HORIZONTAL INSTABILITY OF THE CANADIAN RIVER AND IMPLICATIONS FOR THE NORMAN CITY LANDFILL, OKLAHOMA

By

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CHAPTER I

INTRODUCTION

Background

The Norman City Landfill is a closed municipal landfill located on the floodplain of the Canadian River in Norman, Oklahoma. The landfill was in operation until 1985 at which time it was covered with a clay cap and vegetated. With no liner underlying the covered refuse, at least one subsurface leachate plume composed of landfill material in particulate form has been identified extending south from the landfill in the direction of the river. The plume contains notable amounts of ammonia, nitrogen, phosphorus, iron, manganese, and organic carbon compounds, as well as varying concentrations of trace elements such as arsenic, barium, boron, cadmium, chromium, cobalt, germanium, nickel, selenium, and strontium (Schlottmann, 2001). This plume, located at a depth much greater than channel incision as controlled by base level would be able to reach, does not endanger the river to contamination. Direct erosion of the landfill by fluvial forces, though, is a definite contamination threat to the river.

Examination of the horizontal instability of the Canadian River, by evaluating its horizontal migration, is important in evaluating the erosion potential of the landfill. Inspection of historical air photographs, revealing extensive horizontal migration of the Canadian River over the past 70 years, gives definitive proof that, at times, the active channel flowed at the base of the landfill. Therefore, understanding channel stability is essential to enabling more informed judgments concerning the role of erosion in the mobilization of solid waste contaminants from the landfill.

Purpose

This research project describes and explains the horizontal instability of the Canadian River in the vicinity of the Norman City Landfill. It develops a model with which to assess past and future mobility of the active channel and implications for the landfill.

Objectives

This research was designed to accomplish the following objectives:

1) Creation of a 2-dimensional map of the surface sediments of the floodplain adjacent to the Norman City Landfill that illustrates the spatial distribution of grain size and discrete geomorphic units on the floodplain to enhance identification of areas with higher susceptibility to erosion.
2) Creation of a landfill stability index, using factors identified as affecting erodibility by fluvial forces, to determine the stability of various portions of the landfill cap as a means of identifying areas of higher erodibility
3) Determination of the past, present and future stability of the Canadian River adjacent to the Normal Landfill using Graf's (1984) procedures for a probabilistic assessment of stream channel stability.

Study Area

The Canadian River, originating in the Sangre de Cristo Mountains of New Mexico, flows 1460 km to its confluence with the Arkansas River in eastern Oklahoma. In the vicinity of Norman, Oklahoma, the Canadian River, a low sinuosity, sand-bed river alternating between meandering and braided, flows on a floodplain ranging in width from 2.5 km to 6.5 km and has a contributing drainage area of 25,853 mi^2 (Sauer, 1974). The Norman City Landfill is situated south of the city of Norman, Oklahoma, on the active Canadian River floodplain north of the active channel (Figure 1). The base of the landfill is approximately 3.5 m above the active channel at low flow.

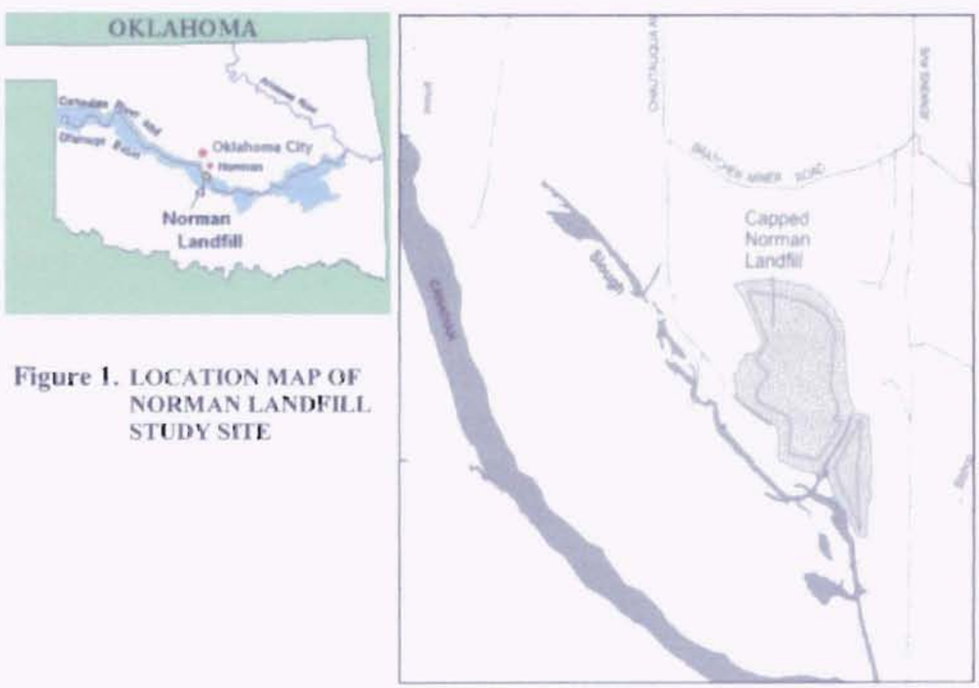

Figure 1. LOCATION MAP OF NORMAN LANDFILL STUDY SITE

(Schlottmann, 2001)

The United States Geological Survey Toxic Substances Program has chosen the Norman City Landfill as a geochemical, sedimentalogic, and geomorphic study site. Information gained by these studies will be used to focus future biological, chemical, mineralogic and hydrologic studies at the site (Schlottmann, 2001). Numerous unlined city landfills exist around the country. Information obtained from the Norman landfill study site will be used to assess hazards posed to other municipal landfills.

CHAPTER II

LITERATURE REVIEW

Floodplain Stability

Active floodplains are one of the most uncontrollable geomorphic settings in nature. Therefore, they serve as poor candidates for landfill development sites. Floodplains are formed by the systematic migration of a stream channel over the adjacent area (Leopold and Wolman, 1957). Lewin (1992) identifies six common sedimentary environments, which together form a floodplain. Lag deposits line the erosional surface of a meandering stream and are characterized by coarse sand and/or gravels atop the scour surface. Channel deposits and their relative proportions, such as dunes, ripples, and point bars are dependent upon stream type. Channel fills are very common and are simply sand, silt and clay deposits that reside in abandoned channels. Channel marginal environments, such as splays and levees, are key in laterally expanding the floodplain. Floodplain/backswamp environments fine outward from the stream channel and are consequences of overbank flows, geometry and vegetation. Finally, colluvial sediments may be seen in arid or glacial environments and may add geomorphic features characteristic of the environments to the floodplain. These sedimentary environments are each based on the fluvial environment surrounding them, so the geometry and nature of the resultant floodplain is dependent on stream type. Therefore, the heterogeneity of floodplain material makes characterizing the floodplain very difficult, and consequently makes estimating its stability nearly impossible. The Canadian River floodplain, adjacent to the Norman City Landfill, contains several of these environments, including coarse lag deposits and channel deposits and fills (Collins, 2001).

The floodplain is not a featureless area (Reid and Frostrick, 1994) and many different geomorphic units can be observed upon the floodplain, including filled cutoffs, dunes and interdunes, and undisturbed vegetated area. The geomorphic units located on the floodplain display a diverse mosaic of topography with mesoscale relief. Lewin and Manton (1975) found that if the scale of mapping was reduced, much more topography could be seen. This is particularly true of the Canadian River floodplain, which exhibits a range in elevation of less than 3 meters.

The Canadian River is a sand-bed meandering to braided stream that exhibits characteristics of both stream types. Around the Norman, Oklahoma, area, the stream more closely approximates a meandering stream. An abundance of mud exists as a thin veneer on top of and interbedded within sand sequences (Davis, 1992). Periodic erosion and deposition of morphostratigraphic units within the floodplain is characteristic of a sand-bed channel like the Canadian River (Schumm and Lichty, 1963). The Canadian River floodplain has undergone extensive reworking and reshaping over its history. Hefley (1935), in an ecological study of the area following a very large flood in 1908, noted that despite the flood significantly widening the channel, which would normally allow floodplain aggradation to occur, no net aggradation or degradation of the channel actually occurred. Because of the lack of quantitative measurement technology in the early 1900's, no record exists of the actual recurrence interval of the 1908 flood, although records suggest it was well above average annual peak flow for the area. According to Curtis and Whitney (2000), any event with a recurrence interval equal to or larger than

5.5 years will cover the floodplain and be in contact with the landfill itself because the floodplain offers little or no natural barrier between the active channel and the landfill. Therefore, most overbank flows are potentially extremely destructive.

Landfill Stability

Much work has been done to assess factors that affect the stability of landfill covers. With all of the municipal landfills located around the country, this subject is becoming paramount in ecological importance. Numerous aspects of the mechanics of landfills and covers have been studied in an effort to determine various circumstances under which these covers fail.

To understand the mechanics of a successful landfill, the material parameters of the landfill and landfill cover, such as unit weight, shear strength and cohesion, must be determined (Babu, 1998). Unit weights vary greatly in any landfill because of the diverse materials contained within the landfill itself (Fassett, 1993). Shear strength properties are very important in the stability assessment (Babu, 1998; Mitchell and Mitchell, 1995) and affect how well the landfill will respond to stress under natural conditions as well as applied stress. This includes the stress applied to the landfill by inundation of a river.

Arguably the most important and most widely studied factor affecting landfill stability is slope gradient. Dvirnoff (1986) states that a national solid waste firm uses a 3:1 gradient (18.4°) for refuse on a firm foundation up to 37 meters (approximately 120 feet) high as the standard for cover stability. Others use this value as a standard slope ratio as well (Babu, 1998). Therefore, a combination of slope angle and limited landfill height is necessary to achieve stability. Landrum et al (2000) recognize the importance of the strength of the soil-geomembrane interface, rather than slope angle and height only, in determining the slope stability of the landfill cover. Variability in the slopes of these geomembranes, because of compaction, pore pressure and soil variability, are potentially more important parameters than mere slope angle. Soil-geomembrane interfaces are difficult to isolate and study, however, so the conventional 3:1 slope ratio continues to be most widely documented. The banks of the Norman Landfill, as discovered in this study, have a relatively consistent gradient of 11^{o}, well below the recommended 18.4^{o} standard. Therefore, failure as a result of oversteepened slope would not be considered an imminent danger for the Norman Landfill.

In addition to the actual physics affecting the stability of landfill cover, an environmental aspect also exists. Normal environmental factors play an important role in determining whether or not a landfill cover fails. Fang et al (1998) addressed this topic extensively. Surface cracking, recognized as a main cause of landfill cover failure, is initiated by many factors, including weathering, bacterial actions, floral and faunal attack, and tectonic movement (Fang et al, 1998). These cracks lead to excessive surface erosion, settlement and subsidence. Extreme thermal gradients (Winterhorn, 1962) and freeze-thaw cycles (Lee, 1996) are key factors in the weathering of the cover system. Oklahoma's variable climate is conducive to freeze-thaw cycles. In January, temperatures can range from daytime highs of 70 degrees Fahrenheit to nighttime lows well below zero (Cooter, 1991). Once weathering and erosion have begun, bacterial action ensues, resulting in decomposition, which, in turn, effectively reduces the integrity of the landfill and cap (Fang et al, 1998). Trees with highly intrusive root systems constitute the primary form of floral attack. Therefore, vegetation must be chosen carefully, paying particular attention to the type of tree planted, avoiding trees with large, penetrating root systems, such as poplars and willow (Fang, 1995). Vegetation on the landfill consists mainly of Bermuda grass and low shrubbery (Schlottman, 2001). At the base of the landfill and further onto the floodplain, various species of willows and cottonwoods thrive, including *Populus deltoides* (Erdman and Christenson, 2000). In addition to understanding and attempting to control the factors affecting the stability of the landfill itself, it is also important to understand and attempt to control factors affecting the stability of the environment in which the landfill is located.

Geomorphology of Sand-Bed Rivers

Little information is available in the literature about sand-bed rivers. Several characteristics of these rivers, such as channel pattern, sinuosity, sediment discharge, flooding, and horizontal migration are important to analyzing and describing its stability. For the purpose of this study, channel stability is defined as the rate and ability of a stream channel to migrate horizontally through time.

Leopold and Wolman (1957, p. 39, 40) define channel patterns as "the planview of a reach of a river as seen from an airplane" and additionally as "limited reaches of the river that can be defined as straight, sinuous, meandering or braided." Finding this categorization unsatisfactory, Church (1992) created new classifications that included twelve channel patterns comprised of various combinations of the originals (Figure 2). The Canadian River valley consists of a sand-bed channel, transitional between meandering and braided (Curtis and Whitney, 2000) located on a relatively homogenous and very wide floodplain. Although the boundaries between patterns are often vague, Knighton (1998) recognizes three major criteria for classifying stream channels as straight, meandering or braided: (1) number of channel threads, (2) channel sinuosity, and (3) meander regularity.

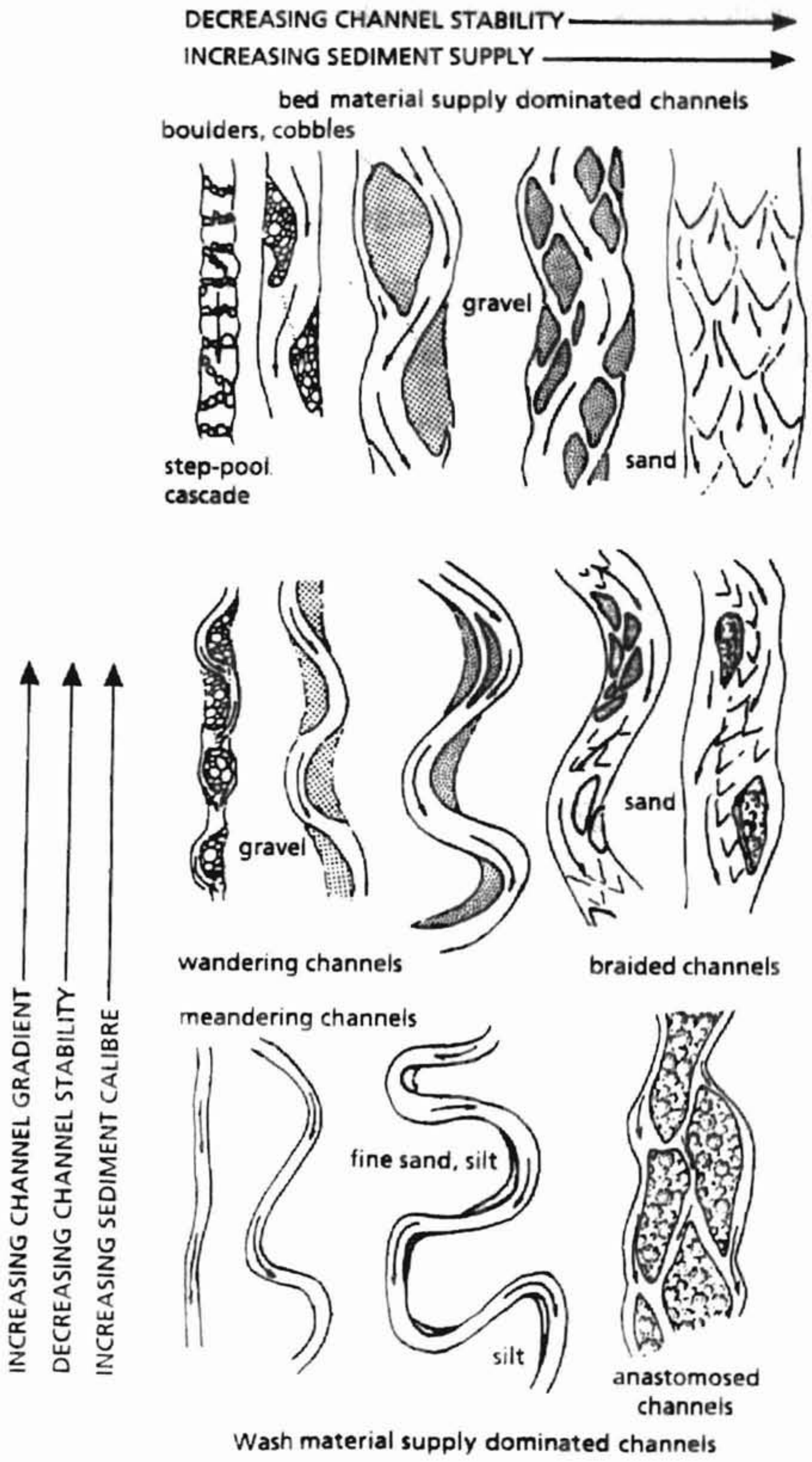

Figure 2. STREAM PATTERNS ACCORDING TO CHURCH (1992)

A single thread channel is defined as either straight or meandering. Straight channels may contain any combination of bedforms, alternating bars, and a meandering thalweg (Knighton, 1998). The thalweg may become sinuous enough that when erosion of the outer bank begins, a meandering stream develops. Channels with multiple threads are either classified as braided or anastamosing streams.

Sinuosity is the degree to which a stream meanders and is determined by dividing channel length by straight-line valley length (Knighton, 1998). In braided channels, this is often called the braiding index and is calculated by dividing the sum of the lengths of all active channels by the length of the axis of the braided belt.

Meander regularity refers to the geometric shape of the meander belt. Kellerhals et al. (1976) cite three classes of regularity: 1) regular or uniform meanders with a repeated pattern of meander bends, 2) irregular or non-uniform meanders with a repeated pattern of meander bends, and 3) tortuous meanders with high amplitudes and low wavelengths (Figure 3). Although the regularity of meandering of the Canadian River has not been reported in the literature, from examination of aerial photographs it would be described as an irregularly meandering stream channel.

The width of the floodplain controls the mobility of a stream, or the degree to which it may move freely about a floodplain. Broad meander belts form on wide floodplains, whereas entrenched meanders develop on narrow, resistant floodplains. The erodibility of the bed material affects the continuum of stream energy. In a stream with highly erodible bed material (like the Canadian River), the stream flow energy is divided between rearrangement of bed material and continuous entrainment of fine material (Laczay, 1973). The stream load within the Canadian River channel is comprised primarily of fine sand in entrainment and silt to clay-size material in suspension and solution. The size of the bed materials and particles in solution greatly affects the shape of the channel. Schumm (1963) illustrates the direct relationship between the amount of fine particles (silt and clay) within the stream channel and the sinuosity of the channel. This relationship is compounded by Schumm et al (1994) in a study that focuses on the clay content of the bank of the Mississippi River and the observation that meanders migrate around resistant clay layers, rather than through them. Therefore, the shape of meander loops is dependent on many variables, including bank erodibility (Forbish, 1991), and the ability of the meander loops to migrate relies heavily on bank resistivity characteristics (Hickin and Nanson, 1984).

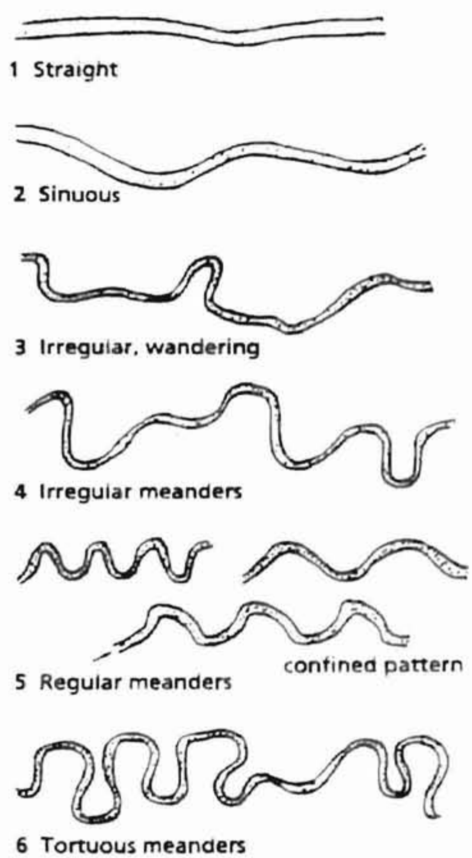

Figure 3. CLASSIFICATION OF CHANNEL PATTERN AND REGULARITY OF MEANDERING (KELLERHALS AND CHURCH, 1989)

Another aspect of stream sediment that affects the pattern of the channel is sediment discharge. High amounts of sediment moving through a straight stream will induce scour where the thalweg is in contact with the outer bank. This process leads to meander formation and widening of the channel. The value of sediment discharge is increased as the meanders form because of the gradual erosion of the outer bank. When enough sediment is present, central bars begin to form and braiding eventually occurs. No sediment discharge study of the Canadian River was available in the literature, but the sediment discharge is closely related to stream discharge. Mean annual discharge for the Canadian River is highly variable depending on climatic conditions (precipitation) and location on channel in relation to tributaries. Mean discharge has ranged from less than 2 cms during heavy drought periods to 30 cms during years with higher amounts of precipitation (USGS Calendar Year Streamflow Statistics). Peak discharges capable of moving large amounts of sediment are relatively common and can occur in magnitudes of several thousand cms.

Vertical Channel Instability

The profile of a stream is controlled by base level at the furthest downstream point (Howard, 1982). When sediment inflow into a reach exceeds the competence and capacity of the reach, deposition begins at the lowest part of the slope and moves upslope (Heede, 1992). When this occurs, the bed of the stream increases in elevation and the depth is compromised. The decrease in depth is often offset by an increase in width because of the shear stress of the volume of water, which does not change with aggradation. Pattern changes from straight to meandering to braided are common when this process occurs. The gradient of the Canadian River adjacent to the Norman City

Landfill is approximately 1.2 m/km (estimated from topographic map). After an event in which large amounts of sediment are released into the active channel of the Canadian River, subsequent low flows often aggrade the streambed (Curtis and Whitney, 2000).

An increase in water discharge, a decrease in sediment supply, and a fall in base level are the main variables that cause stream degradation (Knighton, 1998). This process, on the whole, is very slow, although it may start fast if major disturbances have occurred (Heede, 1992). Degradation begins at lower elevations and, similar to aggradation, proceeds upstream. This incision scours out the bed of the stream and subsequently increases sediment discharge downstream from the areas of degradation. With the added sediment supply, stream patterns will generally decrease in stability as they proceed from straight to meandering to braided. No study describing the aggradation/degradation tendencies of the Canadian River in the vicinity of the Norman City Landfill has been published in the recent past. It would, however, be logical to conclude that sand-bed streams generally degrade during high flood periods and aggrade during low flood periods.

Horizontal Channel Instability

Two major types of abrupt changes in the channel course are often seen in sand-bed channels: cutoffs and avulsions (Figure 4). As meanders erode and deposit sediment, they often form very tight, sinuous bends. If the sinuosity becomes so high that the stream can no longer maintain discharge of water and sediment at current levels, a cutoff may develop anywhere along the meander bend (Knighton, 1998). In a study of floodplain development, Lewin (1992) identified the two most readily recognized types of cutoffs. Neck cutoffs are a product of the breaching of the narrow neck between tortuous channel bends and chute cutoffs are a product of extensive erosion and re-routing of the meander across the floodplain between two adjacent bends. Neck cutoffs may develop from any of three possible causes: (1) overgrowth of the meander bend, (2) shifting of one bend more than its adjacent bend to the extent that they join, or (3) artificial creation by humans (Gagliano and Howard, 1983).

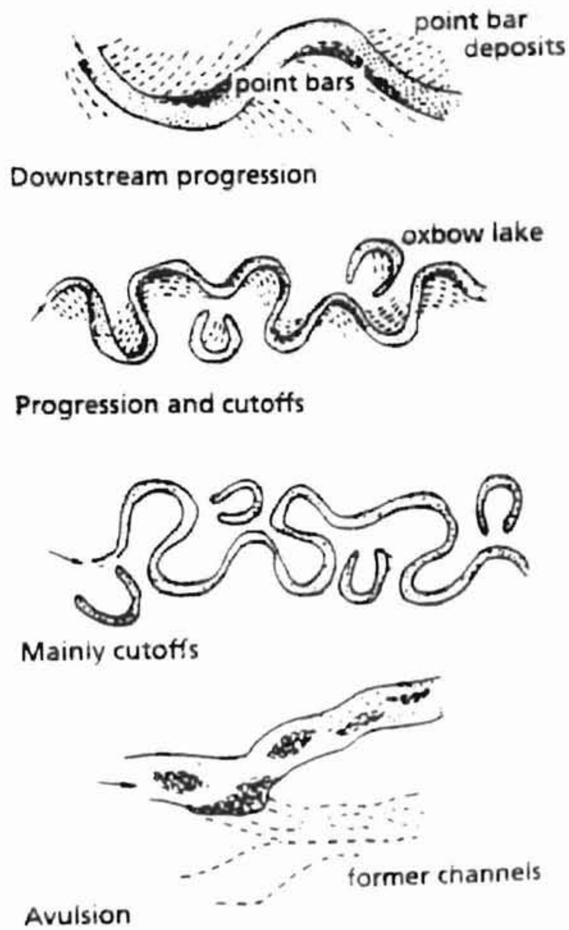

Figure 4. HORIZONTAL INSTABILITIES (KELLERHALS AND CHURCH, 1989)

Neck cutoffs often occur where floodplain gradient is low and sinuosity is high, whereas chute cutoffs form where floodplain gradient is high and material is easily erodible (Lewin, 1992). Cutoffs, which usually occur during large storm events as stream discharge reaches values too high to maintain flow within the channel, are common on the Canadian River.

Avulsions, sudden formations of new channels in response to extreme aggradation and gradient increases, are an integral part of the formation of large floodplains (Lewin, 1992). Repeated avulsions may create a braided channel, therefore making it the least stable of all channel changes (Church, 1992). Humans often induce cutoffs and avulsions to reduce flooding, subsequently increasing total stream stability and allowing the abandoned meanders to infill and revegetate (Stevens, 1994). These abandoned, revegetated meander loops become a part of the floodplain but are often reactivated as preferred channel pathways during floods. The Canadian River, adjacent to the Norman City Landfill, contains a notable example of abrupt channel change. An area known locally as the "slough," an abandoned meander most likely resulting from a chute cutoff during a past flood, is commonly reactivated as part of the active channel during subsequent high flows.

Lateral Translation and Downstream Extension of Meander Loops

Meanders form from a combination of migration of alternate bars and fixation of point bars (Knighton, 1998). Alternate bars are the natural, or "free" response of the straight or mildly wandering channel system (Nelson and Smith, 1989), and develop in response to the secondary helical flow induced by thalweg scour. Eroded material, deposited opposite a cut bank, produces alternate bars. Thalweg sinuosity around newly formed alternate bars continues to erode outer banks of the channel until meandering commences. Once initiated, meander loops can move downstream with no change in geometry (translation), move laterally with no downstream migration (extension), change orientation while keeping the endpoints fixed (rotation), or migrate irregularly and form outgrowths from the original loop (lobing and compound growth) (Knighton, 1998).

Meandering channels that exhibit translation as the main mode of migration have attained some degree of stability (Bettess, 1994). Downstream migration is the natural response for a meandering channel; therefore, a primary product of meander migration is the formation of a floodplain. As meandering channels extend and translate, point bars are abandoned and become incorporated into the floodplain. A study of the history of a meandering stream can reveal the age and residence time of floodplain deposits (Lewin, 1992). The presence of riparian vegetation and cohesive sediment on the floodplain nearest the active channel may effectively increase the stability of the meandering channel because of the control on migration. The Canadian River contains a limited amount of rip-rap on the outside of the meander loop closest to the Norman City Landfill which also decreases the migratory tendency of the river in that location.

Role of Vegetation

In relation to a particular stream reach, vegetation may be separated into two categories, upland and riparian. Both strongly impact the stability of the stream. Upland vegetation ultimately controls the amount of runoff that reaches the stream. Runoff occurs mainly in the form of Hortonian overland flow, while saturation return flow occurs but is of somewhat less importance (Graf, 1988). Riparian vegetation plays a more important role in controlling channel pattern and bank erosion. Because rapid erosion occurs without bank vegetation (Burke, 1984), the shape of a meander loop is dependent on the type and presence of vegetation (Furbish, 1991). As noted earlier, the riparian vegetation on the Canadian River floodplain adjacent to the Norman Landfill is primarily Bermuda grass, shrubbery, and a variety of willows and cottonwoods. This vegetation is vital to maintaining the boundary between the landfill and the river.

In a stream with erodible bed and banks, cross-sectional geometry consists of flat bed throughout most of the stream and steep slopes at bend apexes, with a sharp decrease in depth from outer to inner banks (Thorne, 1993). Therefore, the thalweg has the ability to scour most productively on outer banks, where depth is greatest. The ultimate purpose of bank vegetation is to offer cohesive strength to outer banks (through the soil binding qualities of root systems) and reduce the velocity of water in the meander bend (Thorne, 1993). In his field study on the effect of bank vegetation on flow through meander bends, Thorne (1993) compared a naturally vegetated bank with one covered in sheet plastic to eliminate roughness (vegetation). Without vegetation, flow was super-elevated, producing a secondary current induced by the meander bend. This led to increases in the rates of meander migration upstream from bend entrance and in sediment transport, which in turn led to bar formation. Therefore, meander bends that lacked vegetation on the outer banks exhibited asymmetry in bend shape and migrated downstream, whereas banks with natural riparian vegetation migrated laterally and symmetrically.

Role of Flooding

The effectiveness of a flood refers to its ability to change the fluvial landscape (Wolman and Gerson, 1978) and, to a point, the length of time it takes for the channel to adjust to its post-flood pattern and equilibrium conditions. Floods impact stream reaches by creating cutoffs, inducing scour, widening the channel, and aggrading point bars and the floodplain (Burke, 1984). The degree of scour and deposition in a flood will depend on the magnitude of the event itself and the relative erodibility of the bank materials. Floods may be large and intense enough to completely change the pattern of the stream by differential erosion and deposition. In his study of the effects of the 1965 flood of

Plum Creek, a tributary of the South Platte River in Denver, Colorado, Osterkamp (1987) documented the impact of 360mm of rainfall in four hours on channel morphology, sediment deposits, vegetation and floodplain characteristics. Large amounts of the bed material of Plum Creek, predominantly sand, were transported and deposited downstream. During the flood, Plum Creek widened to 160% of normal low-flow conditions and the channel straightened from a sinuosity of 1.22 to 1.03. Riparian vegetation was destroyed; the only trees left standing were those protected by other larger trees and those located in old meander loops against the valley wall where they were protected.

A major correlation between vegetation and sediment size was also noted. Vegetated areas were associated with finer sediments but trapped larger sediment during the event. Therefore, a bimodal distribution of sediment size was apparent in vegetated areas, representing both pre-event and event sediment deposition. During the flood, the floodplain was destroyed. Following the recession of the floodwaters, numerous islands and near-bank point bars existed, mainly from the preservation of large vegetation on those islands. As anabranch between channel and floodplain narrowed, progressive deposition connected the bar to the floodplain, effectively widening it. Numerous studies similar to this have been completed, including Burkham's 1972 study of the Gila River in Arizona. Large floods from 1905 – 1917 destroyed the floodplain. Reconstruction began only after the subsidence of high water and a prolonged period of low flows, capable of depositing large amount of eroded sediment. All stream responses to large events are, in effect, an adjustment of equilibrium, which may be qualitatively, but even more importantly, quantitatively, analyzed (Chang, 1986). A large flood in 1908 dramatically altered the channel of the Canadian River in the Norman, Oklahoma area, increasing its width from an average of 0.8 km to 3.2 km (Hefley, 1935). Hefley then documented an equilibrium adjustment of the river noting that by 1935 the elevation and channel width had returned to pre-flood measurements.

Quantitative techniques for calculating magnitude and frequency of floods have been completed at various times in the past by the U.S. Geological Survey in cooperation with various other organizations and agencies. The most recent *Flood Characteristics of Oklahoma Streams* publication, in which rating curves are created and recurrence intervals for various floods magnitudes are calculated, was released in 1971. This publication was not recent enough for use in this study.

Role of Human Impacts

The impact of people on the surrounding environment, especially the fluvial environment, has a direct correlation to instability. A reduction of upland and riparian vegetation, from deforestation or livestock overgrazing, for example, will decrease bank and floodplain cohesion. It has also been shown that dams built for irrigation storage, drinking water, flood control, hydroelectric power, and recreation induce vertical instability of the stream because of aggradation above the dam and degradation below (Graf, 1988). Urbanization of a watershed changes the amount of sediment and water entering an area (Graf, 1988). As people build on floodplains, terraces, and the banks of rivers, natural cohesive characteristics of the banks are removed, destabilizing the channel, potentially resulting in the destabilization of the stream. Channels, within a given environment, will eventually reach equilibrium and possibly stability. Human interference can deter or potentially prevent this from occurring. In the case of the Canadian River adjacent to the Norman City Landfill, an asphalt plant located at the base of the landfill removes sand and gravel from the active floodplain, effectively reducing the natural integrity of the floodplain. In addition, concrete rip-rap located downstream of the landfill inhibits natural migration of the meandering thalweg.

Prediction of Channel Erosion

In his 1984 study of Rillito Creek near Tucson, Arizona, Graf developed a probabilistic approach to modeling channel instability that was able to predict areas of the floodplain most susceptible to erosion. Combining statistical, hydrologic, and geomorphic principles, his method quantitatively predicts, for each 100 m x 100 m cell of a given distance from the channel, the logarithmic value of the probability of erosion over time. His study incorporated 400 meters on either side of the active channel for each designated flood period. The model does have limitations, though. Based on past trends of channel migration, the model assumes those trends will continue into the future. It also requires a lengthy record of hydrologic data to establish those trends. Nevertheless, the model is a useful tool with which to examine the history of a stream channel in an attempt to identify areas that are historically prone to extensive erosion.

CHAPTER III

METHODOLOGY

Chapter Overview

The geomorphic characteristics of the Canadian River fluvial environment were described through completion of the following tasks:

1) Sample, analyze, and map surface sediments on the floodplain;
2) Evaluate the stability of the landfill clay cap;
3) Analyze the horizontal stability of the Canadian River.

Analysis of Surface Sediments

A map of the spatial arrangement of the textures of surface sediments on the floodplain was created to better understand the depositional characteristics of the Canadian River and the natural controls present on the floodplain. A hand-held auger was used to penetrate the uppermost 30 cm of sediment, and approximately 350 samples were extracted from the floodplain. The position of each sample was determined using a portable Global Positioning Device (hereafter GPS); distance between samples was maintained at 37 m (~121 ft.). Each sample was analyzed in the field using the "texture-by-feel" method of Northcote (1979) and Gordon et al (1992) (Table 1, Figure 5).

These data were plotted as an overlay onto a rectified and digitized air photograph of the Norman Landfill area utilizing *ArcInfo*®. *ArcEdit*® was then used to construct a polygon map of surface sediment texture. Polygons of the same sediment type were assigned colors, resulting in a visually comprehensible schematic of the various geomorphic units in the floodplain.

Table 1: SOIL TEXTURE CLASSIFICATION BY FEEL (GORDON, 1992, ADAPTED FROM NORTHCOTE, 1979)

Sand	Crumbles readily; cannot be molded; single sand grains adhere to fingers
Loamy sand	Slight coherence; can be sheared between thumb and forefinger to give minimal ribbon of about 6 mm; discolors fingers with dark organic stain
Sandy loam	Bolus just coherent but very sandy to touch; will form a short ribbon; dominant sand grains can be seen felt or heard
Silt loam	Coherent bolus, very smooth to silky when manipulated; may form short ribbon
Sandy clay	Plastic bolus; fine to medium sands can be seen, felt or heard in clayey matrix; will form a thin, long ribbon which breaks easily
Clay flexible	Handles like plasticine, plastic and sticky; will form a long ribbon of 5 cm or more

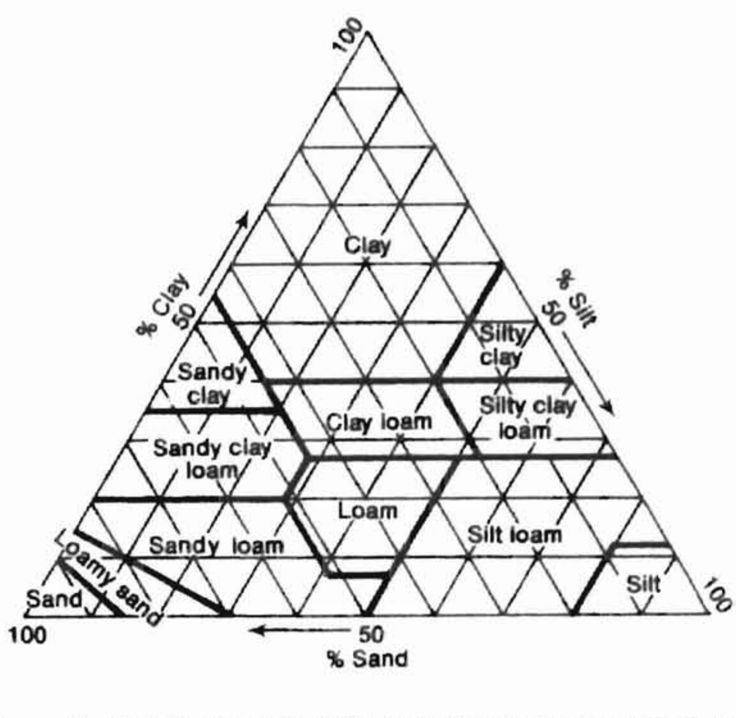

Figure 5. STANDARD U.S. SOIL TRIANGLE (McKNIGHT, 1990)

Analysis of Landfill Cap Stability

The stability of the landfill cap was evaluated to determine its resistance to erosion during floods. The cap, composed of clay and heavily vegetated, was emplaced in 1985 to protect the landfill from erosion and reduce infiltration. The landfill has two cells, designated east cell and west cell; measurements were taken on the south slope of each cell, at intervals of 15 meters, for a total of 47 sample sites. Measurements were acquired approximately one meter above the landfill base, the area initially affected by either flooding or natural stream migration. The position of each sample was determined using a portable GPS.

At each site, a hand-held penetrometer was used to measure the compressive strength of the landfill cap in kg/cm^2. The penetrometer was pressed into the sediment to a depth controlled by the device and the value was read on the scale within the device. Two measurements were taken with the penetrometer at each sample site. The first measurement was obtained by compressing the organic surface sediment and the second reading was taken on the clay pulled out with the auger. A significant difference was apparent between the two sets of values because of the presence of an incoherent, organic soil layer above the cohesive clay cap. Therefore, instead of averaging the two values, each value (two per sample site) was entered into the calculation independently insuring that equal weight was given to both sets of measurements. Offering equality to each value illustrated the importance of the organic upper layer and the cohesive cap layer because both will be affected, although at different times, during floods.

The percent of vegetation cover was estimated within a one square meter area around each sample site location using visual charts by Hodgson (1974). Vegetation, as used here, is defined as all organic, above-ground, living biomass that has a root system and, consequently, offers stability to its substrate, as opposed to ground litter that would wash away immediately upon contact with stream flow.

The final measurement was the slope gradient of the landfill at each sample site. From the top of the landfill, a clinometer was sited directly down the face of the landfill to a fixed point. Slope was then read on a degree scale internal to the clinometer.

All values were entered into a *Microsoft Excel®* spreadsheet and a mean and a standard deviation were calculated for each of the following variables: percent vegetation cover (Veg %), compressive strength of organic layer (Pen-Soil), compressive strength of clay cap (Pen-Cap), and slope percent (Slope %). With this statistical data, a standard normal variate for each variable (Z_{Veg}, $Z_{Pen\text{-}Soil}$, $Z_{Pen\text{-}Cap}$, Z_{Slope}, respectively) at each sample site was determined using the following equation:

$$Z = \frac{\text{numerical value} - \text{arithmetic mean}}{\text{standard deviation}} \qquad \text{Eq. 1}$$

Once this value was calculated, a composite Z-score for each sample site was ascertained according to the following formula:

$$Z_{Total} = Z_{Veg} + Z_{Pen\text{-}Soil} + Z_{Pen\text{-}Cap} - Z_{Slope} \qquad \text{Eq. 2}$$

In doing this statistical transformation, the values were normalized and could be compared to one another. Once all Z-scores were calculated, a percentile rank was established at the 33% and 67% levels. All scores below 33% were classified as "least stable" taking all the variables into account. Z-scores between 33% and 67% were classified as "moderately stable," and those above 67% were classified as "most stable." These categories were plotted on the Surface Sediment Map and regions were color-coded according to rank.

Analysis of Stream Stability

The past, present, and future instability of the Canadian River was evaluated using Graf's (1984) probabilistic method to assess stability of stream channel that combined geographic, geomorphic, hydrologic and statistical techniques. Thirteen air photographs, spanning from 1937 to 1997, delineating the bankfull channel and low-flow active channel of the Canadian River in the Norman City Landfill area, were included in Curtis and Whitney's (2000) paper on the geomorphology and flood characteristics of the Canadian River. Converting each air photograph to a cellular map, in which all cells were exactly the same size and in which each cell represented exactly the same area on all maps, allowed the photographs to be registered to each other and used as base maps for statistical analyses. The following stepwise methodology illustrates exactly how this objective was completed:

1. Air photographs from 1937, 1940, 1949, 1951, 1966, 1971, 1978, 1981, 1985, 1987, 1990, 1995 and 1997 were converted to raster maps and registered to a common geographic grid, with each cell having map scale dimensions of 50 m x 50 m.
2. Each map was inspected to determine whether the low flow active channel occupied each grid cell (assigned 0 if not present, 1 or colored if present) (Appendix A).
3. The number of times the low flow channel occupied each cell was tabulated for the 13 maps, and the frequency of channel occupation for each cell was calculated by dividing the total number of times a cell was eroded (in the entire 60 year interval) by 13 (the total number of maps).

4. A *Microsoft Excel®* chart was created with these probabilities, illustrating zones of historical susceptibility to erosion.
5. The closest stream gaging site to the Norman Landfill Study Site with an appreciable hydrologic record, Canadian River at Noble (active 1960-1975), was used as a base site for flood frequency analysis. The time span of the air photos (1937-1997) was much larger than the available record, therefore, estimations of peak flows in other years had to be accomplished using regression analyses of nearby sites of the Canadian River at Bridgeport, Purcell, and Calvin, as well as the Cimarron River at Perkins. Although the latter was a completely different river, the basic characteristics (load, control, size) of the two rivers were very similar. Peak annual streamflow data for all stations was obtained.
6. A correlation matrix was created by running multiple regressions on the corresponding streamflow data of all possible combinations of sites. The sites that correlated best with Noble (highest r values and lowest p values) were used to estimate missing record for the Noble site.
7. The mean annual flood (hereafter MAF) for the entire period and the departure from the mean annual flood for each year within the period were calculated using the completed Noble data set, and a cumulative departure curve was created.
8. By inspection of the cumulative departure curve, four periods of different flood activity were identified and separated on the basis of shifting trends in annual flood magnitude: 1937-1951 (below MAF), 1951-1966 (above MAF), 1966-1981 (below MAF) and 1981-1997 (above MAF).
9. The peak annual floods of all of years in the available record (1927-1999) were ranked in order of flood magnitude from largest to smallest.

10. The flood recurrence interval for each peak annual flood was calculated using the formula:

$$RI = \frac{n+1}{m} \qquad \text{Eq. 3}$$

where:

RI = recurrence interval of flood;

n = number of years in study; and

m = rank of flood magnitude.

11. On each map at the beginning and end of a flood period (1937, 1951, 1966, 1981 and 1997), three variables were defined:

   - distance from each cell to the active channel in the lateral (north/south) direction in meters (hereafter D_{lm});
   - distance from each cell to the active channel in the upstream/downstream direction in meters (hereafter D_{um});
   - sinuosity of the channel reach (hereafter S);

   and the cumulative flood recurrence interval (hereafter CumRI) for the period was calculated from the flood frequency analysis.

12. The "observed probability of erosion of each type of cell" (Graf, 1984) was determined using the distances calculated in step 9 and the channel location data developed in step 2. The upstream/downstream distance (D_{um}) and lateral distance (D_{lm}) for each cell in the map at the beginning of the flood period were compared with the channel presence data for each cell in the map at the end of the flood period. The number of times cells with a certain distance from the channel in the first map were eroded by the river in the second map (c_e) was divided by

the total number of cells of that distance in the first map (c) to give a probability of erosion ($P_{i,j}$). For example, if a total of 50 cells occurred with distance of 1 cell (50 m) away laterally and 1 cell (50 m) away upstream/downstream in 1937, and 5 were eroded in 1951, $P_{i,j}$ for the ordered pair (50,50) would be 0.1 (or 5/50).

13. A *Microsoft Excel®* file with values of $P_{i,j}$ (between 0 and 1), upstream/downstream distance in meters (D_{um}), lateral distance in meters (D_{lm}), sinuosity (S) and cumulative flood recurrence interval (CumRI) was created for each flood period.
14. *Microsoft Excel®* files for the four flood periods were integrated to create two composite data sets based on average flood magnitude. The low-flood periods (1937-1951 and 1966-1981) were combined to create the low-flood period data set, the high-flood periods (1951-1966 and 1981-1987) were combined to create the high-flood period data set.
15. The *Microsoft Excel®* files created in step 14 were imported into *Statistix®* for Windows and unweighted least squares linear regressions were run on each file to estimate P as a function of D_{um}, D_{lm} and CumRI and P as a function of D_{um}, D_{lm} and S.
16. Because cumulative recurrence interval and sinuosity consisted of only two possible values each, colinearity existed between these variables and P, D_{um} and D_{lm}. Therefore, it was statistically incorrect to apply both variables to the regression analysis. The only way to incorporate both variables in the model was to determine whether or not the high flood model was statistically different from the low flood model. First, a combined unweighted least squares linear regression was performed on the entire period of study, 1937-1997.

17. An analysis of covariance was completed using the residual sum of squares and the number of observations from all three regressions, utilizing the following equation:

$$F = \frac{[\Theta_3-(\Theta_1+\Theta_2)]/(m-1)}{(\Theta_1+\Theta_2)/m(n-1)} \qquad \text{Eq. 4}$$

where $\Theta_1, \Theta_2, \Theta_3$ = residual sum of squares for low flood, high flood and combined models, respectively;

m = number of data set;

n = average number of observations in regressions.

18. Sinuosity was selected as the third independent variable for the regression rather than flood recurrence intervals. The statistical difference between the high-flood and low-flood period models had already been taken into account in the way the data was divided, so it was unnecessary to include flood recurrence intervals again.
19. The high-flood and low-flood regression equations were then applied to the 1997 map.
20. The resulting probabilities were charted in *Microsoft Excel*® to illustrate the prediction from the model of channel erosion in the year 2012 based on the low-flood and high-flood scenarios for the period 1997-2012.
21. The high-flood and low-flood regression equations were both applied to the 1937 data. After tabulating the number of years in each model (31 years in high-flood periods, 30 years in low-flood periods), a weighted average of the two probability results was calculated reflecting the actual occurrence of high-flood and low-flood years between 1937 and 1997.

22. The probabilities estimated by the application of the model to the 1937 data were converted to a *Microsoft Excel*® chart illustrating the ability of the model to predict channel change through time.

23. To test the accuracy of the model, the values of actual frequency of channel location for the 1937-1997 period (calculated in step 3) were subtracted from those estimated by the application of the model to the 1937 data, and a *Microsoft Excel*® chart was created of the residuals. This chart illustrated the ability, or lack thereof, of the model to predict actual change in the course of the channel.

CHAPTER IV

RESULTS AND DISCUSSION

Analysis of Surface Sediments

The map created with the surface sediment data shows some patterns distinctive of meandering to braided stream systems (Figure 6). Obvious ripple and dune complexes occur with interdune areas composed of much finer material, which is indicative of gradual channel migration. Topographically low areas contain a substantially larger proportion of fine-sediment than the surrounding higher areas. In addition, the sand observed in this particular environment responds as quicksand when located close to the water table.

Grain size on the surface of the Canadian River floodplain is rarely larger than medium to coarse sand, and the dune areas exhibit distinct longitudinal patterns running parallel to the channel. These units are similar to the longitudinal bars found in braided streams, although the grain size is smaller than usually found in common braided systems. The reason for this is most likely the distance of the reach from the source of the Canadian River in New Mexico.

In most natural river systems like the Canadian River, this pattern of dune highs with muddy interdune lows can be followed down the floodplain. In this study area, it may be noticed that an obvious discontinuity of sediment patterns occurs from the northwest portion of the map area toward the southeast. Human activity is the main

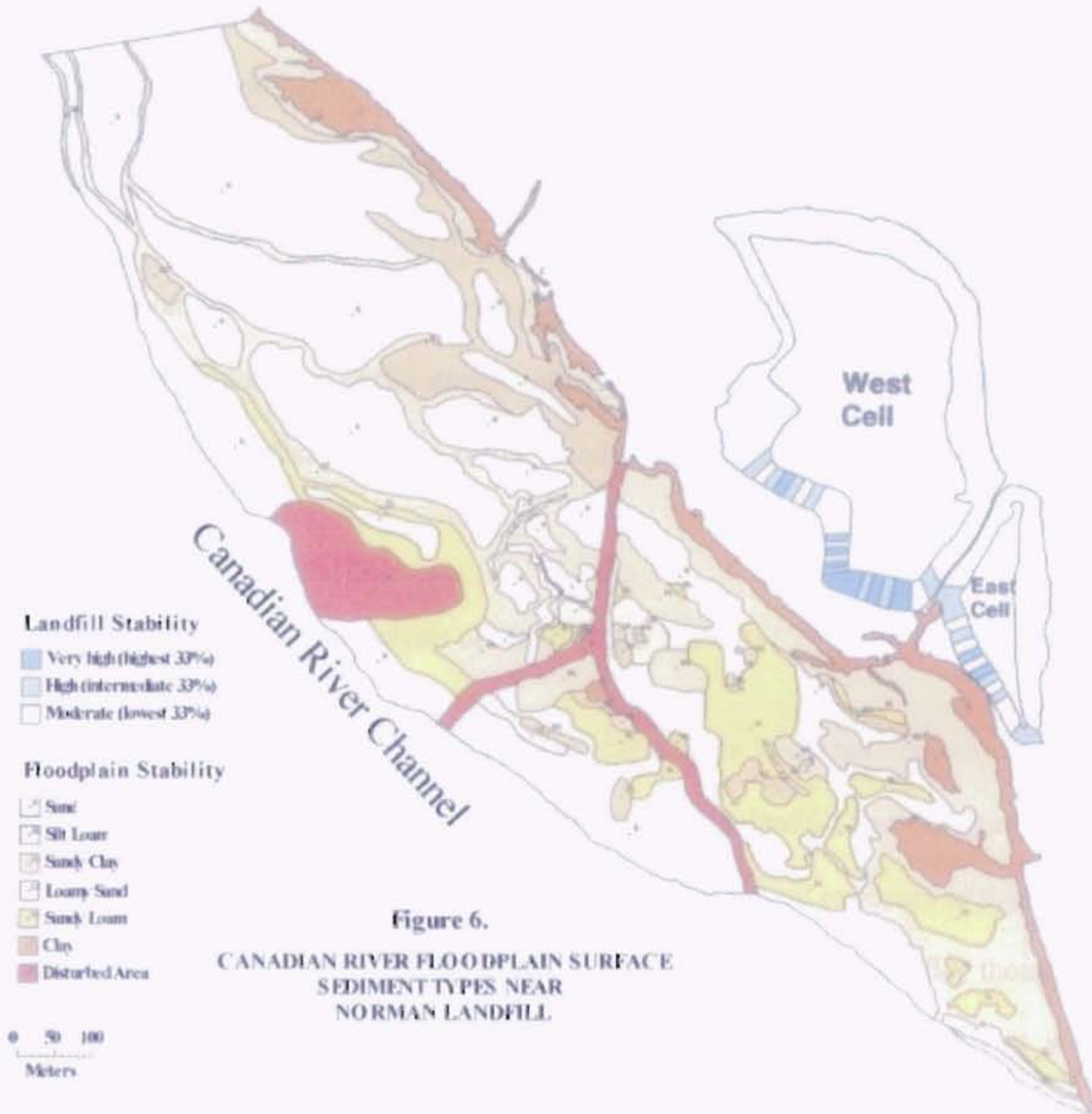

Figure 6.

CANADIAN RIVER FLOODPLAIN SURFACE SEDIMENT TYPES NEAR NORMAN LANDFILL

cause of this disturbance to the natural pattern of sediment in the area. All of the geomorphic patterns in the northwest portion of the map area are continuous and natural, alluding to a long-term lack of disturbance from outside forces. The dunes here are relatively tall, and are amalgamated into very large complexes. In the southeast portion of the map, however, the uppermost layers of sediment have been removed, leaving behind only the underlying finer sediment. An asphalt company extracts sand from the floodplain and active channel to be used in its manufacturing processes. One entire section of the frontal dunes that lie immediately adjacent to the river has been removed, as well as most of the inland dunes toward the asphalt plant. This activity has disrupted the hypothesized patterns of sediment texture on the floodplain, severely reducing the natural integrity of the floodplain and posing a risk to the landfill. Sediment in this area is so fine that the threshold velocity for erosion and entrainment is very low. In addition, the mean elevation of the southeast portion of the floodplain is noticeably lower than the northwest. Any inundation of the stream, either by natural migration or by flood activity, will pass over the southeast portion of the floodplain without barrier until it reaches the landfill.

Analysis of Landfill Cap Stability

Patterns created by the landfill stability data (Table 2) do not necessarily show a preferred region of either instability or stability within the landfill itself (Figure 6). The clay cap is generally homogeneous and becomes very hard upon exposure to the sun. In the event of a flood or natural stream migration to the base of the landfill, though, the clay would again become saturated and would lose any inherent stability it would otherwise have in a dried, hardened state. The clay that composes the landfill cap is tacky and highly cohesive. From external observation only, it also seems to increase in thickness toward the bottom of the landfill, most likely from downslope sediment movement. Portions of the landfill that protrude furthest into the path of floodwaters are no less stable than other portions of the landfill. In addition, the threshold for erosion of the clay cap appears to be very low. A 1986 peak flow of 985 cms, a 30-year event, removed existing rip-rap protection for the landfill, penetrated the clay cap, and eroded 5013 m^3 of landfill contents.

Site #	Veg %	Z_{Veg}	Pen-Soil	$Z_{Pen\text{-}Soil}$	Pen-Cap	$Z_{Pen\text{-}Cap}$	Slope %	Z_{Slope}	Z_{Total}	Rank
1	85	0.147	2.613	0.380	2.375	-1.293	11	-0.348	-0.418	2
2	85	0.147	1.888	-0.661	2.520	-1.090	12	0.334	-1.938	1
3	85	0.147	2.325	-0.033	3.720	0.591	12	0.334	0.372	2
4	85	0.147	2.750	0.577	4.013	1.001	12	0.334	1.392	3
5	85	0.147	2.590	0.348	2.375	-1.293	12.5	0.675	-1.473	1
6	85	0.147	2.150	-0.284	2.325	-1.363	12	0.334	-1.834	1
7	85	0.147	2.650	0.434	3.650	0.493	11	-0.348	1.423	3
9	85	0.147	1.388	-1.379	3.250	-0.067	12	0.334	-1.633	1
10	85	0.147	1.388	-1.379	2.388	-1.276	11	-0.348	-2.159	1
11	85	0.147	3.900	2.229	4.125	1.159	12	0.334	3.201	3
12	85	0.147	1.913	-0.625	2.330	-1.356	12	0.334	-2.168	1
13	85	0.147	2.880	0.764	3.900	0.843	13	1.016	0.739	2
14	85	0.147	1.750	-0.859	3.688	0.546	13	1.016	-1.181	2
15	85	0.147	3.000	0.936	4.050	1.053	14	1.698	0.440	2
16	85	0.147	1.810	-0.773	3.980	0.955	13	1.016	-0.685	2
17	85	0.147	2.910	0.807	4.250	1.334	12	0.334	1.955	3
18	85	0.147	3.125	1.116	3.375	0.108	12	0.334	1.037	2
19	85	0.147	3.975	2.337	4.500	1.684	13	1.016	3.152	3
20	85	0.147	3.775	2.049	4.500	1.684	14	1.698	2.183	3
21	85	0.147	3.650	1.870	4.025	1.018	14	1.698	1.338	3
22	85	0.147	3.475	1.619	4.500	1.684	12	0.334	3.116	3
23	85	0.147	2.460	0.161	3.400	0.143	11.5	-0.007	0.458	2
24	85	0.147	2.900	0.793	3.525	0.318	10.5	-0.689	1.948	3
25	85	0.147	2.120	-0.327	3.500	0.283	10	-1.030	1.133	2
26	85	0.147	2.200	-0.213	4.250	1.334	10.5	-0.689	1.958	3
27	85	0.147	3.050	1.008	3.325	0.038	11	-0.348	1.542	3
28	85	0.147	1.963	-0.554	2.840	-0.642	12	0.334	-1.382	1
29	85	0.147	1.990	-0.514	2.860	-0.614	12	0.334	-1.314	1
30	85	0.147	2.230	-0.169	3.033	-0.371	13	1.016	-1.409	1
31	70	-6.635	2.250	-0.141	3.083	-0.301	11	-0.348	-6.728	1
32	85	0.147	1.738	-0.877	3.300	0.003	11	-0.348	-0.378	2
33	85	0.147	1.875	-0.679	2.080	-1.707	12	0.334	-2.572	1
34	85	0.147	2.000	-0.500	3.350	0.073	11.5	-0.007	-0.272	2
35	85	0.147	1.450	-1.290	2.580	-1.006	11.5	-0.007	-2.141	1
36	85	0.147	2.710	0.520	3.770	0.661	11.5	-0.007	1.336	2
37	85	0.147	1.213	-1.631	2.820	-0.670	11	-0.348	-1.805	1
38	85	0.147	2.938	0.847	3.440	0.199	11	-0.348	1.541	3
39	85	0.147	1.800	-0.787	4.213	1.281	11	-0.348	0.990	2
40	85	0.147	1.530	-1.175	3.588	0.405	12	0.334	-0.955	2
41	85	0.147	2.250	-0.141	3.483	0.260	12	0.334	-0.067	2
42	85	0.147	2.038	-0.446	2.150	-1.609	11	-0.348	-1.559	1
43	85	0.147	2.140	-0.299	2.388	-1.276	11	-0.348	-1.079	2
44	85	0.147	1.738	-0.877	2.025	-1.784	10	-1.030	-1.483	1
45	85	0.147	1.913	-0.625	2.960	-0.474	8	-2.394	1.443	3
46	85	0.147	1.613	-1.056	3.038	-0.365	7	-3.076	1.803	3
47	85	0.147	2.000	-0.500	2.875	-0.593	7	-3.076	2.131	3
Mean	84.674		2.348		3.298		11.5108696		33% Interval = -1.201	
Std Dev	2.212		0.696		0.714		1.46624665		67% Interval = 1.336	

Table 2. LANDFILL STABILITY ANALYSIS DATA (column headings defined in text, p. 25)

Analysis of Stream Stability

The map of actual frequency of channel occurrence revealed specific areas of the floodplain that were particularly prone to channel presence (Figure 7). The area of the floodplain nearest the landfill has relatively high probability values. An overflow channel (the "slough") runs parallel to the base of the landfill. Whenever the level of the river reaches flood stage, water travels through the slough and has the capability to erode material directly from the base of the landfill.

Hydrologic data for stream gaging sites at the Canadian River at Bridgeport, Norman, Noble, Purcell and Calvin as well as at the Cimarron River at Perkins can be found in Appendix C. Because the Canadian River at Noble gage was the closest gage with a useable hydrologic data set, it was chosen as the site from which to ultimately derive recurrence intervals for the peak annual flood. Inspection of the results of the regression analyses comparing every combination of sites (Table 3) allowed the sites with the best correlation with Noble to be located.

The correlation between the Canadian River at Noble and the Cimarron River at Perkins was excellent: the r^2 value was 0.7091, significant at the $p<0.0001$ level. The multiple regression equation acquired from the hydrologic data of the Cimarron River at Perkins was used to estimate missing data in the Canadian River at Noble set for the years 1927-1938, 1940-1944, 1961-1962 and 1976-1991 by the equation:

$$\text{Est. Noble}_1 = 10667 + (0.18608)(\text{Perkins}) \qquad \text{Eq. 5}$$

The Canadian River at Bridgeport and the Canadian River at Calvin were used to estimate data for the remainder of the study period. Neither site had high correlation statistics with Noble, but with the lack of other alternatives, they had to be included in the

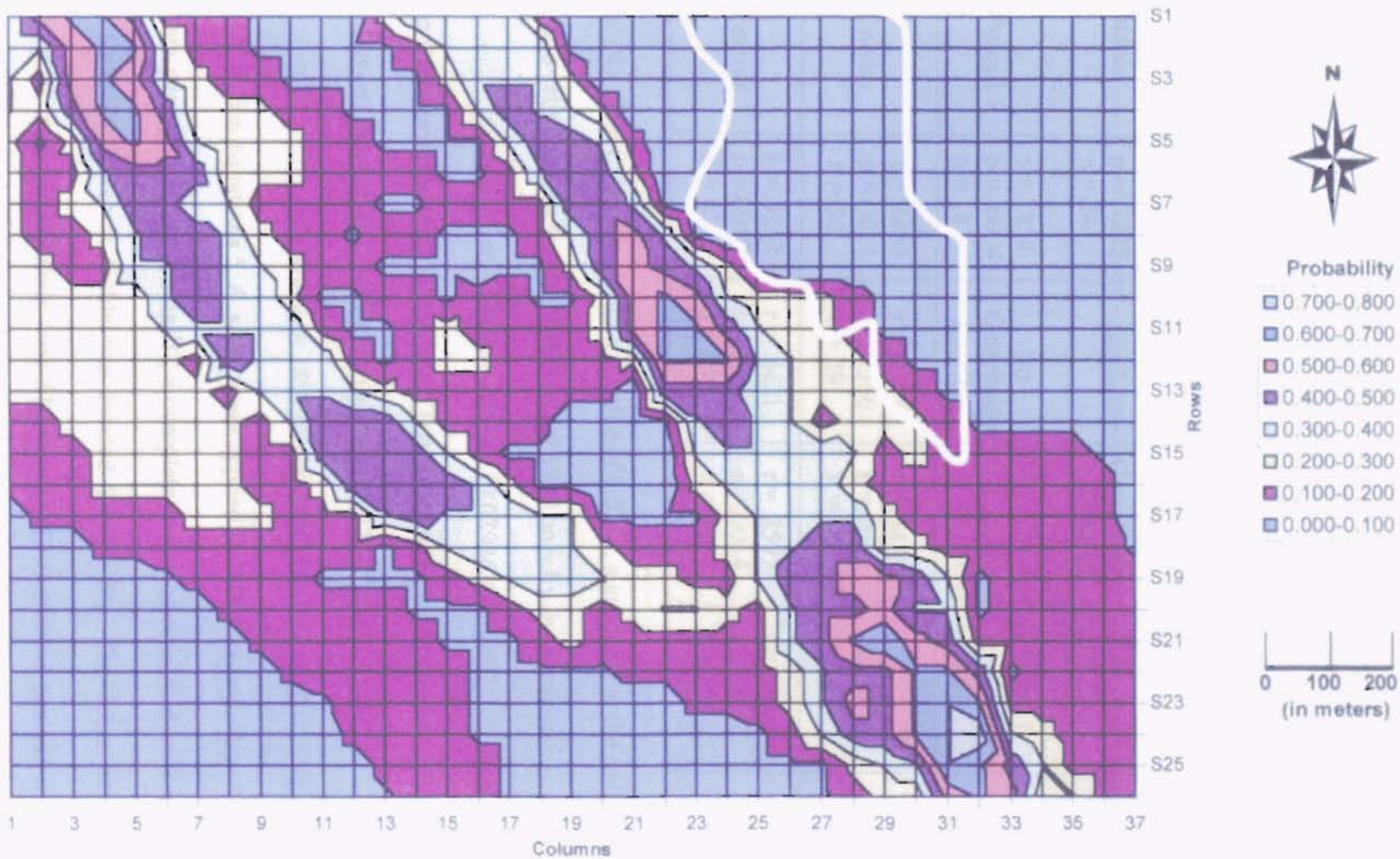

Figure 7. ACTUAL FREQUENCY OF CHANNEL PRESENCE, 1937-1997 (Norman Landfill outlined in white)

Table 3: FLOOD FREQUENCY ANALYSIS CORRELATION MATRIX

	Bridgeport	Noble	Purcell	Calvin	Perkins
Bridgeport	______	r = .2106 p = .3232 n = 24	r = .7454 p = .0004 n = 18	r = .4468 p = .0011 n = 50	r = .4252 p = .0050 n = 42
Noble	r = .2106 p = .3232 n = 24	______	No Correlation Possible	r = .2276 p = .2350 n = 29	r = .8421 p < .0001 n = 24
Purcell	r = .7454 p = .0004 n = 18	No Correlation Possible	______	r = .6421 p = .0041 n = 18	r = .8597 p = .0014 n = 10
Calvin	r = .4468 p = .0011 n = 50	r = .2276 p = .2350 n = 29	r = .6421 p = .0041 n = 18	______	r = .3476 p = .0087 n = 56
Perkins	r = .4252 p = .0050 n = 42	r = .8421 p < .0001 n = 24	r = .8597 p = .0014 n = 10	r = .3476 p = .0087 n = 56	______

analysis. The Calvin site, with a r^2 value of 0.0518, significant at the p=0.2350 level, was used to estimate data for the Noble set for 1939 only by the equation:

$$\text{Est. Noble}_2 = 15869 + (0.03926)(\text{Calvin}) \qquad \text{Eq. 6}$$

The Bridgeport site had a r^2 value of 0.0444, significant at the p=0.3232 level, and was used to estimate missing record for the years 1992-1999 by:

$$\text{Est. Noble}_3 = 16773 + (0.05002)(\text{Bridgeport}) \qquad \text{Eq. 7}$$

When equations 5, 6, and 7 were applied to the hydrologic data for the respective stream gaging sites (Appendix B), a complete record of estimated peak annual flows for the Canadian River at Noble was created (Figure 8). The mean annual peak flow, calculated from these values, was 516.5 cms. To determine periods of different flood activity for use in the model, the departure from the mean annual flood for each year was

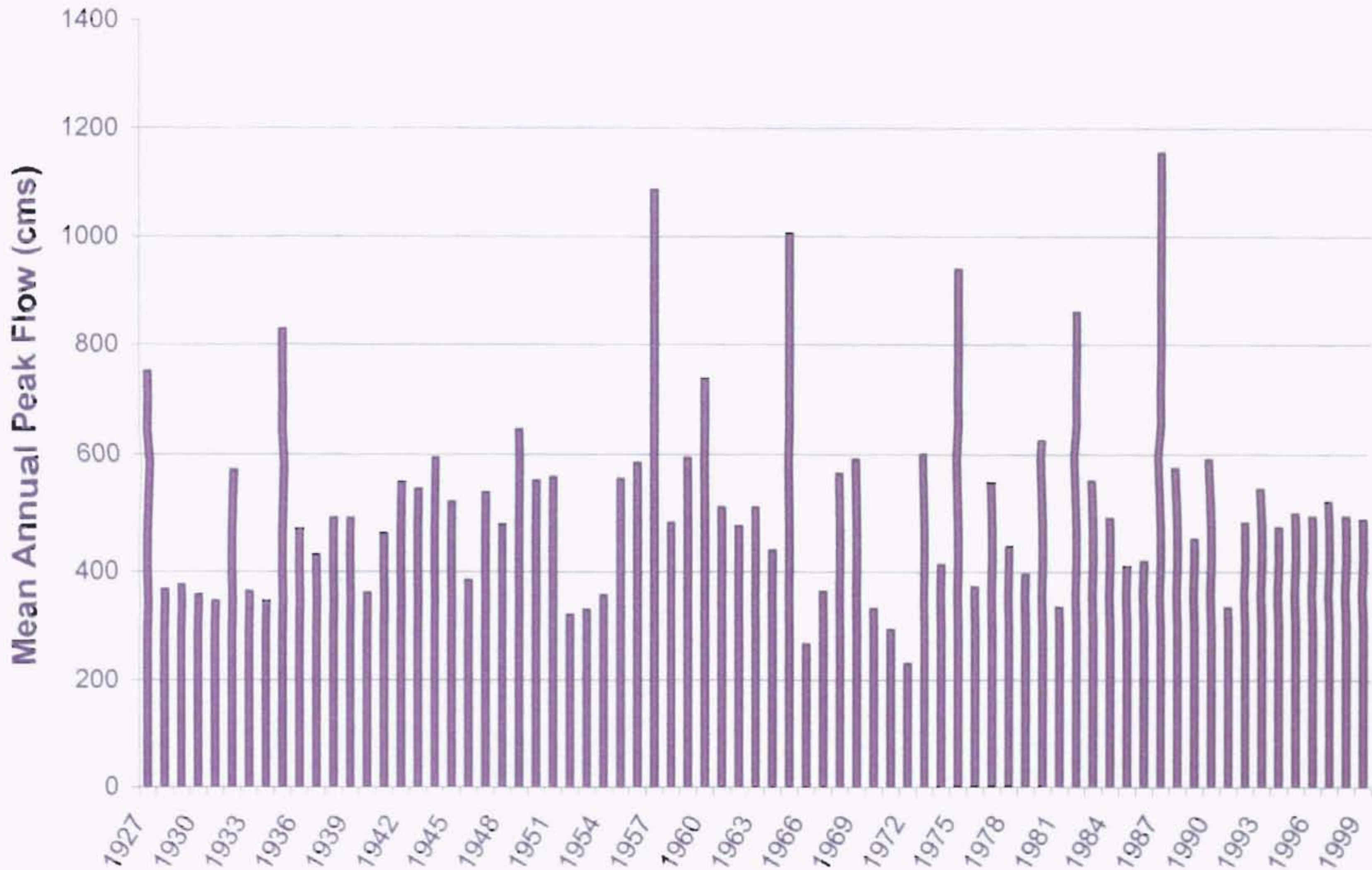

Figure 8. ESTIMATED PEAK FLOWS FOR CANADIAN RIVER AT NOBLE, 1927-1999

determined and a cumulative departure curve was created and graphed (Figure 9). From this graph, four periods of flood activity were established based on shifting trends in hydrologic conditions: 1937-1951 (below MAF), 1951-1966 (above MAF), 1966-1981 (below MAF) and 1981-1997 (above MAF). The ranking of the peak annual flows allowed a recurrence interval to be established for each flood year. (Values of peak annual flood, departure from mean annual flood, cumulative departure from mean annual flood, flood magnitude rank (largest to smallest) and flood recurrence interval can be found in Appendix C.)

To test for normality of the variables $P_{i,j}$, D_{lm}, and D_{um}, frequency distributions were created with the arithmetic values and log transformed values of each for the combined low flood period (1937-1951 and 1966-1981) and the combined high flood period (1951-1966 and 1981-1997). The distributions were inconclusive, so two normality tests for each variable were used to compare the arithmetic value with the log transformed value: skewness (symmetry about the mean, or the appearance of a "tail" of either above or below mean values) and kurtosis (peakedness of the distribution). In a normally distributed data set, both skewness and kurtosis are as close to zero as possible. The results of this test are in Tables 4a and 4b. After studying this data, it was decided that the arithmetic values would be used rather than log transformed values.

The results of the multiple regression analyses studying the dependency of $P_{i,j}$ on D_{lm}, D_{um}, and S are reported in Table 5. To determine whether sinuosity or cumulative flood recurrence interval was the appropriate third independent variable, a test of covariance was performed on the regression equations of the high and low flood periods. This test determined whether the regressions were statistically and significantly different. If the test affirmed that they were different, flood recurrence interval could be omitted as

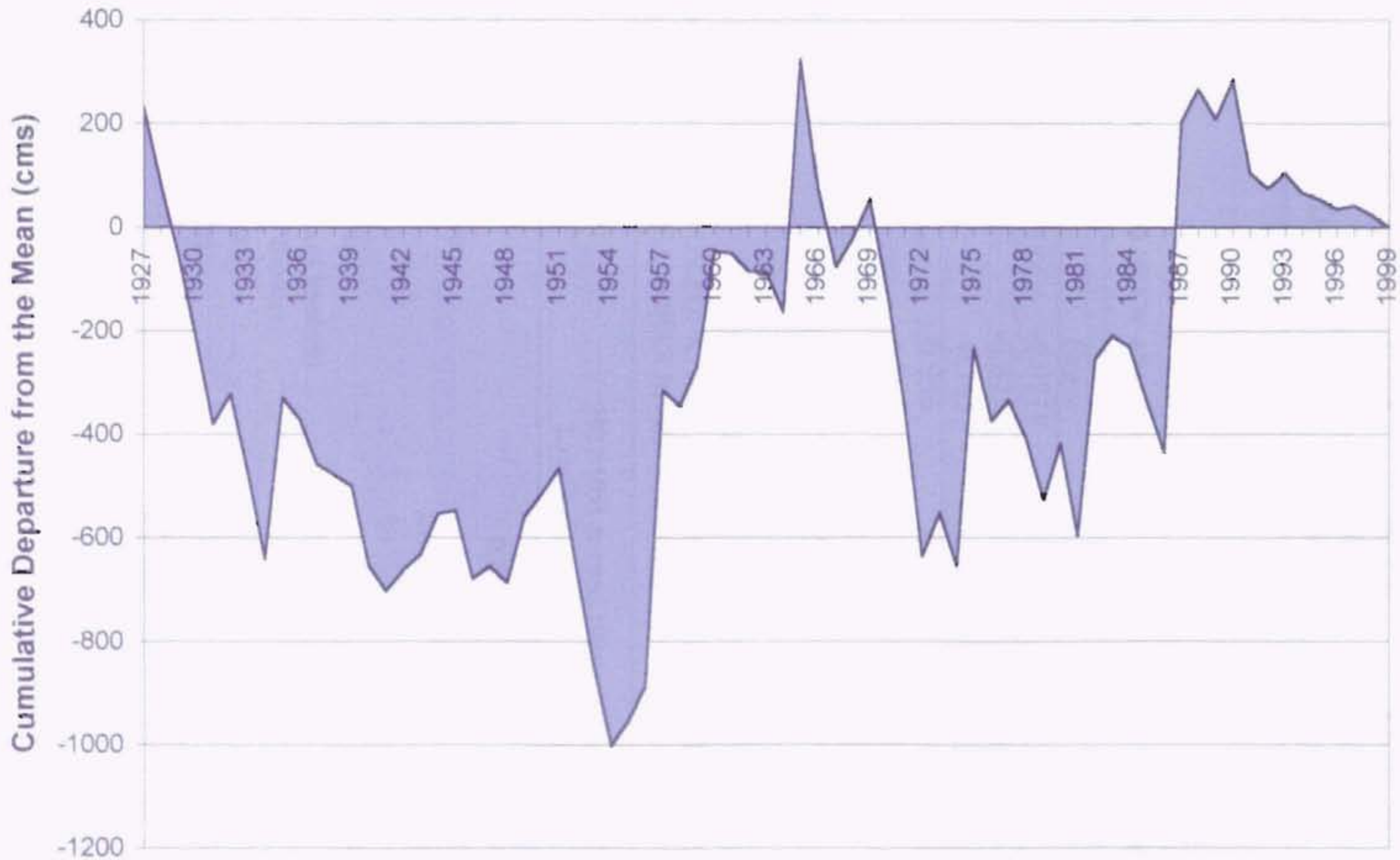

Figure 9. CUMULATIVE DEPARTURE FROM MEAN ANNUAL FLOOD FOR CANADIAN RIVER AT NOBLE, 1927-1999

Table 4a: **TEST FOR SKEW AND KURTOSIS IN LOW FLOOD PERIODS**

	Skew	Kurtosis	n
$P_{i,j}$	0.903	-0.368	89
Log $P_{i,j}$	-0.1288	-0.702	89
D_{lm}	0.457	-0.583	89
Log D_{lm}	-0.488	-0.550	87
D_{um}	0.293	-1.676	89
Log D_{um}	-0.324	-1.221	87

Table 4b: **TEST FOR SKEW AND KURTOSIS IN HIGH FLOOD PERIODS**

	Skew	Kurtosis	n
$P_{i,j}$	-0.0771	-1.671	130
Log $P_{i,j}$	-0.875	-0.0672	128
D_{lm}	0.2651	-1.0933	130
Log D_{lm}	-0.956	0.501	128
D_{um}	-0.267	-1.126	130
Log D_{um}	-1.234	0.651	128

Table 5: SOLUTION FOR EQUATION : $P_{i,j} = a_o + b_1D_{lm} + b_2D_{um} + b_3S$
FOR CANADIAN RIVER AT NORMAN, OK

	1937-1951 & 1966-1981 Low-Flood Periods	1951-1966 & 1981-1997 High-Flood Periods
r (correlation coefficient)	0.665	0.696
r^2 (determination coefficient)	0.442	0.485
p (confidence interval)	<0.0001	<0.0001
n (number of cases)	89	130
RSS (residual sum of squares)	4.185	8.687
$d.f._{reg}$ (regression degrees of freedom)	3	3
$d.f._{res}$ (residual degrees of freedom)	85	126
s^2_{reg} (regression mean square)	1.104	2.721
s^2_{res} (residual mean square)	0.0492	0.0689
S (Standard deviation)	0.222	0.263
F (regression variance ratio)	22.42	39.47
a_0 (constant)	0.508	-0.693
b_1 (coefficient of lateral distance)	1.62×10^{-4}	-1.965×10^{-5}
b_2 (coefficient of upstream distance)	4.23×10^{-4}	0.00111
b_3 (coefficient of sinuosity)	-0.289	0.619

an independent variable because of its inherent presence in the division of the data set. The equation:

$$F = \frac{[\Theta_3 - (\Theta_1 + \Theta_2)]/(m-1)}{(\Theta_1 + \Theta_2)/m(n-1)} \qquad \text{Eq. 8}$$

where Θ_1, Θ_2, Θ_3 = residual sum of squares for low flood, high flood and combined models, respectively;

m = number of data set; and

n = average number of observations in regressions

was solved with the regression data with F = 49.176. This F value was compared to F_c where F_c = (m-1, n-2) or (1, 107.5). Using a standard chart for the derivation of F_c from an ordered pair of m and n values (the closest being 1, 120) and from a p value (the closest being 0.01), F_c was quantified as 6.85. Finally:

$$F >> F_c \qquad \text{Eq. 9}$$

and the regressions were statistically different. Therefore, because of the way in which the years were originally divided, flood activity was already taken into account and sinuosity remained in the regression as the third independent variable.

The r^2 values for low and high flood periods, coupled with the very low P values, indicate that the relationship between distance and probability is not by chance and that distance is a reasonable indicator of probability. The original empirical equation

$$P_{i,j} = a_o + b_1 D_{lm} + b_2 D_{um} + b_3 S \qquad \text{Eq. 10}$$

was then completed for both low and high flood periods as follows:

$$P_{i,j\ \text{low-flood}} = 0.508 + 1.62 \times 10^{-4}\,(D_{lm}) + 4.23 \times 10^{-4}\,(D_{um}) - 0.289\,(S) \qquad \text{Eq. 11}$$

$$P_{i,j\ \text{high-flood}} = -0.693 - 1.965 \times 10^{-5}\,(D_{lm}) + 0.00111\,(D_{um}) + 0.619\,(S) \qquad \text{Eq. 12}$$

The regression analyses produced unexpected results. Graf (1984) used this procedure and concluded that probability of erosion would decrease with increasing distance from the channel. The data processed in the study on the Canadian River indicated something entirely different. Many of the regression coefficients were positive rather than negative, consequently producing an increase in probability values. Therefore, this model, as applied to the data generated in this study, expressed a positive correlation between distance and probability. In Graf's original study, the values entered into the regression equations were the logarithmic values of $P_{i,j}$, D_{lm}, and D_{um}. Therefore, cells located within the actual channel were not taken into account in Graf's regression, because the distance values of each of these cells would be zero, and the log of zero cannot be calculated.

To test the ability of my model to predict channel change in this particular environment, the regression equations were applied to the 1937 distance and sinuosity data. The resultant map (Figure 10), like the map of actual frequency of channel presence (Figure 7), illustrates that the Canadian River is highly mobile and, therefore, capable of eroding areas of the floodplain situated large distances from the active channel, including those on or around the Norman City Landfill.

The residuals map (Figure 11) was created by charting the difference for each cell between the predicted and the true measured data. This map indicates areas in which the model was best able to predict channel erosion as well as identifying areas in which erosion was either overestimated or underestimated. In the immediate vicinity of the channel location at the beginning of the study period, the model acceptably predicted channel movement, especially on the insides of meander bends. This may have been a function of sampling. In Graf's original study, distance was only included to 400 m from the channel in both directions. Distances entered into the regression in the Canadian River study were much greater, particularly in the upstream and downstream directions.

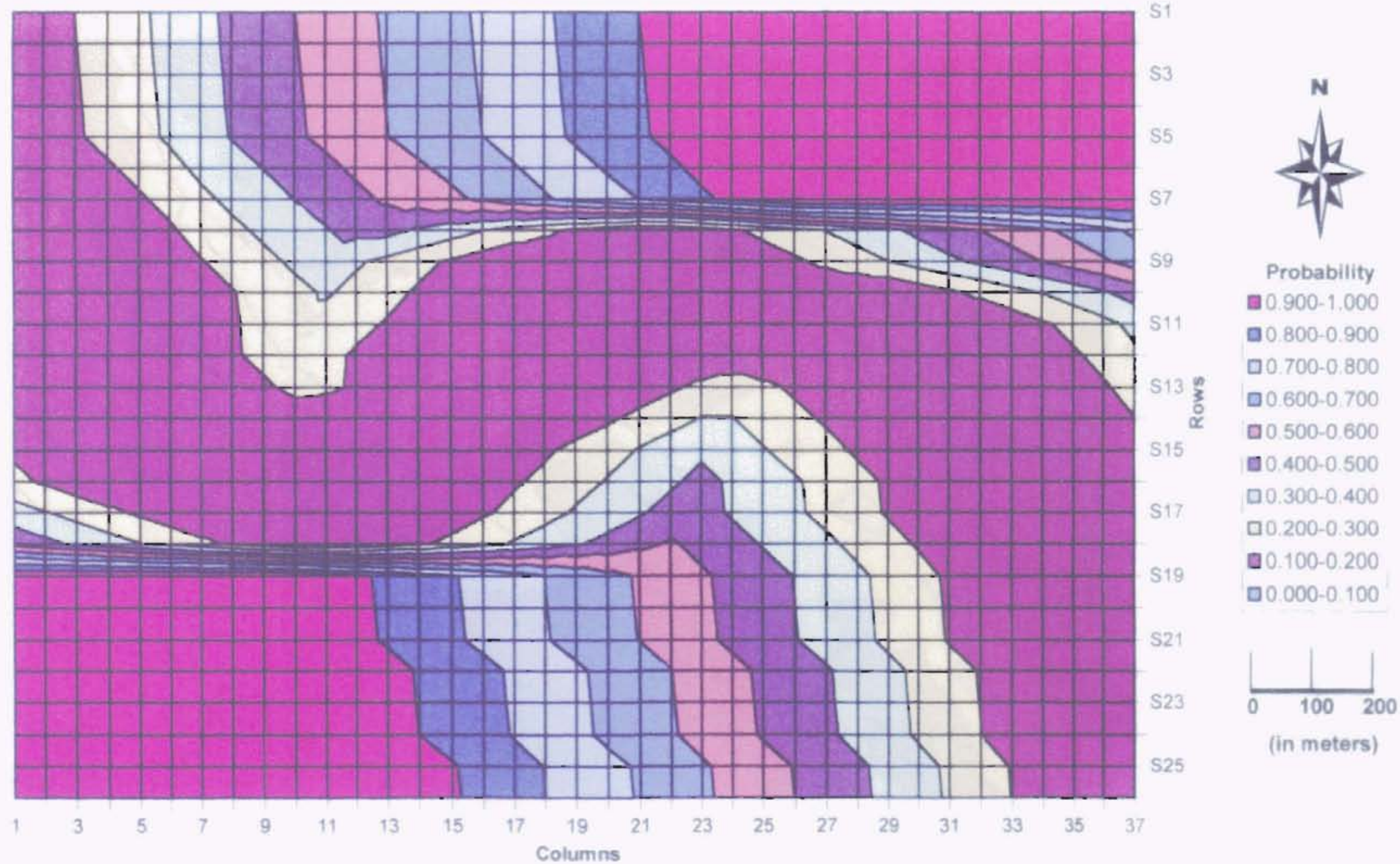

Figure 10. PREDICTED FREQUENCY OF CHANNEL PRESENCE BY MODEL, 1937-1997 (Norman Landfill outlined in white)

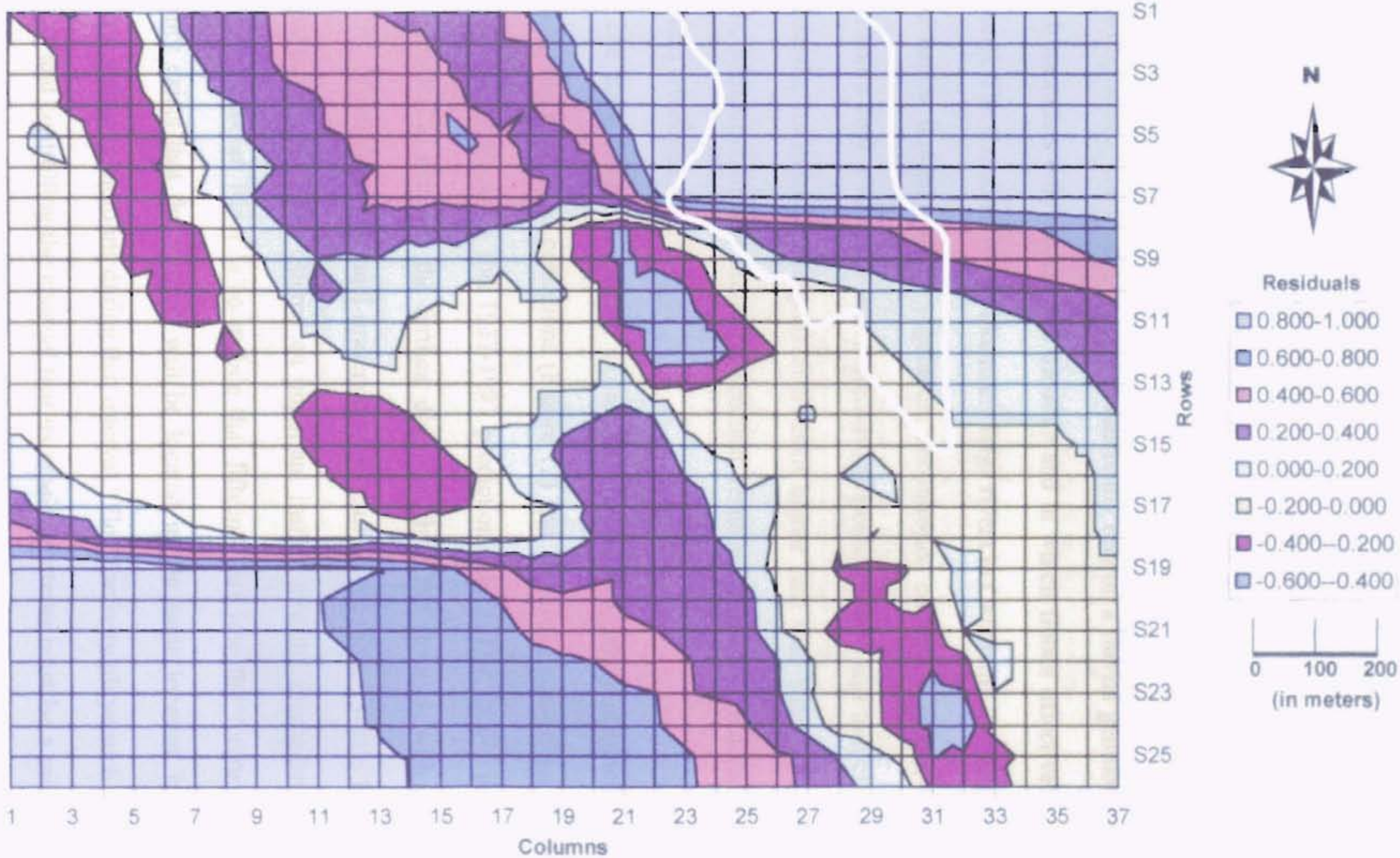

Figure 11. MAP OF RESIDUALS OF PREDICTED FREQUENCY - ACTUAL FREQUENCY, 1937-1997 (Norman Landfill outlined in white)

Therefore, more of the active floodplain was taken into account, and the erosive ability of the river was seen to a much greater extent.

Graf recognized his model was limited in that it assumed constant erosion rates through time. This offers an explanation as to why the model over-predicts erosion on the outside of meander bends (resulting in positive residuals), where thalweg scour initiates migration. The model appears to inherently rely on a fluvial geomorphic system in which meanders only extend and translate and in which floods effectively straighten the channel. The Canadian River, like many large rivers in Oklahoma, has highly erodible bed and banks, limited riparian vegetation, uncontrolled channel margins, low channel gradient and a very wide, very flat floodplain composed of sand and thin clay interbeds. Consequently, its meanders migrate at a much higher rate than many other sand-bed channels, without control or preferred direction, resulting in erosion patterns that at first might seem erroneous.

The maps created to predict erosion of the Canadian River channel in the year 2012 assuming high-flood conditions (Figure 12) and low-flood conditions (Figure 13) replicated the results from the 1937-1997 prediction map. The model predicted the greatest erosion to occur at the furthest distances from the channel, with almost zero probability of continued channel presence in its current location. While these results were counterintuitive, they offered an important insight into the characteristics of the river. The Canadian River is so mobile that fifteen years into the future, little to no probability exists that the channel will be located in the same location it is in now, regardless of flood conditions during that interval. Flood activity plays such a small role in shaping and controlling the channel that its erosion patterns must be a product of bed and bank sediment composition coupled with the presence of a very wide, very flat flood-

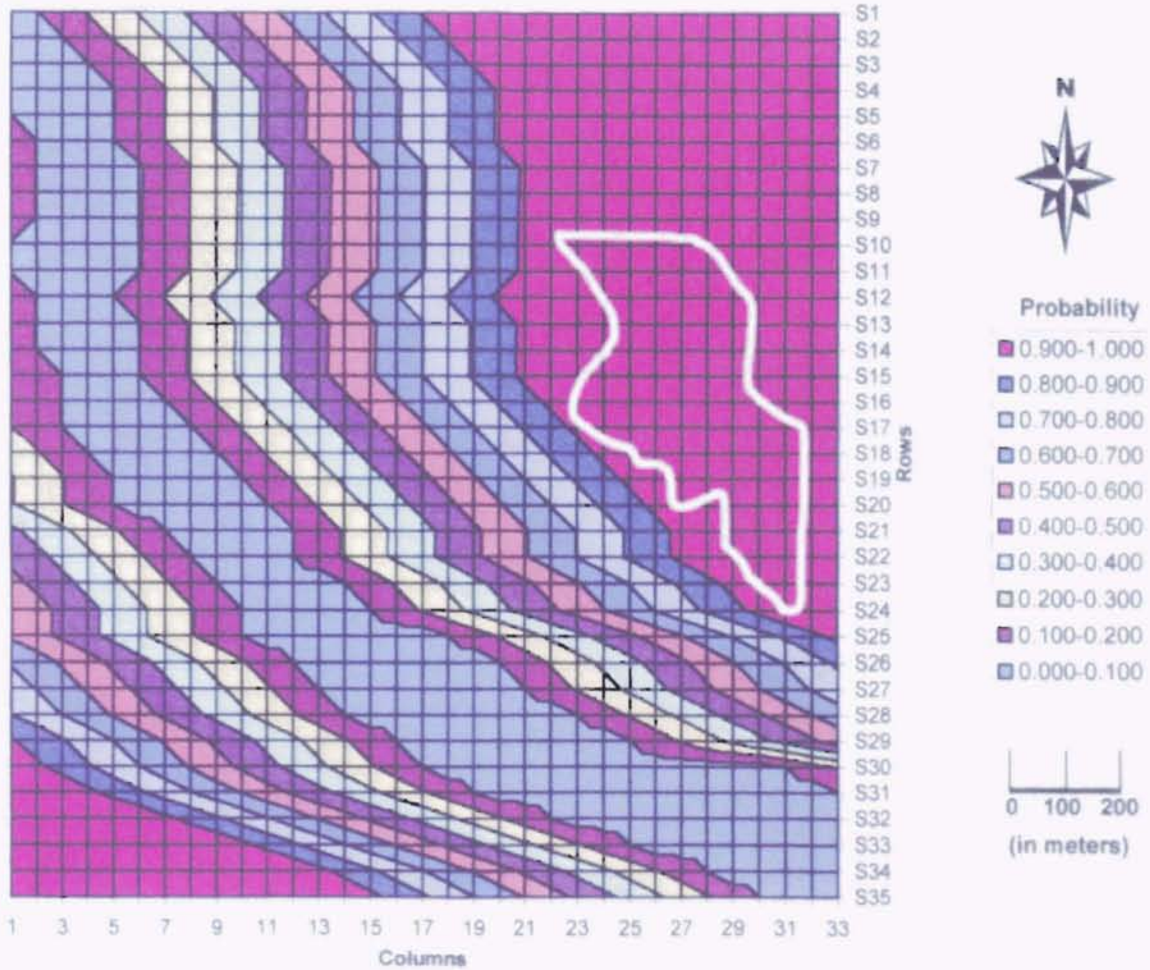

Figure 12. PREDICTED CHANNEL EROSION FOR THE YEAR 2012 ASSUMING HIGH FLOOD CONDITIONS (Norman Landfill outlined in white)

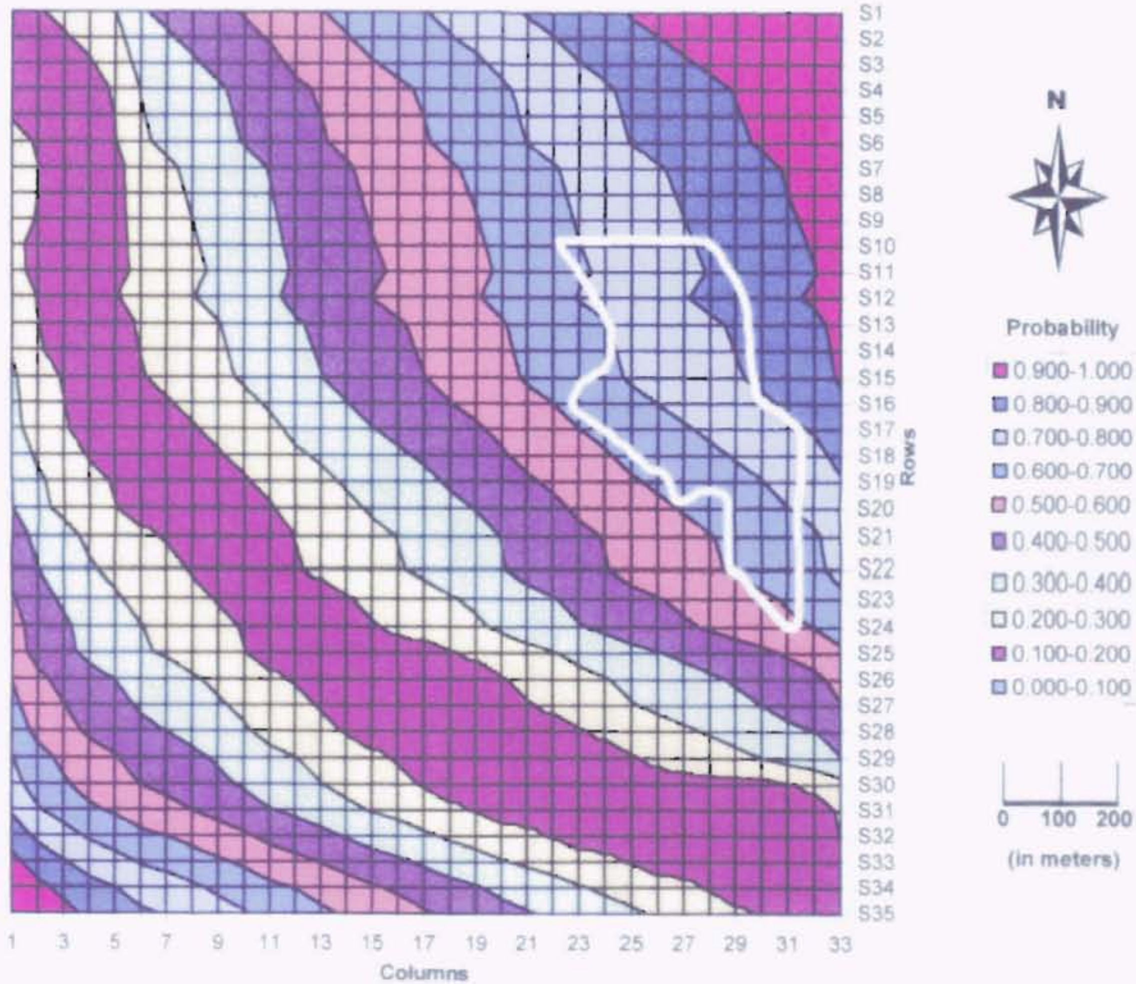

Figure 13. PREDICTED CHANNEL EROSION FOR THE YEAR 2012 ASSUMING LOW FLOOD CONDITIONS (Norman Landfill outlined in white)

plain. Clay interbeds are thin and discontinuous and do not have an important role in channel control. Silt and sand (ranging from fine to coarse) compose the floodplain surface, and the erosion threshold of sediment of that caliber is such that flows less than bankfull stage have the capacity to erode. Therefore, erosion implications for the landfill are that the river can, at any time, migrate across the floodplain and flow at the base of the landfill, actively eroding the cap and releasing solid waste into the channel.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Spatial arrangement of geomorphic units on the Canadian River floodplain near the Norman City Landfill was typical of a meandering to braided river system, outside of the area impacted by sand excavation for the asphalt plant. The map of floodplain surface sediments did illustrate differences in geomorphic units and grain sizes, but did not show any preferred area of susceptibility to erosion. All floodplain sediments are vulnerable to entrainment by floodwaters, and elevation deviation on the floodplain is only a matter of a meter or less, therefore offering no natural barrier to flow. Sand excavation by the nearby asphalt company is effectively removing coarser sediment from the surface and revealing the underlain fine sediments, which in turn have a lower entrainment velocity.

The stability of the landfill cap did vary from place to place but without any distinct patterns with respect to vulnerability to erosion. The clay cap was relatively homogeneous, vegetation was uniformly distributed, and slope varied very little around the southern face of the landfill. Therefore, any flood that attacks the base of the landfill will have the capability to erode large parts of the landfill. As stated before, previous studies have concluded that any flood equal to or greater than a fifteen-year event will inundate the entire floodplain and be present at the base of the landfill.

This probabilistic model of channel instability demonstrates that the Canadian River in the vicinity of the Norman City Landfill is highly mobile and will meander great distances across the floodplain in a relatively short amount of time. A similar future is predicted. Under high-flood conditions, this model predicts a 90-100% chance of fluvial erosion at the base of the landfill. Under low-flood conditions the more susceptible southern face of the landfill is subject to a 60-70% chance of erosion by fluvial forces. As a result, this model predicts that extreme flooding does not necessarily have to occur for appreciable degrees of erosion to take place. The 1986 flood (a 30-year event) eroded over 5,000 m^3 of landfill contents, but subsequent higher flows did no erosive damage to the landfill cap. The difference between 1986 and later years was the location of the active channel of the Canadian River. In 1986, the channel was located adjacent to the landfill, but migrated across the floodplain in the years following the event. Therefore, if the active channel is located adjacent to the landfill, flows of even moderate discharge through the channel have the capability to erode the landfill cap and release solid waste into the channel.

Recommendations

No areas of low susceptibility to erosion exist on the Canadian River floodplain. Therefore, imminent erosion hazards exist for anything that resides on the active floodplain, including the Norman City Landfill. Some external protection to the landfill is justifiable and necessary. Rip-rap, already in place along a sharp meander bend adjacent to the landfill, may be the only means of protecting the landfill from erosion. This structure needs to be extended around the more susceptible southern base of the landfill to reduce the mobility of the clay under inevitable fluvial encroachment.

REFERENCES

Babu, G.L. Sivakumar (1998) Reliability Analysis of Landfill Slopes. In: *Indian Geotechnical Journal* 28, pp. 297-306.

Bettess, R. (1994) Sediment Transport and Channel Stability. In: Calow and Petts (ed) *The Rivers Handbook, Volume 2*. Blackwell Scientific Publications, Oxford, pp. 227-253.

Burke, Michael (1984) Channel Migration on the Kansas River. In: Elliott, C. (ed) *River Meandering: Proceedings of the Conference Rivers '83*. American Society of Civil Engineers, New York, pp. 250-258.

Burkham, D.E. (1972) Channel Changes of the Gila River in Stafford Valley, Arizona 1946-1970. *United States Geological Survey Professional Paper* 665-G.

Chang, H.H. (1986) River Channel Changes: Adjustments of Equilibrium. In: *Journal of Hydraulic Engineering* 112, pp. 43-55.

Church, M. (1992) Channel Morphology and Typology. In: Calow and Petts (ed) *The Rivers Handbook, Volume 1*. Blackwell Scientific Publications, Oxford, pp. 126-143.

Collins, K.L. (2001) Determining Permeability Pathways. Oklahoma State University, M.S. Thesis.

Cooter, E.J. (1991) General Climatology in Oklahoma. In Tortorelli, R.L. *Floods and Droughts: Oklahoma, National Water Summary 1998-89*. U.S. Geological Survey, Water Supply Paper 2375.

Curtis, J. and Whitney, J.W. (2000) Geomorphology and Flood Hazards at a Toxic Landfill on the Canadian River Floodplain, Central Oklahoma. *Publication pending*.

Davis, Jr., R.A. (1992) *Depositional Systems: An Introduction to Sedimentology and Stratigraphy*. Prentice Hall, Englewood Cliffs, NJ.

Dvirnoff, A.H. and Munion, D. W. (1986) Stability Failure of a Sanitary Landfill. In: Fang, H.Y. (ed) *International Symposium on Environmental Geotechnology*, pp. 25-35.

Erdman, J.A. and Christenson, S. (2000) Elements in Cottonwood Trees as an Indicator of Ground Water Contaminated by Landfill Leachate. In *Ground Water Monitoring and Remediation*, Winter, 2000, pp. 120-126.

Fang, H.Y., Inyang, H.I., Daniels, J.L. (1998) Failure Mechanisms of Landfill Covers. In: Sarsby, R.W. (ed) *Contaminated and Derelict Land: The Proceedings of GREEN 2: The Second International Symposium on Geotechnics Related to the Environment* 2, pp. 386-390.

Fassett, J.B. (1993) Geotechnical Properties of Municipal Solid Waste. *Special Project Report*, Purdue University.

Fang, H.Y. (1995) Bacteria and Tree Root Attack of Landfill Liners. In: Sarsby, R. (ed) *Proceedings of GREEN '93: Waste Disposal by Landfill*, pp. 419-426.

Furbish, D.J. (1991) Spatial Autoregressive Structure in Meander Evolution. In: *Geological Society of America Bulletin* 103, pp. 1576-1589.

Gagliano, S. and Howard, P. (1984) In: Elliott, C. (ed) *River Meandering: Proceedings of the Conference Rivers '83*. American Society of Civil Engineers, New York, pp. 147-158.

Gordon, N.D., McMahon, T.A. and Finlayson, B.L. (1992) *Stream Hydrology: An Introduction for Ecologists.* John Wiley and Sons, Chichester.

Graf, W.L.(1981) Channel Instability in a Braided, Sand Bed River. In: *Water Resources Research* 17, pp. 1087-1094.

Graf, W.L. (1984) A Probabilistic Approach to the Spatial Assessment of River Channel Instability. In: *Water Resources Research* 20, pp. 953-962.

Graf, W.L.(1988) *Fluvial Processes in Dryland Rivers*. Springer-Verlag, Berlin.

Heede, B.H. (1992) *Stream Dynamics: An Overview for Land Managers*. Forest Service, US Department of Agriculture, General Technical Report RM-72. Rocky Mountain Forest and Range Experiment Station, Fort Collins, p. 26.

Hefley, H.M.(1935) Ecological Studies on the South Canadian River Floodplain in Cleveland County, Oklahoma. University of Oklahoma, M.S. Thesis.

Hickin, E.J. and Nanson, G.C. (1984) Lateral Migration Rates of River Bends. In: *Journal of Hydraulic Engineering* 110, pp. 1557-67.

Hodgson, J.M. (ed). (1974) *Soil Survey Field Handbook.* Soil Survey Technical Monograph 5, Harpenden, Rathamsted Experiment Station.

Howard, A.D. (1982) Equilibrium and Time Scales in Geomorphology: Application to Sand-bed Alluvial Streams. In: *Earth Surface Processes and Landforms* 7, pp. 303-325.

Kellerhals, R., Church, M. and Bray, D. (1976) Classification of River Processes. In: *Journal of Hydraulics Division American Society of Civil Engineers* 93, pp. 63-84.

Knighton, David (1998) *Fluvial Forms and Processes: A New Perspective*. John Wiley and Sons, New York.

Laczay, I. (1973) Bed-change Processes in a Sand-bearing River. In: *Sediment Transportation 1: International Symposium on River Mechanics*. UNESCO and International Association of Hydrological Sciences, pp. 841-849.

Landrum, J.M., Bourdeau, P.L. and Deschamps, R.J. (1995) Stability Analysis of Landfill Slopes: A Probabilistic Approach. In: Acar, Y.B. and Daniel, D.E. (eds) *Geoenvironment 2000* 2, pp. 1020-1034.

Lee, J.Y. (1996) The Evaluation of Landfill Design for Stability in Seismic Zones. In: *Proceedings: 3rd International Symposium on Environmental Geotechnology* 1, pp. 579-588.

Leopold, L. and Wolman, M.G. (1957) River Channel Patterns: Braided, Meandering and Straight. *United States Geological Survey Professional Paper* 282B.

Lewin, J. (1972) Floodplain Construction and Erosion. In: Calow and Petts (eds) *The Rivers Handbook, Volume 1*. Blackwell Scientific Publications, Oxford, pp. 144-161.

Lewin, J. and Manton, M.M.M. (1975) Welsh Floodplain Studies: The Nature of Floodplain Geometry. In: *Journal of Hydrology* 25, pp. 37-50.

McKnight, T.L. (1990) *Physical Geography*, 3rd edition: Prentice hall, Englewood Cliffs.

Mitchell, R.A., Bray, and Mitchell, J.K. (1995) Material Interactions in Landfills. In: *Proceedings of Geoenvironment 2000: Geotechnical Special Publication* 46, pp. 1020-1034.

Nelson, J. and Smith, D. (1998) Flow in Meandering Channels with Natural Topography. In: Ikeda and Parker (eds) *River Meandering*. American Geophysical Union, Washington, D.S., pp. 69-102.

Northcote, K.H. (1979) *A Factual Key for the Recognition of Australian Soils*. Rellim Technical Publications, Adelaide.

Osterkamp, W.R. and Costa, J.E. (1987) Changes Accompanying an Extraordinary Flood on a Sand-bed Stream. In: Mayer, L. and Nash, D. (eds) *Binghampton 18th Symposium in Geomorphology*. Allen and Unwin, Inc., London, pp. 201-224.

Reid, I. and Frosrtick, L.E. (1994) Fluvial Sediment Transport and Deposition. In: Pye, K. (ed) *Sediment Transport and Depositional Processes*. Blackwell Scientific, Oxford, pp. 89-155.

Sauer, V.B. (1974) Flood Characteristics of Oklahoma Streams: Techniques for Calculating Magnitude and Frequency of Floods in Oklahoma, With Compilations of Flood Data Through 1971. *U.S. Geological Survey Water-Resources Investigation 52-73*, pp. 1-239.

Schlottmann, J.L. (2001) Water Chemistry Near the Closed Norman Landfill, Cleveland County, Oklahoma, 1995. *U.S. Geological Survey Water-Resources Investigations Report 00-4238*, pp. 1-44.

Schumm, S.A. (1963) A Tentative Classification of Alluvial River Channels. *United States Geological Survey Circular* 477.

Schumm, S.A., Rutherford, I.D. and Brooks. J. (1994) Pre-Cutoff Morphology of the Lower Mississippi River. In: Schumm and Winkley (eds) *The Variability of Large Alluvial Rivers*. American Society of Civil Engineers, Washington, D.C., pp. 13-44.

Schumm, S.A. and Lichty, R.W. (1963) Channel Widening and Floodplain Construction Along Cimarron River in Southwestern Kansas. *U.S. Geological Survey Professional Paper* 352-D, pp. 1-88.

Stevens, M.A. (1994) The Citanduy, Indonesia – One Tough River. In: Schumm and Winkley (eds) *The Variability of Large Alluvial Rivers*. American Society of Civil Engineers, Washington, D.C., pp. 201-220.

Thorne, S.D., Croup, V. and Furbish, D.J. (1993) Modern Fluvial Processes in a Sand-bedded Meandering Stream: Flow Structure, Sediment Transport, Bed Forms and Bend Migration. In: Kish S.A. (ed) *Geologic Field Studies of the Coastal Plain in Alabama, Georgia, and Florida: Field Conference Guidebook* 33, Southeaster Geological Society, Tallahassee, pp. 75-89.

Winterkorn, H.F. (1962) Behavior of Moist Soils in a Thermal Energy Field. In: *Proceedings of the 9th National Conference on Clays and Clay Minerals*, pp.. 85-103.

Wolman, M.G. and Gerson, R. (1978) Relative Scales of Time and Effectiveness of Climate in Watershed Geomorphology. In: *Earth Processes* 3, pp. 189-208.

Appendix A

Excel Outlines of Active Channel

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK
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1995

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK
1																																					
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31													1	1	1	1	1	1	1																		
32														1	1	1	1	1	1	1																	
33															1	1	1	1	1	1	1	1															
34																	1	1	1	1	1	1	1	1													
35																		1	1	1	1	1	1	1	1	1	1	1	1	1							
36																				1	1	1	1	1	1	1	1	1	1	1	1	1					
37																							1	1	1	1	1	1	1	1	1	1					
38																										1	1	1	1	1	1	1					
39																													1	1	1	1	1				
40																															1	1	1				

1997

Appendix B

Annual Peak Flows from 1927-1999 for Stream Gaging Sites

Year	Canadian at Bridgeport	Canadian at Norman	Canadian at Noble	Canadian at Purcell	Canadian at Calvin	Cimarron at Perkins
1927						2406
1928						362
1929						396
1930						311
1931						255
1932						1472
1933						334
1934						241
1935					1217	2830
1936					1132	934
1937					3821	693
1938					1189	1033
1939					1186	
1940					804	320
1941					4245	894
1942					2830	1367
1943					3679	1319
1944					934	1576
1945	440				2575	1186
1946	224				1112	453
1947	1613				2505	1288
1948	4245				4217	976
1949	1189				4132	1848
1950	792				4924	1387
1951	1840				2287	1421
1952	263				744	117
1953	280				1709	155
1954	456				1460	311
1955	883				2887	1404
1956	872				1460	1520
1957	1149				3792	4217
1958	889				2943	991
1959	1616				2106	1571
1960	1024		736		2465	2790
1961	679		515		923	1981
1962	807				1070	962
1963	504				1265	1143

Year	Canadian at Bridgeport	Canadian at Norman	Canadian at Noble	Canadian at Purcell	Canadian at Calvin	Cimarron at Perkins
1964	470		439		1305	722
1965			1005		993	1757
1966			268		171	224
1967			365		1868	965
1968			572		1293	379
1969			591		957	801
1970	391		334		1503	425
1971	693		294		3679	242
1972	408		231		475	199
1973	645		600		1469	1211
1974	1095		413		1896	2006
1975	713		940		1078	2830
1976	275				764	379
1977	498				804	1373
1978	359				1078	764
1979	198				1223	512
1980	233			192	413	1740
1981	254			161	121	194
1982	2437			1429	1964	3000
1983	1104			676	1639	1390
1984	226				4075	1033
1985	14				2188	583
1986	753			572	1421	625
1987	1885			2887	4358	4585
1988	379			368	2355	1491
1989	439			1251	1208	841
1990	357			897	4132	1562
1991	22			168	739	188
1992	229			773	1757	
1993	1449			2380	2643	
1994	61			252	589	
1995	563			869	2606	
1996	453			501	1947	
1997	965	512		549	1684	
1998	467	617		628	2694	
1999	351			569	2739	

Appendix C

Actual and Estimated Flood Frequency Data, 1927-1999, Canadian River at Noble

YEAR	Qpk (cms)	Qpk-MAF (cms)	CumDepart (cms)	Rank	RI
1927	750	233	233	7	10.6
1928	368	-149	85	58	1.28
1929	376	-140	-55	56	1.32
1930	359	-157	-212	62.5	1.18
1931	348	-168	-381	64.5	1.15
1932	574	58	-323	18	4.11
1933	365	-151	-474	59.5	1.24
1934	348	-168	-642	64.5	1.15
1935	829	313	-330	6	12.3
1936	475	-41	-371	45	1.64
1937	430	-86	-457	50	1.48
1938	495	-21	-478	37	2
1939	495	-21	-499	37	2
1940	362	-154	-654	61	1.21
1941	467	-50	-703	46	1.61
1942	558	41	-662	24.5	3.02
1943	546	30	-633	26.5	2.79
1944	594	78	-555	12.5	5.92
1945	524	7	-548	29.5	2.51
1946	385	-132	-679	55	1.35
1947	541	24	-655	28	2.64
1948	484	-33	-688	42	1.76
1949	645	129	-559	9	8.22
1950	560	44	-515	22.5	3.29
1951	566	50	-466	20	3.7
1952	323	-194	-659	70	1.06
1953	331	-185	-845	69	1.07
1954	359	-157	-1002	62.5	1.18
1955	563	47	-955	21	3.52
1956	586	69	-886	16	4.63
1957	1087	570	-316	2	37
1958	487	-30	-345	40.5	1.83
1959	594	78	-267	12.5	5.92
1960	736	219	-48	8	9.25
1961	515	-1	-50	31.5	2.35
1962	481	-35	-85	43	1.72
1963	515	-1	-86	31.5	2.35

YEAR	Qpk (cms)	Qpk-MAF (cms)	CumDepart (cms)	Rank	RI
1964	439	-78	-164	49	1.51
1965	1005	488	324	3	24.7
1966	268	-249	75	72	1.03
1967	365	-151	-76	59.5	1.24
1968	572	55	-21	19	3.89
1969	591	75	54	14.5	5.1
1970	334	-183	-128	68	1.09
1971	294	-222	-351	71	1.04
1972	231	-285	-636	73	1.01
1973	600	83	-552	11	6.73
1974	413	-103	-655	52	1.42
1975	940	423	-232	4	18.5
1976	374	-143	-375	57	1.3
1977	558	41	-334	24.5	3.02
1978	444	-72	-406	48	1.54
1979	396	-120	-527	54	1.37
1980	625	109	-418	10	7.4
1981	337	-180	-597	66.5	1.11
1982	860	344	-254	5	14.8
1983	560	44	-210	22.5	3.29
1984	495	-21	-231	37	2
1985	410	-106	-337	53	1.4
1986	419	-98	-435	51	1.45
1987	1155	638	203	1	74
1988	580	64	267	17	4.35
1989	458	-58	209	47	1.57
1990	591	75	284	14.5	5.1
1991	337	-180	104	66.5	1.11
1992	487	-30	75	40.5	1.83
1993	546	30	104	26.5	2.79
1994	478	-38	66	44	1.68
1995	504	-13	53	33	2.24
1996	498	-18	35	34.5	2.14
1997	524	7	42	29.5	2.51
1998	498	-18	24	34.5	2.14
1999	492	-24	0	39	1.9

VITA

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