Water Resources Research

RESEARCH ARTICLE
10.1029/2018WR023793

Special Section:
Dynamics in Intensively Managed Landscapes: Water, Sediment, Nutrient, Carbon, and Ecohydrology

Key Points:
- A conceptual sketch is used to depict distinct knickpoint migration mechanisms in a channelized semicohesive stream
- Knickpoint migration in semicohesive streams is governed by coplay of flow and stratigraphic controls that can change in space and time
- Heterogeneity in substrate properties can lead to preferential erosion of material, controlling the mechanisms that drive the migration

Supporting Information:
- Supporting Information S1
- Table S1
- Table S2

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Citation:
Papanicolaou, A. N. (. T.)., Thomas, J. T., Wilson, C. G., Abban, B. K. B., Bettis, E. A., III, & Elhakeem, M. (2019). The migration diary of a knickpoint in a channelized stream with a cohesive bed. *Water Resources Research*, *55*, 3433–3451. https://doi.org/10.1029/2018WR023793

Received 29 JUL 2018
Accepted 29 MAR 2019
Accepted article online 9 APR 2019
Published online 29 APR 2019

The Migration Diary of a Knickpoint in a Channelized Stream With a Cohesive Bed

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Abstract This paper examines the coevolutionary roles of variable flow features and heterogeneous substrates on knickpoint migration. A conceptual model is used to depict distinct migration mechanisms in a channelized headwater system of a representative intensively managed watershed in the Deep Loess Region of the U.S. Midwest. Throughout this region, entrenched streams have eroded into alluvial-based strata that are horizontally consistent but vertically heterogeneous. Variable flow in these streams switches between vented conditions, where water shoots from the knickpoint face as an aerated plunging jet, and unvented conditions, where water clings close to its face through suction. These switches affect hydrodynamic mechanisms controlling migration but cannot explain fully observed alternating slow-fast migration rates. It is hypothesized that vertically heterogeneous strata in entrenched streams, specifically strong-over-weak layers, facilitate observed changes in knickpoint migration rates. Preferential erosion of weaker sublayers is thought to trigger other erosional mechanisms to accelerate migration even at low flows. Herein, a migration "diary" documents a representative knickpoint's displacement over time with flow measurements and site stratigraphy. Slower migration occurred from 2006 to 2009 through fluvial erosion of a resistant silt loam cap. From 2009 to 2012, migration accelerated as the knickpoint face reached a critical height through scour. A flow back roller formed, which preferentially eroded a weaker sand sublayer. Undercutting/cantilever failure cycles persisted, causing 30 m of retreat within 2 months (i.e., 62.5% of the total migration over 78 months). Comparisons with established fluvial hydraulics-based and undercutting/cantilever-based migration models confirm the hypothesis and importance of both stratified substrates and hydrodynamic controls on knickpoint migration.

1. Introduction

Channelization of streams and land use change during the early twentieth century of the Deep Loess Region in the U.S. Midwest has turned flowing marshes and shallow meandering streams into straight, incised ditches with oversteepened banks. Often, the channels incise through the upstream migration of a knickpoint (Papanicolaou et al., 2008, 2012).

A knickpoint in channelized streams with cohesive beds is defined as a discontinuity along the longitudinal stream bed profile due to incision and base level lowering (Phillips et al., 2010; Wohl & Ikeda, 1997). Translating the effects of lowering base level, knickpoints migrate upstream at different rates (e.g., Bennett et al., 2000). In addition, as the channel deepens due to the bed incision, the banks destabilize and collapse, when they reach a critical height, resulting in the widening of the downstream channel (Millar & Quick, 1998; Schumm et al., 1984; Simon & Rinaldi, 2000). As a result, deep incised channelized streams are characterized by a pattern of constrictions and expansions.

Changes in the stream aspect ratio (i.e., width/depth) from the developing expansions and contractions are suggested to affect local (i.e., stream reach) hydrodynamic and fluvial erosion mechanisms governing knickpoint migration by regulating the drop in the bed elevation, and consequently the knickpoint face height (Bressan et al., 2014). The mechanisms adjust with flow conditions (Pasternack et al., 2007). At knickpoints with high face drops and relatively low to medium approach flow depths (i.e., with a face height to approach flow depth ratio greater than 8), a plunging jet prevails in which back roller effects drive the upstream knickpoint migration (May, 1989). In this case, the jet is fully aerated, or vented, and follows an arch profile. At

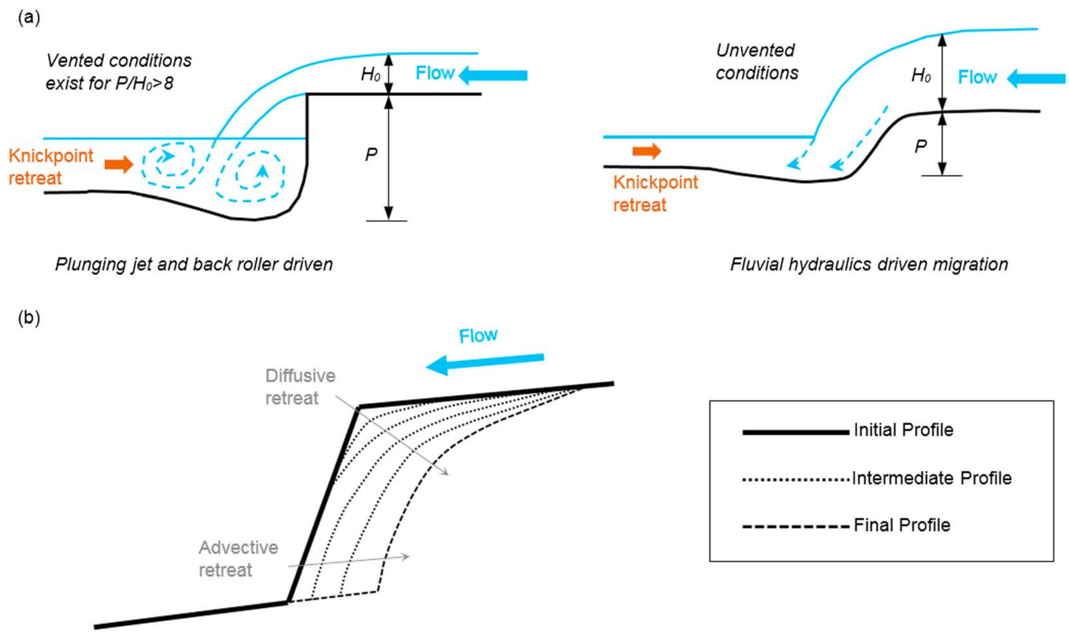

Figure 1. Conceptual sketch of a flow types and b modes of knickpoint retreat.

low face drops with relatively high approach flow depths (i.e., with a face height to approach flow depth ratio generally less than 8), the water clings close to the knickpoint face through suction below the nappe, creating an unvented condition and leading to increased shear action along the face that drives the migration (May, 1989; see Figure 1a).

Current knowledge about knickpoints in channelized, headwater streams is limited to back roller effects. A handful of conceptual, mechanistic models (e.g., Alonso et al., 2002; Bennett & Alonso, 2005; Flores-Cervantes et al., 2006) have been developed to capture the relationship between back roller effects and geomorphic controls in knickpoints under vented conditions. Even fewer studies (e.g., Begin et al., 1981; Gardner, 1983) have explored unvented flows.

Bressan et al. (2014) built on these concepts and provided a semitheoretical fluvial hydraulics modeling framework applicable to knickpoint migration in channelized, semicohesive streams, which was tested for a relatively short period (2007–2009) in Mud Creek, IA, in the Deep Loess Region. In these streams, flow is highly variable and unvented flow conditions can be ubiquitous. The knickpoint migration undergoes an “advective/diffusive retreat” pattern as illustrated in Figure 1b. “Advective retreat” refers to the upstream migration of the face and tends to be larger for higher knickpoint face drop heights because the morphology favors increased shear action and erosion along the entire face. “Diffusive retreat,” or “flattening”, leads primarily to a change in the inclination and shape of the knickpoint face and tends to be larger with higher approach flow depths because of increased shear stress at the knickpoint crest (Holland & Pickup, 1976).

Despite the mechanistic advancements in the Bressan et al. (2014) study in terms of simulating fluvial hydraulics driven “advective-diffusive retreat” using the Burger equation, use of their model for simulating additional years of retreat data (2009–2012) in Mud Creek revealed that it underpredicts the observed knickpoint migration rates for this period. The disparity between the Bressan et al. (2014) model and the field observations suggested that other factors may also be contributing to higher knickpoint migration rates, which were not accounted for in the Bressan et al. (2014) modeling study. Recent work by Baynes et al. (2018) suggests that substrate properties could exert an important dominant control on knickpoint migration, while other studies in bedrock and unconsolidated sediment literature have proposed alternative mechanisms for migration, for example, drag-related toppling of fractured rock failure (Lamb & Dietrich, 2009), undercutting and cantilever failure in the presence of strong-over-weak layers (Haviv et al., 2010), and successive development of scour holes controlled by vertical drilling of the plunge pool (Scheingross et al., 2017). Further consideration of our problem led to the realization that the heterogeneous stratigraphic setting of the Deep Loess Region, an unlithified environment, could also play a role on the enhanced knickpoint migration rate along with the prevalent flow features. Throughout the Deep Loess Region, modern entrenched streams have eroded deep into a horizontally consistent stratigraphy of vertically heterogeneous, loess-derived, alluvial deposits (Bettis, 1990).

The present hypothesis is that the presence of vertical heterogeneity in the horizontally consistent stratigraphy, specifically exposure of a weaker layer to the flow action, may be a contributing factor to the observed increase in knickpoint migration rate in addition to the hydrodynamic controls under vented or unvented conditions. Thus, vertical heterogeneity in the stratigraphy must be considered together with the flow features to explain the accelerated knickpoint migration. We postulate that distinct mechanisms present at different points in time controlled the migration rates for the given strata. Fluvial hydraulics is believed to have been dominant when the knickpoint resided in a homogeneous substrate, but in the presence of a stratified substrate with strong-over-weak layers, preferential erosion of the weaker layer is thought to have promoted other dominant mechanisms that accelerated the migration rate.

Very few studies in unlithified environments have examined the importance of vertical heterogeneity in the stratigraphy of loess-derived, alluvial deposits (e.g., Holland & Pickup, 1976; Stein & LaTray, 2002) and how its coplay with hydrodynamic controls affects knickpoint retreat. Unlike bedrock systems, we postulate that knickpoint migration rates in unlithified environments with heterogeneous sublayers can be both slow and fast, due to the presence or absence of strong layers. Adding to the above complexity is that for channelized headwater systems, flow is quite variable, as discussed earlier, thereby affecting the switch between vented and unvented conditions and the associated hydrodynamic and erosion mechanisms. This may further affect the rate of migration when interfaced with vertical substrate heterogeneity.

The unique features of knickpoint retreat, of both slow and fast migration, in channelized streams of the Deep Loess present a unique opportunity to understand how the coplay of flow variation and heterogeneity in the stratigraphic setting develops distinct erosion mechanisms, which in turn control the migration rates for a given strata. Understanding knickpoint migration over time, that is, the diary of a knickpoint in unlithified environments offers some other benefits as well. We suggest that the role of stratified substrate properties on knickpoint migration in cohesive bed streams can be used as an analog for understanding the role of lithological controls in bedrock systems. Therefore, understanding the role of stratified substrate properties through direct, field-based monitoring of migration at seasonal scales could be used to draw some parallels between bedrock and unlithified environments.

The goal of this paper is to examine the coevolutionary roles of variable flow features and heterogeneous substrate properties on knickpoint migration in a stratified semicohesive system and to provide a conceptual model that depicts the distinct mechanisms of migration. To develop a diary for migration, the study combines soil core profile analysis with hydraulic and fluvial erosion information in a representative, intensively managed watershed of the Deep Loess Region of Iowa, namely, the Mud Creek watershed (Papanicolaou et al., 2008). The study revisits data from Papanicolaou et al. (2008, 2012) collected from May 2006 to November 2012 (i.e., a 78-month period), which have not been analyzed before, in order to characterize the substrate strength at the site and extend consideration of the knickpoint migration within the context of both flow mechanisms and vertical heterogeneity in substrate properties. A diary of the knickpoint migration is provided from channel surveys, photographs, and laser distance sensor measurements. The site stratigraphy is established using field/laboratory characterization of borehole cores, while surface hydraulic conditions are determined using stage/flow measurements. Alternative retreat mechanisms are considered to explain observed migration rates using the fluvial hydraulics model and a model for migration in the presence of strong-over-weak substrates.

2. Site Description and Geological Background

Mud Creek (Figure 2) flows south through a 97.5-km^2 intensively managed, agricultural watershed to the West Nishnabotna River. The monitored knickpoint was located at N41°05′51″, W95°31′00″ at the start of the study, approximately 4.44 km above the confluence with the West Nishnabotna River (Figure 2) and about 109 m downstream of a county road bridge, which is protected by a sheet pile weir. Mud Creek was channelized significantly in the late 1940 to early 1950s and is now approximately 18-m wide and deeply incised with 5-m high banks.

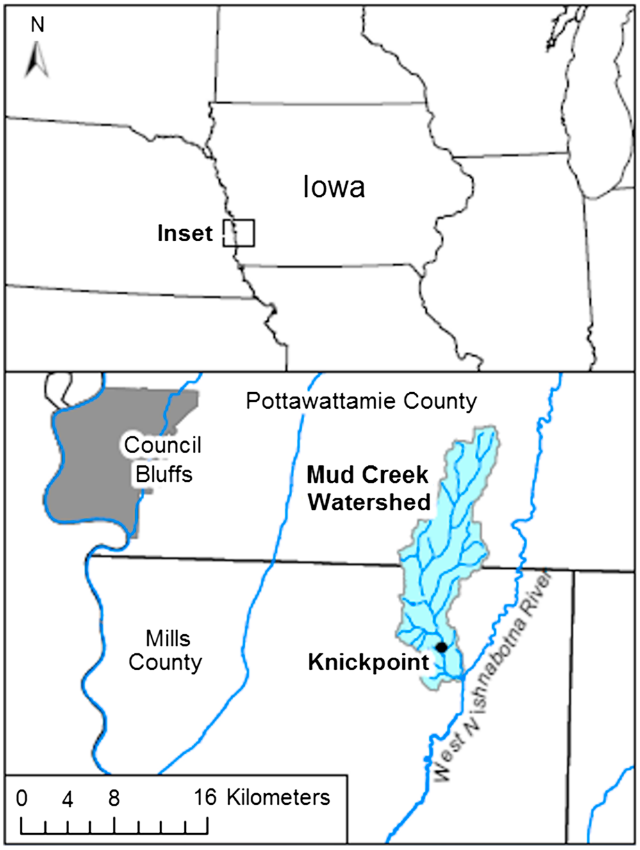

Figure 2. Map showing the Mud Creek watershed in the Deep Loess Region of western Iowa.

The geological setting at Mud Creek is representative of Western Iowa. Thick layers of Peoria loess were deposited during the last glacial period covering most of Iowa (Bettis et al., 2003). Some of this loess was eroded during the Holocene and redeposited in the valley bottoms. This loess-derived alluvium, called the DeForest Formation, consists of three principal units (Figure 3a; Bettis, 1990). The Camp Creek Member is a thin layer of postsettlement alluvium. It overlies dark gray, moderately well-drained, stratified silt- and clay loam soils of the Roberts Creek Member. The Roberts Creek Member is separated from the underlying Gunder Member by a fluvial erosion surface (see the dashed line in Figure 3b). Gunder deposits range from a reduced, greenish gray, stratified, calcareous silt loam-loam-sand soil containing secondary iron oxide accumulations to a yellowish brown, massive, calcareous to noncalcareous, oxidized silt loam soil. The upper Gunder soil contains an abundance of krotovina (Figure 3c), or animal burrows filled with a mixture of organic matter and sandier, less dense mineral fill. The krotovina are more vulnerable to scour than the surrounding bed soils and preferentially erode to form potholes on the channel bed. The Gunder Member sits atop an older coarse-grained alluvium, underlain by glacial till, and then bedrock at depth. Throughout the Deep Loess Region, streams have eroded deep channels into the DeForest Formation deposits (Bettis, 1990).

3. Methods

To test the proposed hypothesis, the channel bed/bank composition was characterized using field/laboratory techniques, knickpoint migration was monitored with relative surveys and laser distance sensors, and measurements of stage/flow discharge were made via the use of pressure transducers (Figure 4a). Observed knickpoint migration was then compared with two sets of numerical simulations to decipher between fluvial hydraulics-driven and cantilever failure-driven contributions to knickpoint retreat dynamics. The details of the approach are provided below.

3.1. Properties of the Eroded Material

Two deep borehole cores (>10-m deep) were collected from the top of each stream bank in Shelby tubes using a truck-mounted drill (Figure 4b). Four shallow cores (<2.5-m deep) were also taken from the channel bed using a hand probe (Figure 4c). The soil in the deep borehole cores and the four shallow cores were characterized for geotechnical and pedological properties following methods by the U.S. Natural Resources Conservation Service (Table 1).

Bulk density was determined using nonintrusive gamma attenuation (Papanicolaou & Maxwell, 2006; Sutarto et al., 2014; see Figure S1 in the supporting information). The gamma radiation scanning system consisted of a 550-mCi Americium-241 source and a Harshaw 6S2/2-X Thallium-doped Sodium Iodide detector with an integrated photomultiplier. Collimation was provided using a 9.5-mm thick, lead plate with a 6.35-mm circular hole for the source beam and a 0.889-mm × 36.8-mm slit for the detector.

A QuickBASIC program controlled the stepper motor and gamma counter. Scans were performed every 15 mm along the length of the core. The system was calibrated in advance using soil from the site with known bulk density. The recorded gamma count rates were regressed to develop an equation that related bulk density to attenuation (e.g., Papanicolaou & Maxwell, 2006).

The mechanical strength and internal friction angles of the soil were determined using a direct shear device, based on ASTM D3080-98. Subsamples from the Shelby tube were fit into the shear box (diameter = 63.4 mm; height = 25 mm). Each sample was consolidated by gradually increasing the normal stress using ASTM D2435-96 for the following loads: 7, 12, 25, 50, 100, and 200 kPa. Each load was

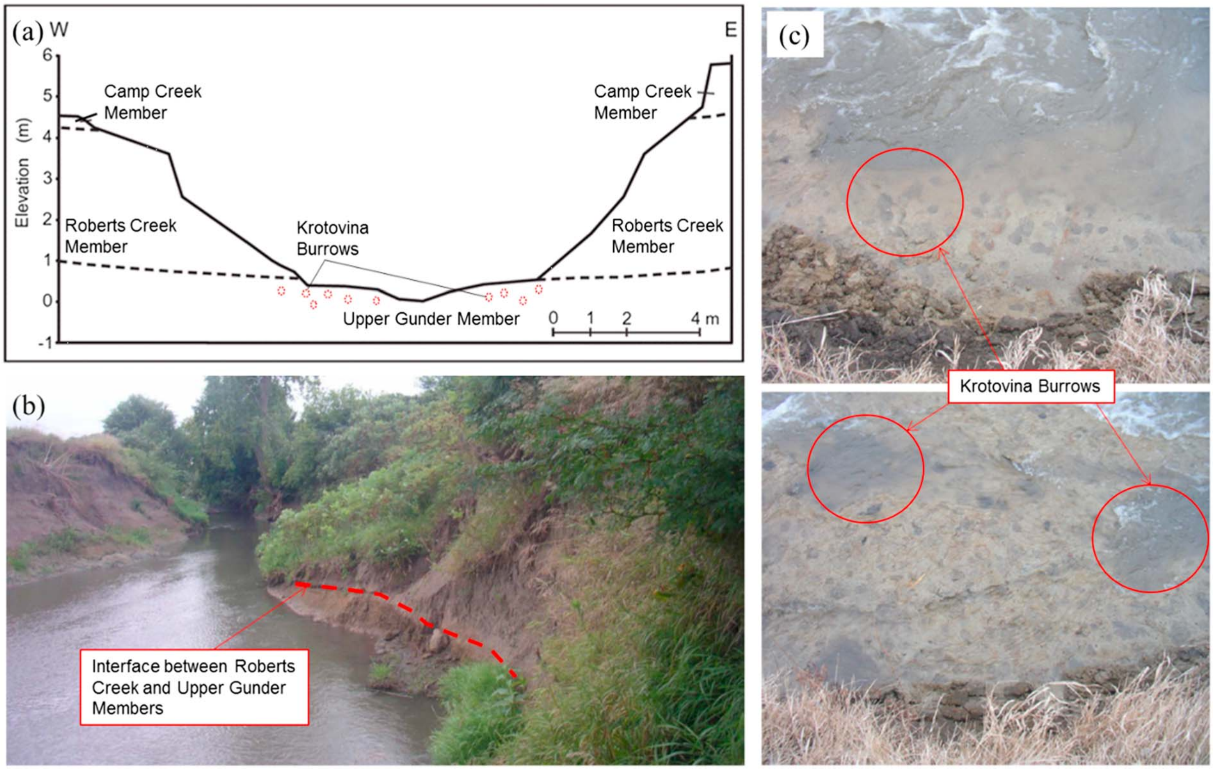

Figure 3. (a) Stratigraphy of the knickpoint cross section in Mud Creek showing the different members of the DeForest Formation. (b) Dashed line represents the fluvial erosion contact between the Roberts Creek and underlying Gunder Member. (c) Examples of krotovina burrows.

applied to the sample until 90% consolidation was attained. After consolidation, the horizontal and vertical deformations, as well as the corresponding applied shear stresses, were recorded simultaneously. This procedure was repeated for a range of at least three normal stresses per sample. The slope of the best fit line through these data points provided the internal friction angle, and the *y* intercept provided the mechanical strength.

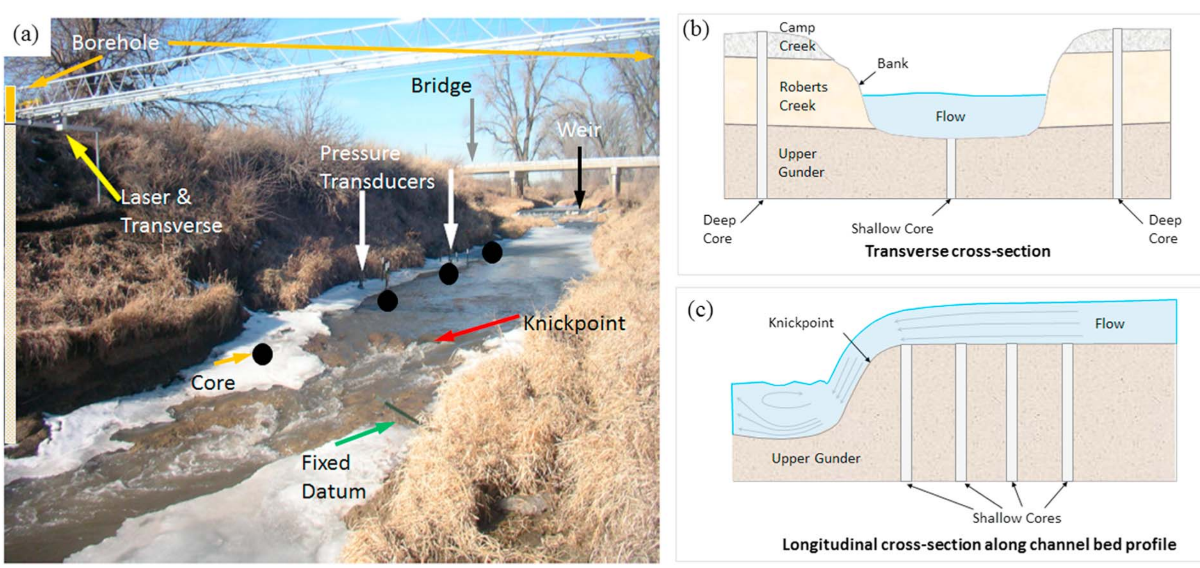

Figure 4. (a) The Mud Creek study reach where the arrows highlight key monitoring instruments and infrastructure. (b) Idealized schematic of transverse cross section of the study reach showing the deep boreholes. (c) Idealized schematic of longitudinal cross section of the study reach showing the shallow cores.

Table 1
Pedological Properties of the Gunder Member Surface Strata From the Borehole Samples

Strata	Bulk density (kg/m^3)	Mechanical strength (Pa)	Clay (%)	Silt (%)	Sand (%)
Silt loam cap	1,353 ± 165	751 ± 434	19 ± 1	48 ± 3	32 ± 2
Loam	1,315 ± 132	607 ± 351	15 ± 5	32 ± 13	53 ± 17
Sand	970 ± 134	125 ± 87	7 ± 4	16 ± 5	78 ± 9
Sandy loam	1,314 ± 201	804 ± 882	11 ± 3	31 ± 7	58 ± 9

3.2. Stage and Flow Measurements

Stage was measured hourly using two submersible pressure transducers (Figure 4a). The pressure transducers were installed upstream of the knickpoint, approximately 10 m apart. They were mounted 10 cm above the stream bed in stilling wells that were located approximately 60 cm from the channel bank. Fence posts were placed 1 m upstream of each stilling well to capture and shed floating debris. The data were recorded on self-contained loggers mounted atop the bank that were connected to the transducers through vented cables, allowing for equilibration with atmospheric pressure.

A rating curve was developed for the site using stage and velocity measurements. An acoustic Doppler velocimeter (FlowTracker) was used during low flows to obtain point velocity measurements, which were integrated across the channel transect to provide discharges (Kennedy, 1984). At higher flows, large-scale particle image velocimetry was used to measure free surface velocity vectors over an area by estimating the displacement of floating markers captured using commercially available video equipment (Muste et al., 2011).

3.3. Knickpoint Migration Surveys

Eight topographical surveys of the study reach were performed using a total station to provide snapshots of the knickpoint's migration. Surveys were conducted in May 2006, June 2007, September 2007, April 2008, July 2008, November 2008, March 2009, and October 2010. All surveys were referenced to the upstream county road bridge.

Additional measurements of the knickpoint ledge and surface were conducted using photographs of the knickpoint face relative to a fixed datum and a laser distance sensor (Figure 4a). The photographs were taken in December 2009, February 2010, April 2010, August 2010, September 2011, and November 2012. The laser distance sensor was used in the summer of 2008 to collect semi-automated measurements of the distance from a fixed datum to the water surface. The sensor was mounted along a traverse positioned above the knickpoint (Figure 4a). The traverse was 4-m long and spanned 12 m across the channel width. Measurements using the laser sensor were discontinued when bank instability caused by knickpoint migration threatened the traverse supports.

3.4. Estimates of Knickpoint Migration

Estimation of knickpoint migration was done using two knickpoint migration models: the Bressan et al. (2014) for fluvial hydraulics and the Stein and LaTray (2002) model for migration in the presence of stratification with strong-over-weak layers. Both models are described briefly below. The applicability of each of the models to the prevalent flow features was examined using a time series of the ratio of the knickpoint face height, P, to the upstream approach flow depth, H_0, and the criteria established by May (1989) for vented and unvented flows (i.e., vented flows exist when $P/H_0 > 8$).

3.4.1. Fluvial Hydraulics Model

A key feature of the Bressan et al. (2014) model is the inclusion of shear-induced fluvial erosion as the key mechanism driving migration under unvented conditions. The model can handle dual advective-diffusive modes of knickpoint retreat (as described in Figure 1b). The fluvial bed shear stress is treated similar to flow on the leeside of a submerged obstacle to derive the governing equation, which is a generalized Burgers' equation, as follows:

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$$\left\{\frac{\partial z}{\partial t} - C\frac{\partial z}{\partial x} - D\frac{\partial^2 z}{\partial x^2} = 0\right. \tag{1a}$$

$$\left\{C = \left(\frac{Pk_d\gamma_w}{1-\lambda_s}\right)\ S_0MA\right. \tag{1b}$$

$$\left\{D = \left(\frac{Pk_d\gamma_w}{1-\lambda_s}\right)S_0H_0MB\right. \tag{1c}$$

where z (m) is the bed elevation measured along the thalweg; C (m/s) and D (m^2/s) denote *advection* and *diffusion* coefficients, respectively; t (s) and x (m) are time and space coordinates, respectively; P (m) is the knickpoint face height; k_d (m^2s/kg) is the soil erodibility; λ_s $(\cdot)$ is the soil porosity; γ_w (kg/m^2 s^2) is the specific weight of water; S_0 $(\cdot)$ is the bed slope; H_0 (m) is the approach flow depth upstream of the knickpoint; and M,A,B are user-specified parameters that correspond to localized phenomena at the knickpoint reach. Equations (1a)–(1c) is solved numerically with the second-order accurate implicit Briley-McDonald scheme.

The advection (C) and diffusion (D) coefficients in equations (1a)–(1c) represent unique hydraulic and sedimentological properties. Bressan et al. (2014) demonstrated the applicability of the model to Mud Creek and used a modified Peclet number to analyze the advective-diffusive nature of the knickpoint migration within the system.

The coefficient M represents the increase in shear stress due to accelerating flow approaching the knickpoint (i.e., M2 curve) and can be approximated by the square of the ratio of the upstream flow depth, H_0, to the upstream critical flow depth, H_c, that is, $M = (H_0/H_c)^2$. The coefficients A and B signify the role of expansion-constriction in the channel cross section and change in the slope of the knickpoint face due to diffusion, respectively. Bressan et al. (2014) provided physical ranges of the shear stress variation across the face of the knickpoint and provided the following ranges of A and B for Mud Creek: $A = [0 - 1.3]$ and $B = [0 - 1]$ where the upper limit for A implies dominance of the advective mode of migration and the upper limit for B implies dominance of the diffusive mode of migration.

Following Bressan et al. (2014), the soil erodibility, k_d, is estimated in this study using the Hanson and Simon (2001) formula, which is applicable to semicohesive materials and relates the erodibility with the critical erosional strength. Contrary to the mechanical strength, which is a macroscale property, the erosional strength is a microscale property that correlates well with the erodibility (Sutarto et al., 2014). Herein, the critical erosional strength is determined using the Julian and Torres (2006) formula for cohesive soils based on silt-clay content.

3.4.2. Model for Migration in Stratified Soils

The Stein and LaTray (2002) model is a two-dimensional model that predicts knickpoint migration in the presence of strong-over-weak soil layers. Migration is considered to occur as a series of discrete cantilever failures caused by undercutting in a plunge pool immediately downstream the knickpoint with back roller effects. The length scale of migration from one failure episode is modeled as the failure of the cantilever slab in bending. The corresponding time scale of migration is determined by the rate of scour and undercutting that lead to critical conditions for failure of the cantilever slab. The length scale of migration, b, is determined from the following relationship of moments about the failure axis that takes hydrodynamic loading into account:

$$[\gamma_{bw}P_1 + \gamma_w(H_0 - H_T)]b^2 + [\gamma_w 2H_0S(t + 2e/3)]b + \left[\gamma_w {H_T}^2(e/3 - H_T/3) - (2\sigma_t/3)\left(t^2 + te\right)\right] = 0 \tag{2}$$

where P_1 is the height of the cantilever slab, H_0 is the approach flow depth, H_T is the tailwater height above the slab bottom, e and t are distances along the failure plane, S is the longitudinal bed slope, σ_t is the maximum tensile strength of the slab, and γ_{bw} and γ_w are the specific weights of the slab and water, respectively.

The time scale of migration (dimensionless), ΔT^*, is determined from the following relationship for the scour progression:

$$\Delta T^{*} = \left[\left(d^{*} - d^{*2}\right)^{0.5}\left(1 - \frac{2}{d^{*} - 1}\right) - 1.5\sin^{-1}(2d^{*} - 1)\right]_{d_i^{*}}^{d_f^{*}} \quad (3)$$

where $d^{*} = d_s/d_e$, $d_i^{*} = d_i/d_e$, and $d_f^{*} = d_f/d_e$, d_s is the scour depth, d_e is the equilibrium depth, d_i is the initial scour depth at the beginning of a failure cycle immediately after slab failure, and d_f is the maximum scour depth reached at the end of a failure cycle immediately prior to slab failure. The scour depths are collectively estimated with the following relationships:

$$d_e = \left[\frac{\gamma_w \sin\phi}{2.3g(\gamma_s - \gamma_w)\sin 2\phi}\right]^{0.8} \frac{6.8V_0^{1.6}Y_0^{0.6}\sin\chi}{d_{50}^{0.4}} \quad (4a)$$

$$d_f = \frac{(b + X_n)\tan\phi\tan\chi'}{\tan\chi' - \tan\phi} \quad (4b)$$

$$d_i = d_f - C_s b \quad (4c)$$

where γ_s is the sediment specific weight, ϕ is the sediment angle of repose, d_{50} is the mean sediment size, g is the gravitational constant, and V_0, Y_0, and χ are the velocity, thickness, and impingment angle of the jet at the plane bed elevation. χ' is the corrected impingement angle in the pool and X_n is the distance from the knickpoint face to the impingement location. C_s is an empirical scour hole coefficient that was calibrated directly from retreating headcut experiments.

With the length scales and time scales estimated, the rate of migration, C_c, is estimated as

$$C_c = \frac{b}{\Delta T^{*} T_r} \quad (5)$$

where T_r is a reference time scale estimated as $T_r = \gamma_{bd} d_e / \kappa \tau_c^{1.5}$, in which γ_{bd} is the dry sediment bulk density, κ is a coefficient that was calibrated, and τ_c is the critical erosional strength.

4. Results

The results below discuss in sequence the stratigraphy at the site, the stage and flow discharge over the study period, and the diary of the knickpoint migration based on the channel surveys and visual inspections. This is followed by the estimated knickpoint migration due to fluvial hydraulics and stratification using the models described above.

4.1. Stratigraphy and Sediment Analysis

4.1.1. Cross-Sectional Stratigraphy at Study Site

A stratigraphic cross section was developed using the deep boreholes collected at the top of the stream banks and the shallow boreholes collected from the stream bed. Approximately 0.5–1 m of the Camp Creek Member covers the Roberts Creek Member. The Roberts Creek Member, which is 3.5–4 m deep, sits atop the Gunder Member.

Both the Roberts Creek and the upper Gunder Member generally classify as loams, but they have significantly different particle size distributions, as well as bulk densities, as seen by the gamma attenuation measurements (Papanicolaou et al., 2008; t tests, $p < 0.001$). The Roberts Creek soils contain less sand and more silt than the upper Gunder soils, as well as slightly lower bulk densities. The upper Gunder soils contain krotovina in more abundance than the Roberts Creek soils (Figure 3c). The krotovina are more vulnerable to scour than the surrounding Gunder soils and preferentially erode to form scour holes on the channel bed.

The channel bed at the study site has eroded through the Roberts Creek Member and into the upper Gunder Member (see Figure 3b). Thus, the focus hereafter is on the upper Gunder Member since the knickpoint falls solely within this unit and its migration is controlled by the upper Gunder soil characteristics. A description of the layers of the upper Gunder Member at the study reach, relevant to the knickpoint migration, is provided below.

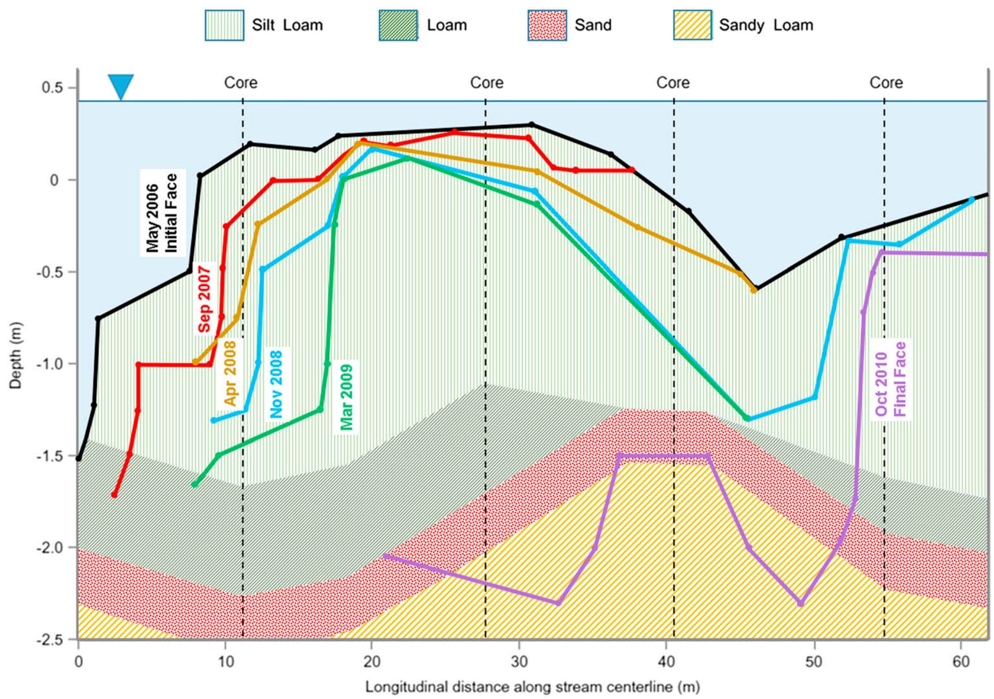

Figure 5. Stratigraphic profile of the channel bed along the longitudinal stream axis with profiles of the knickpoint surface over time superimposed. Knickpoint profiles represent the maximum upstream extent of each surveyed contour along the stream axis. Vertical dashed lines show the location of the shallow cores along the channel bed.

4.1.2. Layers of the Upper Gunder Member

A longitudinal stratigraphic cross section was developed along the channel bed for the upper Gunder Member at the study reach using the bed surface hand cores along with the deep borehole cores. For context, the surveyed locations of the knickpoint face and elevations of the knickpoint surface over time are superimposed over this longitudinal stratigraphy in Figure 5.

As seen in Figure 5, the upper Gunder Member consists of four layers: a silt loam cap at the surface, then loam, sand, and sandy loam sublayers consecutively at depth (Table 1). Bulk density measurements for each layer correspond with changes in texture and decrease moving from the silt loam cap (1,353 ± 165 kg/m^3) to the loam (1,315 ± 132 kg/m^3) and the sand (970 ± 134 kg/m^3) sublayers, before increasing again with the sandy loam (1,314 ± 201 kg/m^3) sublayer. The statistical significance of the differences in bulk density between the layers was established using an analysis of variance test ($\alpha = 0.05$; $p < 0.001$).

Changes in bulk density is usually correlated with changes in soil strength (e.g., Sutarto et al., 2014). Soil mechanical strength obtained from the direct shear tests for our study are summarized in Table 1, which shows an increase in mechanical strength with increase in bulk density. The internal friction angle of the soils was generally around 0.55 ± 0.08. These ranges correspond well with values reported by Akiyama (1964) for loess-derived soils in western Iowa.

4.2. Flow Depth and Discharge

Figure 6 presents the time series of observed flow stage data over the monitoring period. Low flows were generally experienced during most of the period, as only one runoff event had a peak flow discharge greater than 16 m^3/s and a corresponding flow depth exceeding 1.45 m. For reference, bankfull depth at the site is 3.87 m, with a corresponding flow discharge of 109 m^3/s. Thus, the majority of flows were less than one third of bankfull conditions. The highest runoff event occurred on 12 June 2008, from a 56-mm rainfall event that produced a peak flow discharge of 55 m^3/s and corresponding depth of 2.73 m.

4.3. Diary of Knickpoint Migration

Changes in the knickpoint location and face are described below for seven periods dictated by the field survey and monitoring dates. Each period is described in terms of eroded substrate strength, hydrology, and

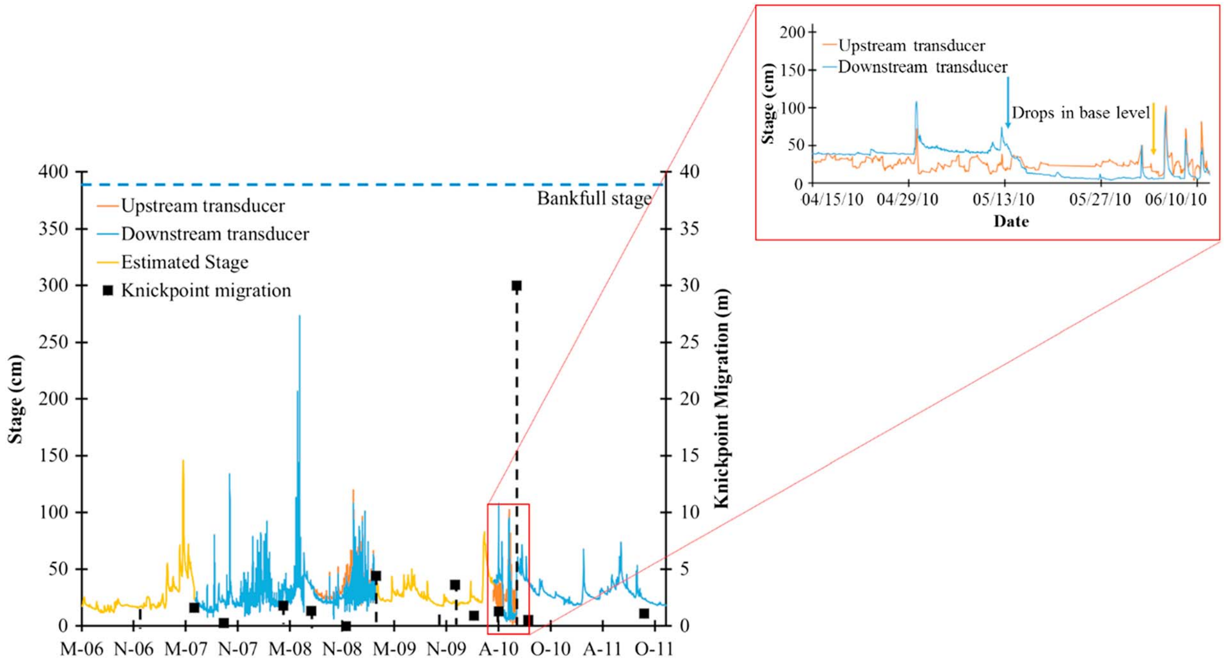

Figure 6. The compiled hydrograph for the Mud Creek reach using data from the two pressure transducers and the rating curve from Papanicolaou et al. (2008). The outset shows a close-up of the drop in base level of the hydrographs as the knickpoint passed through this reach in spring 2010.

knickpoint migration rates. Combined, the periods cover knickpoint migration from the start of the study in May 2006 to the end in November 2012.

1. *May 2006 to September 2007* (16-month interval): At the start of the monitoring period (i.e., 21 May 2006), the knickpoint face was located 109 m downstream of the county road bridge. There was an initial 0.6-m elevation drop from the knickpoint ledge and then a second 0.6-m drop approximately 6 m downstream. The knickpoint was primarily in the silt loam layer of the upper Gunder member, with the toe of the second drop just falling within the loam layer.Five measureable runoff events took place between May 2006 and September 2007, with the largest producing a maximum flow depth of 1.45 m. The survey on 14 June 2007 showed that the knickpoint face had migrated 1.61 m since May 2006, while the next survey on 25 September 2007, recorded an additional migration of 0.26 m (Figure 5) for a time-averaged migration rate of 0.12 m/month for the entire period. The toe of the second drop was well into the loam layer at the end of the period. The scour hole at the bottom of the knickpoint widened by more than 1.25 m over the period.
2. *September 2007 to April 2008* (7-month interval): The knickpoint face migrated an additional 1.78 m over this period at a time-averaged rate of 0.25 m/month. Low flows persisted with 13 small runoff events having peak flow depths less than 1.45 m. There was flow concentrating along a developing chute at the knickpoint. This chute was a narrow “channel” that began to downcut into the bed surface at the knickpoint crest leading to the ledge. The chute extended 2.19 m upstream from the face. The flow eroded the top surface of the knickpoint and the face thereby flattening the knickpoint face slope as it retreated. This smoothing of the face slope is seen in the April 2008 profile shown in Figure 5.
3. *April 2008 to July 2008* (3-month interval): The knickpoint migrated another 1.32 m by the 23 July 2008 survey, indicating a time-averaged migration rate of 0.44 m/month. The highest runoff event (a 56-mm rainfall) of the whole study occurred during this period on 12 June 2008, producing a maximum flow depth of 2.73 m. The slope of the knickpoint face steepened. Additionally, the chute that developed in the previous period deepened and widened.
4. *July 2008 to March 2009* (8-month interval): There was essentially no movement in the knickpoint face between August and November 2008 per the 19 November 2008 survey. A visual assessment on 11 February 2009, indicated a net migration of ~0.80 m between November 2008 and February 2009, and a survey on 3 March 2009, revealed a further migration of 3.59 m. Overall, the time-averaged

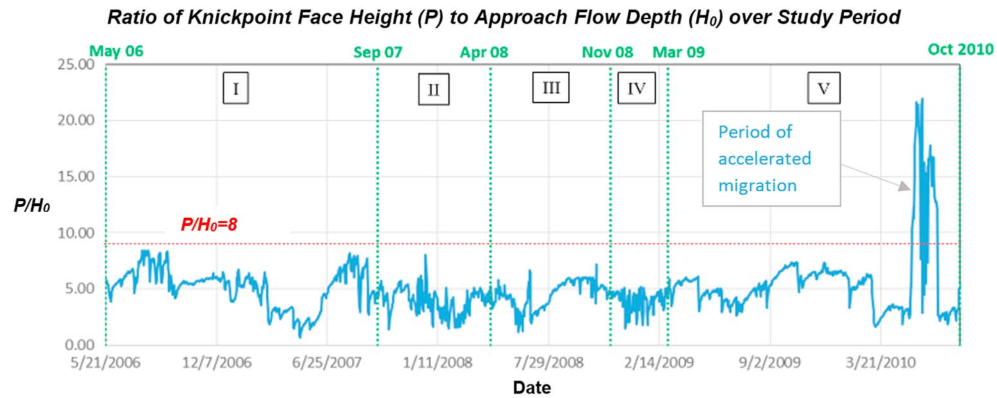

Figure 7. Time series of ratio of knickpoint face height, P, to approach flow depth, H_0, over study period.

migration rate for this period was 0.55 m/month.The chute on top of the knickpoint further deepened to a depth of 1.2 m and widened to a distance of 1.1 m. The surveys also showed the evolution of a 3.3 m wide scour hole on the *upstream* side of the chute (Figure 5). This scour hole remained in the silt loam layer, and no further evolution of the hole was noted between November 2008 and March 2009.Stream flow records indicated low flows with depths less than 1.15 m over the entire period. In mid-December 2008, ice attached to the knickpoint in several places around the channel margin for an approximate 2-week period. Rapid warming of more than 20 °C and consequential melting on 26 December 2008 led to the plucking of frozen blocks of soil from the channel bed.

5. *March 2009 to April 2010* (13-month interval): Visual assessments during this period indicated the knickpoint migrated 3.6 m between April and December 2009, followed by 0.9 m of migration from January 2010 to February 2010, and then a further migration of 1.3 m by 30 April 2010. The time-averaged migration rate overall was 0.48 m/month. Stream flow during this period was low with the largest runoff event in March 2010 only producing a maximum flow depth of 0.88 m.
6. *April 2010 to October 2010* (6-month interval): A visual assessment conducted on 1 July 2010 revealed that the knickpoint face had migrated 30 m within a 2-month period at a time-averaged migration rate of 15 m/month. This migration was confirmed by a survey on 11 August 2010 and also noted in the records of both pressure transducers, as the water stage dropped significantly while the knickpoint migrated past their locations on 12 May 2010 and 1 June 2010, for the downstream and upstream transducers, respectively (Figure 6).The large knickpoint migration rate occurred under persistently low stream flow throughout the period. The largest storm event during the period produced 53 mm of rainfall on 30April 2010, resulting in a maximum flow depth of 1.06 m.The October 2010 survey showed that the scour hole downstream of the knickpoint had now eroded deeper, beyond the loam and sand layers, into the sandy loam layer (Figure 5). Furthermore, the width of the channel at the original knickpoint location was more than 50% wider than it was during the initial survey in May 2006, revealing a constriction-expansion pattern instigated by knickpoint migration through the semicohesive reach.
7. *October 2010 to November 2012* (25-month period): A final visual assessment on 15 November 2012 showed that the knickpoint had only advanced an additional 2.3 m, at a net rate of 0.085 m/month.

4.4. Simulation of Knickpoint Migration

A time series of the ratio of the knickpoint face height, P, to the upstream approach flow depth, H_0, is shown in Figure 7. The threshold for vented flow conditions, that is, $P/H_0 = 8$ is also shown in the figure. The ratio was less than 8 for most of the study period, except during the summer of 2010 where the ratio was larger than 8 and vented conditions were prevalent. The Bressan et al. (2014) model is applicable for P/H_0 ratios less than 8 was used to "reproduce" the observed knickpoint migration over the study period considering that fluvial hydraulics was the primary mechanism driving migration. Since the knickpoint face was primarily in the silt loam cap, the soil properties used for the simulation were those corresponding to the silt loam layer. In addition, a sensitivity analysis was performed using the properties of the loam layer that was directly below the silt loam layer.

Table 2
Observed and Modeled Knickpoint Migration

Date range	Measured retreat, MR (m)	Predicted retreat, PR (m)	Time-averaged migration rate (m/month)	Relative difference (MR-PR)/PR
05/21/2006–06/13/2007	1.61	1.91	0.1	0.2
06/14/2007–09/24/2007	0.26	0.56	0.1	0.5
09/25/2007–04/15/2008	1.78	1.01	0.3	0.8
04/16/2008–07/22/2008	1.32	0.43	0.4	2.1
07/23/2008–11/18/2008	0.00	0.66	0.0	1.0
11/19/2008–03/02/2009	4.38	0.94	1.3	3.7
03/03/2009–11/30/2009	3.60	1.53	0.4	1.4
12/01/2009–02/03/2010	0.90	0.42	0.4	1.1
02/04/2010–04/29/2010	1.30	0.39	0.5	2.3
04/30/2010–06/30/2010	**30.00**	**0.55**	**14.8**	**53.5**
07/01/2010–08/10/2010	0.52	0.15	0.4	2.5
08/11/2010–09/14/2011	1.10	3.2	0.1	0.7
09/15/2011–11/15/2012	1.20	0.7	0.1	0.7

Note. Date format month/day/year. The bold text shows that the fluvial hydraulics model is unable to account for the observed increase in knickpoint retreat rate from 04/30/2010 to 06/30/2010, which is an order of magnitude larger.

Estimated critical erosional strength and erodibility values of 16 Pa and 5.0×10^{-8} m^2/s/kg, respectively, were adopted for the silt loam cap layer. Values for the model coefficients A and B were also set to 1 and 0.08, respectively, based on the calibrated values provided by Bressan et al. (2014). The other model parameters were obtained from the field surveys and flow measurements. For the sensitivity analysis with the loam layer properties, an estimated critical erosional strength of 12 Pa and a corresponding erodibility of 5.7×10^{-8} m^2/s/kg were adopted.

Simulated fluvial hydraulics-driven knickpoint migration corresponding to the survey and visual assessment periods is summarized in Table 2 for the silt loam cap. For comparison, the observed migration distances are also presented along with a column showing the relative difference between the observed and simulated migrations. Overall, the results show the same order of magnitude of retreat rates between the model and field observations for the first 30 months, from May 2006 to November 2008, with differences less than 2.2 times the simulated rates for all the monitoring intervals within the period. The correspondence between the model predictions and the field observations in the following 17-month period, that is, from November 2008 to April 2010, also show the same order of magnitude with differences between observed and simulated rates ranging between 1.1 and 3.7 times the simulated rates. However, the model was unable to account for the total knickpoint migration in the 2-month period between May 2010 and June 2010, where the difference between the observed and simulated rate was 53 times the simulated rate, indicating that the observed rate was an order of magnitude larger than the simulated rate. After this period, the model predictions and observations were again in good correspondence until the end of the study in November 2012, with observed and model differences in rates ranging between 0.7 and 2.5 times the simulated rates.

The good correspondence between the model predictions and observed migration rates for most of the study period, that is, 76 out of 78 months, suggests that the knickpoint migration can be explained by the fluvial hydraulics concept for the most part. However, the poor correspondence between the model prediction and observed knickpoint migration from May to June 2010 suggests that other mechanisms were responsible the order of magnitude increase in the migration rate during the period.

Figure 8 presents the results of the sensitivity analysis and shows cumulative knickpoint migration from the field surveys and the predicted cumulative knickpoint migration based on the fluvial hydraulics model using both the silt loam and loam layer properties. The overall difference in the predicted migration between these soil properties is less than 1 m over the entire study period. Two “jumps” in the observed migration are readily apparent that are absent in the predicted migration lines. The first jump occurs around March 2009, and the second jump occurs around June 2010. Besides these two jumps, the slopes of the two lines are overall in agreement, confirming the dominant role of fluvial hydraulics in driving knickpoint migration in these periods. The likely cause for the jumps in the observed cumulative migration may be understood by re-

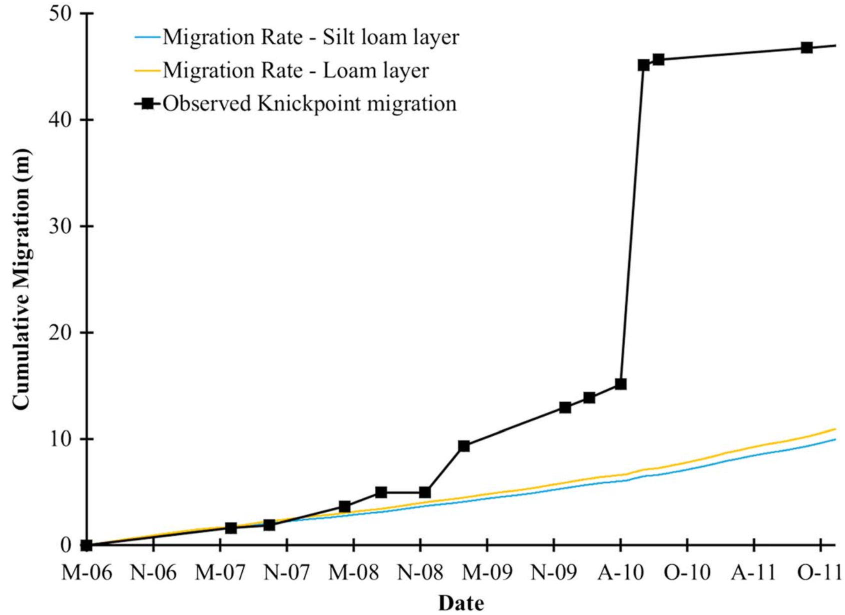

Figure 8. Cumulative knickpoint migration. The black line represents the measured values, and the blue and orange lines are modeled data using Bressan et al. (2014) with the pedological properties of the silt loam cap and loam layers respectively.

examining the surveyed knickpoint profiles superimposed on the stratigraphy of the upper Gunder member in Figure 5. Two important things can be noted. First, all the knickpoint faces prior to March 2009 fall predominantly within the silt loam layer. Second, the knickpoint profile in August 2010, after the big 30-m jump, has eroded below the sand layer into the sand loam layer. This implies that prior to March 2009, knickpoint migration was primarily governed by the characteristics of the silt loam and loam layers. It also implies that at some point between March 2009 and August 2010, knickpoint migration was controlled not only by the silt loam and loam layers but also by sand layer.

Given that vented conditions were present between April and June 2010 (based on the P/H_0 trends in Figure 7) and so the flow type during this period would have comprised a plunging jet with back roller effects, the mechanism driving knickpoint migration at some point in the period would have been undercutting in the sand layer and cantilever failure of the cap. Thus, the Stein and LaTray (2002) model was used to estimate the contribution of the cantilever failure mechanism to total migration within that period. Values of the coefficients C_s and $\varkappa$ were respectively set to their calibrated values of 0.073 and 0.17 in the Stein and LaTray (2002) study. Using the soil properties described above, an estimated migration of 45.8 m was determined for the period using the model. This migration is the same order of magnitude as the observed migration, with a small relative difference (see Table 2) of 0.3. The significantly smaller relative difference of 0.3 for the undercutting/cantilever mechanism compared to 53 for the fluvial hydraulics mechanism suggests that undercutting and cantilever failure contributed to the knickpoint migration during the period.

Additional numerical simulations were performed using the 3ST1D model (Papanicolaou et al., 2004) to examine the influence of the scour hole upstream of the knickpoint face (see Figure 5) on the knickpoint migration. The predicted flow fields suggested that flow velocities were generally low in the vicinity of the scour hole and that the presence of the scour hole did not influence the migration of the knickpoint between September and March 2009 (see Figure S2 of the supporting information for an illustration of the results). Between March 2009 and October 2010, the effect of the hole would have been to result in a reduction in the knickpoint face height as it migrated past. Based on the P/H_0 trends, the plunging jet and back roller would have been the predominant mechanisms controlling the knickpoint migration during this period and not the evolution of the hole directly.

The flow field predictions also explained the evolution of the upstream scour hole over the entire study period. The bed shear stress increased on the downstream side of the hole as flow sped up toward the knickpoint lip (see Figure S3 in the supporting information). The net result of this increase in bed shear stress was erosion on the downstream side of the hole, leading to its observed growth in the downstream direction in Figure 5.

5. Discussion

Comparison between the observed knickpoint migration rates and predictions from the fluvial hydraulics-based model of Bressan et al. (2014) revealed that for much of the 78-month period examined in this study, knickpoint migration in Mud Creek can largely be explained by fluvial hydraulics. However, considerable underprediction of the knickpoint migration between May and June 2010 (i.e., a relative difference between observed and predicted rates that is 53 times the predicted rate) indicated that there were other mechanisms of equal or greater significance than fluvial hydraulics driving the migration in the period. Examination of the stratigraphy and flow features over the time window suggested a period of knickpoint migration governed by a plunging jet and back roller effects, and undercutting and cantilever failure in the presence of a stronger silt loam/loam cap over a weaker sand layer. This was further attested by the Stein and LaTray (2002) model, which predicted a knickpoint migration estimate that was the same order of magnitude as the observed migration (i.e., a relative difference of 0.3), indicating that heterogeneity in substrate properties along with the hydrodynamic controls had exerted an important influence on migration rates.

Based on the observations and modeling results, a conceptual "diary" sketch is proposed in Figure 9 to illustrate the processes that controlled knickpoint migration rates over the study period, highlighting the roles of both flow type and stratigraphy. The stages of knickpoint migration illustrated show an initial period (May 2006 to May 2010) dominated by unvented conditions and fluvial erosion, followed by a period dominated by a vented plunging jet, back roller effects, and cyclic patterns of undercutting and cantilever failure facilitated by stratigraphy (May 2010 to June 2010) and then back to unvented conditions and fluvial erosion (July 2010 onward).

In the first monitoring period (May 2006 to September 2007; Figure 9a), unvented conditions were dominant, with a mean P/H_0 ratio of 5.1, causing the jet to flow along the face of the knickpoint leading to shear-induced erosion and an advective-diffusive knickpoint migration. The lowest mean P/H_0 value of 3.9 during the study occurred in the second period (September 2007 to April 2008; Figure 9b). Unvented conditions were prevalent and shear-induced erosion led to mostly diffusive knickpoint migration as the jet tended to shoot away from the face. Low flows and unvented conditions continued to dominate in the third period (April 2008 to November 2008; Figure 9c) with a mean P/H_0 of 4.5, leading to further advective-diffusive migration caused by the jet flowing along the face. A chute was incised at the top of the knickpoint during this period. In the fourth period (November 2008 to March 2009; Figure 9d), shear-induced erosion and jet impingement in the chute led to a lowering of the base level of the chute along with an advective-diffusive retreat. Unvented conditions were still prevalent with a mean P/H_0 of 4.3. During the fifth period (March 2009 to May 2010; Figure 9e), continued shear-induced erosion and jet impingement would have led to a continued advective-diffusive retreat along with lowering of the base level of the plunge pool into the loam layer. The mean P/H_0 ratio was 5.0 for this period. In the sixth period (May 2010 to June 2010; Figures 9f–9g), the mean P/H_0 increased to 11.7 due to the increase in knickpoint face height and decrease in flow rates and depths. Vented conditions would have developed in this case (May, 1989) leading to a plunging jet and back roller. These features would have led to an advective retreat and further scouring of the plunge pool bed, driving it deeper into the weaker sand layer where undercutting would have initiated due to faster removal of the sand layer. Continued undercutting would have led to a threshold where cantilever failure of the overlaying silt loam/loam cap would have occurred. Thereafter, cycles of undercutting and cantilever failure would continue as long as the plunging jet and back roller remained effective. Some fluvial erosion would have occurred during the period as well (though minimal) with fluctuations in the P/H_0 ratio (see Figure 7). The mean P/H_0 decreased to 5.3 in the last monitoring period (from July 2010 onward; Figure 9h), indicating a return to unvented conditions. An advective-diffusive retreat continued to dominate this period.

The above conceptual model of knickpoint migration recognizes that changes in substrate properties at the bed can lead to preferential erosion of material, controlling the rate of knickpoint migration. The importance of the substrate properties on knickpoint migration has recently been demonstrated by Grimaud et al. (2016) and Baynes et al. (2018) for bedrock systems. However, both studies focused only on unvented conditions,

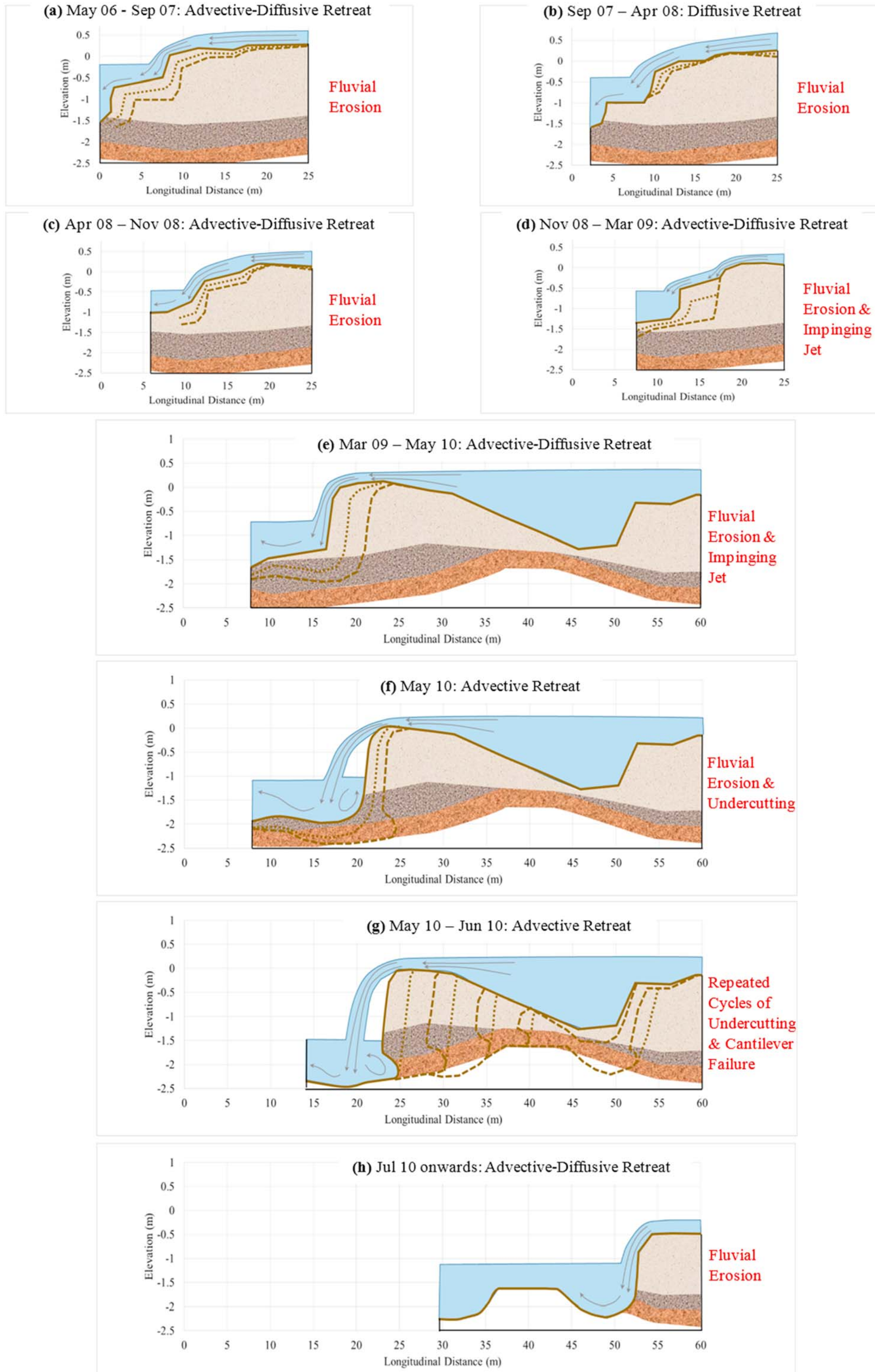

Figure 9. (a–h) Stages of knickpoint migration describing periods dominated by fluvial erosion and a cyclic pattern of undercutting and cantilever failure that is facilitated by the stratigraphy.

and while Baynes et al. (2018) found that changes in the flow did not affect the migration rate due to adjustments in the channel morphology, our study suggests that changes in the flow can result in changes in the mechanisms controlling the knickpoint migration (i.e., fluvial shear action versus undercutting due to a plunging jet and back roller effects), with implications to the knickpoint profile and migration rates. The differences in the findings between the two studies could be attributed to the time scale of processes considered and the nature of the substrates.

Several aspects of the processes driving the knickpoint migration in our system are similar to those observed in other studies focused on both bedrock and unconsolidated systems. The knickpoint profiles we observed between August 2008 and March 2009 suggested that the action of jet impingement in the chute that had developed would have led to the lowering of the plunge pool bed into the sand layer over a short period of time, which would then have triggered undercutting due to sand removal by back roller effects. The vertical lowering of the plunge pool bed has also been noted by Scheingross et al. (2017) in rock environments, where they propose that sediment-laden jets impinging on the rock cause vertical drilling leading to erosion and lowering of the plunge pool bed. Scheingross et al. (2017) noted that downstream controls on the plunge pool lip influenced the rate of lowering of the plunge pool bed. In our study, relatively low tailwater depths during the period would have ensured the effectiveness of the plunging jet in scouring the plunge pool bed, driving it deeper into the sand layer.

The effects of strong-over-weak stratigraphy on knickpoint migration have been presented by a few studies in both rock (e.g., Gilbert, 1907; Haviv et al., 2010; May, 1989) and unconsolidated (e.g., Holland & Pickup, 1976; Stein & LaTray, 2002) systems. The concensus among these studies is that the mode of erosion is basal sapping of the weaker layer at the bottom resulting in undercutting and subsequent cantilever failure of the stronger layer when a critical length of undercutting is reached. The exact cause of the undercutting, however, differs between the various environments examined. For example, whereas Haviv et al. (2010) considered weathering, buckling, and mass failure of the weaker layer as the cause, May (1989) noted that erosion of the weaker layer was a result of the back roller action from the plunging jet, which was affected by the tailwater elevation. Lamb et al. (2007) have also shown field evidence suggesting that plunge pool erosion may cause undercutting of weaker sublayers. In our study, the flow records between May and June 2010 suggest that vented conditions existed at the knickpoint, where a plunging jet and back roller effects were dominant (see Figure 7). The presence and persistence of the back roller would have promoted repeated cycles of undercutting of the sand layer and consequent cantilever failure of stronger layer above. The fast rate of removal of the sand layer would have caused a faster rate of knickpoint migration compared to a scenario in which it was not present, leading to the jump in migration rate that was observed.

A scour hole was present upstream of the knickpoint face (approximately 40 m) for most of the study period. The formation of this scour hole appears to be due to the presence of a grade control structure upstream of the study region (see Figure S4 of the supporting information). Though other studies have proposed scour hole growth at the top of knickpoints as a mechanism for upstream knickpoint migration (e.g., Scheingross et al., 2017), this does not appear to be the case in our study. The numerical analysis performed herein suggests that the effect of the upstream scour hole would only have been to result in reduction in the knickpoint face height as it migrated past, but the predominant mechanisms for knickpoint migration were not explicitly related to the hole. Instead, the effects of the plunging jet and back roller were determined to be the most likely predominant mechanisms that led to the large migration due to the undercutting and cantilever action that was triggered once the sand layer was reached. This is illustrated with the trends of P/H_0 over the study period in Figure 7. While the scour may have indirectly influenced the value of P in the figure due to the lowering of the knickpoint face height, the flow and migration data clearly suggest that the plunging jet and back roller were the main contributors to the fast knickpoint migration, although some fluvial erosion may have occurred during the period.

The proposed conceptual model of knickpoint migration presented herein is inferred from borehole reconstruction of the soil stratigraphy along the studied reach, and field surveys of knickpoint migration over a 78-month period. While direct field observations of undercutting and cantilever failure were not made in the study, this erosion mechanism has been observed with stratified sediment and is known to result in rapid retreat of the face (Daniels, 1960; May, 1989; Simon & Thomas, 2002; Stein & LaTray, 2002), which supports our hypothesis and the empirical evidence provided herein.

Holland and Pickup (1976) have suggested that the presence of stratified sediment, with layers of sand intercalated between layers of cohesive material, can reduce knickpoint retreat rates compared to homogenous cohesive substrates. In their study, two intercalated sand beds led to knickpoint forming horizons that generated three stepped knickpoints, each of which traveled at a different speed. The manifestation of steps and multiple plunging pools acts to dissipate the flow energy in a couple of ways, including energy losses as the jets plunge into the pools (Alonso et al., 2002) and the entrainment of air with boundary layer growth (Chanson, 2002). The net effect of the steps in the Holland and Pickup (1976) study was therefore to split the amount of energy available for migration between the three knickpoints, with the first knickpoint having the most amount of energy available and the last knickpoint having the least. Consequently, it was observed that the first knickpoint in the series migrated faster than the second knickpoint, which in turn also migrated faster than the third knickpoint. In the homogeneous case without the horizons, all the energy would have been available at only one knickpoint, meaning that the migration rate for this knickpoint would be faster than any of the knickpoints in the intercalated case described above. The conditions in our study correspond to the case of one knickpoint but with a weaker layer present at the bottom of the knickpoint. Under this scenario, the above-mentioned studies (i.e., Daniels, 1960; May, 1989; Simon & Thomas, 2002; Stein & LaTray, 2002) have found that accelerated retreat of the knickpoint occurs due to erosion of the weaker layer leading to the undercutting and cantilever failure of the top layer. An important question arising, therefore, from the studies is how the location of the weak layer or layers in relation to the knickpoint face (not just at the bottom) affects the overall retreat rate (i.e., the degree of acceleration or deceleration). Further laboratory and field observations are recommended to shed some more light on the knickpoint retreat mechanisms proposed herein for the semicohesive streams with stratified sediments. Several knickpoint studies focused in bedrock streams (e.g., Gilbert, 1907; Haviv et al., 2010) have adopted novel techniques for understanding the mechanisms that drive knickpoint migration. Analogs can be drawn between these bedrock streams and the unlithified, semicohesive streams studied herein to develop similar techniques for understanding knickpoint migration mechanisms in unlithified semicohesive systems.

6. Conclusion

Migration of a knickpoint in Mud Creek, a semicohesive stream in the deep loess region of the U.S. Midwest, has been examined for a 78-month period in this study. Comparison of field-observed knickpoint migration with migration predicted using the fluvial hydraulics-driven knickpoint migration model of Bressan et al. (2014) revealed a 2-month period in which fluvial hydraulics alone could not explain the observed migration rate (i.e., the knickpoint migrated a total of 30 m, whereas the fluvial hydraulics contributions were estimated to be 0.55 m). Further examination of our field data revealed that the likely cause of the accelerated migration was undercutting and cantilever failure in the presence of stratification where a strong upper silt loam layer was underlain by a sand layer that was more readily erodible.

The importance of episodic migrations has been observed by Baynes et al. (2015) for bedrock systems, which is a good analogy for the unconsolidated systems examined herein. Their study suggests that though current techniques ignore episodic contributions when considering long-term migration rates, field evidence indicates that the episodic contributions actually contribute significantly to the long term rates and so there is a bias in migration estimates. For unconsolidated stratified systems, our study suggests that undercutting and cantilever failure mechanisms can be important episodic events that drive knickpoint migration and that they must be considered along with fluvial erosion mechanisms when predicting migration rates in order to avoid bias.

A shortcoming of the study is that direct evidence of cantilever failure at the knickpoint was not observed in the field due to the measurement techniques employed. We recommend that future studies are performed using suitable approaches to more directly examine the different mechanistic hypotheses of knickpoint propagation that have been proposed for semicohesive streams such as the one studied herein. Another potential shortcoming is better quantifying the role of ice observed in the mid-December 2008 period and freeze-thaw period on bed erosion as a prelude of knickpoint migration.

Novel techniques have been adopted in several studies for studying mechanisms that drive knickpoint migration in bedrock streams (e.g., Gilbert, 1907; Haviv et al., 2010). Analogs can be drawn from these studies to develop similar techniques for understanding knickpoint migration mechanisms in unlithified, semicohesive streams similar to the one studied herein. In addition to bedrock systems, loess soils that experience knickpoints and headcuts can be found in other regions of the United States (e.g., western Tennessee and

Mississippi) and the globe (e.g., Chinese Loess Plateau). The findings of this study can be a basis for the research in these regions.

Acknowledgments
This study was funded by the Hungry Canyons Alliance and Iowa Highway Research Board. This research is also partially supported by the NSF grant EAR-1331906 for the Critical Zone Observatory for Intensively Managed Landscapes (IML-CZO), a multi-institutional collaborative effort. We would like to thank Dimitrios Dermisis for his project help along with Pete Haug, Brandon Barquist, Trevis Huff, Achilleas Tsakiris, Phil Ellis, Kevin Denn, and Joe Wortman for their help with field work and truss structure installation. The data (observed and modeled) for Figures 7–9 are provided herein as supporting information. All other data and model inputs are provided under the methods section (section 3).

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