harrison	41.84	230,400
Keg	137.0 - 149.0	Mills	21.10	103,600
Keg	149.0 - 163.0	Mills	40.88	201,200
Keg	163.0 - 181.0	Mills	17.09	84,100
Keg	181.0 - 190.0	Mills	47.42	233,300
Total			371.52	$1,535,300

Keg Creek had an estimated $622,200 in land voiding costs on four channelized drainage area intervals. The cost on Keg Creek was just over 40 percent of the total land voiding costs. The average land voided on Keg Creek was 31.6 acres. The total cost for all eight channelized drainage area intervals on Willow Creek and Keg Creek was $1,535,300. The average cost of land voiding due to stream degradation from initial channelization through 1991 was $4,100 per acre.

Table 5.9 shows the estimated historical costs to rural infrastructure investments. Total costs to rural infrastructure investments including traffic re-routing on the channelized segments of Willow Creek and Keg Creek were an estimated $11,335,500. Impacts to highway bridges were $10,143,200 or 89 percent of the total costs. Railroad bridges accounted for $614,100 of the total or 5.4 percent. Increased travel costs due to bridge closures for repair were $411,600 or 3.6 percent. These costs varied widely by drainage area interval due to large variations in average daily traffic for bridges crossing the streams. The fourth largest estimated impact to rural infrastructure investments was for pipelines due to large natural gas lines crossing Keg Creek. Telephone and electric lines were both less than 1% of the total costs, respectively.

Combining the total from Table 5.8 and 5.9, the estimated total costs of stream degradation from initial channelization through 1991 on Willow Creek and Keg Creek was $12,870,800. Land voiding accounted for 13.5 percent of the total cost of stream degradation. highway bridges and traffic-rerouting costs were 82 percent of the total cost.

Table 5.9 Estimated historical costs of stream degradation with respect to rural infrastructure investments and traffic re-routing on the channelized segments of Willow Creek and Keg Creek, in 1992 dollars.

Stream	Drainage area interval	County	Highway bridges	Railroad bridges	Pipelines	Telephone lines	Electric lines	Increased travel cost
Willow	69.3 - 87.2	Harrison	$935,100	$0	$0	$0	$8,300	$38,400
Willow	87.2 - 108.0	Harrison	1,816,900	0	0	0	0	21,600
Willow	108.0 - 118.0	Harrison	1,251,800	0	0	0	0	4,200
Willow	118.0 - 129.0	Harrison	1,558,000	0	0	2,600	0	31,800
Keg	137.0 - 149.0	Mills	1,558,900	0	0	2,400	0	78,000
Keg	149.0 - 163.0	Mills	1,162,500	0	0	7,100	0	90,000
Keg	163.0 - 181.0	Mills	348,400	0	0	1,600	0	98,400
Keg	181.0 - 190.0	Mills	1,511,600	614,100	144,600	0	0	49,200
Total			$10,143,200	$614,100	$144,600	$13,700	$8,300	$411,600

VI. PREDICTIVE ANALYSIS OF STREAM DEGRADATION

Method of Analysis

As stream channels degrade, a tendency exists for stream banks to become unstable. The occurrence of mass stream bank erosion as a result of this instability can be predicted through principles of soil mechanics. This section of the analysis applies these principles in an engineering approach to the prediction of stream widening and land voiding on the segments of Willow Creek and Keg Creek categorized as currently degrading or expected to degrade.

The currently degrading segments of Willow Creek are located in Monona and Harrison counties. The currently degrading segment of Keg Creek is located in Pottawattamie county. The segments of Willow Creek that are expected to degrade are located in Crawford and Monona counties. The segments of Keg Creek that are expected to degrade are located in Shelby, Harrison, and Pottawattamie counties. The drainage area intervals listed in Table 4.2 were subdivided into smaller stream segments for the prediction of stream widening and land voiding. Tables 6.1 and 6.2 list the degrading stream segments considered in the predictive analysis.

These segments of Willow Creek and Keg Creek were analyzed in a two stage predictive model. The first stage predicts the vertical degradation for a given stream segment based on a tractive force model of stream degradation (Levich, 1994). The second stage utilizes the results from the first stage in a theoretic planar-surface failure model of stream widening (Lohnes, 1991). A computer program was designed to operationalize the model developed by Lohnes (1991) to predict future stream widening land voiding.

Table 6.1 Currently degrading segments of Willow Creek and Keg Creek

Stream	Cumulative drainage area (mi.^{2})	Length of stream segment (miles)	Drainage area of stream segment (mi.^{2})
Willow	30.03	1.0	1.81
Willow	31.84	1.0	1.81
Willow	33.65	1.0	1.81
Willow	48.25	1.1	14.60
Willow	52.06	0.9	3.81
Willow	55.75	1.0	3.69
Willow	59.06	1.0	3.31
Willow	62.08	1.0	3.02
Willow	64.87	1.0	2.79
Willow	67.48	1.0	2.61
Willow	69.95	1.0	2.47
Keg	83.92	2.0	1.82
Keg	87.57	2.1	3.65
Keg	91.40	1.1	3.83
Keg	95.23	0.9	3.83
Keg	99.50	1.0	4.27
Keg	103.76	1.0	4.26
Keg	111.00	1.7	7.24

Table 6.2 Segments of Willow Creek and Keg Creek expected to degrade

Stream	Cumulative drainage area (mi.^{2})	Length of stream segment (miles)	Drainage area of stream segment (mi.^{2})
Willow	4.15	3.86	4.15
Willow	7.11	0.93	2.96
Willow	7.58	0.59	0.47
Willow	9.08	1.40	1.50
Willow	11.26	0.28	2.18
Willow	13.44	2.43	2.18
Willow	22.27	0.41	8.83
Willow	25.44	1.62	3.17
Willow	27.27	1.08	1.83
Keg	17.12	7.0	17.12
Keg	20.20	1.1	3.08
Keg	22.79	0.9	2.59
Keg	25.66	1.0	2.87
Keg	37.14	2.0	11.48
Keg	50.4	1.2	13.26
Keg	52.34	0.8	1.94
Keg	54.76	1.0	2.42
Keg	57.18	1.0	2.42
Keg	59.6	1.0	2.42

Estimation of Vertical Degradation

A tractive force model of stream degradation developed by Massoudi (1981) and modified by Levich (1994) provided estimates of the expected future vertical degradation on the study streams. The tractive force model of stream degradation is based on hydraulic principles of stream channel erosion. The model depends on back calculating the erosion resistance of a given stream segment based on the geometry of a stable segment of the degrading stream. At the stable segment, the calculated tractive (or shear) force is equal to the erosion resistance. The unstable channel upstream is divided into equal segments wherein the cross-sectional area, streambed elevation, drainage area, channel slope, and distance from the headwater are measured or calculated.

The model begins at the stable segment and calculates the tractive force of the upstream, unstable segment using the discharge, cross-sectional area, and channel slope. The tractive force is compared to the erosion resistance and, if the tractive force is greater than the erosion resistance, the streambed is lowered and a new tractive force is calculated. The new tractive force is less than the previous tractive force due to an increase in channel capacity and a decrease in channel slope resulting from lowering the streambed in the upstream segment. The calculations are repeated until the tractive force is less than or equal to the erosion resistance. Channel degradation continues until the shear stress equals the erosion resistance. At that point, the segment becomes stable and the model similarly considers each upstream segment in an iterative routine (Baumel et. al., 1994).

Streambed profiles for currently degrading segments were obtained for Willow Creek in 1966 and Keg Creek in 1980. Streambed profiles were obtained for segments expected to degrade in 1992-1993. Based on these profiles, the tractive force model provided an estimate of the final stable profile elevation for each degrading segment. In this analysis, the tractive force model was based a calculated value of erosion resistance which predicted maximum vertical degradation. The difference between the elevations obtained in the original profile and the predicted final elevations was used as an estimate of the expected vertical degradation.

For each stream segment included in the predictive analysis, an average estimate of the expected vertical degradation was obtained by taking the difference of the average of the predicted final elevation and the average original elevation. This procedure provided the average expected vertical degradation for each stream segment measured at the midpoint of each segment.

Rate of Vertical Degradation

The assumption was made that vertical degradation and stream widening begin at the same time, however; the rate of vertical degradation and stream widening may be different over time. A rational model for predicting the rate of vertical degradation was used to integrate time into the predictive analysis (Lohnes, 1980). The base level for Willow Creek was 938 feet. The base level for Keg Creek was 988 feet. Each base level was determined from United State Geological Survey topographic maps of the study streams. Equation 6.1 was used to estimate the number of years over which vertical degradation would occur.

$$\ln\left[\frac{h_1}{h_0}\right] = -k' \,(t_1 - t_0)\ , \qquad (6.1)$$

where:

h_1 = the average streambed elevation above base level of stream segment i at time t_1 ,

h_0 = the average streambed elevation above base level of stream segment i at time t_0 ,

$-k'$ = the rate of vertical degradation,

t_1 = the year that vertical degradation ends, and

t_0 = the year corresponding to the streambed profile.

The rate of vertical degradation, $-k'$, was estimated for Willow and Keg Creek based on data obtained from bridge inspection reports (Yang, 1994). Equation 6.1 was solved for $(t_1 - t_0)$ for each segment of the study streams included in the predictive analysis. This result provided an estimate of the time span over which the predicted vertical degradation occurred. The expected vertical degradation estimates over time were then used as input values in the computer simulation of stream widening.

Stream Widening and Land Voiding

A theoretic planar-surface failure model of stream widening (Lohnes,1991) was used to predict future stream widening for the degrading segments of the study streams. The model assumes that stream widening results from mass bank movement and is based upon well established principles of soil mechanics and slope stability analysis. A soil mass becomes unstable if the shearing stresses within the mass exceed the shear strength of the mass. The shear strength of soil is manifest in the soil cohesion and friction angle while the stresses result from the unit weight of the soil. In general, higher and steeper slopes will be most likely to be unstable. As streams degrade, their channel side slopes become steeper and higher until landslides occur to produce more gentle slopes. The model follows this process until the slope angles are gentle enough to be stable (Baumel et al., 1994).

In order to predict stream widening and land voiding, the simulation program of the model developed by Lohnes (1991) required the following soil mechanics characteristics to be determined: the soil cohesion, the unit weight of the soil, and the angle of internal friction. The soil mechanics characteristics for this analysis were based on the Mullenix stratigraphic unit of loess derived alluvium soil. These characteristics were based upon measured data and selected to result in maximum stream bank instability (Lohnes, 1994). Moreover, the data selected for the predictive analysis provided a maximum stream widening and land voiding scenario on Willow Creek and Keg Creek.

In addition to the expected vertical degradation and the soil mechanics parameters, the simulation program required the following data inputs to predict stream widening and land voiding: the initial stream channel side slope, the existing stream channel depth, and the length of the degrading reach of stream. The initial stream channel side slope was an assumed 80 degrees. Existing stream channel depths for the currently degrading segments were obtained from previous engineering studies (Daniels, 1960, Massoudi, 1981) and Iowa Department of Transportation bridge inspection reports. Stream segment lengths were estimated from the United States Geological Survey topographic maps of Willow Creek and Keg Creek. The computer simulation of stream widening provided estimates of the additional widening and land voiding for each stream segment categorized as currently degrading or expected to degrade.

A final stream width was obtained for each drainage area interval by equation 6.2.

$$FW_i = SW(t) + \Delta SW_{(cs)} , \tag{6.2}$$

where:

FW_i = the estimated final stream width in drainage area i,

$SW(t)$ = the stream width in year t, corresponding to the year of the streambed profile, and

$\Delta SW_{(cs)}$ = the predicted additional widening from the computer simulation.

An estimate of the stream width for each currently degrading drainage area interval of Willow Creek was based on two regression equations developed by Massoudi (1981). The regression equations related stream channel geometry to distance from the drainage divide for the Willow Creek channel. The first equation related the width to depth ratio of the Willow Creek channel to distance from the drainage divide as follows:

$$W/D = .077X + 5.23 \tag{6.3}$$

where:

W/D = the width to depth ratio of the Willow Creek channel, and

X = the distance from the drainage divide, in miles.

The second equation related the channel bottom width of Willow Creek to distance from the drainage divide. Equation 6.4 shows this relationship.

$$B = 1.67X + 12.79 \tag{6.4}$$

where:

B = the bottom width of the Willow Creek channel, and

X = the distance from the drainage divide, in miles.

Equations 4.15 and 4.16 were used to calculate an estimate of the stream width for each currently degrading drainage area interval on Willow Creek. Channel side slopes were assumed to be 1:1 and the depth was calculated by equation 4.17:

$$D = \left[\frac{BW}{(W/D - 2)}\right] \tag{6.5}$$

Multiplying the calculated depth by the width to depth ratio provided an estimate of the Willow Creek channel width in 1966 for the degrading stream segments under consideration.

An estimate of the channel width for the currently degrading segments of Keg Creek in 1980 was obtained from bridge inspection reports. An average width was obtained from the inspection reports for the three county highway bridges located in the currently degrading drainage area interval of Keg Creek.

An estimate of the 1992 stream width for each segment expected to degrade was obtained from the adjusted 1992 weighted average SCS measurements made by personnel from the Soil Conservation Service of the United States Department of Agriculture.

The Data

Predicted Vertical Degradation

The predicted vertical degradation for each currently degrading segment of Willow Creek and Keg Creek is listed in Table 6.3. The estimated predicted vertical degradation for each segment expected to degrade on Willow Creek and Keg Creek is listed in Table 6.4.

Estimated Rate of Vertical Degradation

The estimated rate of vertical degradation used to integrate time into the predictive analysis of land voiding for Willow Creek and Keg Creek is shown in Table 6.5. The estimated values of (-k') were obtained from Yang (1994). The values are based on data from department of transportation and county bridge inspection reports. The bridge inspection reports used to estimate the rate of vertical degradation showed the stream bed elevations over time at each bridge location. These measurements provided the necessary data to estimate the rate of vertical degradation on Willow Creek and Keg Creek.

Stream Widening and Land Voiding

The soil mechanics characteristics used in the computer simulation of the stream widening model are listed in Table 6.6. The mullenix stratigraphic unit of loess derived alluvium soil was used in the model of stream widening and land voiding. The computer simulation was based upon the characteristics of this unit and the values were selected to result in maximum stream bank instability.

Table 6.3 Streambed elevations and predicted vertical degradation for currently degrading segments of Willow Creek and Keg Creek, in feet.

Stream	Cumulative drainage area (mi.^{2})	Profile date	Elevation of streambed (feet)	Predicted final elevation of streambed (feet)	Predicted vertical degradation (feet)	Average predicted vertical degradation (feet)
Willow	30.03	1966	1197.00	1157.50	39.50	41.50
Willow	31.84	1966	1178.00	1145.75	32.25	35.88
Willow	33.65	1966	1164.50	1135.50	29.00	30.63
Willow	48.25	1966	1150.50	1125.00	25.50	27.25
Willow	52.06	1966	1139.50	1118.00	21.50	23.50
Willow	55.75	1966	1130.50	1111.25	19.25	20.38
Willow	59.06	1966	1124.00	1105.00	19.00	19.13
Willow	62.08	1966	1118.00	1098.75	19.25	19.13
Willow	64.87	1966	1112.00	1092.50	19.50	19.38
Willow	67.48	1966	1106.50	1086.25	20.25	19.88
Willow	69.95	1966	1099.50	1079.75	19.75	20.00
Keg	83.92	1980	1129.38	1105.38	24.00	24.00
Keg	87.57	1980	1115.09	1091.34	23.75	23.75
Keg	91.40	1980	1100.10	1076.85	23.25	23.38
Keg	95.23	1980	1090.95	1070.45	20.50	21.88
Keg	99.50	1980	1080.18	1063.93	16.25	18.38
Keg	103.76	1980	1070.01	1058.26	11.75	14.00
Keg	111.00	1980	1060.30	1049.80	10.50	11.13

Table 6.4 Streambed elevations and predicted vertical degradation for segments of Willow Creek and Keg Creek expected to degrade, in feet.

Stream	Cumulative drainage area ($mi.^2$)	Profile date	Elevation of streambed (feet)	Predicted final elevation of streambed (feet)	Predicted vertical degradation (feet)	Average predicted vertical degradation (feet)
Willow	4.15	1992	1324.25	1303.00	21.25	21.25
Willow	7.11	1992	1313.05	1289.80	23.25	22.25
Willow	7.58	1992	1305.94	1282.69	23.25	23.25
Willow	9.08	1992	1289.07	1265.56	23.51	23.38
Willow	11.26	1992	1285.70	1262.45	23.25	23.38
Willow	13.44	1992	1256.42	1235.52	20.50	21.88
Willow	22.27	1992	1251.48	1231.98	19.50	20.00
Willow	25.44	1992	1231.96	1219.46	12.50	16.00
Willow	27.27	1992	1218.93	1213.18	5.75	9.13
Keg	17.12	1992	1287.91	1265.16	22.75	22.75
Keg	20.20	1992	1276.26	1255.26	21.00	21.88
Keg	22.79	1992	1267.01	1248.01	19.00	20.00
Keg	25.66	1992	1256.74	1240.74	16.00	17.50
Keg	37.14	1992	1245.37	1227.87	17.50	16.75
Keg	50.4	1992	1237.78	1220.53	17.25	17.38
Keg	52.34	1992	1231.86	1216.11	15.75	16.50
Keg	54.76	1992	1224.09	1211.09	13.00	14.38
Keg	57.18	1992	1213.92	1206.42	7.50	10.25
Keg	59.6	1992	1206.42	1202.92	3.50	5.50

Table 6.5 Values of -k' and results of estimation for Willow Creek and Keg Creek.

Stream	-k'	Standard Error	R^2	p-value
Willow Creek	.002583	.0005025	.59	.0001
Keg Creek	.001208	.0001876	.46	.0001

Source: Yang (1994).

Table 6.6 Soil characteristics used in the computer simulation of stream widening.

Stratigraphic Unit	Soil cohesion (c) (psf)	Mean angle of internal friction (phi)	Saturated unit weight of soil (pcf)
Mullenix	221	27°	118.5

Source: Modified after Lohnes (1991).

Results

Currently Degrading Segments of Willow Creek and Keg Creek

The predictive results for the currently degrading segments of Willow Creek and Keg Creek are listed in Table 6.7. The greatest predicted stream widening occurred in the stream segment beginning at 30.03 square miles of drainage area on Willow Creek. The average predicted stream widening for the currently degrading segments of Willow Creek was 24.4 feet. The average predicted land voiding for the currently degrading segments of Willow Creek was 2.96 acres. The average estimated time over which degradation would occur was 68 years on Willow Creek. The total land voided on the currently degrading segments of Willow Creek was predicted to be 32.6 acres.

Table 6.7 Predicted stream widening, land voiding, and estimated time of degradation for currently degrading segments of Willow Creek and Keg Creek.

Stream	Cumulative drainage area ($mi.^2$)	County	Predicted additional widening (feet)	Predicted land voiding (acres)	Estimated time for degradation to occur (years)
Willow	30.03	Monona	55.09	6.68	82
Willow	31.84	Monona	29.08	3.52	77
Willow	33.65	Monona	26.04	3.16	71
Willow	48.25	Monona	24.10	3.21	68
Willow	52.06	Monona	21.93	2.39	63
Willow	55.75	Harrison	20.16	2.44	58
Willow	59.06	Harrison	17.61	2.13	57
Willow	62.08	Harrison	17.63	2.14	60
Willow	64.87	Harrison	18.14	2.20	64
Willow	67.48	Harrison	19.18	2.32	69
Willow	69.95	Harrison	19.44	2.36	74
Keg	83.92	Pottawattamie	26.01	3.15	111
Keg	87.57	Pottawattamie	25.86	6.26	114
Keg	91.40	Pottawattamie	25.63	6.52	123
Keg	95.23	Pottawattamie	23.77	2.59	124
Keg	99.50	Pottawattamie	31.09	3.76	110
Keg	103.76	Pottawattamie	22.87	2.77	89
Keg	111.00	Pottawattamie	16.35	3.37	76

The average predicted stream widening for the currently degrading segments of Keg Creek was 24.5 feet. The average predicted land voiding for the currently degrading segments of Keg Creek was 4.06 acres. The total predicted land voiding for the currently degrading segments of Keg Creek was 28.4 acres. The average estimated time over which degradation would occur was 107 years on Keg Creek.

Overall, the average predicted stream widening for the maximum degradation scenario was 24.4 feet. The average maximum predicted land voiding was 3.38 acres. The total predicted land voiding on the currently degrading segments of both study streams was 61 acres. The average time for degradation to occur was an estimated 83 years for currently degrading segments.

Segments Expected to Degrade on Willow Creek and Keg Creek

The predictive results for the segments of Willow Creek and Keg Creek expected to degrade are listed in Table 6.8. The greatest predicted stream widening occurred in the stream segment beginning at 13.44 square miles of drainage area on Willow Creek. The average predicted stream widening for the segments of Willow Creek expected to degrade was 29.4 feet. The average predicted land voiding for the currently degrading segments of Willow Creek was 5.48 acres. The total predicted land voiding on the segments of Willow Creek expected to degrade was 49.4 acres. The average estimated time over which degradation would occur was 27 years on Willow Creek.

The average predicted stream widening for the segments of Keg Creek expected to degrade was 23.25 feet. The average predicted land voiding for the segments of Keg Creek

Table 6.8 Predicted stream widening, land voiding, and estimated time of degradation for segments of Willow Creek and Keg Creek expected to degrade.

Stream	Cumulative drainage area ($mi.^2$)	County	Predicted additional widening (feet)	Predicted land voiding (acres)	Estimated time for degradation to occur (years)
Willow	4.15	Crawford	37.32	17.65	25
Willow	7.11	Crawford	25.51	2.88	27
Willow	7.58	Crawford	26.12	1.87	29
Willow	9.08	Crawford	26.20	4.45	30
Willow	11.26	Crawford	27.32	0.93	31
Willow	13.44	Crawford	40.09	11.81	31
Willow	22.27	Monona	36.07	1.79	30
Willow	25.44	Monona	28.99	5.69	25
Willow	27.27	Monona	17.38	2.28	15
Keg	17.12	Shelby	24.12	20.47	56
Keg	20.20	Shelby	23.60	3.15	54
Keg	22.79	Shelby	19.19	2.17	51
Keg	25.66	Shelby	28.73	3.48	46
Keg	37.14	Harrison	27.74	7.72	46
Keg	50.40	Harrison	29.02	4.22	49
Keg	52.34	Pottawattamie	27.78	2.69	47
Keg	54.76	Pottawattamie	23.60	2.86	42
Keg	57.18	Pottawattamie	15.81	1.92	31
Keg	59.60	Pottawattamie	12.92	1.57	17

expected to degrade was 5.02 acres. The total predicted land voiding for the segments of Keg Creek expected to degrade was 50.3 acres. The average estimated time over which degradation would occur was 44 years on Keg Creek.

Overall, the average predicted stream widening for the maximum degradation scenario was 26.18 feet. The average maximum predicted land voiding was 5.24 acres. On both study streams, the total predicted land voiding was 94.6 aces. The average time for degradation to occur was an estimated 36 years for currently degrading segments.

VII. AN ECONOMIC MODEL FOR THE OPTIMAL PLACEMENT OF GRADE STABILIZATION STRUCTURES

Grade Stabilization Methods in Western Iowa

Grade stabilization is a method by which stream degradation is inhibited by controlling the stream's energy. Grade stabilization in western Iowa usually takes the form of one or more full flow check dams placed in the stream channel in problem areas. The structures are defined as full flow structures because they are capable of allowing a specified discharge to pass through them without restricting the rate of flow within the stream channel. The grade stabilization structure raises the flow line of the channel upstream and creates an area of flat, slow flowing water. Lower stream velocities upstream are responsible for the deposition of suspended sediments. A sediment prism forms with a depth equal to the height of the stabilization structure. The newly formed sediment prism forms a new stable streambed slope upstream that neither degrades or aggrades (Lohnes et al., 1994).

The majority of grade stabilization structures placed on western Iowa streams have been placed at or near highway bridges and other specific infrastructure investments. The need to control degradation on a specific reach of a degrading stream has created a great diversity among stabilization structure designs in western Iowa in the past. Various structures used to control degradation in western Iowa include reinforced concrete flumes, sheet pile designs, H-pile designs, gabion flume designs, and rock sills.

According to Hanson et. al. (1986), reinforced concrete flume grade stabilization structures in western Iowa cost between $300,000 and $1,200,000 during the period 1979 to 1986. The high costs of these stabilization structure designs has established the need to seek alternative designs and materials for grade stabilization structures. In the same study, the performance of a newly designed gabion flume structure in Pottawattamie County was monitored. The structure had an initial cost estimate of $85,000 with a finished construction cost of $108,000.

Other, more recent design designs have dominated grade stabilization efforts in the past few years (Lohnes, 1994). H-pile and sheet pile designs along with rock sill designs have been used to economically control degradation in the face of diminishing county and state budgets. In the loess region of eastern Nebraska, rock sills and h-pile structures were used to control degradation on Elm Creek in Decatur County (Magner, 1994).

Method of Analysis

In order to facilitate decision making with regard to the placement of grade control structures, an economic optimization model is developed in this chapter. Moreover, the model has the specific objective of developing a method for use in making limited resource allocation decisions for the protection of land and rural infrastructure investments from the impacts of stream degradation.

The model estimates the costs and benefits of constructing grade stabilization structures on several sites based on the prediction of degradation and land voiding in Chapter VI. The structure selected for use in the model was an H-pile design due to its low material and construction costs and its effectiveness in controlling stream degradation. Each site selected reflects the need to control stream degradation and prohibit damage to rural infrastructure investments and the loss of land on specific stream segments. In addition, a site on Keg Creek that was the subject of a previous benefit cost analysis is included (Baumel et al., 1994). Costs and benefits for this stream segment were taken directly from the previous study. Table 7.1 lists the predicted stream widening, land voiding and segment length for each site included in the model.

Table 7.1 Selected sites for stream stabilization structure analysis.

Stream	Cumulative drainage area (mi^2)	County	Predicted stream widening (feet)	Predicted land voiding	Length of stream segment (miles)
Willow	9.08	Crawford	26.20	4.45	1.40
Willow	25.44	Monona	28.99	5.69	1.62
Willow	48.25	Monona	24.10	3.21	1.10
Keg	20.20	Shelby	23.60	3.15	1.10
Keg	37.14	Harrison	27.74	7.72	2.00
Keg	50.40	Harrison	29.02	4.22	1.20
Keg	59.60	Pottawattamie	12.92	1.57	1.00

Estimation of the Costs of Stream Stabilization

Estimation of the cost of grade control was based on a simple diagnostic analysis of the channel geometry for each stream segment listed in Table 7.1. The assumption was made that the cost of grade stabilization for a given length of stream can be estimated by the drop in elevation resulting from the placement of a particular structure. The horizontal projection method was used to estimate the length of stream that would be stabilized as a result of the placement of an H-pile grade stabilization structure. The horizontal projection method provides a lower bound for estimating channel stabilization by projecting a horizontal line from the top of the proposed structure to its intersection with the streambed profile. The length of the projected line is an estimate of the length stabilized by the structure. Equation 7.1 and Figure 7.1 illustrate the method of horizontal projection.

$$R = \frac{d}{S_0} \tag{7.1}$$

where:

R = the length of the stream segment controlled by the stabilization structure in miles,

d = the vertical drop of the structure in feet, and

S_0 = the streambed gradient in feet per mile.

Given the length for each stream segment, the gradient was calculated from Table 6.3 and 6.4. Equation 7.1 was then solved for d, the necessary drop to control each stream segment with an H-pile grade stabilization structure.

A cost per foot of drop was estimated from data on five H-pile stabilization structures constructed for stream stabilization in Decatur County, Nebraska . Each of the structures had a vertical drop of ten feet and controlled various lengths of stream, depending on the stream gradient. Dates of construction ranged from 1989 to 1994. Table 7.2 lists the five H-pile stabilization structures and their construction cost in the year built and in current dollars.

Table 7.2 Finished construction costs and 1994 costs for five H-pile stabilization structures located in Decatur County, NE.

Cost	Year built	Drop (feet)	1994 cost	1994 cost per foot of drop
$57,130	1989	10	$69,507	$6,951
68,843	1990	10	80,537	8,054
53,210	1991	10	59,854	5,985
55,965	1992	10	60,532	6,053
57,619	1994	10	57,619	5,762

Source: Magner, 1994.

Current cost estimates were made at a 4 % compound interest rate from the date of construction.

The costs for the five H-pile structures ranged from a low of $53,210 to a high of $68,843. The drop was a constant of 10 feet which indicates that specific conditions at each site may have been the cause for the variability in costs. Based on Table 7.2, an average cost per foot of drop in current dollars was $5,467. This cost was used to estimate the cost of grade stabilization with H-pile design structures on each site included in the model.

Table 7.3 lists the calculated drop and the estimated cost of grade stabilization for each stream segment included in the analysis. The costs of grade stabilization ranged from $41,003 to $106,721 for the selected sites. The total drop in feet for the selected sites ranged from a low of 7.50 feet to a high of 19.52 feet. The costs of grade stabilization in this analysis reflect the need to economically control stream degradation based on low cost structures with little or no maintenance costs.

Table 7.3 Estimated costs of grade stabilization with an H-pile design structure for selected sites on Willow Creek and Keg Creek in current dollars.

Stream	Cumulative drainage area (mi^2)	Stream segment length (miles)	Calculated drop (feet)	Average estimated H-pile cost (1994 dollars)
Willow	9.08	1.40	16.87	$92,228
Willow	25.44	1.62	19.52	106,721
Willow	48.25	1.10	13.75	75,171
Keg	20.20	1.10	11.65	63,685
Keg	37.14	2.00	11.36	62,105
Keg	50.40	1.20	7.59	41,495
Keg	59.60	1.00	7.50	41,003

Estimation of the Benefits of Stream Stabilization

The benefits of grade stabilization were defined as the costs of stream degradation in the absence of grade control structures. Moreover, the benefits of placing a grade stabilization structure were the cost savings to land and rural infrastructure investments at each location resulting from the predicted land voiding and stream widening. The prediction of the costs of degradation on Willow Creek and Keg Creek were based on the estimated parameter, β, from Equation 5.2. In order to better predict the costs of stream degradation, a 95 percent confidence interval was constructed for the parameter. Equation 7.2 shows the confidence interval for β.

$$95\%\ \text{C.I.} = \hat{\beta} \pm (S_{\hat{\beta}})\ t_{.025,\ 10} \tag{7.2}$$

The 95% confidence interval from equation 7.2 was {0.61, 0.85}. The benefits of stream stabilization were calculated with the estimated parameter, 0.73, and the upper and lower bounds of the confidence interval in order to capture the true value of the estimated parameter and future degradation costs.

Estimation of the Future Economic Impact of Land Voiding

The total predicted land voiding for each stream segment was allocated over time and the annual future costs were discounted back to current dollars. The difference in the stream width in two consecutive years for each stream segment was defined as:

$$SW(t) - SW(t-1) = \frac{(FW - IW)}{(t_f - t_0)^{\beta}} \left[(t - t_0)^{\beta} - ((t-1) - t_0)^{\beta} \right], \tag{7.3}$$

where:

$SW(t)$	= the stream width in year n,
$SW(t - 1)$	= the stream width in year $(t - 1)$,
FW	= the final stream width in year t_f ,
IW	= the initial stream width at t_0 ,
t_f	= the year that the stream stabilizes, and
t_0	= the year corresponding to the streambed profile.

Dividing both sides by the total change in stream width, the equation can be written as:

$$\frac{SW(t) - SW(t-1)}{\Delta SW} = A\left[(t - t_0)^{\beta} - ((t-1) - t_0)^{\beta}\right]\frac{1}{\Delta SW}\ , \tag{7.4}$$

where:

A = a constant, and

ΔSW = the predicted additional stream widening.

Equation 7.4 is an estimate of the percentage change in stream width in each year. Multiplying equation 7.4 by the predicted land voiding resulted in an estimate of the predicted land voiding for each year shown in equation 7.5.

$$LV_{it} = A\left[(t - t_0)^{\beta} - ((t-1) - t_0)^{\beta}\right]\frac{1}{\Delta SW}(\Lambda_i)\ , \tag{7.5}$$

where:

LV_{it} = the predicted land voiding in year t in drainage area interval i in acres,

Λ_i = the predicted total land voiding in drainage area i.

The total future cost of the predicted land voiding in current dollars for each stream segment was calculated by equation 7.6.

$$LC_i = \sum_{t_0}^{t_f} (V_t)(LV_{it})(P|F\ r,\ t)\ , \tag{7.6}$$

where:

LC_i = the total cost of land voided in stream segment i in current dollars,

V_t = the value of one acre of land in year t_0 ,

LV_{it} = the predicted land voiding in stream segment i in year t in acres,

$(P|F)$ = a present value given a future value in year t,

r = a long run real interest rate of four percent,

t_0 = the year corresponding to the streambed profile (1993)

t_f = the year degradation ends,

n = the estimated number of years that degradation would occur.

Estimation of Future Economic Impacts to Rural Infrastructure Investments

Each stream segment was located and inventoried for the presence of rural infrastructure investments. Rural infrastructure investments included in the stream segments included highway bridges, rural water lines, and natural gas pipelines. Table 7.4 lists the infrastructure for each stream segment included in the model.

Based on previous analyses of the costs to rural infrastructure investments as a result of stream degradation (Baumel et al., 1994), it was assumed that highway and railroad bridges would need extension when the stream segment widened five feet. It was further assumed that the extent of repair would reflect the total predicted widening of the stream.The benefits of stream stabilization to highway and railroad bridges were calculated and discounted back to current dollars based on the time for each segment to widen five feet. Per unit costs were obtained from the Pottawattamie County Engineering Office.

Table 7.4 Rural infrastructure investments crossing each stream segment on Willow Creek and Keg Creek.

Stream	Drainage area (mi^2)	Infrastructure investment	Location or number	Average daily traffic
Willow	9.08	Highway bridge	Willow 128320	55
Willow	9.08	Highway bridge	Willow 128300	30
Willow	25.44	Highway bridge	S - 3	15
Willow	25.44	Highway bridge	Willow 128410	30
Willow	48.25	Highway bridge	S27 - 3	15
Willow	48.25	Highway bridge	S22 - 1	190
Keg	20.20	Highway bridge	C90 35 11	10
Keg	20.20	Highway bridge	C90 25 21	20
Keg	20.20	3" Water line	T79N R40W 26	NA
Keg	20.20	2" water line	T79N R40W 24	NA
Keg	37.14	Highway bridge	WASH 15	30
Keg	37.14	Highway bridge	WASH 16	25
Keg	50.40	Highway bridge	MI - 1	55
Keg	50.40	Highway bridge	WASH 21	70
Keg	59.60	Highway bridge	MI - L66	500
Keg	59.60	Highway bridge	IA 83	770
Keg	59.60	8" Gas line	T77N R41W 14	NA
Keg	59.60	2" Gas line	T77N R41W 11	NA

Equation 7.7 was used to estimate future damage from stream degradation to bridges.

$$B_{b\,i} = (C_b)(\Delta SW_i)\left[\frac{1}{(1 + r)^n}\right] \tag{7.7}$$

where:

B_{bi} = the discounted benefit of stream stabilization to bridge b in stream segment i in current dollars,

b = 1 if the bridge is a railroad bridge,

b = 2 if the bridge is a highway bridge,

C_b = the estimated per foot cost of reconstructing bridge i in current dollars,

$1,300 if b = 1

$2,000 if b = 2,

ΔSW = the total predicted stream widening in stream segment i in feet,

r = a long run real interest rate of 4%, and

n = the number of years for stream segment i to widen five feet.

Benefits of stream stabilization to rural water and natural gas lines crossing segments of Keg Creek were calculated under the same assumptions as in equation 7.7, however; the per foot cost of reconstructing water and natural gas lines varied by the diameter of the pipeline. Per foot costs were taken from Table 5.6 and adjusted to current dollars. Equation 7.7 was then used to calculate the benefits to rural water and natural gas lines from the placement of stream stabilization structures.

Estimation of Future Economic Impacts Resulting from Traffic Re-routing

Each bridge was assumed to be closed for a 60 day period to undergo reconstruction. During this period, traffic re-routing costs were calculated. An average cost of $40.00 per average daily traffic was used to estimate the benefits of stream stabilization to traffic re-routing (Baumel et al., 1994). This cost was then discounted back to current dollars from the year of repair in Equation 7.7. Estimates of average daily traffic for each bridge were taken from Iowa Department of Transportation bridge inspection reports. The ADT estimates varied from a low of 10 to a high of 770.

Benefit - Cost Analysis

Table 7.5 shows the benefit and cost of stream stabilization and the benefit-cost ratio for each site with β = 0.73, 0.61, and 0.85. In general, the lower bound of the confidence interval resulted in higher discounted benefits. The upper bound resulted in lower discounted benefits. The costs of stream stabilization were constant for all sites irrespective of the value of beta, however; the lower bound for beta resulted in a benefit cost ratio of less than one for one site.

Figure 7.1 illustrates the upper and lower bounds for stream widths over time based on Keg Creek, 37.14 square miles of drainage area. The initial, 1992 width was estimated at 70 feet and the predicted final stream width was 98 feet. The estimated time for degradation to occur on this segment was 46 years. The lower bound (0.61), caused the stream to widen more in the early years. This resulted in higher estimates of the discounted benefits of stream stabilization. The upper bound (0.85), resulted in a more gradual increase in stream width

Table 7.5 Benefit and cost of stream stabilization for selected sites on Willow Creek and Keg Creek in current dollars.

Stream	Cumulative drainage area (mi^2)	Stream segment length (miles)	Total benefits (1994 dollars)	Total cost (1994 dollars)	Benefit-cost ratio
			Beta = 0.61		
Willow	9.08	1.40	$104,356	$92,228	1.13
Willow	25.44	1.62	113,673	106,721	1.07
Keg	20.20	1.10	82,177	63,685	1.29
Keg	37.14	2.00	105,939	62,105	1.71
Keg	50.40	1.20	110,729	41,495	2.67
Keg	59.60	1.00	94,300	41,003	2.30
			Beta = 0.73		
Willow	9.08	1.40	$96,635	$92,228	1.05
Willow	25.44	1.62	109,290	106,721	1.02
Keg	20.20	1.10	75,960	63,685	1.19
Keg	37.14	2.00	97,695	62,105	1.58
Keg	50.40	1.20	102,372	41,495	2.47
Keg	59.60	1.00	87,260	41,003	2.13
Keg[b]	87.57	1.50	224,193	150,000	1.49
			Beta = 0.85		
Willow	9.08	1.40	$89,309	$92,228	0.97
Willow	25.44	1.62	105,098	106,721	0.98
Keg	20.20	1.10	70,230	63,685	1.10
Keg	37.14	2.00	90,625	62,105	1.46
Keg	50.40	1.20	94,668	41,495	2.28
Keg	59.60	1.00	83,930	41,003	2.05

[b] Source: Baumel et al., 1994.

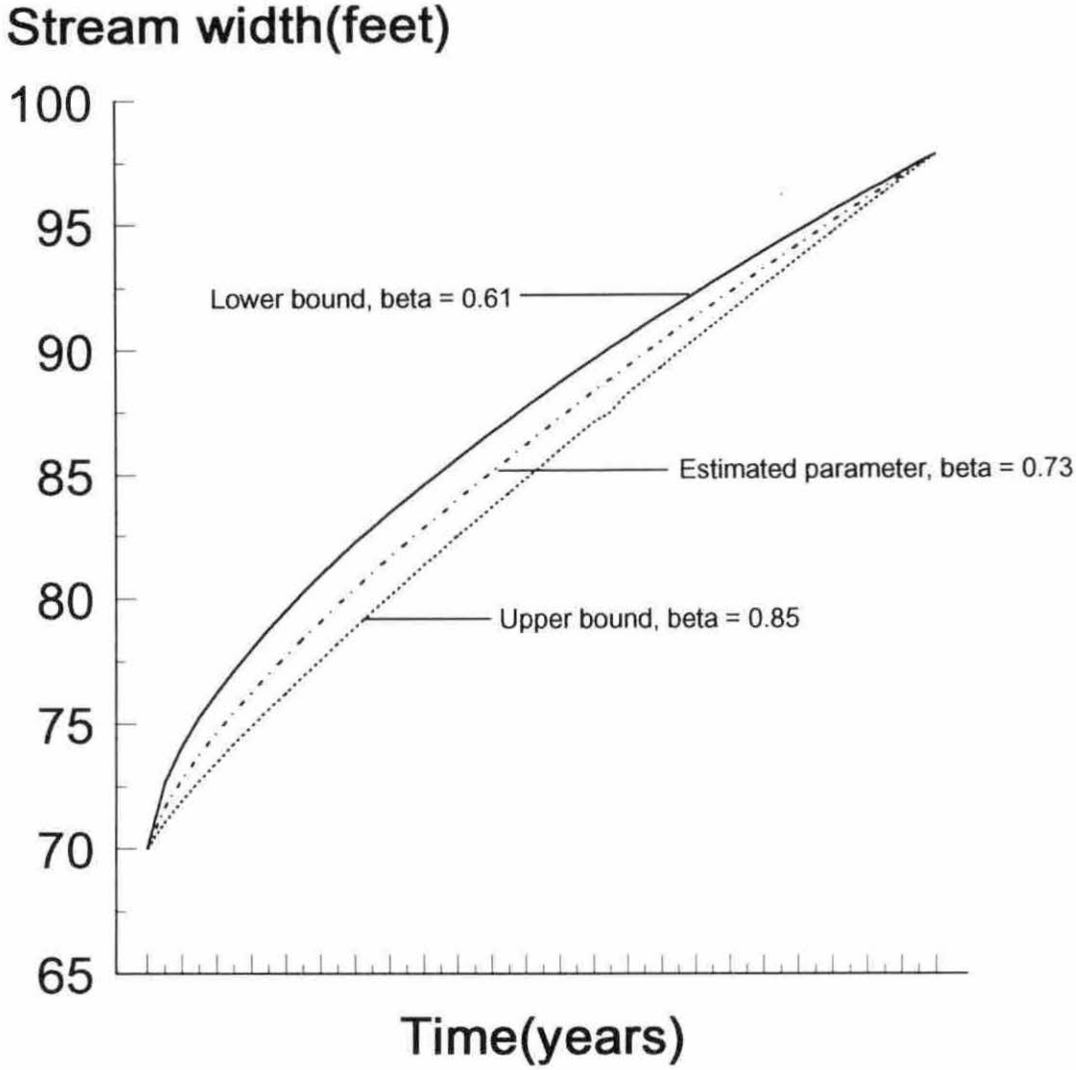


Figure 7.1 Estimated parameter and confidence interval bounds for the model of stream widening over time, Keg Creek 37.14 square miles of drainage area.

over the period, which caused the discounted benefits to be lower.

With beta = 0.73, the site beginning at 48.25 square miles of drainage area on Willow Creek had a benefit-cost ratio of 0.45. This segment was omitted from the analysis as a possible location for a stabilization structure. All other sites included in the analysis had positive benefit-cost ratios. The site on Keg Creek beginning at 50.4 square miles of drainage area had the highest benefit-cost ratio of 2.47. The lowest benefit-cost ratio was 1.02 on Willow Creek beginning at 25.44 square miles of drainage area. The total benefit of stream stabilization for all sites combined was $793,675. The total cost of stream stabilization was $557,237.

With beta = 0.61, the benefit of stream stabilization increased for all stream segments. The highest benefit-cost ratio occurred on Keg Creek beginning at 50.4 square miles of drainage area. The lowest ratio occurred on Willow Creek beginning at 25.44 square miles of drainage area. The total benefit of stream stabilization was $611,174. The total cost of stream stabilization was $407,237.

With beta = 0.85, the benefits of stream stabilization decreased. The highest benefit-cost ratio again occurred on Keg Creek beginning at 50.4 square miles of drainage area. The lowest benefit-cost ratio was 0.97 on Willow Creek beginning at 9.08 square miles of drainage area. The second lowest benefit-cost ratio was 0.98 on Willow Creek beginning at 25.44 square miles of drainage area.

These segments had a benefit cost ratio under one, indicating that the return on one dollar invested in stream stabilization would yield less one dollar in benefits. Thus , each was excluded as a possible choice for stream stabilization. The total benefit of stream stabilization excluding Willow Creek (25.44 mi^2 and 9.08 mi^2) was \$339,453. The total cost of stream stabilization was \$208,228.

Resource Allocation for Stream Stabilization

Given the estimated future benefits and costs of stream stabilization, the obvious next step is to make investment decisions regarding the optimal placement of stabilization structures given a resource constraint. A simple comparison of the benefit-cost ratios listed in Table 7.5 would allow a decision maker to consecutively select those locations that would give the highest return until the total budget was exhausted. This type of resource allocation method examines each potential site individually and may result in a sub-optimal decision (Yang, 1994). An alternative to this method is to maximize the total benefit of all sites considered simultaneously. In the following sections, both methods of resource allocation are examined with respect to the benefits and costs of stabilizing the stream segments listed in Table 7.5.

Method One: Benefit-Cost Ratio Ranking

Table 7.6 shows the ranked benefit-cost ratios and the costs of stream stabilization for each stream segment on Willow Creek and Keg Creek with each value of β.

Assuming a total budget of \$300,000 for the construction of stream stabilization structures on Willow Creek and Keg Creek, the stream segments were consecutively chosen in order of benefit-cost ratio until the budget was exhausted. With $\beta = 0.61$, the analysis indicated {Keg-50.40, Keg-59.60, Keg-37.14, and Keg-20.20} were the best investment choices. The total cost of stabilizing these segments was $208,288 for a total discounted benefit of $393,145.

Table 7.6 Benefit-cost ratio and cost of stream stabilization for segments of Willow Creek and Keg Creek under different values of beta.

	Benefit-cost ratio				
Stream segment	$\beta = 0.61$	$\beta = 0.73$	$\beta = 0.85$	Cost (1994 dollars)	Cumulative cost (1994 dollars)
Keg - 50.40	2.67	2.47	2.28	$41,495	$41,495
Keg - 59.60	2.30	2.13	2.05	41,003	82,498
Keg - 37.14	1.71	1.58	1.46	62,105	144,603
Keg - 20.20	1.29	1.19	1.10	63,6857	208,288
Willow - 9.08	1.13	1.05	0.97	92,228	300,516
Willow - 25.44	1.07	1.02	0.98	106,721	407,237

With $\beta = 0.73$, the selected stream segments were {Keg-50.40, Keg-59.60, Keg-37.14, and Keg-20.20}. The total cost of stream stabilization was the same for a total discounted benefit of $363,287.

With $\beta = 0.85$, the best investment choices were {Keg-50.40, Keg-59.60, Keg-37.14, and Keg-20.20}. The total cost of stabilizing these stream segments was the same for a total discounted benefit of $339,453. The upper bound of the confidence interval for β caused the benefit-cost ratio for two stream segments, {Willow-9.08 and Willow-25.44}, to fall below one. These segments were not chosen under any value of β.

Suppose the total budget for the construction of stream stabilization structures is decreased by \$100,000, for a total budget of \$200,000. With a smaller total budget, the best investment choices were {Keg-50.40, Keg-59.60, and Keg-37.14} with a total cost of stream stabilization of \$144,603. With β = 0.61 the total discounted benefit of stream stabilization was \$ 310,968. With β = 0.73 the total discounted benefit of stream stabilization was \$287,327. With β = 0.85 the total discounted benefit of stream stabilization was \$ 269,233.

Under either budget constraint and all three values for the parameter β, no stream segments on Willow Creek were chosen as possible sites for stream stabilization projects. With a total budget for the construction of stream stabilization structures of \$300,000 the stream segments {Keg-50.40, Keg-59.60, Keg-37.14, and Keg-20.20} should be chosen. The total estimated cost of stabilizing these stream segments is \$208,228. The total discounted benefit of stabilizing these stream segments is between \$339,453 and \$393,145.

With a total budget for the construction of stream stabilization structures of \$200,000 the stream segments {Keg-50.40, Keg-59.60, and Keg-37.14} should be chosen. The total estimated cost of stabilizing these stream segments is \$144,603. The total discounted benefit of stabilizing these stream segments is between \$269,223 and \$310,968.

The benefit-cost ranking above excludes the stream segment on Keg Creek beginning at 87.57 square miles of drainage area considered by Baumel et al., 1994. The benefit and cost of this stream segment was based on β = 0.73 and considered two H-pile stream stabilization structures on a 1.5 mile segment of Keg Creek.

Table 7.7 shows the benefit cost ranking for the stream segments analyzed during this research with β = 0.73 and the stream segment considered by Baumel et al., 1994.

Table 7.7 Benefit-cost ratio and cost of stream stabilization for segments of Willow Creek and Keg Creek.

Stream segment	$\beta = 0.73$	Cost (1994 dollars)	Cumulative cost (1994 dollars)
Keg - 50.40	2.47	$41,495	$41,495
Keg - 59.60	2.13	41,003	82,498
Keg - 37.14	1.58	62,105	144,603
Keg - 87.57[b]	1.49	150,000	294,603
Keg - 20.20	1.19	63,685	358,288
Willow - 9.08	1.05	92,228	450,516
Willow - 25.44	1.02	106,721	557,237

[b] Source: Baumel et al., 1994.

The total cost of stream stabilization for the 1.5 mile segment beginning at 87.57 square miles of drainage area on Keg Creek was an estimated $150,000. This cost included the construction of two H-pile structures. The total discounted benefits of stream stabilization were an estimated $224,193. These estimates were based on a detailed analysis of the 1.5 mile segment of Keg Creek (Baumel et al., 1994).

Assuming a total budget for stream stabilization on Willow Creek and Keg Creek of $300,000, the following sites were determined to be the best investment: {Keg-50.40, Keg - 59.60, Keg-37.14, and Keg-87.57}. The total cost of stream stabilization for these stream segments was $294,603. The total discounted benefit of stream stabilization for these stream segments was $511,552.

Assuming a total budget for stream stabilization on Willow Creek and Keg Creek of $200,000, the following sites were determined to be the best investment: {Keg-50.40, Keg - 59.60, and Keg-37.14}. The total cost of stream stabilization for these stream segments was $144,603. The total discounted benefit of stream stabilization for these stream segments was $287,327. When ranked comparatively with other stream segments by benefit-cost ratio, the segment {Keg-87.57} would not be chosen with a budget constraint of $200,000. With a larger budget, however; this segment would be selected for a stream stabilization structure.

Method Two: An Optimization Model for Resource Allocation

The previous benefit-cost analysis implies that all stream segments with a benefit-cost ratio greater than one should be considered as potential sites for stream stabilization. Consecutively choosing those stream segments with positive a net benefit (total benefit - total cost) until the budget resource is exhausted is a method by which alternative investments can be chosen. This method will maximize the benefit of the investment subject to the resource constraint only if there are no interrelationships to be considered. Ranking by benefit-cost ratio examines each investment alternative independent of one another and may not produce the best solution. In this section, an optimization model is developed as an alternative to the benefit-cost ranking method. The model has the specific objective of maximizing the net benefit of constructing stream stabilization structures given the benefits and costs of stabilizing alternative stream segments subject to a budget constraint. This type of model would be very useful in allocating a scarce budget for stream stabilization projects.

The problem of maximizing the net benefit of stream stabilization subject to a budget constraint is one of mathematical programming. There are two major classes of mathematical programming problems: linear programming (LP) problems and integer linear programming (IP) problems. Linear programming problems require that the mathematical statement of the objective function and the constraint(s) be linear relationships. The major difference between linear programming and linear integer programming is in the assumption of divisibility.

Divisibility requires that the solution value(s) of the decision variable(s) can take on noninteger values in linear programming problems. In linear integer programming problems, however; the solution value(s) of the decision variable(s) are constrained to integer values (Zionts, 1974). In many applied problems, the decision variables have a useful meaning only if they have integer solution values. For example, suppose that in choosing from among alternative stream segments for the construction of stabilization structures subject to a budget constraint, that a linear programming model was used. It is possible under this framework that the optimal solution would require the construction of 0.25 of a stabilization structure for a given stream segment. This solution is not practical when the specific stabilization structure for that stream segment was predetermined based on the channel geometry of the stream segment.

An alternative to linear programming to solve this problem is integer linear programming. The specification for (IP) problems requires that the solution values of the decision variables take on integer values. A survey of integer programming applications and uses can be found in Balinski (1965). Other applications are available in Dantzig (1960). The practical applications for linear integer programming problems are virtually unlimited. Some examples include the assignment model, the fixed charge model, the plant location model, and the project selection model (Murty, 1976; Pfaffenberger and Walker, 1976).

In the problem of selecting the optimal combination of stream segments for stream stabilization projects subject to a budget constraint, the values should be constrained to {0 or 1}. Fortunately, a class of (IP) problems allows for this type of solution. Binary integer programming constrains all integer decision variables to {0 or 1}. The problem specification used for the model under consideration was a binary linear integer programming model. The model maximizes the total discounted net benefit of stream stabilization considering the stream segments listed in Table 7.5 subject to the budget constraint for constructing stabilization structures. Equation 7.8 shows the model used in the economic analysis.

$$\text{Maximize } U = \sum_{i=1}^{n} b_i \, \delta_i$$
$$\text{s. t. } \sum_{i=1}^{n} c_i \, \delta_i \leq I \qquad (7.8)$$

where:

U = the total discounted net benefit from stream stabilization in current dollars,

n = the number of potential sites considered for stream stabilization,

b_i = the discounted benefit of stabilizing stream segment i in current dollars,

c_i = the cost of stream stabilization for stream segment i, defined as the cost of the grade stabilization structure.

δ_i = a binary decision variable

= 1 if stream segment i is stabilized, and

= 0 if stream segment i is left to degrade, and

I = the total budget available for the construction of stream stabilization structures.

Equation 7.8 was programmed in GAMS (General Algebraic Modelling System). A copy of the program is included in Appendix B. Equation 7.8 evaluates all stream segments together to produce the optimal combination of projects which maximizes the total net benefit of stream stabilization on Willow Creek and Keg Creek. The solution to equation 7.8 takes the form of a vector consisting of a value {0 or 1} for the decision variable δ, and a current dollar value for U. Each entry in the solution vector corresponds to a stream segment. With $\delta = 0$, the corresponding segment should be left to degrade. With $\delta = 1$, the corresponding stream segment should be stabilized by constructing an H-pile structure with the necessary drop to stabilize the segment. The GAMS program was run with a budget of $300,000 and $200,000 for each value of β. This allowed for the comparison of solutions under the method of benefit-cost ratio ranking and net benefit optimization.

Optimization Model Results

With a total budget for the construction of stream stabilization structures of $300,000 and $\beta = 0.61$, the optimal solution was as follows:

$\{\delta_1, \delta_2, \delta_3, \delta_4, \delta_5, \delta_6\} = \{0, 1, 0, 1, 1, 1\}$,

with U = $424,640.

where $\delta = 1,2, \ldots 6$ represents the stream segments on Willow Creek and Keg Creek

{Willow-9.08. Willow 25.44, Keg 20.20, Keg-37.14, Keg-50.40, Keg-59.6}. The values of the decision variables indicate that four stream segments should have stabilization structures constructed. The optimal solution in this case is to stabilize {Willow-25.44, Keg-37.14, Keg-50.40, and Keg-59.6} for a total discounted net benefit of $424,640.

With a total budget for the construction of stream stabilization structures of $300,000 and $\beta = 0.73$, the optimal solution was as follows:

$\{\delta_1, \delta_2, \delta_3, \delta_4, \delta_5, \delta_6\} = \{0, 1, 0, 1, 1, 1\}$,

with U = $321,020.

The values of the decision variables indicate that three stream segments should have stabilization structures constructed. The optimal solution in this case is to stabilize {Willow-25.44, Keg-37.14, Keg-50.40, and Keg-59.6} for a total discounted net benefit of $321,020.

With a total budget for the construction of stream stabilization structures of $300,000 and $\beta = 0.85$, the optimal solution was as follows:

$\{\delta_3, \delta_4, \delta_5, \delta_6\} = \{1, 1, 1, 1\}$

with U = $339,453.

The values of the decision variables indicate that all four stream segments should have stabilization structures constructed. The optimal solution in this case is to stabilize {Keg-20.20, Keg-37.14, Keg-50.40, and Keg-59.6} for a total discounted net benefit of $339,453. Only the four sites with a benefit-cost ratio greater than one were considered with $\beta = 0.85$. The total cost of stream stabilization for these stream segments was $208,288 which resulted in choosing all sites due to a non-binding budget constraint.

With a total budget for the construction of stream stabilization structures of $200,000 and $\beta = 0.61$, the optimal solution was as follows:

$$\{\delta_1, \delta_2, \delta_3, \delta_4, \delta_5, \delta_6\} = \{1, 0, 0, 1, 1, 0\}$$

with U = \$321,020.

The values of the decision variables indicate that three stream segments should have stabilization structures constructed. The optimal solution in this case is to stabilize {Willow-9.08, Keg-37.14, and Keg-50.40,} for a total discounted net benefit of \$321,020.

With a total budget for the construction of stream stabilization structures of \$200,000 and $\beta = 0.73$, the optimal solution was as follows:

$$\{\delta_1, \delta_2, \delta_3, \delta_4, \delta_5, \delta_6\} = \{0, 1, 0, 0, 1, 1\}$$

with U = \$298,920.

The values of the decision variables indicate that three stream segments should have stabilization structures constructed. The optimal solution in this case is to stabilize {Willow-25.44, Keg-50.40, and Keg-59.60,} for a total discounted net benefit of \$298,920.

With a total budget for the construction of stream stabilization structures of \$200,000 and $\beta = 0.85$, the optimal solution was as follows:

$$\{\delta_3, \delta_4, \delta_5, \delta_6\} = \{0, 1, 1, 1\}$$

with U = \$269,220.

The values of the decision variables indicate that three stream segments should have stabilization structures constructed. The optimal solution in this case is to stabilize {Keg-37.14, Keg-50.40, and Keg-59.60} for a total discounted net benefit of \$269,220. Only the four sites with a benefit-cost ratio greater than one were considered with $\beta = 0.85$.

Reconsidering the stream segments in this thesis and the segment analyzed by Baumel et al., 1994 with a total budget for the construction of stabilization structures of \$300,000 and $\beta = 0.73$, the optimal solution was found:

$$\{\delta_1 , \delta_2 , \delta_3 , \delta_4 , \delta_5 , \delta_6 , \delta_7\} = \{0, 0, 0, 1, 1, 1, 1\}$$

with U = \$511,520.

The values of the decision variables indicate that four stream segments should have stabilization structures constructed. The optimal solution in this case is to stabilize {Keg-37.14, Keg-50.40, and Keg-59.60,and Keg 87.57} for a total discounted net benefit of \$511,520.

With $\beta = 0.73$ and a total budget of \$200,000 the same sites were examined and the optimal solution was:

$$\{\delta_1 , \delta_2 , \delta_3 , \delta_4 , \delta_5 , \delta_6 , \delta_7\} = \{0, 0, 0, 0, 1, 0, 1\}$$

with U = \$326,560.

The values of the decision variables indicated that only two sites should be stabilized with a budget of \$200,000. These sites were {Keg-50.40 and Keg-87.57}. With either budget constraint and $\beta = 0.73$, the site analyzed by Baumel et al., 1994 should have a stabilization structure investment.

Comparison of Results for Method One and Method Two

Table 7.8 shows the selected sites under different budgets for each value of β, excluding the stream segment analyzed by Baumel et al., 1994. The optimization model results indicated that the stream segment {Willow-25.44} should be in the optimal solution under a budget of \$300,000 with $\beta = 0.61$ and $\beta = 0.73$. The benefit-cost ranking indicated

Table 7.8 Comparison of the results of two resource allocation methods for the construction of stream stabilization structures.

Method One: Benefit-Cost Ranking					
B = $300,000			B = $200,000		
β = 0.61	β = 0.73	β = 0.85	β = 0.61	β = 0.73	β = 0.85
Keg - 50.40	Keg - 50.40	Keg - 50.40	Keg - 50.40	Keg - 50.40	Keg - 50.40
Keg - 59.60	Keg - 59.60	Keg - 59.60	Keg - 59.60	Keg - 59.60	Keg - 59.60
Keg - 37.14	Keg - 37.14	Keg - 37.14	Keg - 37.14	Keg - 37.14	Keg - 37.14
Keg - 20.20	Keg - 20.20	Keg - 20.20			

Method Two: Net Beneft Optimization					
B = $300,000			B = $200,000		
β = 0.61	β = 0.73	β = 0.85	β = 0.61	β = 0.73	β = 0.85
Keg - 50.40	Keg - 50.40	Keg - 50.40	Keg- -50.40	Keg - 50.40	Keg - 50.40
Keg - 59.60	Keg - 59.60	Keg - 59.60	Keg - 37.14	Keg - 59.60	Keg - 59.60
Keg - 37.14	Keg - 37.14	Keg - 37.14	Willow - 9.08	Willow - 25.44	Keg - 37.14
Willow - 25.44	Willow - 25.44	Keg - 20.20			

that no Willow Creek segments should be considered for stream stabilization. This is not the best solution.

Under a budget of $200,000 a similar result occurs. With a value of β = 0.61 and β = 0.73, two Willow Creek segments were chosen in the optimization model. Rather than ranking benefit-cost ratios, the optimization model maximizes the total discounted net benefit of placing stream stabilization structures on the selected sites. The solutions from the optimization model should be used for selecting stream segments for stabilization in this case.

Table 7.9 shows the results of the benefit-cost ranking method and the net benefit optimization model with β = 0.73 including the site analyzed by Baumel, et al., 1994. The site analyzed by Baumel et al., 1994 was chosen in the benefit-cost ranking under a budget of $300,000, and β = 0.73, however; this segment was not chosen under a budget of $200,000. In the optimal solution, the stream segment analyzed by Baumel et al., 1994 was

Table 7.9 Comparison of the results of two resource allocation methods for the construction of stream stabilization structures with β = 0.73.

B = $300,000		B = $200,000	
B/C	IP	B/C	IP
Keg - 50.40	Keg - 50.40	Keg - 50.40	Keg - 50.40
Keg - 59.60	Keg - 59.60	Keg - 59.60	Keg - 87.57
Keg - 37.14	Keg - 37.14	Keg - 37.14	
Keg - 87.57	Keg - 87.57		

chosen under both budget constraints with $\beta = 0.73$. This site had a comparatively large discounted net benefit. The site analyzed by Baumel et al., 1994 was chosen in the benefit-cost ranking under a budget of $300,000, and $\beta = 0.73$, however; this segment was not chosen under a budget of $200,000. In the optimal solution, the stream segment analyzed by Baumel et al., 1994 was chosen under both budget constraints with $\beta = 0.73$. This site had a comparatively large discounted net benefit and was chosen when maximizing the total discounted net benefit.

Relying upon the estimated parameter, $\beta = 0.73$ the optimal solution to the problem of selecting stream segments for stabilization projects including the site analyzed by Baumel et al., 1994 was: Keg-37.14, Keg-50.40, Keg-59.6, and Keg 87.57 under a budget constraint of $300,000. The total net discounted benefit was $511,520. The same solution under a budget of $200,000 was: Keg-50.40, and Keg-87.57 with a net discounted benefit of $326,560.

Conclusions

The objective of this chapter was to develop an economic method for the optimal placement of stream stabilization structures. The method illustrates an optimal method for selecting stream segments for stabilization structures under estimates of maximum stream degradation and land voiding. The results do not suggest that stabilization structures should actually be constructed at the solution locations. Rather, they suggest a method to determine the best investment choices for stream stabilization projects. Each site should be examined individually to estimate benefits and costs.

For investment decision purposes, the net benefit optimization model will always result in the best investment choices whereas the benefit cost ranking method will result in the best investment choices under a less binding budget constraint. Based on the results of this analysis, it can be concluded that the benefit cost ranking method of allocating stream stabilization funds is acceptable with a large budget and relatively few stream segments to consider. The net benefit optimization method will always provide the optimal solution and should be especially useful when considering a large number of potential investments with a small budget.

VIII. CONCLUSIONS

Summary of the Study

Stream degradation has imposed substantial costs on land and rural infrastructure investments in western Iowa since the turn of the century. The channelization (straightening) of streams and rivers in western Iowa's loess region has been cited as a possible major cause of stream degradation. Since the channelization projects were completed, many of the streams and rivers in western Iowa have degraded from 1.5 to 5 times their original channelized depths. This vertical degradation has been accompanied by width increases of 2 to 5 times the original channelized widths, resulting in considerable land loss or voiding. Land voiding, in turn, has been responsible for much of the damage to rural infrastructure investments in western Iowa's loess region.

The objectives of this study were to develop and clarify methods by which the impacts of stream degradation can be estimated, and to develop information, systems, and methods for use in making resource allocation decisions for the protection of land and rural infrastructure investments from the impacts of stream degradation.

A detailed historical analysis of the channelized and degrading segments of Willow Creek and Keg Creek in western Iowa's loess region was undertaken. The analysis considered the impacts of stream degradation on land and rural infrastructure investments from the dates of initial channelization through 1992. Estimates of the economic cost of stream degradation over this period were obtained by estimating the change in stream width in each year with an empirically based rate function of stream widening. Initial channelized stream widths were obtained from historical drainage district records. The 1992 stream widths were measured from SCS aerial photographs of Willow Creek and Keg Creek and adjusted using current bridge inspection reports. An inventory of the rural infrastructure crossing the channelized segments of Willow Creek and Keg Creek was made. Data were collected from county engineers, railroad, pipeline, electric, telephone, and waterline companies on the per unit costs to infrastructure resulting from stream widening. In addition, a time series data set was compiled for land values in each county over the historical period. These values, combined with the rate of stream widening over time, permitted the estimation of the economic impact of stream degradation on the channelized segments of Willow Creek and Keg Creek. A present value model of asset prices was developed to estimate these costs in 1992 dollars. Also, estimates of the costs of traffic re-routing due to bridge closures for repair as a result of stream degradation were made using TRANSCAD, a geographic information system software package.

The estimated total costs of land voiding on the channelized segments of Willow Creek and Keg Creek was \$1,535,300. The estimated total cost to rural infrastructure investments crossing the channelized segments of Willow Creek and Keg Creek, including traffic re-routing was \$11,335,500. Highway bridges accounted for 89% of the total costs. Railroad bridges were 5.4% of the total costs. The remaining infrastructure investments had less than 5% of the total costs, respectively.

Predictions of maximum future stream widening and land voiding on Willow Creek and Keg Creek were made using a two stage engineering analysis. The predictive analysis considered small stream segments on Willow Creek and Keg Creek categorized as currently degrading or expected to degrade. Predictions were made for the currently degrading segments of Willow Creek from 1966. Predictions were made for the currently degrading segments of Keg Creek from 1980. Predictions for segments expected to degrade were made from 1992-1993 for both Willow Creek and Keg Creek.

The first stage predicted the maximum vertical degradation for each segment using a tractive force model of stream degradation (Levich, 1994). The time over which each segment was expected to degrade was estimated by a rational model for the rate of vertical degradation (Lohnes et al., 1994). The second stage predicted maximum future stream widening and land voiding for each segment categorized as currently degrading or expected to degrade. These predictions were based on a computer simulation of a planar-surface failure model of stream widening (Lohnes, 1991). A FORTRAN program was written to simulate stream widening based on the well established principles of soil mechanics in the model.

The average predicted stream widening and land voiding for currently degrading segments of Willow Creek was 24.4 feet and 2.96 acres, respectively. The average time for degradation to occur on the currently degrading segments of Willow Creek was 68 years. The average predicted stream widening and land voiding for currently degrading segments of Keg Creek was 24.5 feet and 4.06 acres, respectively. The average time for degradation to occur on the currently degrading segments of Keg Creek was 87 years.

The average predicted stream widening and land voiding for segments expected to degrade on Willow Creek was 29.4 feet and 5.48 acres, respectively. The average time for degradation to occur on segments expected to degrade on Willow Creek was 27 years. The average predicted stream widening and land voiding for segments expected to degrade on Keg Creek was 29.4 feet and 5.48 acres, respectively. The average time for degradation to occur on segments expected to degrade on Keg Creek was 44 years.

An economic model for the optimal placement of stream stabilization structures was developed for use in making resource allocation decisions for the protection of land and rural infrastructure investments from the impacts of stream degradation. The model considered the predicted land voiding and stream widening on several stream segments. The model estimated the benefits and costs of stream stabilization structures for each stream segment. Costs of stream stabilization were defined as the cost of constructing an H-pile stabilization structure for each stream segment. The costs were obtained from previously constructed H-pile structures in Decatur county, NE. Based on these costs, a method of horizontal projection was used to estimate the cost of an H-pile grade stabilization structure for each stream segment included in the model. The costs of stream stabilization structures ranged from \$41,003 to \$106,721 for the selected sites.

Benefits of stream stabilization structures were defined as the costs savings from prohibiting stream degradation. A confidence interval was constructed for the estimated parameter of the stream widening model. Three sets of benefits were estimated: one for the estimated parameter, one for the lower bound of the confidence interval, and one for the upper bound of the confidence interval. The lower bound of the confidence interval, $\beta = 0.63$ resulted in the highest discounted net benefits, while the upper bound of the confidence interval, $\beta = 0.85$, resulted in the lowest discounted net benefits.

A benefit-cost analysis was performed for each stream segment under each value of the estimated parameter. Benefit-cost ratios were ranked in order for each value of the estimated parameter and the best investment choices were made subject to an assumed budget constraint. Budget constraints of $300,000 and $200,000 for the construction of grade stabilization structures assumed. Each stream segment was examined individually and successively chosen until the budget for the construction of stream stabilization structures was exhausted.

An integer programming (IP) model was developed to maximize the net benefit of all stream stabilization projects considered simultaneously subject to the assumed budget constraints. The optimization model was programmed in GAMS (General Algebraic Modelling System) and offered the optimal solution based on a binary decision variable. An optimal solution for the net benefit of stream stabilization was found for each confidence interval bound of the estimated parameter. These results were then compared to the results of simply ranking the benefit-cost ratios.

The benefit cost ranking model resulted in sub-optimal investment decisions when compared to the integer programming optimization model under a more constraining budget. Moreover, both methods provided the optimal solution of stream segments to stabilize under a non-binding budget constraint, however; the optimization model maximized the net benefit with all investment choices considered simultaneously and therefore provided the optimal solution in all cases.

Limitations of the Analysis

There are several limitations to this analysis. The rate of stream widening for the channelized segments of Willow Creek and Keg Creek were assumed to have been the same in the historical analysis. Based on engineering literature, this may be an oversimplifying assumption. The rate of stream degradation with respect to stream widening may vary by stream system. In addition, the data set used to estimate the function of stream widening over time was very limited and may not be representative of other degrading streams, however; this data set was the only available data on stream widths over time.

The 1992 stream width measurements did not accurately reflect the actual stream channel top widths due to scale, resolution, and vegetation cover problems in the SCS slides. The method of correcting these measured channel widths to an estimated channel top width relied upon county bridge inspection reports. These reports included diagrams of the stream channel at each bridge location on Willow Creek and Keg Creek. The method for adjusting the SCS measurements to an estimated top of channel width assumed the stream channel widths near bridges are the same as stream channel widths far from bridges. There is some evidence that stream channels may be wider near bridge crossings. Thus, the estimated 1992 stream width measurements may have been slightly overestimated.

In the analysis of traffic re-routing, the percentage of type of travel is from a survey conducted in 1982 of Shelby County, IA. The assumption was made that the travel pattern for each county was similar to that of Shelby County and travel patterns have remained constant. Since the time of the survey, the distribution may have changed. In addition, other counties may have different travel patterns. In the traffic re-routing analysis, a node selected near a bridge crossing Willow or Keg Creek was the assumed origin, while a node in the nearest town or county seat town was selected as the destination. These travel patterns may not be realistic.

In the predictive analysis of stream degradation, a tractive force model (Levich, 1994) was used to predict maximum vertical degradation. The parameters of the model were set to result in very large estimates of future vertical degradation. Comparing the predicted vertical degradation from Chapter VI of this thesis to a more realistic estimate found in Levich, 1994 illustrates the magnitude of the maximum degradation scenario followed in this thesis.

The estimates of the time for degradation to occur were based on the model developed by Lohnes et al., 1980. This model suggests that the rate of vertical degradation over time for a specific stream segment should vary by the discharge through that segment. Because of data limitations, the rates of vertical degradation used in this analysis were estimated for entire stream systems. Moreover, it was assumed that the rate of vertical degradation was constant for a stream system when the actual rate may vary as a function of drainage area.

It was assumed in this analysis that there is essentially no time lag between the beginning of vertical degradation and stream widening. Again, due to data limitations, it was impossible to estimate such a lag, if one exists. It was assumed, therefore, that vertical degradation and stream widening begin in the same year and end in the same year. Thus, a lag of up to one year was implicit in the analysis, however, it has no empirical base.

The computer simulation of stream widening was also programmed to result in maximum stream degradation in the from of stream widening and land voiding. A saturated unit weight of soil was used rather than a dry unit weight. Soil cohesion was also set low enough to create maximum widening.

The costs of stream stabilization structures may vary, depending upon the conditions at each specific stream segment. The benefit-cost analysis assumed that conditions would be the same for each site. The costs of stream stabilization structures were a function of vertical drop only.

The benefits of stream stabilization may also vary, depending upon specific conditions on each stream segment. The benefits of stream stabilization were a function of the rate of widening and the total predicted widening for rural infrastructure investments and land voiding. A detailed analysis of each stream segment may increse or decrease the estimates of the benefits of stream stabilization.

REFERENCES CITED

Adkins, Martin. "Research Proposal for Stream Stabilization in Western Iowa." Golden Hills RC&D Degrading Streams Task Force, Presented to the Highway Research Advisory Board, June 26, 1992.

Banard, Charles H., and John Jones. "Farm Real Estate Values in the United States by Counties, 1850-1982." U.S. Department of Agriculture, Economic Research Service, Statistical Bulletin No. 751, Washington, D.C.

Balinski, M. L., "Integer Programming: Methods, Uses, Computation." Management Science, Vol. 12, p. 253-313, 1965.

Baumel, C. Phillip, Landon L. Morris, Marty J. McVey, and Xing Yang. "Impacts of Degrading Western Iowa Stream on Private and Public Infrastructure Costs." Agriculture and Home Economics Experiment Station, Iowa State University, Ames, Iowa,in cooperation with Golden Hills Resource Conservation and Development, Oakland, Iowa, May 1994.

Baumel C. Phillip, Landon L. Morris, Marty J. McVey, and Robert A. Lohnes. "Estimates of the Future Impacts of Degrading Streams on Private and Public Infrastructure Costs." Agriculture and Home Economics Experiment Station, Iowa State University, Ames, Iowa, in cooperation with Golden Hills Resource Conservation and Development, Oakland, Iowa, November 1994.

Baumel, C. Phillip, Landon L. Morris, Marty J. McVey, and Robert A. Lohnes. "Estimated Benefits and Costs of a Grade Stabilization Structure on Keg Creek in Western Iowa."Agriculture and Home Economics Experiment Station, Iowa State University, Ames, Iowa, in cooperation with Golden Hills Resource Conservation and Development, Oakland, Iowa, November, 1994.

Baumel. C. Phillip, Sherry Brennan Miller, Gregory Pautsch, and Cathy Hamlett. The Local Rural Road System, Alternative Investment Strategies. CARD Technical Report 89-TR6, Iowa DOT Project HR 242, Sponsored by the Highway Division of the Iowa Department of Transportation and the Iowa Highway Research Board, Iowa State University, Ames, Iowa, 1989.

Baumel C. Phillip, Stephen B. Baumhover, Michael A. Lipsman, and Marty J. McVey. Alternative Investments in the Rural Branch Railroad and County Road Systems. Midwest Transportation Center, Iowa State University, Ames, Iowa, March 1991.

Brooke, Anthony, David Kendrick, and Alexander Meeraus. GAMS: A User's Guide. The Scientific Press, San Francisco CA, 1988.

Brown, Scott A. "Prediction of Channel Bed Grade Changes at Highway Stream Crossings." Transportation Research Record 896, Transportation Research Board, National Academy of Sciences, National Science Foundation, Washington, D.C., 1982, p. 1-7.

Board of Supervisors, Fremont County, Iowa. "Walnut Creek Drainage District No. 2." 1921 [available from C. Phillip Baumel, Department of Economics, Iowa State University, Ames, Iowa].

Board of Supervisors, Mills County, Iowa. "Keg Creek-Pony Creek Proposed Drainage District." 1927 [available from C. Phillip Baumel, Department of Economics, Iowa State University, Ames, Iowa].

Board of Supervisors, Mills County, Iowa. "Silver Creek Number 2." 1927 [available from C. Phillip Baumel, Department of Economics, Iowa State University, Ames, Iowa].

Board of Supervisors, Shelby County, Iowa. "Indian Creek Drainage District 7." 1913 [available from C. Phillip Baumel, Department of Economics, Iowa State University, Ames, Iowa].

Daniels, R. B. "Entrenchment of the Willow Drainage Ditch, Harrison County, Iowa." American Journal of Science 258, March 1960, p. 161-176.

Daniels R. B. and R.H. Jordan. Physiographic History and the Soils, Entrenched Stream Systems and Gullies, Harrison County, Iowa. U.S.Department of Agriculture Technical Bulletin 1348, September 1966.

Dantzig, George B. "On the Significance of Solving Linear Programming Problems with Some Integer Variables." Econometrica, 28, No1, January 1960, p. 30-44.

Dasgupta, Ajit K. and D. W. Pearce. Cost-Benefit Analysis: Theory and Practice. Macmillan Press Ltd., London, 1978.

Dirks, William Kermit. "Geomorphic Approach to Predicting Degradation of Streams in Western Iowa." M.S. thesis, Iowa State University, Ames, Iowa, 1981.

Duffy, Michael D., Elizabeth Appish, and Daniel Koster. "1992 Iowa Land Value Survey," Iowa State University, Ames, IA University Extension, Fm-1825, Revised March 1993.

Federal Highway Administration. Methods for Assessment of Stream-Related Hazards to Highways and Bridges. Offices of Research & Development Environmental Division, Washington D.C., Rept. No. FWHA/RD-80/160, March 1981.

Hanson, G.J., R.A. Lohnes, and F.W. Klaiber. "Final Report on Phases II and III, Evaluation of Control Structures for Stabilizing Degrading Stream Channels in Western Iowa." Iowa State University, Ames, Iowa, ISU-ERI, July 1985.

Larimer, O.J. Drainage Areas of Iowa Streams. Prepared by the U.S. Geological Survey, Water Resources Division, in cooperation with the Iowa State Highway Commission, Iowa Highway Research Board, Bulletin No. 7, Iowa State Highway Commission, Iowa Natural Resources Council, reprinted March 1974.

Levich, Bradley Allen. "Studies of Tractive Force Models on Degrading Streams." M.S. thesis, Iowa State University, Ames, Iowa, 1994.

Lohnes, R. A., F. W. Klaiber, and M. D. Dougal. Alternate Methods of Stabilizing Degrading Stream Channels in Western Iowa. Submitted to the Highway Division of the Iowa Department of Transportation and the Iowa Highway Research Board, Department of Civil Engineering, Engineering Research Institute, Iowa State University, Ames, Iowa, ISU-ERI-Ames-81047, Iowa DOT HR-208, September 1980.

Lohnes, R.A., "A Method for Estimating Land Loss Associated with Stream Channel Degradation," Engineering Geology 31, 1991, p. 115-130.

Lohnes, R.A., Brad Levich, and Jeff Magner. "Final Report on Stream Stabilization Research," to Golden Hills Resource Conservation and Development Inc." Department of Civil and Construction Engineering, Iowa State University, Ames, Iowa, September, 1994.

Magner, Jeffrey L., "Guidelines for Grade Stabilization Structure Placement." M.S. thesis , Iowa State University, Ames, Iowa, 1994.

Massoudi, Heidargholi. "Hydraulics of River Bed Degradation, Willow Creek, Iowa." Ph.D. dissertation, Iowa State University, Ames, Iowa, 1981.

Mayne, J.H. "Proposal, Contract, and Specifications for the Mosquito Creek Ditch No. 8, Shelby County, IA." Council Bluffs, Iowa, 1915.

Morris, Landon L., Marty J. McVey, Xing Yang, and C. Phillip Baumel. "Impact of Degrading Streams on Transportation and Utility Infrastructure Costs." Paper presented at the 36th annual meeting of the Transportation Research Forum, Daytona Beach, Florida, November, 1994.

Murty, Katta G. Linear and Combinatorial Programming. John Wiley & Sons, New York, 1976

Pfaffenberger, Roger C and David A. Walker. Mathematical Programming for Economics and Business. The Iowa State University Press, Ames, Iowa, 1976.

Ruhe, R.V. Quaternary Landscapes in Iowa. Iowa State University Press, Ames, Iowa 1969.

Smith, J.H. History of Harrison County, Iowa. Iowa Printing Co., Des Moines, Iowa, 1888.

U.S. Bureau of the Census, Statistical Abstract of the United States, Washington, D.C., various years.

Western Iowa Degrading Streams Task Force. "Western Iowa Hungry Canyons Stream Channel Stabilization Project Plan." Sponsored by Western Iowa Degrading Streams Task Force, of Golden Hills Resource Conservation and Development, with assistance from the United States Department of Agriculture, Soil Conservation Service, December, 1991.

White, John A., Marvin H. Agee, and Kenneth E. Case. Principles of Engineering Economic Analysis, John Wiley and Sons, New York, NY, 1989.

Yang, Xing. "Impact of Degrading Streams on Bridges and Rural Travel Patterns." M.S. thesis, Iowa State University, Ames, Iowa.

Zionts, Stanley. Linear and Integer Programming. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1974.

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APPENDIX A. SIMULATION PROGRAM OF STREAM WIDENING AND LAND VOIDING

The following program predicts the maximum land voiding and stream widening for a specified segment of a degrading stream. The program was written for the mullenix stratigraphic unit of loess derived alluvium soil, appropriate for the analysis of Willow Creek and Keg Creek.

Input variables:

HMP	expected vertical degradation
H	existing stream channel depth
AB	initial stream channel side slope

Program:

```
DIMENSION       H(2), HMP(2), HS(2), DH(2), L(2), AB(2), IB(2), IA(2)
DIMENSION       IS(2), ISS(2), WA(2), AREA(2), ACRES(2)

CHARACTER*34    FILE 1
CHARACTER*34    FILE 2
INTEGER         I, NOBS

REAL            H, HMP, HS, HC, DH, L, AB, IB, IA, IS, ISS, PI, RAD,
RAD90, C
REAL            GAMMA, WA, AREA, ACRES, PHI

FILE1=          ' / path / filename.dat '
FILE2=          ' / path / filename.out '

OPEN            ( 6, FILE=FILE1, STATUS= 'OLD' )
OPEN            ( 8, FILE=FILE2, STATUS= 'NEW' )

REWIND          (6)

FORMAT          (4F10.2)

READ            (6, *)  NOBS

DO              20  I=1, NOBS
```

READ (6, 9) HMP(I), H(I), AB(I), L(I)

FORTRAN will not use degree measures of angles, therefore the program converts all degree measurements to radians.

Variables:

PI	3.14
RAD	conversion factor
RAD90	radian measure of 90 degrees

The following variables are necessary to calculate a functional relationship between the critical stream bank height and the streambank slope angle. Saturated unit weight was used to create maximum streambank instability and stream widening.

Variables:

C	soil cohesion (shear strength), (lb/ft^2)
GAMMA	unit weight of the soil (lb/ft^3)
PHI	angle of internal friction

Program:

```
C=221
GAMMA=118.5
PHI=27⁰

IB(I)= AB(I)*RAD
HS(I)=H(I) + HMP(I)

HC(I)= (4*C*SIN(RAD90)*COS(PHI)) /( GAMMA*(1-COS(RAD90-PHI)))

IF (HMP(I)  .GT.  HC(I))        THEN
      DH(I) = HMP(I) - HC(I)
      IF (DH(I)    .GT.   10)    GOTO 390
      IA(I) = ((75*RAD*HC(I) + IB(I)*H(I)) / HS(I))
      HC(I) = (4*C*SIN(IA(I))*COS(PHI)) / (GAMMA*(1-COS(IA(I) - PHI)))
      IF (HS(I)     .GT.   HC(I))        THEN
```

```
                IS(I) = (IA(I) + PHI) / 2
1               HC(I) = (4*C*SIN(IS(I))*COS(PHI))/ (GAMMA*(1 - COS(IS(I) - PHI)))
        IF (HS(I)       .GT.    HC(I))          THEN
                ISS(I) = ((IS(I) + PHI/2))
                WA(I) = HS(I)*(1/TAN(ISS(I))) - H(I)*(1/TAN(IB(I)))
        ELSE
                WA(I) = HS(I)*(1/TAN(IS(I))) - H(I)*(1/TAN(IB(I)))
        END IF
ELSE
        WA(I) = HS(I)*(1/TAN(IA(I)))
END IF
ELSE
        IA(I) = ((RAD90*HMP(I) + IB(I)*H(I))/HS(I))
        HC(I) = (4*C*SIN(IA(I)*COS(PHI)) / (GAMMA*(1 - COS(IA(I) - PHI)))
        GOTO 400
390     IA(I) = ((75*RAD*HC(I) = RAD90*DH(I) + IB(I)*H(I)) / HS(I))
        HC(I) = (4*C*SIN(IA(I))*COS(PHI)) / (GAMMA*(1 - COS(IA(I) - PHI)))
400     IF HS(I)        .GT.    HC(I))          THEN
                IS(I) = ((IA(I) + PHI)/2)
1               HC(I) = (4*C*SIN(IS(I))*COS(PHI)) / (GAMMA*(1 - COS(IS(I) - PHI)))
                IF HS(I)        .GT.    HC(I))          THEN
                ISS(I) = ((IS(I) + PHI)/2)
                WA(I) = HS(I)*(1/TAN(ISS(I)))-H(I)*(1/TAN(IB(I)))
                ELSE
                WA = HS(I)*(1/TAN(IS(I)))- H(I)*(1/TAN(IB(I)))
                END IF
        ELSE
                WA(I) = 0
        END IF
END IF
AREA(I) = L(I)*WA(I)
ACRES(I) = AREA(I) / 43560

15      FORMAT (6F10.2)

        WRITE (8, 15)           HMP(I), H(I), AB(I), L(I), WA(I), ACRES(I)

20      CONTINUE

        END
```

APPENDIX B. OPTIMIZATION PROGRAM: GENERAL ALGEBAIC MODELLING SYSTEM

The following GAMS (General Algebraic Modelling System) program was written to maximize the discounted net benefit of stream stabilization, U, subject to a budget constraint over different sites on Willow Creek and Keg Creek. The program specifies an integer programming optimization model and solves for the optimal vector of the binary decision variable, δ.

Program:

```
SETS

        I       potential sites for stream stabilization  / A, B, C, D, E, .... ,I/;

PARAMETERS

        B(I)    discounted benefit of stream stabilization for site i

                /       A               96635
                        B               109290
                        C               75960
                        D               97695
                        E               102372
                        F               87260
                        G               224193/

        C(I)    cost of stream stabilization for site i

                /       A               92228
                        B               106721
                        C               63685
                        D               62105
                        E               41495
                        F               41003
                        G               150000/;
```

```
SCALAR M   budget constraint        /200000/;


VARIABLES

        U       discounted net benefit of stream stabilization
        δ(I)    dummy variable;

BINARY VARIABLE         δ;

OPTION OPTCR = 0.0;

EQUATIONS
        UTILITY                define objective function
        CONSTRAINT             budget constraint

UTILITY..                      U = E= SUM(I,  δ(I)*B(I));

CONSTRAINT..                   SUM(I, C(I)*X(I)) =L= M;

MODEL BUDGET   /ALL/

SOLVE BUDGET USING MIP MAXIMIZING U
```