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An assessment of the erodibility of Holocene lithounits comprising streambanks in northeastern Kansas, USA

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ABSTRACT

Streambanks are the primary source of sediment for watersheds in the Midwestern USA. In much of this region, deposits of fine-grained Holocene alluvium comprising streambanks have been assigned to a single lithostratigraphic unit, the DeForest Formation. This study examines the stratigraphic relationships and measures the erodibility of the different members of the DeForest Formation in three watersheds in northeastern Kansas. Distinct differences in erodibility, measured in terms of critical shear stress (τ_c) by a submerged jet-test device, were observed between the different members of the DeForest Formation. The most erodible member is the Camp Creek Member (average $\tau_c = 1.0$ Pa) while the most resistant is the Gunder Member (average $\tau_c = 10.4$ Pa). Variability in erodibility between and within the members of the DeForest Formation is attributed to the magnitude of post-depositional soil-forming processes, including the presence of buried soils, as well as the inherent natural variability in the different parent materials. A weak positive correlation was found between percent clay and τ_c. Resistance to erosion by fluid flow was found to be significantly greater where clay contents exceed 28%.

Although the Camp Creek Member was found to be the most erodible, it always occurs, stratigraphically, as the uppermost member. Available bankfull stage indicators suggest that bankfull discharges rarely attain elevations sufficient to erode Camp Creek Member deposits. Therefore, other members of the DeForest Formation are able to exert some control on the rate of bank erosion by hydraulic flow. Furthermore, given the observed differences in lithology, soil development and erodibility, the susceptibility to mass wasting processes is also likely to vary between the different members. Therefore, lithostratigraphic and soil-stratigraphic relationships have important implications for streambank erodibility and are crucial for accurately determining areas prone to streambank erosion in alluvial settings.

1. Introduction

The significance of streambanks as sediment sources has long been recognized, especially with regard to constructing accurate sediment budgets for watersheds (e.g., Roehl, 1962; Dietrich et al., 1982; Trimble, 1983). Many studies have demonstrated that streambank erosion contributes a large portion of the sediment yield in a drainage system (e.g., Simon, 1989; Grissinger et al., 1991; Trimble, 1997). Streambanks in the Midwestern United States have been shown to contribute as much as 80% of total watershed sediment yield (Simon et al., 1996). In general, however, while extensive effort has been made to reduce upland erosion, efforts aimed at controlling sediment contributions from streambanks have been relatively ignored.

Although a complex process, streambank erosion is ultimately controlled by two variables: streambank characteristics and hydraulic/gravitational forces (Thorne, 1982; Osman and Thorne, 1988; Simon et al., 2000). Our study focused on the lithology of streambank materials, especially alluvium, as a measure of bank erodibility. The lithology of alluvium is largely controlled by sediment source and weathering history. Deposits of fine-grained Holocene alluvium comprising streambanks in northeastern Kansas are members of the DeForest Formation, a formal lithostratigraphic unit originally defined in western Iowa and subsequently recognized in most of the eastern Plains (Bettis, 1995; Mandel and Bettis, 2001). In Kansas, the DeForest Formation consists of five formal members: the Camp Creek, Roberts Creek, Honey Creek, Gunder, and Corrington. Because the different members have different lithologies, their erodibility likely varies. Hence, determining their distribution in a drainage basin is important to the identification of areas that are prone to streambank erosion and, therefore, the identification of sediment sources.

The primary objectives of our study were to i) determine the stratigraphic relationships and ii) measure the erodibility of the different members of the DeForest Formation in three northeast Kansas watersheds. In addition to alluvial fills, we measured the erodibility of glacial till as these deposits commonly comprise the bank material in low order tributaries and may provide an important sediment source to axial channels. We also mapped the spatial distribution of the various

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members of the DeForest Formation and tested whether particular soil series shown on county soil survey maps corresponded to particular members. The results of our investigation shed new light on the relationship between the lithology of bank materials and streambank erosion in the Midwestern United States and may be applicable to a broad range of alluvial settings.

2. Study area

This study is part of a larger effort to construct sediment budgets for small, agricultural watersheds in northeastern Kansas (see Foster et al., 2012). The study area comprises three watersheds upstream from small impoundments: Atchison County, Banner Creek, and Centralia lakes (Figs. 1 and 2).

2.1. Physiography and bedrock geology

The study area is located in the northeastern corner of Kansas within the glaciated region of Fenneman's (1931) Central Lowland physiographic province. The glaciated region is bordered on the south by the Kansas River and on the west by the Flint Hills. During the early and middle Pleistocene, a continental ice sheet covered this area. The ice sheet buried pre-glacial stream valleys, cut new valley segments, and leveled the uplands (Mandel and Bettis, 2001). Streams subsequently dissected the drift plain that was left by the ice sheet, leaving glacial deposits high in the landscape. Hence, this region is referred to as the Dissected Till Plain (Schoewe, 1949).

Pennsylvanian and Permian marine and near-marine rocks crop out and significantly influence landscape form and processes in the project area. Exposed rocks are primarily limestone and shale of the Shawnee, Wabaunsee, and Admire (upper Pennsylvanian) and Council Grove (Permian) groups (Merriam, 1963).

2.2. Quaternary geology

The Pleistocene stratigraphy of the Dissected Till Plain beyond the Wisconsin and Illinoian glacial limits is based on a framework of pre-Illinoian glacial tills and intercalated volcanic ashes and of younger loesses. These deposits are regional in extent and thus provide references to which more localized fluvial and colluvial units can be stratigraphically related.

Deposits associated with at least two and as many as five pre-Illinoian glacial episodes have been described from localities in northeastern Kansas (Frye and Leonard, 1952; Dort, 1966, 1985; Bayne et al., 1971; Aber, 1988, 1991; Mandel and Bettis, 2001). Aber (1991) assigned all of these glacial deposits to the Independence Formation. In the project area, glacial tills comprising the Independence Formation are generally calcareous, loamy, matrix-supported diamictons.

The interfluves and Pleistocene terraces in northeastern Kansas are mantled by late Quaternary loess. At least three stratigraphically superposed loesses occur in the region: the Loveland, Gilman Canyon, and Peoria. The combined thickness of loess deposits in the project area is generally <4 m, and in many areas, the Loveland and Gilman Canyon loesses have been eroded from the uplands and only a thin mantle (<2 m) of Peoria Loess remains (Bettis et al., 2003). The Peoria Loess typically is a calcareous, massive, light yellowish tan to brown colored silt loam.

Holocene deposits in northeastern Kansas mostly consist of alluvium and colluvium. A few local deposits of eolian sand are also found that date to the Holocene. All deposits of fine-grained Holocene alluvium

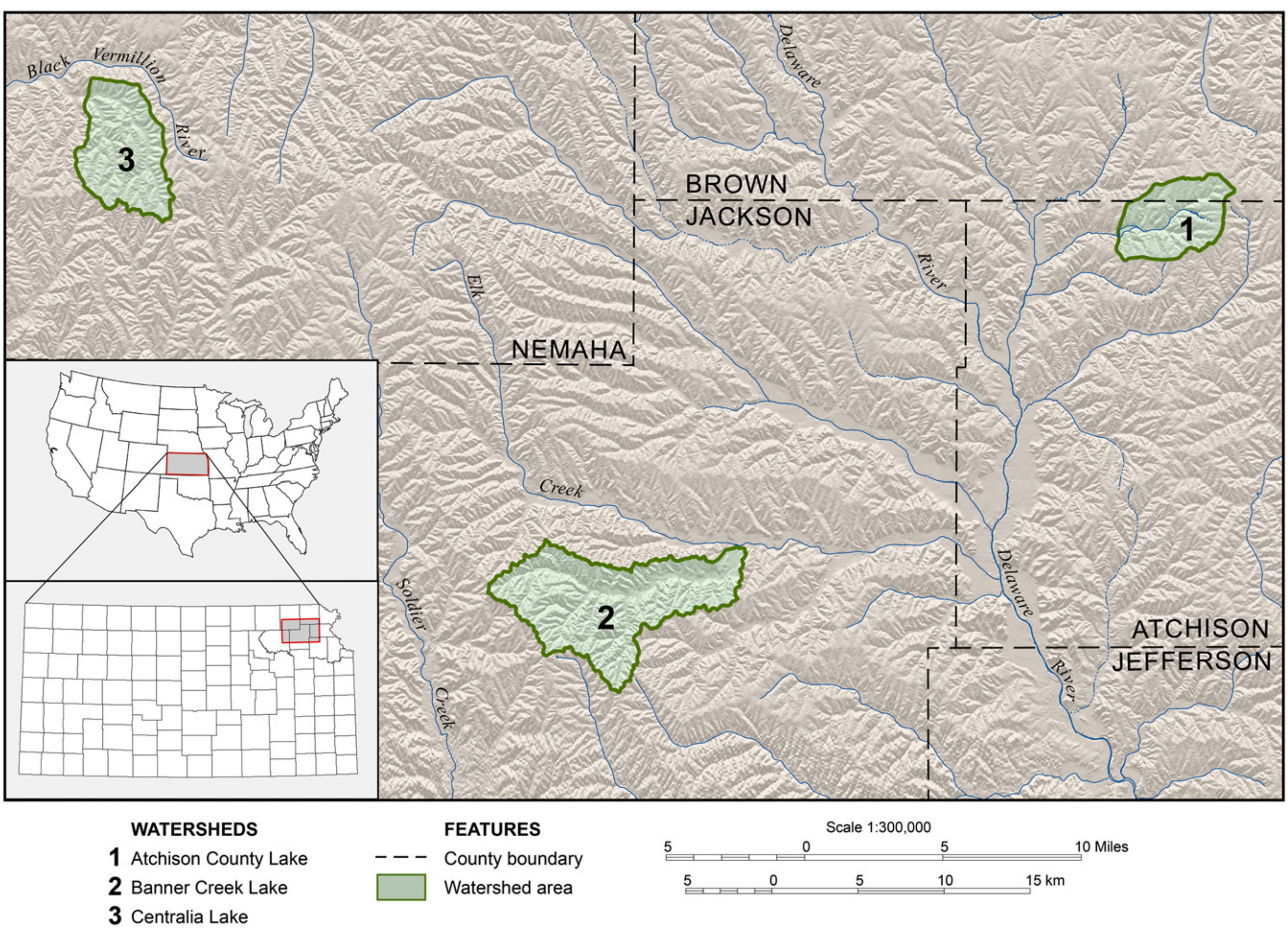

Fig. 1. Location of study watersheds in northeastern Kansas.

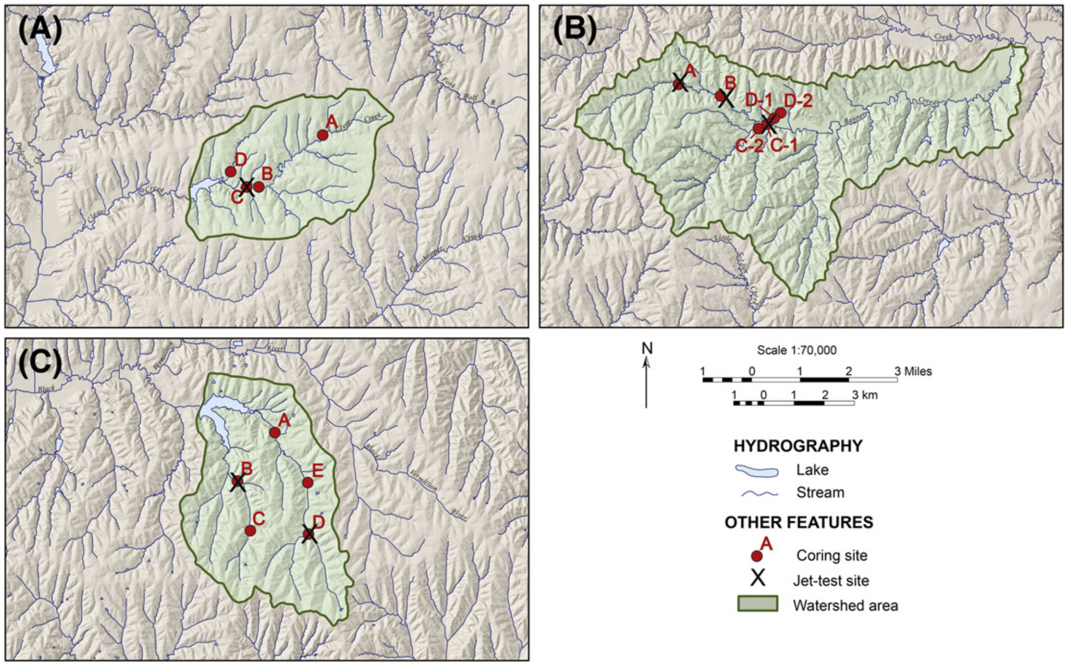

Fig. 2. Location of coring sites at (A) Atchison County Lake, (B) Banner Creek Lake, and (C) Centralia Lake.

and colluvium in northeastern Kansas have been assigned to a single lithostratigraphic unit: the DeForest Formation (Mandel and Bettis, 2001). Several studies have demonstrated that the DeForest Formation is regional in extent (e.g., Daniels et al., 1963; Bettis, 1990, 1995; Fosha and Mandel, 1991; Mandel et al., 1991; Dillon, 1992; Mandel and Bettis, 1992, 1995, 2001, 2003; Mandel, 1994a, 1994b, 1996; Bettis et al., 1996; Dillon and Mandel, 2008; Beeton and Mandel, 2011). The DeForest Formation consists of eight formal members, one of which, the Honey Creek Member, is new (Dillon and Mandel, 2008). Five members of the formation — the Camp Creek, Roberts Creek, Honey Creek, Gunder, and Corrington (Fig. 3) — occur in the project area. Typical physical, pedological, and chronological properties of these five members are given in Table 1.

2.3. Climate

The climate of northeastern Kansas is continental with extremes in precipitation. Mean annual precipitation is about 90 cm for the study area (High Plains Regional Climate Center, 2013a, 2013b). June and January are normally the wettest and driest months, respectively. Approximately 75% of the precipitation falls during the six months of the growing season, April through September, largely because of frontal activity. Pacific and polar air masses that flow into the central Plains during spring and summer usually converge with warm, moist maritime-tropical air flowing north from the Gulf of Mexico. The collision of these air masses often produces intense rainfall of short duration along the zone of convergence. During late summer, convectional thunderstorms also can produce heavy rainfalls. Periodic intensification of westerly (zonal) airflow, however, prevents moist Gulf air from penetrating the central Plains. This condition and the development of strong anticyclonic (high pressure) activity in the upper atmosphere over the midcontinent tend to cause drought in the region (Borchert, 1950; Bryson and Hare, 1974; Namias, 1983).

2.4. Vegetation

The natural vegetation of the region is tall grass prairie interspersed with deciduous forests (Küchler, 1964). The prairies are dominated by big bluestem (*Andropogon gerardii*), little bluestem (*Andropogon scoparius*), Indian grass (*Sorghastrum nutans*), and switch grass (*Panicum virgatum*). Upland deciduous forest is dominated by black walnut (*Juglans nigra*), bur oak (*Quercus macrocarpa*), white oak (*Quercus alba*), black oak (*Quercus velutina*), shagbark hickory (*Carya ovata*), bitternut hickory (*Carya cordiformis*), and green ash (*Fraxinus pennsylvanica*). Cottonwood (*Populus deltoides*), black willow (*Salix nigra*), hackberry (*Celtis occidentalis*), and American elm (*Ulmus americana*) dominate gallery forests along streams. In the watersheds of Atchison County Lake and Centralia Lake, modern vegetation mostly consists of cultivated crops and grassland. However, the Banner Lake watershed has minimal cultivated crops, and the land cover is dominated by pasture and grassland.

3. Background

Streambanks are the primary source of sediment in Midwestern watersheds (Simon and Rinaldi, 2000; Simon et al., 2000; Juracek and Ziegler, 2007). The delivery of bank material to the stream channel typically occurs by a combination of hydraulic forces acting on the channel boundary (i.e., fluvial erosion) and gravitational forces acting on the channel banks (i.e., mass wasting) (e.g., Thorne, 1982; Osman and Thorne, 1988; Simon et al., 2000). Alluvial sediments erode when the shear stress, exerted by flowing water, at the channel boundary (τ_0) exceeds the critical shear stress (τ_c) of the bank material. The critical shear stress (τ_c) is defined as the shear stress at which sediment detachment begins. Whether sediment is entrained is a function of the properties of fluid flow and the physiochemical properties of the sediment. In the Midwest, streambanks are typically composed of cohesive sediments — the entrainment of which are complicated by the presence of electrochemical bonds that bind particles together.

Numerous properties have been shown to influence the resistance of cohesive materials to erosion, including moisture, clay content and mineralogy, bulk density, structure, organic content, water chemistry, and root density (e.g., Grissinger, 1982; Wynn and Mostaghimi, 2006). The erodibility characteristics of a material are typically parameterized as a coefficient, k. However, k and τ_c are difficult to estimate because of the range of properties that influence resistance to erosion. One method that has shown success in accurately measuring these parameters is the in situ submerged jet-test device. This device was developed by

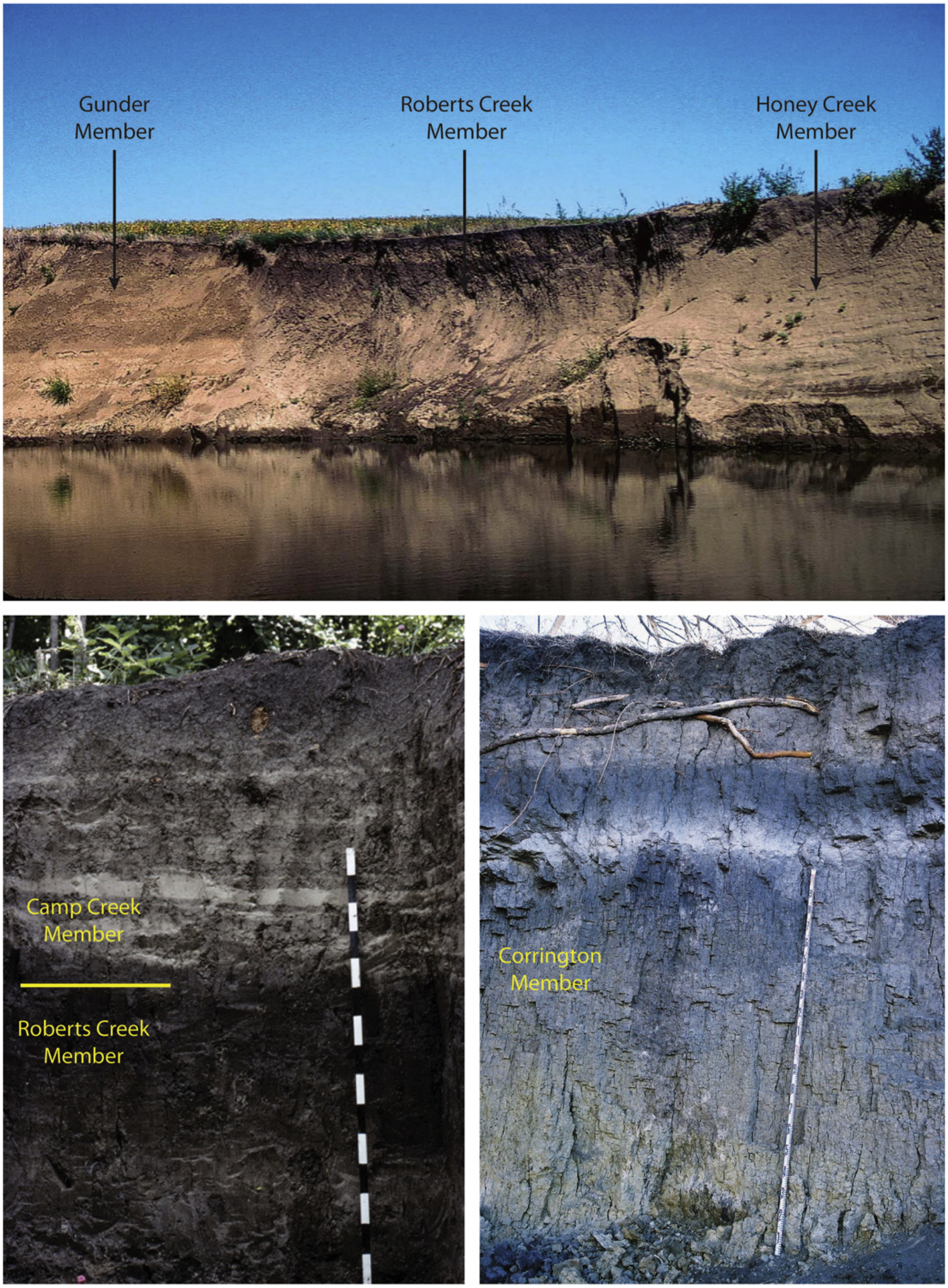

Fig. 3. Outcrop examples of members of the DeForest Formation typically found in Midwestern streams.

Hanson (1990) based on the knowledge of the hydraulic characteristics of a submerged jet and the properties of cohesive materials that influence erosive resistance.

Several studies have successfully employed submerged jet-test devices to determine the erodibility of alluvial sediments (e.g., Hanson and Simon, 2001; Clark and Wynn, 2007; Thoman and Niezgoda, 2008; Simon et al., 2010). Hanson and Simon (2001) conducted 83 tests on cohesive streambeds in southeastern Nebraska, southwestern Iowa, and north-central Mississippi. They observed a wide variation in the erosion resistance of bed material, spanning six orders of magnitude for τ_c (0.003–400 Pa) and four orders of magnitude for k (0.001–3.75 cm^3/Ns). In general, the most erodible materials were in Iowa and Nebraska where beds consist of loess-derived alluvium.

Other studies have also noted a large variation in τ_c and k. For example, Shugar et al. (2007) reported six orders of magnitude variation for τ_c but only one order of magnitude for k from 10 jet-tests conducted on till in southern Ontario, Canada. Thoman and Niezgoda (2008) report ranges of 0.11–15.35 Pa for τ_c and 0.27–2.38 cm^3/Ns for k from cohesive materials in the Powder River Basin, Wyoming. Similarly, Clark and Wynn (2007) found ranges of 0–21.91 Pa for τ_c and 0.04–1.07 cm^3/Ns for k from 93 tests conducted at 25 field sites in southwest Virginia. The variability observed in these studies is typically attributed to

Table 1
Typical physical, pedological, and chronological properties of the members of the DeForest Formation (table compiled from Bettis (1990, 1995), Mandel and Bettis (1992, 2001), and Dillon and Mandel (2008)).

	Camp Creek Member[a]	Roberts Creek Member	Honey Creek Member	Gunder Member	Corrington Member
Facies	Fluvial: overbank	Fluvial: channel fills and sometimes flood drapes	Fluvial: overbank facies coarsening downward to gravelly channel facies. Multiple entrenched channel fills	Fluvial: overbank. Lower parts may be reduced and/or coarse grained	Alluvial fan[b] and colluvial apron
Color	Brown to dark brown and dark grayish brown	Very dark gray to grayish brown	Dark grayish brown	Yellowish brown to brown (oxidized); dark brown, dark gray, light olive gray (reduced)	Very dark brown to yellowish brown
Texture	Silt loam to clay loam, though some deposits may be coarser	Loam to clay loam	Silt loam	Loam to silt loam	Loam to clay loam with interbedded lenses of sand and gravel
Thickness	Variable; few cm to >2 m	1–2 m	Typically 3 to >6 m	>6 m	Typically 3 to >6 m
Surface soils	Entisols	Mollisols[c]	Mollisols, Entisols, and Inceptisols	Mollisols	Mollisols
Horizonation	A–C	A–C or A–Bw	Cumulic A–C or A–Bw	A–Bt	A–Bt
Buried soils	None	Common	Common	Uncommon	Common
Stratigraphic relationships	Inset into or unconformably overlies Gunder, Corrington, Honey Creek, and Roberts Creek Members	Overlies Gunder and Corrington Members, coarse-grained older alluvium, loess, and till. Separated from Camp Creek Member by either a fluvial erosion surface or an unconformity marked by a buried soil	Draped over or laterally inset against the Gunder Member. Often mantled by the Camp Creek Member. Stratigraphic relationship between Roberts Creek and Honey Creek Members is not clearly understood	Unconformably overlies coarse-grained and often organic-rich older alluvium, loess, glacial till, or bedrock. Separated from younger members by a fluvial erosion surface or an unconformity marked by a buried soil	Buries coarse-grained older alluvium, glacial till, loess, or bedrock, and can grade laterally into Gunder Member deposits.
Age	Less than ca. 500 B.P.	Ca. 3000 to 500 B.P.	Ca. 3700 to 400 B.P.	Ca. 10,500 to 4000 B.P.[d]	Ca. 9000 to 2500 B.P.

[a] The Camp Creek Member encompasses deposits that were formerly and informally referred to as 'post-settlement alluvium.'
[b] Fans are located along the margins of valley floors where small streams (first- through third-order) enter large valleys.
[c] Surface soils developed in the Roberts Creek Member are morphologically less well expressed and have darker colored B and C horizons than soils developed in the Honey Creek, Gunder, and Corrington Members.
[d] The Gunder Member is often represented in two separate fills: a strongly oxidized fill (early Gunder; ca. 10,500 B.P. to 6000 B.P.) and a moderately oxidized fill (late Gunder; ca. 6000 B.P. to ca. 4000 B.P.).

varying degrees of subaerial exposure as well as natural variability in physical and chemical properties. While previous studies have provided important constraints on erodibility, they typically have not considered the lithostratigraphy of streambanks.

4. Methodology

4.1. Field methods

Prior to fieldwork, a GIS basemap was prepared for each of the three studied watersheds. The maps included a DEM, based on U.S. Geological Survey (USGS) topographic data, and Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) data. All GIS data were downloaded from the Kansas Data Access and Support Center (DASC) at the Kansas Geological Survey. The GIS basemaps were used to identify landform sediment assemblages comprising valley floors. In addition, because specific soil series tend to be associated with the different members of the DeForest Formation, the SSURGO data were used to prepare preliminary maps showing the spatial patterns of the members. Soil series maps and maps showing the surficial stratigraphic units are provided as Supplementary material. Ground testing was subsequently used to confirm the relationship between the soil series and members comprising surface deposits.

In order to determine the character of alluvial sediments in the study area, 15 cores (5.0 cm in diameter and between 2.3 and 4.2 m in length) were collected from 13 sites (Fig. 2) with a Giddings hydraulic soil probe. Fourteen cores were collected from alluvial valley fills and one core on an alluvial fan. In addition, one cutbank profile was described to document the characteristics of glacial till. Surfaces of alluvial landforms in the project area were numbered consecutively from stream level upward, with floodplain and terrace surfaces designated as T-0 and T-1, respectively. Detailed descriptions of the litho- and soil-stratigraphy were prepared using standard procedures and terminology outlined by Soil Survey Staff (1993) and Birkeland (1999).

Based on the stratigraphy described from the 13 core sites, six sites were selected for testing the erodibility of streambanks (Fig. 2). Site selection also was determined by the availability of sufficient water in the channel to conduct erodibility testing. This limitation prevented us from testing the erodibility of the Robert's Creek Member and restricted us to only one site in the Atchison County Lake watershed. Additionally, we did not test the Corrington Member because its limited spatial extent and confinement to valley margins resulted in a lack of suitable outcrops for testing.

A total of 43 erodibility tests were performed using a modified, portable version of the submerged jet-test device (a 'mini' jet-test) originally developed by Hanson (1990) (Fig. 4). This modified device has been shown to produce similar results to the original submerged jet-test device (Simon et al., 2010). The 'mini' jet-test consists of a 12-cm diameter base ring that is driven into the bank face. Water is pumped directly into the device, filling the submergence tank and creating a 3.2-mm diameter jet that impinges on the alluvial sediments at a 90° angle. The pressure of the jet is measured with a pressure gauge, and changes in scour depth are measured at regular intervals during the test with a point gauge. As the depth of scour increases over time the applied shear stress decreases because of the increasing dissipation of energy (Stein and Nett, 1997). Erosion is initially high and asymptotically approaches zero as the shear stress generated by the jet approaches the critical shear stress of the bank material. Hanson and Cook (1997) developed analytical procedures for estimating τ_c and k from submerged jet-test results. The τ_c is determined by fitting a hyperbolic logarithmic equation developed by Blaisdell et al. (1981) to the scour results. The coefficient k is determined by fitting the scour measurements to the excess shear stress equation developed by Partheniades (1965). For this study, each bank face was cut back ~30 cm with a shovel before installing the jet-test. Tests were then conducted at varying elevations on the bank face depending on the litho- and soil-stratigraphy. We were unable to test all soil horizons at a given site because (i) the A horizons tended to be very friable and were susceptible to scour around the base of the jet-test device, and (ii) deep horizons, described from cores, were often covered with slumped bank toe material.

4.2. Laboratory methods

Soil and sediment samples were collected from select representative cores and from all jet-test locations for laboratory analysis. Soils were sampled by horizon using standard procedures (Soil Survey Staff, 1993). Samples were air-dried or oven-dried at 40 °C and ground to pass a 2-mm sieve. Prepared samples were then analyzed for particle size distribution by the pipette method (Soil Survey Staff, 1982).

5. Results

5.1. Soils and stratigraphy

5.1.1. Atchison County Lake watershed

Four cores were taken on the T-0 surface in the Atchison County Lake watershed. The surface soil at each coring site is mapped as the Kennebec series. Soil descriptions and grain size analysis data for Atchison County Lake are provided in Supplementary Tables 1 and 2. In cores A, B, and C, the surface soil is developed in the Honey Creek Member of the DeForest Formation (Fig. 5). The Honey Creek Member comprises the upper 1–2 + m of T-0 fill and consists of silty clay loam, silt loam, and loam. The color of unweathered sediment (C horizons) is dark gray (10YR 4/1, dry) and grayish brown (10YR 5/2, dry). Some yellowish red (5YR 5/8) mottles occur in the subsoil in core A.

Sediments of the Honey Creek Member have been moderately modified by pedogenesis and typically exhibit A–Bw horizonation. The matrix color of the soil comprising A and Bw horizons is typically dark grayish brown (10YR 4/2, dry) and brown (10YR 5/3, dry). The Bw horizons are ~30 cm thick and have weak to moderate, subangular blocky structure and friable consistence. Core A contains a weakly developed buried soil (soil 2) 95 cm below the surface. Grain size data for the Honey Creek Member in core A differs from core C, with core A containing less sand (4 to 27%) than core C (23 to 42%). The total sand fraction in both cores indicates a fining-upward sequence within the Honey Creek Member.

In cores B and C, the Honey Creek Member overlies the Roberts Creek Member (Fig. 5). Because of its higher organic matter content, the Roberts Creek Member is typically darker than the Honey Creek Member. Matrix colors of soils developed in the Roberts Creek Member range from dark gray (10YR 4/1, dry) to dark grayish brown (10YR 4/2, dry) and gray (10YR 5/1, dry). Buried soils developed in the Roberts Creek Member have A–C or A–AC–C horizonation and the A horizon typically is overthickened (>1 m thick). Grain size distributions of the Roberts Creek and Honey Creek Members are similar.

Although the surface soil at each coring site in the Atchison County Lake watershed is mapped as the Kennebec series, the soils and sediments at locality D differ from the other localities. The upper 45 cm of core D comprises overbank facies of the Camp Creek Member (Fig. 5). Minimal soil development in the Camp Creek Member distinguishes it from the Honey Creek Member. The surface soil (soil 1) developed in the Camp Creek Member has a weakly expressed Ap–A–C profile. Grain size data indicate higher silt content (75 to 85% silt) in the Camp Creek Member compared to other members of the DeForest Formation.

In core D, the Camp Creek Member mantles fine-grained facies of the Gunder Member that have been strongly modified by pedogenesis. The soil developed in the Gunder Member (soil 2) is over 3 m thick and has a well-expressed AB–Bt profile (Fig. 5). The matrix colors of the Btb horizon are grayish brown (10YR 5/2, dry) and gray (10YR 5/1, dry), and prominent yellowish red (5YR 5/8) mottles are common. Compared to the other members of the DeForest Formation, the Gunder Member has high clay content (33 to 44%). Evidence for clay illuviation is present in the form of many prominent black (10YR 2/1) clay films and clay flows on ped faces and in macropores, respectively.

5.1.2. Banner Creek Lake watershed

In the Banner Creek watershed, two cores (B and C-1) were taken on the T-0 surface and three cores (A, C-2, and D-1) were taken on the T-1 surface. In addition, one core (D-2) was taken on an alluvial fan that grades to the T-1 surface. Soil descriptions and grain size analysis data for Banner Creek Lake are provided in Supplementary Tables 3 and 4.

The surface soil on the T-0 surface is mapped as the Kennebec series. In cores B and C-1, this surface soil (soil 1) is developed in the Camp Creek Member (Fig. 5). Soils formed in the Camp Creek Member have weakly expressed Ap–A–AC–C profiles, weak granular and subangular blocky structure, and friable consistence. Soil profiles are between 75 and 115 cm thick and consist of very dark grayish brown (10YR 3/2,

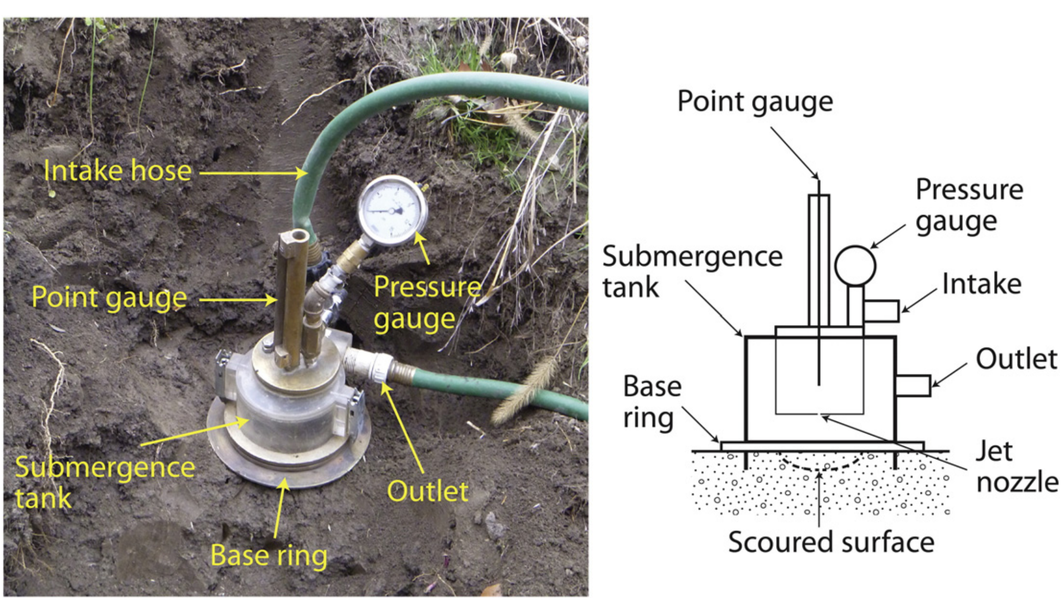

Fig. 4. Portable (mini) jet-test device used to test erodibility.

dry), dark grayish brown (10YR 4/2, dry), and brown (10YR 4/3, dry) silty loam and loam. Fine brown (10YR 5/3) and pale brown (10YR 6/3) silty laminae are common in C horizons.

In cores B and C-1, the Camp Creek Member mantles the Honey Creek Member and the Gunder Member, respectively (Fig. 5). Core B contains two buried soils (soils 2 and 3) developed in the Honey Creek Member. Soils 2 and 3 are moderately developed and are morphologically similar to soils developed in the Honey Creek Member at Atchison County Lake. Buried Bw horizons are ~30 cm thick and consist of dark grayish brown (10YR 4/2, dry) and dark gray (10YR 4/1, dry) silty loam with moderate, subangular blocky structure and friable consistence. Grain size is fairly uniform throughout the Honey Creek Member in core B, with clay contents ranging from 24 to 31% and silt contents ranging from 49 to 57%.

Surface soils on the T-1 surface are mapped as the Reading and Chase soil series. Cores A, C-2, and D-1 indicate that these surface soils are developed in the Gunder Member (Fig. 5). The Gunder Member also occurs in core C-1 but is buried beneath the Camp Creek Member (Fig. 5). Soils developed in the Gunder Member typically consist of well-expressed A–Bt–BCt profiles with thick Bt horizons (77 cm to over 3 m) that have moderate, prismatic, and blocky structure; firm to very firm moist consistence; and hard to very hard dry consistence. Clay illuviation is also evident in the form of dark grayish brown (10YR 4/2) continuous and discontinuous clay films on ped faces and black (10YR 2/1) clay flows in macropores. The Bt horizon typically is a brown (10YR 4/3 and 5/3, dry) or yellowish brown (10YR 5/4, dry) silt loam or silty clay loam. The matrix colors (10YR 4/1 and 10YR 4/2, dry) of the Bt horizon in core A are darker than the Bt horizons in the other cores. Also, prominent yellowish brown (10YR 5/6) mottles occur in the C horizon in core A. These features are indicative of somewhat poorly drained conditions and are consistent with the mapped soil series (Chase) at the core A location.

The clay content of the Bt horizon in cores A and C-2 is higher (31–39%) than the clay content of other members of the DeForest Formation and similar to soils developed in the Gunder Member at Atchison County Lake. However, grain size data for core C-1 indicate lower clay content (23–27%) and higher sand content (15–26%) in the Bt horizon compared to cores A and C-2. Clay content typically peaks in the uppermost Bt horizon.

Core D-2 was taken from an alluvial fan that grades to the T-1 terrace. The surface soil on the fan is mapped as the Chase series and is developed in the Corrington Member of the DeForest Formation. Soil development in the fan is similar to that described for the Gunder Member in other cores. The surface soil is over 1 m thick and has a well-expressed Bt horizon with dark grayish brown (10YR 4/2, dry) and grayish brown (10YR 5/2, dry) colors and moderate, prismatic structure. Prominent, continuous clay films are common on ped faces in the Bt horizon. Also, Core D-2 contains a well-developed buried soil at a depth of

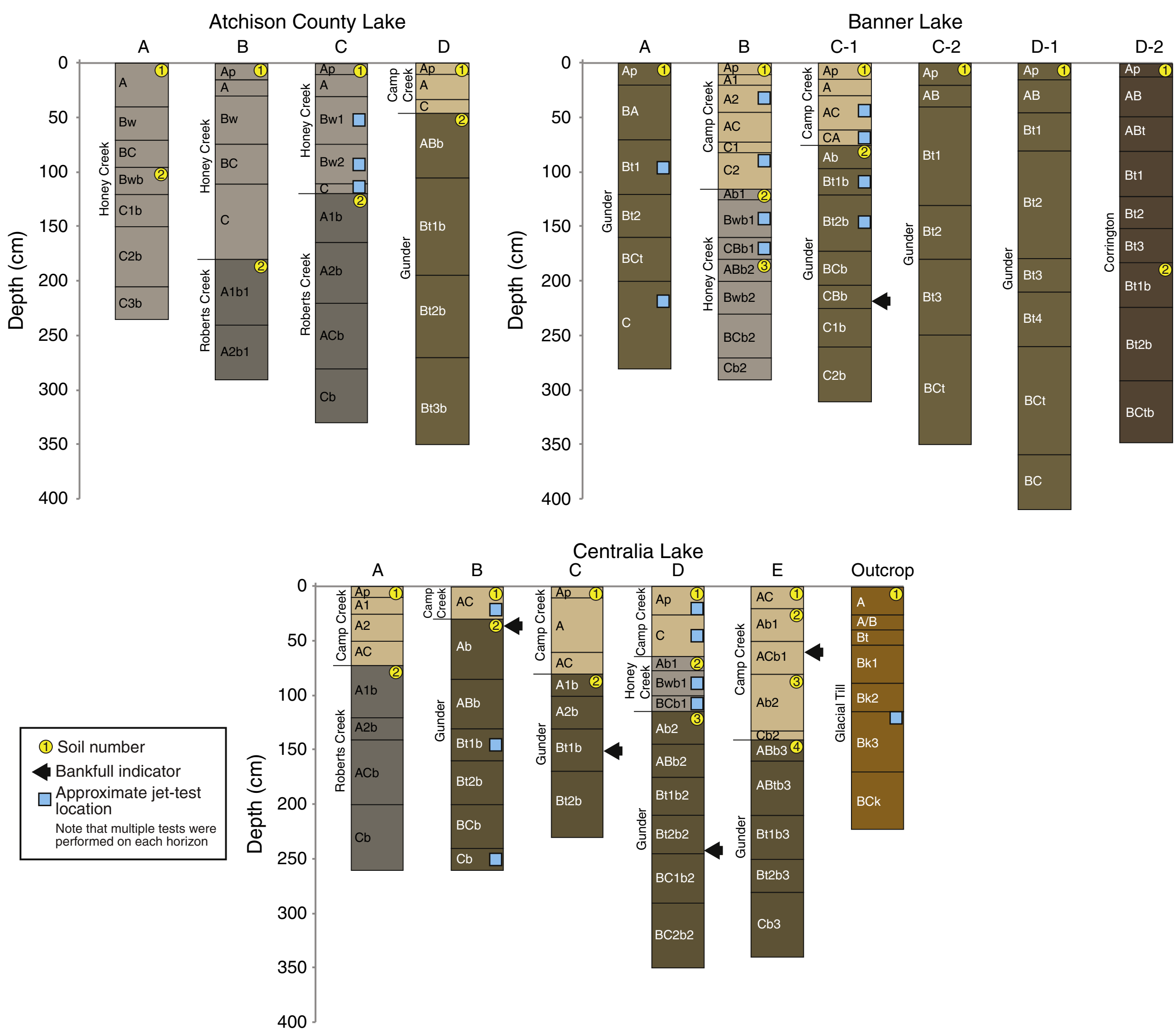

Fig. 5. Lithostratigraphy and soil stratigraphy compiled from cores and outcrops in the study area watersheds.

185 cm. The buried soil consists of yellowish brown (10YR 5/4, dry) sandy loam with a thick (>1 m) Bt horizon. The Btb horizon has moderate to strong prismatic structure and many prominent clay films on ped faces. Prominent yellowish red (5YR 5/6) mottles occur throughout the buried soil.

5.1.3. Centralia Lake watershed

Five cores were taken at in the Camp Creek Member (Fig. 5). Soil descriptions and grain size analysis data for Centralia Lake are provided in Supplementary Tables 5, 6 and 7.

The Camp Creek Member typically is 60–80 cm thick and has surface soils with Ap–A–AC horizonation (cores A, C, and D). However, in core B the soil is only 30 cm thick and is represented by an AC horizon. In core E, the Camp Creek Member is thicker (140 cm) and has multiple buried soils (soils 2 and 3). Overall, soils developed in the Camp Creek Member in the watershed above Centralia Lake have weakly expressed profiles, though some A horizons have moderate, blocky and prismatic structure. Such structure probably is a product of the fine-grained parent material instead of pedogenesis. As Birkeland (1999) noted, clay content is an important factor in the formation of blocky structure. In the watershed above Centralia Lake, the Camp Creek Member consists of silty clay loam compared to loam and silt loam in the other watersheds. Furthermore, grain size data for core A at Centralia Lake indicates that the clay content is relatively high (31–39%), promoting the formation of moderate, subangular and angular blocky structure in the A horizon of the surface soil at this location.

The Camp Creek Member mantles other members of the DeForest Formation in all cores (Fig. 5). In core A, Camp Creek alluvium overlies the Roberts Creek Member. The Roberts Creek Member is similar to that described at Atchison County Lake. A prominent dark gray (10YR 4/1, dry) cumulic soil (soil 2), with a 2-m-thick A horizon and an A–AC–C profile occurs (Fig. 5). This soil has a silt loam to silty clay loam texture and weak granular and subangular blocky structure.

In cores B, C, and E the Camp Creek Member overlies the Gunder Member (Fig. 5). The Gunder Member also occurs in core D, buried by Honey Creek and Camp Creek alluviums. Soils developed in the Gunder Member have strongly expressed A–Bt profiles with similar morphologies to those described in the other watersheds. The Bt horizons are 60 cm to 120 cm thick and have weak to moderate prismatic structure, firm and hard consistence, and typically are brown (10YR 4/2, dry) and grayish brown (10YR 5/2, dry) silty clay loams. The darker color of the Bt horizon in core D (dark gray and gray) was similar to core A at Banner Creek, which is mapped as the Chase series. Also, clay films in the Bt horizon were less prominent in core A compared to the other cores. Grain-size data for the Gunder Member is similar to the Gunder in the other watersheds, with clay peaks in the uppermost Bt horizon and relatively high clay contents (31–37%).

In core D, the Honey Creek Member is between the Camp Creek Member and the Gunder Member (Fig. 5). The soil developed in the Honey Creek Member at the core D locality is similar to soils developed in the Honey Creek Member in the other watersheds. In core D the surface soil has a moderately expressed A–Bw–BC profile. The Bw horizon is 23 cm thick and consists of dark grayish brown (10YR 4/2, dry) silt loam with moderate, subangular blocky structure.

In addition to the five cores, an outcrop of glacial till was described in the Centralia Lake watershed. The outcrop was located 100 m upstream of the core B site. The till is a clay loam with a well-expressed soil over 2 m thick. The surface soil, mapped as the Burchard series, has a well-expressed Bt horizon with yellowish brown (10YR 5/4, dry) color, moderate prismatic structure and common, discontinuous clay films on ped faces. The Bk horizon is 1.2 m thick and has yellowish brown (10YR 5/4 and 10YR 5/8, dry) colors, moderate prismatic and angular blocky structure, and common, fine soft carbonate masses. Grain size is relatively uniform throughout the profile, with clay contents ranging from 26 to 32% and silt contents ranging from 38 to 41%.

5.2. Erodibility

The results of 43 jet-tests are presented in Fig. 6. Values of τ_c range from 0.04 to 19.0 Pa, and k values range from 1.4 to 32.5 cm^3/Ns. As expected and noted in other studies (e.g., Hanson and Simon, 2001), we observe an inverse relationship between τ_c and k ($R^2 = 0.61$). Sites with the lowest τ_c values (high k values) can be expected to erode at the highest rates. We use a classification scheme similar to the one used by Thoman and Niezgoda (2008), based on Hanson and Simon (2001), to assess the relative erosion resistance of alluvium.

The relative resistance to erosion for the various members of the DeForest Formation is shown in Fig. 6B. The majority of bank materials tested in this study (80% of tests) were classed as erodible to moderately resistant. Distinct differences in the susceptibility to fluvial erosion exist between the different members. The most erodible member is the Camp Creek Member, which consists of predominantly very erodible to erodible bank material (average $\tau_c = 1.0$ Pa). The Honey Creek Member is mostly comprised of erodible to moderately resistant materials (average $\tau_c = 2.2$ Pa). The most resistant member of the DeForest Formation is the Gunder Member, which consists of moderately resistant to resistant material (average $\tau_c = 10.4$). Glacial till (average $\tau_c = 7.0$ Pa) displayed a similar erosive resistance and distribution of τ_c values to the Gunder Member. As the erodibility data are not normally distributed, median values (Table 2) may provide a better estimate of the central tendency of the data. In general, we did not observe a significant difference in the erodibility of the members of the DeForest Formation between different watersheds.

Grain size data from samples collected at jet-test locations indicates a statistically significant ($p = 0.002$) but weak positive correlation ($R^2 = 0.229$) between percent clay content and τ_c (Fig. 7). Overall, clay content and τ_c values for the Gunder Member were much higher compared to the Camp Creek and Honey Creek Members. No clear relationship was observed between grain size data and the erodibility coefficient, k.

6. Discussion

6.1. Soils and stratigraphy

Surface soils on the T-0 floodplain in all watersheds were mapped as the Kennebec series. The official Kennebec series consists of moderately well drained soils on floodplains (Soil Survey Staff, 2013). The typical pedon is described as a silt loam with an Ap–A–AC–C profile (Soil Survey Staff, 2013). Results of our study indicate that in Banner and Centralia Lake watersheds the T-0 surface soil is developed in Camp Creek Member. Atchison County soils are the exception where, in three of the four cores (A, B and C), the surface soils are developed in the Honey Creek Member. The official description of the Kennebec

Table 2
Critical shear stress (τ_c) data by stratigraphic member/unit.

Member/unit	No. of tests	Average τ_c	Median τ_c	Min τ_c	Max τ_c	Standard deviation
Camp Creek	12	1.0	0.8	0.1	3.1	0.9
Honey Creek	14	2.2	2.1	0.1	5.1	1.7
Gunder	13	10.4	9.3	1.9	19.0	5.9
Till	4	7.0	7.7	1.5	11.3	4.1

series allows for the presence of a Bw horizon, as found in soils developed in Honey Creek alluvium. However, this limits the usefulness of SSURGO data to identify the particular stratigraphic member on the basis of soil series.

Surface soils on T-1 are mapped as the Chase or Reading series. The official Chase series consists of somewhat poorly drained and moderately well drained soils formed in alluvium on floodplains (Soil Survey Staff, 2013). Results confirm the somewhat poorly drained nature of Chase soils in the study area (i.e., darker Bt horizon colors). However, in the Banner Creek Lake watershed, mapping indicates that the Chase series was formed in T-1 fill but not in floodplain alluvium. The Reading series consists of well drained or moderately well drained soils formed in alluvium on stream terraces (Soil Survey Staff, 2013). The typical pedon for the Chase and Reading series has an Ap–A–BA–Bt–BC–C and Ap–A–Bt–C profile, respectively. Results indicate that the Chase and Reading series accurately represent the Gunder Member of the DeForest Formation.

6.2. Erodibility

A wide range of variability in jet-test results (Fig. 6) has been observed in other studies (e.g., Hanson and Simon, 2001; Shugar et al., 2007; Thoman and Niezgoda, 2008) and typically has been attributed to varying degrees of subaerial streambank exposure operating on the bank face. Subaerial processes, such as frost heave and soil desiccation, are climate-controlled weathering phenomena that weaken the strength of bank material, making it more susceptible to erosion (Thorne, 1982; Couper, 2003). However, in our study each bank face was cleaned before jet testing in an attempt to remove bank material exposed to subaerial processes. Of greater importance is the recognition that each member of the DeForest Formation has a different weathering history, indicated by the different degrees of soil formation and the presence of buried soils (Fig. 5). Therefore, variability in the erodibility observed within each member (Fig. 6) can, in part, be attributed to different magnitudes of post-depositional soil-forming processes (e.g., horizonation). Table 3 shows critical shear stress values for different soil horizons within each member. Generally, the data suggest that pedogenic processes reduce the critical shear stress of fine-grained bank material. For example, A and Bt horizons in the Camp Creek and Gunder members, respectively, were found to be more erodible than C horizons. The A horizons in the Camp Creek generally have extremely friable granular structure and numerous biogenic features that tend to loosen the soil matrix. The C horizons, however, are commonly stratified (fine laminae) and have few biogenic features. The Bt horizons of the Gunder Member typically have prismatic structure that parts to subangular and angular blocky structure. The fracture planes along ped faces provide an avenue of weakness that may be exploited by flowing water compared to the more massive and cohesive C horizons tested in outcrops.

Variability in the erosive resistance within each member also can be explained by the inherent variability of the alluvial parent material. This intrinsic variability can be seen in the range of particle size distributions for unweathered (C horizon) DeForest Formation alluvium (Supplementary Tables 2, 4 and 6). Clark and Wynn (2007) noted that

Table 3
Critical shear stress (τ_c) data for soil horizons within members of the DeForest Formation.

Member	Number of tests	Soil horizon	Average τ_c	Min τ_c	Max τ_c	Standard deviation
Camp Creek	6	A	0.5	0.1	0.9	0.3
	6	C	1.4	0.1	3.1	1.0
Honey Creek	8	Bw	2.4	0.4	5.1	1.5
	6	C	2.2	0.1	4.9	2.1
Gunder	6	Bt	5.0	1.9	9.3	3.0
	6	C	15.0	9.3	19	3.1

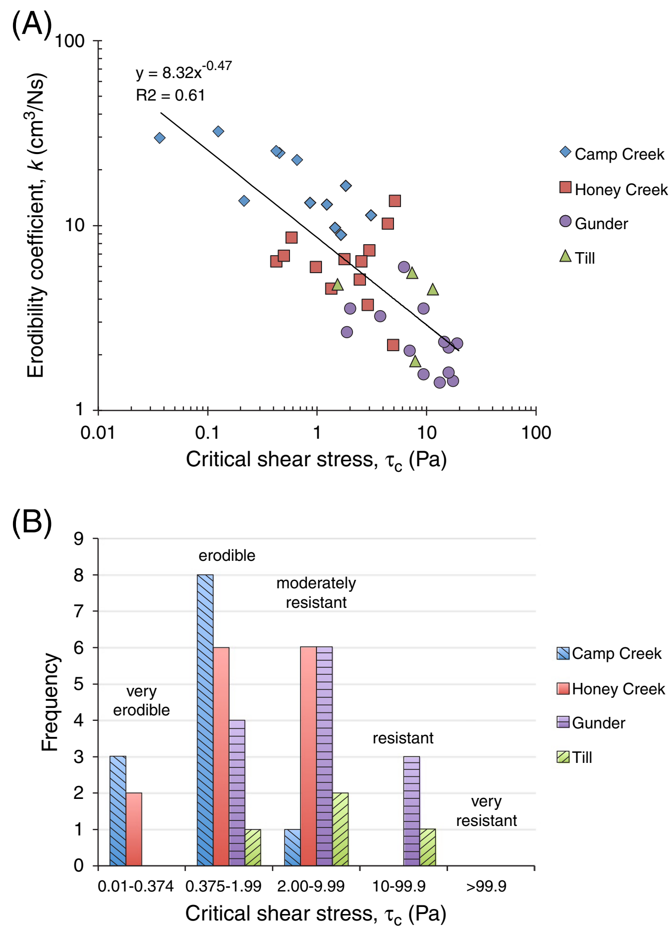

Fig. 6. (A) Relationship between critical shear stress (τ_c) and the erodibility coefficient (k) by stratigraphic member; (B) frequency distribution of critical shear stress values from jet-test results by stratigraphic member.

variability in jet-test erodibility results likely reflects the range of factors shown to influence erodibility. As already noted, these factors include soil moisture and structure, clay content and mineralogy, density, organic content, and water chemistry (Grissinger, 1982). Because these factors vary both within and between different soil horizons, the nature of stratification is an important consideration for assessing streambank erodibility. Overall, we conclude that the wide variation in τ_c and k observed in this study reflects the strong lithologic and pedologic contrast between the various members of the DeForest Formation.

Erodibility results show a statistically significant but weak positive correlation between percent clay and τ_c (Fig. 7). Previous studies have shown statistically significant correlations between particle size and τ_c (e.g., Julian and Torres, 2006; Clark and Wynn, 2007). The correlation between percent clay and τ_c in this study can be partly attributed to the strong contrast in texture between the different members of the DeForest Formation. Grain size results indicate that resistance to erosion by fluid flow (i.e., higher τ_c values) is significantly greater where clay contents exceed around 28%, likely from increased cohesive forces. Among the different members tested, only the Gunder Member has clay contents exceeding 28%.

A recent report and supplemental data provided by Watershed Institute, Inc. (Emmert, 2013) provided cross-sectional profiles of streambanks and bankfull indicators for five localities investigated in this study (see Fig. 5). The effectiveness of a flow event (i.e., the ability to transport sediment) is measured by both magnitude and frequency (Wolman and Miller, 1960). Bankfull discharges are those for which channel maintenance is most effective and typically have a 1.5-year recurrence interval (Dunne and Leopold, 1978). In the study area, Foster et al. (2012) found that streamflow resulting from strong storms in May and June transported 97% and 71% of the annual sediment load for 2011 in the Banner Lake and Centralia Lake watersheds, respectively. The discharges associated with these storms may represent bankfull events in these watersheds. Although jet-test results indicate that the Camp Creek Member was the most erodible member of the DeForest Formation, it always occurs, stratigraphically, as the uppermost member. The limited bankfull stage data indicate that bankfull discharges rarely attain elevations sufficient to erode Camp Creek Member deposits at these locations (Fig. 5). Therefore, other members of the DeForest Formation, particularly the more resistant Gunder Member, are able to exert some control on the rate of bank erosion.

We should note that the entrainment of sediment by fluid flow is not the only mechanism of streambank erosion. In particular, streambank failures from mass-wasting processes (i.e., gravitational forces) can contribute significant amounts of sediment to stream channels (see Thorne, 1982; Simon et al., 2000). The erosion of sediments by fluvial processes, particularly at the bank toe, typically increases the height and angle of the bank to the point where gravitational forces exceed the shear strength of the bank material, promoting streambank failure (Osman and Thorne, 1988). Furthermore, Couper (2003) notes that mass wasting and fluvial processes may operate on different zones of the streambank resulting in a 'vertical zoning' of erosive mechanisms. As distinct differences in erodibility were observed between the different members of the DeForest Formation, the susceptibility to mass wasting processes also is likely to vary among stratigraphic members. Therefore, determining the vertical stratigraphy in streambanks may be important, not only for assessing differences in erodibility but also for accurately assessing sediment contributions from streambank failures.

Other causes of streambank failure include positive pore water pressure after rapid drawdown (Simon et al., 2000), groundwater seepage (Fox et al., 2007), and the formation of tension cracks (Thorne, 1982). Also, mass wasting processes are driven by the degree of channel adjustment. For example, Simon and Rinaldi (2000) identified mass wasting processes as the dominant adjustment process in unstable stream channels in the Midwest. These channels are undergoing systemwide adjustment as a result of human modifications, including channel dredging and straightening. Therefore, considering human alterations to stream channels and drainage basins is crucial when determining areas prone to streambank erosion.

The results of recent investigations in our study area underscore the significance of channelization and land modification. According to Foster et al. (2012) and Emmert (2013), sediment yields are higher in the Centralia Lake watershed compared to the Atchison and Banner Creek watersheds. Annual sediment yields from in-channel sources were estimated at 2065 tons/mi^2 for Centralia, but only 943 tons/mi^2 for Atchison (Emmert, 2013). Measurements of sediment yields from USGS monitoring sites between March 2009 and September 2011 indicate that total sediment yields at Centralia were about 2.7 times that of Atchison and Banner (Foster et al., 2012). Human modifications are a significant factor in the Centralia watershed. For example, Foster et al. (2012) highlighted the degree of channel straightening, a reduction in riparian buffers, and a high frequency of tile drainage and upstream subimpoundments. In terms of channel straightening, the average sinuosity in the Centralia watershed is 1.05 compared to 2.02 and 1.71 in Atchison and Banner, respectively (Emmert, 2013). Centralia streams have also been shown to be more entrenched and have greater stream power because of channelization (Emmert, 2013), which increases the likelihood of streambank failures and consequently the amount of sediment contributed to the channel. The average width-to-depth ratio for Centralia streams is 6.0 compared to 16.4 and 9.0 in Atchison County and Banner, respectively (Emmert, 2013). Numerous bank failures were observed in the Centralia watershed (Fig. 8) suggesting that mass wasting may be the dominant adjustment process to human modification in this watershed, as documented more generally by Simon and Rinaldi (2000) for Midwestern streams.

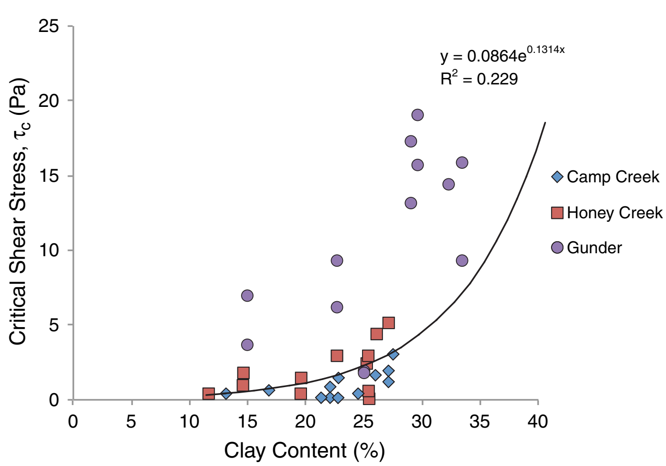

Fig. 7. Relationship between clay content and critical shear stress (τ_c) by stratigraphic member.

7. Conclusions

The primary objectives of this study were to examine the stratigraphic relationships and measure the erodibility of the different members of the DeForest Formation in three watersheds in northeastern Kansas. Distinct differences in erodibility were observed between the different members of the DeForest Formation, which has important implications for streambank erosion by hydraulic flow. The most erodible member is the Camp Creek Member, which largely consists of very erodible to erodible bank material. The Honey Creek Member is mostly comprised of erodible to moderately resistant materials. The most resistant member of the DeForest Formation is the Gunder Member, which consists of moderately resistant to resistant material. Glacial till displayed a similar erosive resistance and distribution of τ_c values to the Gunder Member.

Based on grain size analysis, variability within members of the DeForest Formation occurs. This variability is attributed to the magnitude of weathering from pedogenic processes as well as the inherent variability in the parent materials, which highlights the importance of assessing litho- and soil-stratigraphic relationships in streambanks. Resistance to erosion by fluid flow (i.e., higher τ_c values) was found to be significantly greater where clay contents exceeded ~28%.

Although jet-test results indicate that the Camp Creek Member was the most erodible member of the DeForest Formation, it always occurs, stratigraphically, as the uppermost member. Limited bankfull stage data suggest that bankfull discharges rarely attain elevations sufficient to erode Camp Creek Member deposits. Therefore, other members of the DeForest Formation, particularly the more resistant Gunder Member, are able to exert some control on the rate of bank erosion. However, consideration of other mechanisms of bank erosion is important when assessing sediment contributions from streambanks. Our study has shown that the erodibility of the different members of the DeForest Formation varies, and it is therefore likely that the susceptibility to mass wasting processes also varies between the different members. Investigating the relationship between the erodibility of streambanks and the geotechnical strength of the bank material, in the context of stratigraphic relationships, should be a focus of future study in order to better quantify sediment contributions from streambanks. Furthermore, given the higher sediment yields documented in the Centralia watershed, an assessment of the degree of human modification to stream channels is crucial. Overall, determining the presence of and the vertical relationships between the different members of the DeForest Formation is important for accurately determining likely areas of streambank erosion in Midwestern streams. Furthermore, the findings of this study likely

Fig. 8. Active bank slumping in the Centralia Lake watershed.
Photo courtesy of Brock Emmert.

warrant investigation of the erodibility of other alluvial lithounits, not only in the United States but also in other alluvial settings worldwide.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.geomorph.2014.01.003.

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