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Key Points:
- We model expansion of fluvial networks into low-relief landscapes with depressions, representing the postglacial U.S. Central Lowland
- When depressions are connected to channels, evolution is rapid and network morphology is distinctive relative to the disconnected case
- Connection/disconnection of depressions is a stronger control on the rate of evolution than fluvial or hillslope erosion coefficients

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Modeled Postglacial Landscape Evolution at the Southern Margin of the Laurentide Ice Sheet: Hydrological Connection of Uplands Controls the Pace and Style of Fluvial Network Expansion

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Abstract Landscapes of the U.S. Central Lowland were repeatedly affected by the Laurentide Ice Sheet. Glacial processes diminished relief and disrupted drainage networks. Deep valleys carved by meltwater were disconnected from the surrounding uplands. The upland area lacking surface water connection to the drainage network is referred to as noncontributing area (NCA). Decreasing fractions of NCA on older surfaces suggest that NCA becomes drained over time. We propose that the integration could occur via (1) capture of NCA as channels propagate into the upland or (2) subsurface or intermittent surface connection of NCA to external drainage networks providing increased discharge to promote channel incision. We refer the two cases as “disconnected” and “connected” since the crucial difference between them is the hydrological connection of the upland to external drainage. We investigate the differences in evolution and morphology of channel networks in low-relief landscapes under disconnected and connected regimes using numerical simulations. We observe substantially faster rates of erosion and integration of the channel network in the connected case. The connected case also creates longer, more sinuous channels than the disconnected case. Sensitivity tests indicate that hillslope diffusivity has little influence on the evolution and morphology. The fluvial erosion coefficient has significant impact on the rate of evolution, and it influences the morphology to a lesser extent. Our results and a qualitative comparison with landscapes of the glaciated U.S. Central Lowland suggest that connection of NCAs is a potential control on the evolution and morphology of postglacial landscapes.

1. Introduction

Landscapes in the glaciated portions of the Central Lowland physiographic province (Fenneman & Johnson, 1946) of the United States were repeatedly affected by the southernmost portions of the Laurentide Ice Sheet during the Quaternary (Colgan et al., 2003; Fullerton et al., 2003). In this region, different locations have been most recently glaciated at ~25 ka (Wisconsin Episode), ~130 ka (Illinois Episode), and >500 ka (Pre-Illinois Episodes) (Figure 1, Curry et al., 2011). Depositional glacial processes diminished preglacial relief by filling valleys and left constructional landforms including low-relief till plains and relatively high relief moraines (D. Brown et al., 1998; Colgan et al., 2003). As the ice retreated, meltwater collected in subglacial or proglacial lakes leaving fine-grained, sorted sediment in the form of glacial lake plains (e.g., Johnson et al., 1999). Glacial lakes episodically drained in outburst floods, carving deep valleys (e.g., Lord & Kehew, 1987; Teller, 2003). For example, Glacial Lake Agassiz stored much of the meltwater from the Des Moines Lobe following the Last Glacial Maximum and draining of the glacial lake caused ~70 m of vertical incision of the Minnesota River Valley (Belmont et al., 2011; Gran et al., 2013). Valleys carved by meltwater incision provide the majority of the postglacial landscape relief in areas occupied by the southern portions of the Wisconsin Episode Des Moines and Lake Michigan Lobes.

However, meltwater valleys did not provide a landscape-wide integrated drainage network (Figure 2). Instead, a significant fraction of the area of low-relief till plains and glacial lake plains was occupied by closed depressions and remained unconnected to external drainage networks (e.g., Miller et al., 2009). This area is referred to by hydrologists as noncontributing area (NCA) because it does not typically contribute surface runoff to stream networks. The water table in NCA in this region is typically near or above the ground surface, resulting in poorly drained soils and, prior to the advent of intensive agriculture, large areas of wetland (Figure 2). The prevalence of NCA varies as a function of the time since most recent glaciation with older surfaces characterized by well-integrated drainage networks and few undrained depressions (Ruhe, 1952). The

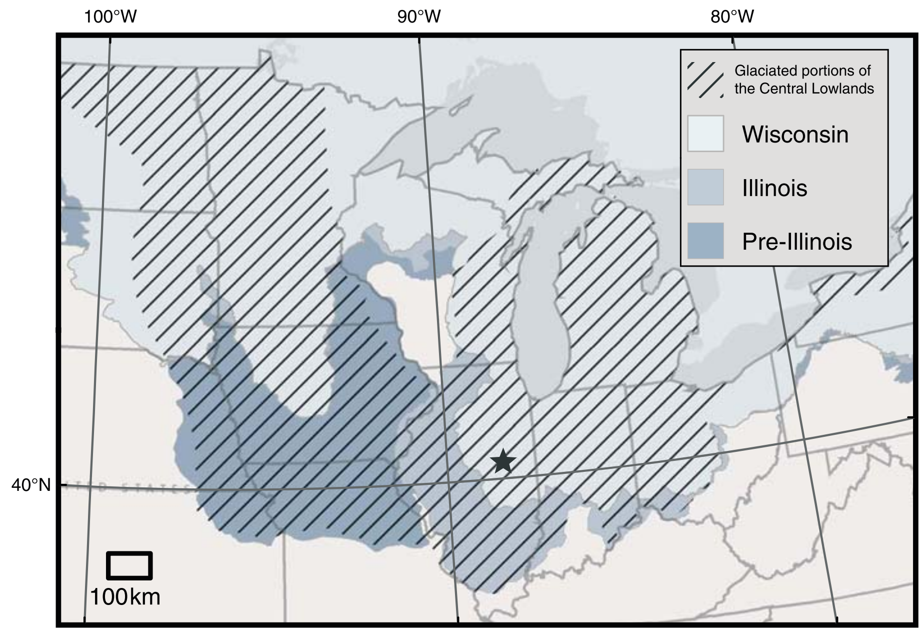

Figure 1. The glaciated portions of the Central Lowlands of the Interior Plain physiographic province of the United States (Fenneman & Johnson, 1946) are indicated by the hashed line. Within this region, ice advanced many times during the Pleistocene with different portions glaciated most recently during the Wisconsin Episode (Marine Isotope Stage 2–4), shown in light blue, the Illinois Episode (Marine Isotope Stage 6), shown in medium blue, and during multiple episodes in the early and middle Pleistocene, referred to as Pre-Illinois Episodes (Fullerton et al., 2003). This region, therefore, contains areas most recently glaciated ~10,000 years ago and areas most recently glaciated >500,000 years ago. The star shows the location of Upper Sangamon River basin in east central Illinois.

boundary of the Late Wisconsin Des Moines Lobe was mapped by Ruhe (1952) using the contrast in drainage network maturity between the poorly drained areas within the lobe and the mature drainage networks developed in Pre-Illinois Episode glacial till blanketed by Wisconsin Episode loess. Beyond the Late Wisconsin Des Moines Lobe boundary, fluvial networks had >500,000 years to develop with the most recent glaciation leaving only a blanket of ~5 m of loess draped over the topography (Bettis et al., 2003).

We propose that the integration of NCA into external drainage networks could occur via at least two different paths: (1) through capture of NCA as channel heads propagate into the upland or (2) through connection, perhaps intermittent, of NCA to the external drainage network via spillover of surface water from a closed depression or groundwater flow across surface water divides. The crucial difference between these two mechanisms is the fate of precipitation falling on the upland NCA. If the water delivered to the upland NCA is lost to the atmosphere through evapotranspiration or infiltrates into deep aquifers, then the integration of NCA requires headward extension of channels that eventually breach the drainage divide separating the NCA from the externally drained area. In this case, which we refer to as the “disconnected” case, the growth of a channel network causes drainage of upland closed depressions. Alternatively, if water that falls on the upland NCA is routed to external fluvial networks as spillover from lakes filled to capacity or as shallow groundwater flow, then this drainage of water off the uplands can cause channel incision within the established tributary and/or along surface flow paths. In this case, which we call the “connected” case, the NCA defined by subtle surface topographic divides are misnamed as the NCA do contribute to external drainage. The low relief of some postglacial uplands coupled with the occurrence of near-surface water tables increases both the possibility of filling of shallow lakes to the point of spilling out of closed depressions and the likelihood that the groundwater divide and surface water divide are not colocated. Both of these situations allow for precipitation falling within surficial closed depressions to flow into integrated drainage networks.

We investigate the difference in morphology and rate of growth of channel networks in low-relief landscapes under disconnected and connected drainage regimes using numerical simulations of fluvial and hillslope processes. We hypothesize that drainage network growth is more rapid when the landscape is hydrologically connected than when areas of internal drainage remain isolated from external drainage networks. We further

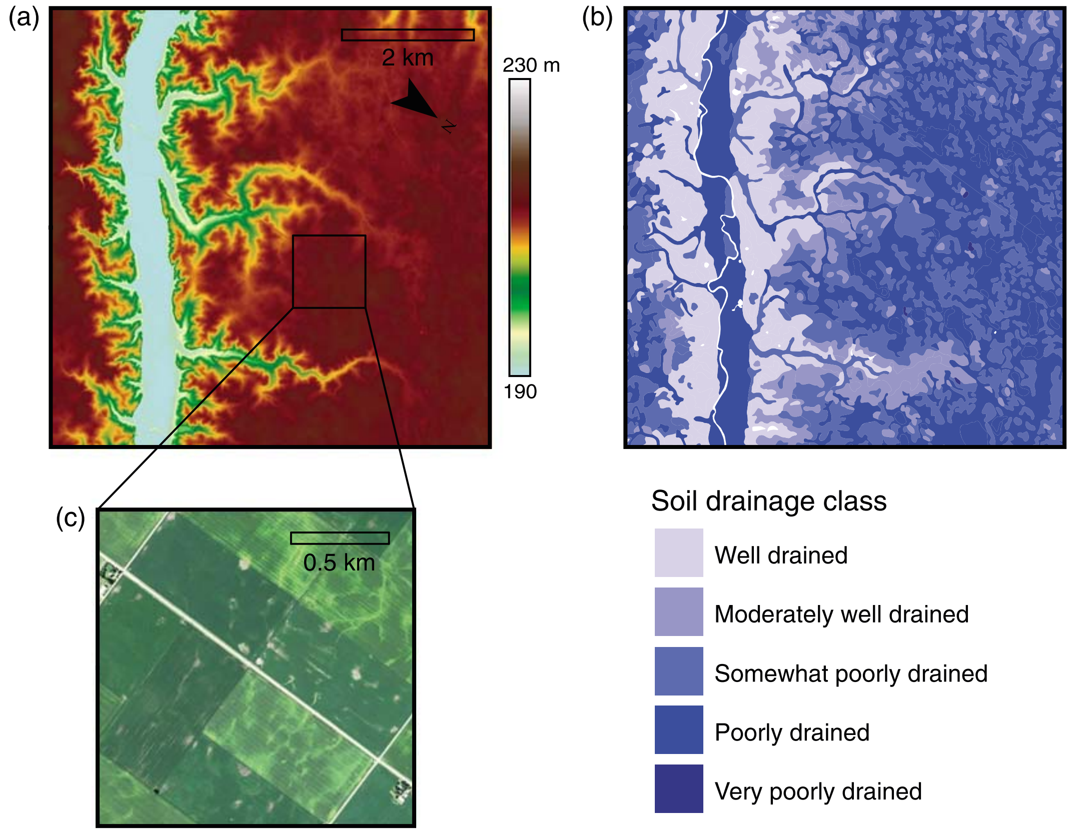

Figure 2. (a) A 1-m resolution digital elevation models constructed from light detection and ranging data (Illinois State Geological Survey) from the Sangamon River in east central Illinois, shows an incised valley ~15-m deep cut during recession of Late Wisconsin Episode glaciers ~20,000 years ago (Grimley, Anders, & Stumpf, 2016). Three large tributaries extend from the northwest side of the valley into a flat, low-relief upland that lacked integrated drainage prior to agricultural ditching. Soil survey data in panel b (retrieved from Web Soil Survey, Soil Survey Staff et al., 2018), colored by drainage class, show that soils formed under very poor drainage are common across the upland, indicating that saturation to the soil surface was common and standing water was likely present, at least seasonally, in closed depressions on the upland. Mottled colors within agricultural fields in aerial photography in panel c (Illinois State Geological Survey) reflect differences in soil moisture related to microtopography that persist despite artificial subsurface drainage.

hypothesize that the morphology of channel networks grown under connected and disconnected drainage conditions differs significantly. We use a set of idealized models to test these hypotheses and then qualitatively compare our models with a real landscape in Illinois. Uncertainty in both the postglacial and the preagricultural landscapes of Illinois and the glaciated Central Lowland more generally prevents a rigorous validation of the model, which is not intended to simulate the evolution of a particular place. Instead, we view the simulations and their comparison with real topography as motivating a hypothesis that channel networks in the glaciated Central Lowland reflect frequent hydrologic connection of greater portions of the landscape than expected from the surface topography as a target for future research.

2. Background

As process-oriented study of postglacial drainage network development is limited, we begin by noting that drainage networks expand into unchannelized areas in a number of geomorphic settings including surfaces blanketed by debris during volcanic eruptions and surfaces emerging from water via relative base level fall. These cases motivate our exploration of network integration under conditions with hydrologically connected versus disconnected uplands. Drainage network integration in a hummocky debris avalanche that resulted from the 1980 eruption of Mount St. Helens was observed to occur under both connected and disconnected regimes (Janda et al., 1984; Simon, 1999). However, network integration at Mount St. Helens was completed within a few years, aided by the lack of vegetation to stabilize the surface and the high relief. Lower-relief settings of channel network growth include passive margin great escarpments and tidal flats. Passive margin great escarpments are similar to the landscapes we are studying in that closed depressions dominate both. In the glaciated portion of the Central Lowland, valleys cut into the upland create the relief, while passive margin escarpments concentrate relief along the coast-parallel escarpment bounding a low-relief upland. Evolution of the escarpment is frequently modeled as headward propagation of channels disconnected from the upland (e.g., Colberg & Anders, 2014; Kooi & Beaumont, 1994; Matmon et al., 2002) and proceeds at very slow rates in some places (R. Brown et al., 2002; Heimsath et al., 2000). The upland above the escarpment typically includes a developed drainage network routing water away from the escarpment, which decreases the possibility of hydrological connection of the uplands to streams on the escarpment face relative to what may occur on the immature uplands of the glaciated Central Lowland. Growth of channel networks on tidal flats has been observed at rates of up to meters per year (Pethick, 1969) and numerical modeling, which includes the effects of vegetation, erosion, and sedimentation, suggests that headcutting into a disconnected upland is the major mechanism of channel network expansion on tidal flats (D'Alpaos et al., 2005).

Headward erosion of channels is a long-standing model of channel network development on immature surfaces (e.g., Dunne, 1980; Kooi & Beaumont, 1994). In a review of channel network development, Dunne (1980) differentiated between different mechanisms of runoff generation (Hortonian overland flow and shallow subsurface flow) and found that headward growth of channels is observed in both cases and theoretically requires exceeding a threshold overland flow length or a threshold drainage area, respectively. In both cases, the water supplied to the channel head is a first-order control on headward erosion (Dunne, 1980). In a detachment-limited erosion case headward migration of channel heads requires sufficient water supply and relief (Howard, 1994). We assert that detachment-limited erosion is appropriate for the fluvial networks we model based on the findings of Gran et al. (2013) who compare the modeled evolution of the Le Sueur River to measured morphology and ages of strath terraces. The Le Sueur River, a tributary of the Minnesota River, incised into Late Wisconsin Episode glacial till following the catastrophic drainage of Lake Agassiz through the Minnesota River Valley (e.g., Belmont et al., 2011). The knick zone and strath terraces observed in the Le Sueur River cannot be reproduced using a transport-limited erosion model but are better fit with a detachment-limited model (Gran et al., 2013). Glacial till is less cohesive than well-lithified bedrock but is frequently overconsolidated when dewatered (e.g., Boulton & Paul, 1976) and has been observed to erode in stream beds in competent clasts, rather than by disaggregation. When channel heads cut into low-relief landscapes with hydrologically disconnected uplands, both the water supply and the channel slope are limited and provide little energy for further headward erosion. For example, passive margin great escarpments commonly cut into uplands which slope gently away from the escarpment, limiting drainage area of channel heads above the escarpment and slowing their rates of propagation (Matmon et al., 2002). In postglacial low-relief landscapes, if the uplands are hydrologically disconnected, both water supplies and slope are limited by the low relief of topography. Therefore, we predict that growth of channels in low-relief postglacial landscapes proceeds at slow rates when the uplands remain disconnected. However, if surface topography does not define the true catchment supplying water to the channel head, the speed of headward erosion should increase as water from connected uplands is routed to channels, either via groundwater flow or through spillover from lakes and wetlands.

The erosion of spillways out of closed depressions is another model for the growth of channel networks that has been previously explored (Simon, 1999; Spencer & Pearthree, 2001). When a closed depression's water storage capacity is exceeded, water pours out through the lowest portion of the boundary, referred to as the spillway. If the shear stress of the flow over the spillway exceeds the threshold for incision, a channel may be carved during a spillover event, as has been studied in the context of the overtopping of earthen dams (e.g., Hanson, 1991). In addition to driving the erosion of spillways, the spillover event potentially provides an additional source of water from the upland to a channel head. This water is not derived from the drainage area of the channel but comes from a region of NCA that becomes connected during the spillover event to the external drainage network (Figure 3). Thus, even if spillover events do not generate sufficient shear stress to erode channels in the low-slope uplands, they increase the erosive power of the growing channel network, favoring more rapid propagation of channel heads than in the case in which NCAs are always unconnected. In addition to surface water connection of NCA to external networks during spillover events,

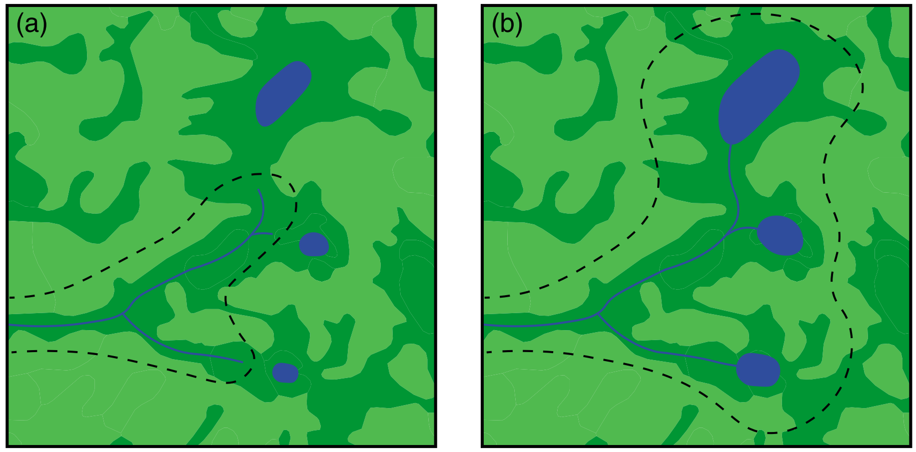

Figure 3. (a) The disconnected drainage case is illustrated where a channel, shown as a blue line, receives water from the catchment defined by the black dashed line. Dark green areas are regions of poorly drained soil with light green areas better drained. Lakes formed in closed depressions remain isolated from the channel network until the channel head extends into their basins. (b) In the connected case, the drainage network receives water from a larger area, despite the fact that subtle topographic divides may separate closed depressions from the channel network. During spillover events, like that shown in (b), lakes connect to the external drainage network effectively increasing the drainage area.

we consider the possibility that some of the precipitation falling on NCA may be passed to external drainage networks via groundwater flow over topographic divides. The subtle topography, humid climate, and layered stack of glacial sediments present over much of the glaciated Central Lowland favor both spillover and groundwater connection of NCA and motivate our consideration of these factors as potential drivers of channel network evolution in this region.

Prior to the conversion to intensive agriculture, the glaciated Central Lowlands province hosted extensive wetlands (Zedler, 2003) indicating that surface water ponding was common, at least seasonally. At times of high water, spillover from closed depressions is likely to have connected to external drainage networks. Gradual sedimentation in closed depressions diminished their storage capacity over time, increasing the likelihood of spillover events. The shallow depth of the water table and low relief of upland topography favors the lateral transport of groundwater from uplands to fluvial networks. The surficial geology of the Central Lowlands typically includes tens to more than a hundred meters of glacially derived sediments including till, outwash, and loess (Soller et al., 1999). Deposits of sorted sand and gravel occur in a range of geometries including isolated lenses, long and thin stringers, and thin laterally extensive sheets above basal till (Grimley, Anders, & Stumpf, 2016). Permeability contrasts between glacial till and outwash promote lateral flow within sorted sediments typically found at the upper surface of till sheets (Atkinson et al., 2014). Additionally, lateral flow of water at the interface between loess and underlying till is observed in streambanks. Contributions of groundwater from beyond the surface water divide to streamflow in a formerly glaciated, generally low relief basin in Ontario have been suggested by Dickinson and Whiteley (1970) based on observations of spring discharge and streamflow. Additionally, in the Prairie Potholes region of North Dakota, glaciated during the Wisconsin Episode, groundwater flow directions have been observed to reverse during dry versus wet years, requiring groundwater flow across surface water divides (Winter & Rosenberry, 1998). Therefore, the connection of upland closed depressions to external drainage networks is plausible in the glaciated portions of the Central Lowlands of the United States.

We explore the ramifications of such connections for the pace of evolution and the morphology of drainage networks using a set of numerical simulations. We hypothesize that channel networks can expand more rapidly into low-relief glacial uplands when water from these uplands is routed to growing channels than if upland NCAs remain hydrologically disconnected and that network morphology differs in these two cases. We test this hypothesis by comparing the relative rates of channel network integration in connected and disconnected drainage regimes in a numerical landscape evolution model build on the LandLab platform (Hobley et al., 2017) and consider a wide range of parameter values for the fluvial incision constant and hillslope diffusivity.

3. Method

We use the Landlab model platform (Hobley et al., 2017) to simulate the evolution of postglacial landscapes, starting from a flat low-relief surface. The surface evolves via detachment-limited fluvial incision and hillslope diffusion. The model is coupled with a new flow routing algorithm (Barnes et al., 2014a) that represents upland connection by spillover of water from closed depressions.

3.1. Governing Equations

The model presented here simulates the evolution of upland topography relative to a preexisting valley incised by meltwater. The elevation, *h,* measured relative to a base level is constrained by conservation of mass, giving:

$$\frac{\mathrm{d}h}{\mathrm{d}t} = U - \nabla\cdot\boldsymbol{q} \tag{1}$$

where t is time, $\boldsymbol{q}$ is the volume flux of transportable sediment per unit width of the land surface, U is the rate of change of elevation relative to base level, and ∇ represents divergence of a variable. We assume that U is 0 because the Central Lowlands are tectonically stable. Postglacial isostatic adjustments are neglected because of the complicated temporal history and relatively low magnitude of isostatic change in this region. Migration of the forebulge through the Central Lowland caused changes in sign of the isostatic motion through time with current rates of subsidence of ~1 mm/year in much of the province (Sella et al., 2007). The impacts of this wave of uplift and subsidence may have driven incision of large rivers, but we examine the growth of small tributaries to a large valley incised during glacial melting and assume that the incision of the master valley was larger than any later isostatic response. The total sediment flux, $\boldsymbol{q}$, includes fluxes through fluvial processes and hillslope processes. The sediment flux therefore can be expressed as a sum of these components:

$$\nabla\cdot\boldsymbol{q} = \nabla\cdot\boldsymbol{q_f} + \nabla\cdot\boldsymbol{q_h} \tag{2}$$

where $\boldsymbol{q_f}$ is fluvial sediment flux and $\boldsymbol{q_h}$ is hillslope sediment flux.

Fluvial sediment transport ($\boldsymbol{q_f}$) requires both detachment of bed material and transport of these materials. Following Gran et al. (2013), we use a detachment-limited erosion rule for incision into glacial till. We assume that all of the sediments are moved out of the model domain and deposition of sediment is not allowed. Specifically, we use the stream power law with a threshold to represent the fluvial erosion process (Howard, 1994; Whipple & Tucker, 1999), which gives the fluvial sediment flux as follows:

$$\nabla\cdot\boldsymbol{q_f} = K(A^m S^n - \theta_c) \tag{3}$$

In the above equation, K is the effective fluvial erosion coefficient, A is drainage area, S is slope, m and n are positive constant, and θ_c is a threshold minimum power required for channel formation. K is a dimensional coefficient that is sensitive to lithology and climate with units of $L^{1\text{-}2m}T^{-1}$. We use standard m and n values of 0.5 and 1(Whipple & Tucker, 1999). Many landscape evolution models using the stream power incision law include an erosion threshold or critical shear stress required to initiate erosion (e.g., Howard, 1994; Perron et al., 2008). A field study in the coastal mountains of Oregon and California (Montgomery & Dietrich, 1992) found that at channel heads, the product of slope and the square root of drainage area ($A^{0.5}S$) is on the order of 10 m. In the low-relief landscapes of the Central Lowland, we know of no similar analysis of the relationship between slope and drainage area at channel heads. The pervasive and extensive modification of this landscape for agriculture, including both extension of the drainage network to 2–3 times its presettlement length by ditching (e.g., Rhoads et al., 2016) and the creation of grassed waterways, designed to drain surface runoff while preventing gullying (Chow et al., 1999), makes it difficult to identify preagricultural channel heads or assess their slopes prior to human modification. Acknowledging the poor analog to Montgomery and Dietrich (1992), we use their threshold value of 10 m as we have no better constraint. The threshold for incision is crucial to include because we solve the equations on a finely spaced grid and do not expect that fluvial incision can be assumed to occur within each grid cell.

We idealize hillslope processes with a diffusion equation as is commonly done for landscapes with low to moderate hillslope gradient (e.g., Perron et al., 2008). Specifically, the hillslope sediment flux is proportional to the topographic gradient:

$$\boldsymbol{q_h} = -D\nabla h \tag{4}$$

where D is the diffusivity and ∇h represents the topographic gradient. Our modeled landscapes have low-relief and low hillslope gradient, making equation (4) an adequate description of hillslope processes.

With our assumptions, equations (1)–(4) yield a description for the time evolution of the topography:

$$\frac{\mathrm{d}h}{\mathrm{d}t} = -K(A^m S^n - \theta_c) + D\nabla^2 h \tag{5}$$

3.2. Model

We discretize equation (5) and numerically solve it using the modeling platform LandLab (Hobley et al., 2017). LandLab is an open-source community model that allows users to couple surface process modules acting on a gridded terrain. Existing Landlab modules allow for representation of diffusive hillslope transport and threshold stream power-based fluvial incision. We model fluvial erosion through *FastscapeEroder* module, and we use *LinearDiffuser* module to represent hillslope processes. The *FlowRouter* module can calculate flow direction and accumulation from topography based on the steepest decent (D8) algorithm. We develop and implement two additional modules to represent the filling and spilling of isolated depressions. The *PitFiller* module implements the priority-flood depression-filling algorithm described by Barnes et al. (2014b). This module fills the depressions by flooding the whole domain inward from the open boundaries, and a priority queue is used to guarantee that all the depressions are filled up to their spillover points. The *FlowRouterOverFlat* module calculates the flow direction across topography with flats created by the *PitFiller* module. This approach is presented by Barnes et al. (2014a), and it operates by calculating a gradient away from higher edges of depressions as well as a gradient toward lower edges of depressions, resulting in a convergent flow field without changing the actual topography.

We differentiate between connected and disconnected upland cases by considering two different flow routing schemes across the land surface. In the disconnected case, the flow routing method is D8 algorithm, that is, the water is passed to a single neighboring cell along the path of steepest descent. Precipitation falling into the catchments of closed depressions is assumed to evaporate or infiltrate into deep groundwater. Thus, there is no hydrologic connection between the closed depressions and the incised valley. Alternatively, in the connected case we assume that all the closed depressions are always filled with water to their spill points and precipitation falling on the upland flows through these lakes and across flat land surfaces into the river channel network. The routing of flow across flats is similar to common conditioning of digital elevation models (DEMs) to force all areas to be externally drained. In this case, water added to channels provides additional energy for the propagation of channel heads into the upland. There is no erosion of flat surfaces along flow paths because stream power erosion goes to 0 where the slope is 0. The routing used in the connected case is a reasonable simulation of the surface pathways for water spilling out of closed depressions and contributing to channel networks. This routing is not necessarily a good approximation of how groundwater may be routed and future work is needed to explore other potential routing scenarios. Nevertheless, we suggest that the rate of network evolution in the connected case is likely fairly insensitive to the routing scheme given the assumption that all NCA actually contributes water to external drainage networks. Thus, our simulations likely provide an illustration of the first-order impact of connected versus disconnected NCA on channel network evolution even if connection is largely occurring through groundwater flow.

In all cases we use drainage area as a proxy for precipitation, which is equivalent to imposing a steady and uniform precipitation rate. We do not model stochastic storm events and do not explicitly model discrete spillover events or erosion of spillways. Instead, we focus on the integrated effects of connected uplands versus disconnected uplands. We acknowledge that an intermediate condition between the two end-member scenarios we model is more likely to have occurred in the real landscapes of the Central Lowlands but chose to focus on identifying the differences in evolution rate and channel morphology for the end-member cases as a means of constraining the potential importance of routing for network evolution.

3.3. Spatial Domain, Initial Conditions, and Boundary Conditions

The model domain is a 5-km square grid of 10-m by 10-m pixels. The size of this domain is consistent with typical spacing of meltwater valleys in Central Lowland. The initial conditions of the model include a low-relief upland surface. We use a high-resolution model to allow for future investigations of the impacts of small-scale glacial geomorphic features such as ribbed moraines and subglacial fluting on channel

Table 1
Description of Numerical Experiments

Experiment	Drainage regime	K
C_base	Connected	0.0001
C_soft	Connected	0.001
C_hard	Connected	0.00001
D_base	Disconnected	0.0001

Note. The value of *D* is 0.001 in all experiments.

network evolution. For this first study, we use a flat upland surface represented by a mean elevation with noise normally distributed about 0 with a standard deviation of 0.4 m. This initial condition is meant to simulate a glacial lake plain, which represents an end-member of a homogeneous surface with no preferred flow directions. The noise is chosen to be similar to that observed presently in some glacial lake plains from the Central Lowland that date from the Late Wisconsin glaciations. Specifically, 1-m resolution light detection and ranging data from the bed of Glacial Lake Minnesota in southwestern Minnesota have a standard deviation of 0.67 m about a constant mean elevation. Similarly, the standard deviation of elevation in a 1-m resolution DEM of the Glacial Lake Leveritt basin of south central Illinois is 0.34 m. All simulations start from the same initial seed so that differences in channel networks between cases do not result from the initial condition. We note that in the connected flow routing case the initial topography determines the size and shape of the catchments providing water to the open boundary.

The left boundary of the domain is open in terms of flow routing, which means that mass can flow across this boundary. The other three boundaries are closed and do not allow mass transfer across them. These boundary conditions slow the growth of channels as the domain approaches a fully integrated channel network, however, for the majority of our simulation the channel network does not approach full integration. The open boundary represents an important component—the valley incised by meltwater at the end of the most recent glaciation. Its elevation is determined by a prescribed meltwater valley depth. The depth of such valleys is usually several tens of meters: the upper Sangamon River valley in central Illinois is 10- to 20-m deep, the Minnesota River catastrophically carved a 70-m deep valley during drainage of Glacial Lake Warren (Belmont et al., 2011), the Illinois River carved a gorge ~40- to 50-m deep during the Kankakee Torrent (Hajic, 1990), and the Wabash River carved a similar valley ~30- to 40-m deep (Wayne & Thornbury, 1951). We impose a valley depth of 40 m in our model. The incised valley has no slope and acts only as a boundary of the domain, imposing a base level on tributaries. The other three boundaries have the same elevation as the uplands. All the boundaries have fixed elevations for the duration of the model run.

3.4. Experiment Design

The simulations presented in this paper were run for 30,000–1,500,000 years. The duration of the model runs is comparable to the range of time since most recent glaciation observed across the southern margin of the Laurentide Ice Sheet in the Central Lowlands (Figure 1, Curry et al., 2011; Roy et al., 2004). Our model therefore represents various stages of postglacial evolution, or, equivalently, fluvial network development on surfaces of different age. *FastscapeEroder* module in LandLab uses implicit time integration to ensure stability. We explored a range of time steps to check for convergence, and based on these results, we use a time step of 100 years as it is stable and efficient for long-term simulations.

We explored the sensitivity of the model to variation in the erosional parameters—fluvial erosion coefficient, *K*, and diffusivity, *D*. We use values 0.001, 0.0001, and 0.00001 for *K*. We also examined cases with values 0.01, 0.001, and 0.0001 for *D*. These values are in the range typical of numerical landscape evolution models (e.g., Han et al., 2015; Perron et al., 2008). The fluvial erosion coefficient represents effects of both lithology and climate (Whipple & Tucker, 1999). High values of *K* represent wet climates and/or easily eroded bedrock. We find that the impact of variation in *K* in the disconnected case is minimal. Similarly, we do not observe substantial impacts on the morphology and evolution of landscapes as a result of changes in *D* for both the connected and disconnected cases. Therefore, we focus on two different flow routing schemes, representing connected NCA with different values of *K* (Experiments C_base, C_soft, and C_hard) and disconnected NCA (Experiment D_base; Table 1).

4. Results

4.1. Disconnected Versus Connected

Our primary goal is to determine the impact of two different flow routing schemes on the rate of growth of channel networks and morphology of modeled landscapes. Unsurprisingly, tributary channels grow much more quickly in the connected case than in the disconnected case (Figure 4). When the upland NCA remains disconnected from the external drainage network, most of the upland remains unchanged after 50,000 years

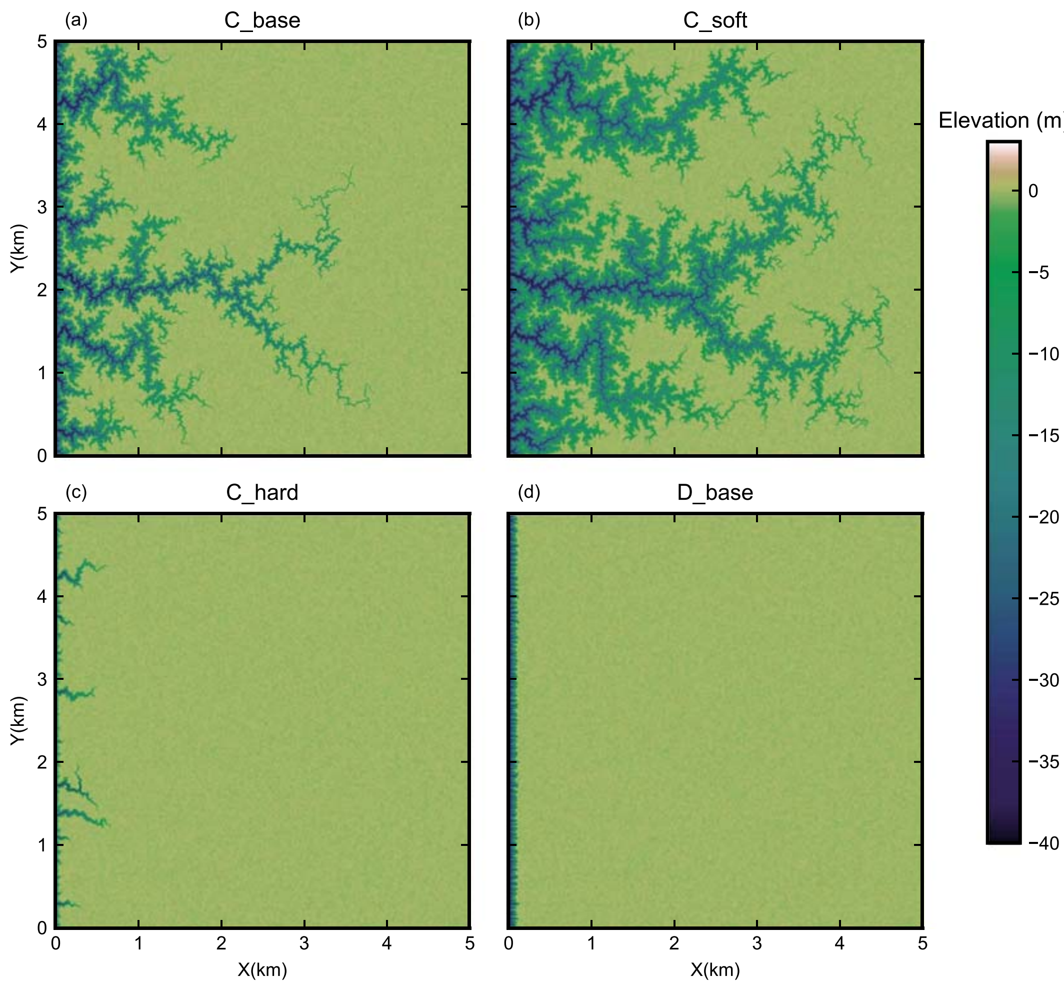

Figure 4. The modeled landscapes after 50,000-year evolution, case parameters given in Table 1. (a–c) Results of connected case with different fluvial erosion coefficient values. (d) The result of the disconnected case. The diffusivity value is 0.001 in all four simulations.

of evolution (Figure 4d), and channel growth occurs only near the preexisting valley. In contrast, in the connected case, several long channels have begun to dissect the upland after 50,000 years of evolution (Figure 4a). Fluvial erosion is sensitive to the fluvial erosion coefficient (Figures 4a–4c), but the importance of flow routing is greater. When the fluvial erosion coefficient is 1 order of magnitude smaller, the connected case still produces longer channels than the disconnected case with unchanged fluvial erosion coefficient (Figures 4c and 4d). Additionally, the channels in connected cases show more variation in length, and they are more sinuous than channels in disconnected cases (Figure 4).

We quantify the evolution of channel networks by calculating the percent of the domain which is connected by a strictly downslope path to the preexisting incised glacial valley and refer to this quantity as "integrated" into the external drainage network. The faster rate of channel expansion in the connected case results in more rapid increase in integrated area than in the disconnected case (Figure 5a). The increase in integrated area is equivalent to the decrease of NCA. Thus, both connected and disconnected cases predict that NCA becomes integrated over time (Figure 5a). After 50,000 years of evolution, in the disconnected case, less than 5% of the initial NCA has become integrated into the channel network (solid gray line in Figure 5a). In the connected, however, almost 30% of the initial NCA becomes integrated after 50,000 years (solid black line in Figure 5a). The rate of integration is sensitive to the fluvial erosion coefficient, but the flow routing scheme is still the primary control on integration. Even when the fluvial erosion coefficient is 1 order of magnitude lower, the increasing rate of percent integrated in the connected case is still faster than the disconnected case (dashed black line in Figure 5a).

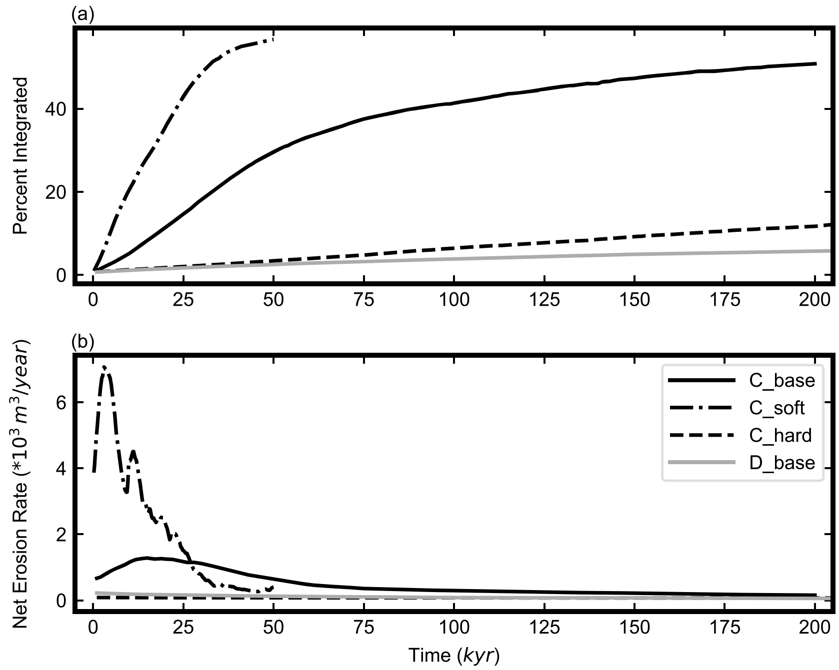

Figure 5. The evolution of percent integrated and net erosion rate over time. Black lines are results of connected cases with different fluvial erosion coefficient values, and the result of the disconnected case is shown as gray line. The diffusivity value is 0.001 in all four simulations. (a) The evolution of percent integrated. (b) The evolution of total mass loss rate.

The increase in percent integrated in the disconnected case (gray line in Figure 5a) is more linear than in the connected case, showing that the channel network grows at a constant rate. In the connected case, the integration and channel growth are initially rapid and decrease over time (Figure 5a).

We also compute the volume of material eroded within the domain as a function of time. The rate of volume loss follows a similar pattern to that of integration (Figure 5b). The volume loss rate in the disconnected case is much smaller than in the connected case, and it is constant over time (black and gray solid lines in Figure 5b). In the connected case, the volume loss rate increases early in the simulation, reaches a peak value after ~12,500 years, then the rate starts to decrease. Flow routing is an important control on volume loss rates, but the fluvial incision constant also plays a strong role. When the fluvial erosion constant is an order of magnitude smaller in the connected case, it produces a trend in total erosion that is similar to the disconnected case (black dashed line and gray solid line in Figure 5). This result indicates that there is a significant difference in the relationship between integration and total volume loss in the connected versus the disconnected cases. We probe this difference by comparing landscapes at the same state of drainage integration in the connected and disconnected cases.

Different flow routing regimes result in different landscape morphology even when the same fraction of the landscape is integrated into external drainage networks (Figure 6). For a base case fluvial erosion constant 15% of the landscape is integrated in 25,600 years in the connected case and 1,326,000 years in the disconnected case (Figures 6a and 6d). Fluvial networks in the connected case have longer and more sinuous channels than the disconnected case. The channels in the disconnected case are closely spaced and of similar length. Many channels in the disconnected case are 500- to 1,000-m long (Figure 7d). In contrast, in each of the connected cases, there are several long channels that are over 1-km long, and their lengths are more variable (Figure 7b) than channels in the disconnected case. Both connected and disconnected cases generate many short channels that are less than 500 m (Figures 7a and 7d).

The total eroded volume required to accomplish the same amount of integration of the landscape into external drainage networks is very different in the connected and disconnected cases (Figure 8). To accomplish the same degree of integration, the connected case removes much less sediment than the disconnected case, indicating that the connected case is more efficient in integration than the disconnected case. For

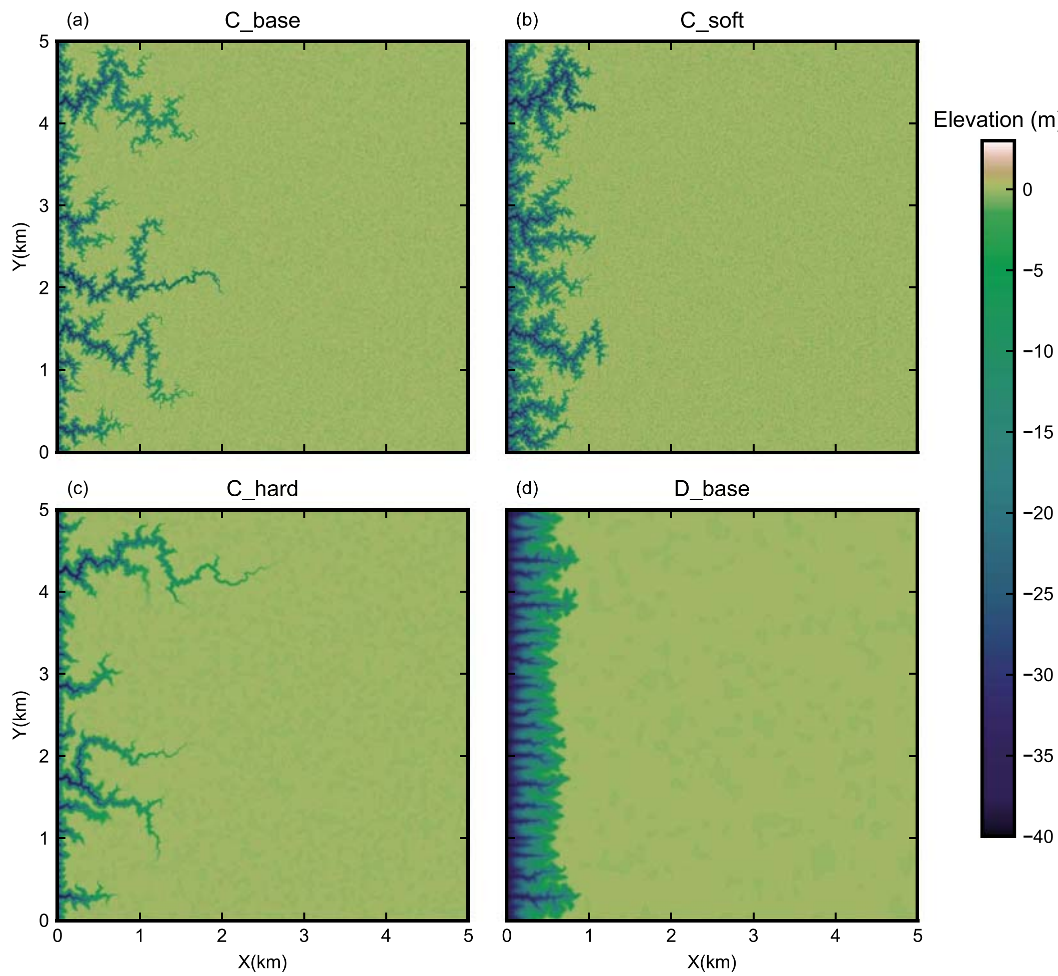

Figure 6. The modeled landscapes when 15% of the upland is integrated. (a–c) Results of connected case with different fluvial erosion coefficient values. (d) The result of the disconnected case. The diffusivity value is 0.001 in all four simulations.

example, when 10% of the upland is integrated, the total volume loss in the disconnected is twice as much as the connected case (black and gray solid lines in Figure 8a). In the disconnected case the rate of erosion is much slower and the total amount of erosion needed to achieve integration is larger than in the connected case. Thus, the very slow evolution of the disconnected case depends on both slow rates of erosion and inefficiency of erosion in producing integration of area into external drainage networks.

The difference between the disconnected and connected cases in their efficiency of integrating area into external drainage networks creates significant differences in hypsometry (Figure 9). When 15% of the upland is integrated, in the connected case, 40% of the integrated area remains high and does not change much compared to initial elevation (black solid line in Figure 9b). In the disconnected case, however, only 10% of the integrated area remains high (gray solid line in Figure 9b). Instead, 40% of the integrated area is lower than the half-depth of the preexisting valley.

The difference in efficiency of erosion and integration between the connected and disconnected cases can also be observed by comparing the net erosion and percent integrated when the accumulated discharge is the same (Figure 10). Essentially, this is comparing the landscapes under the two flow routing regimes when they have been shaped by the same amount of flow out of the domain. The accumulated discharge is computed by assuming a precipitation rate of 1 m/year and summing the product of drainage area and precipitation within the integrated portion of the landscape through time. Total erosion and percent integrated in the disconnected case initially changes more rapidly with increasing accumulated discharge than the connected case (gray solid line versus black solid line in Figure 10). The disconnected case is more

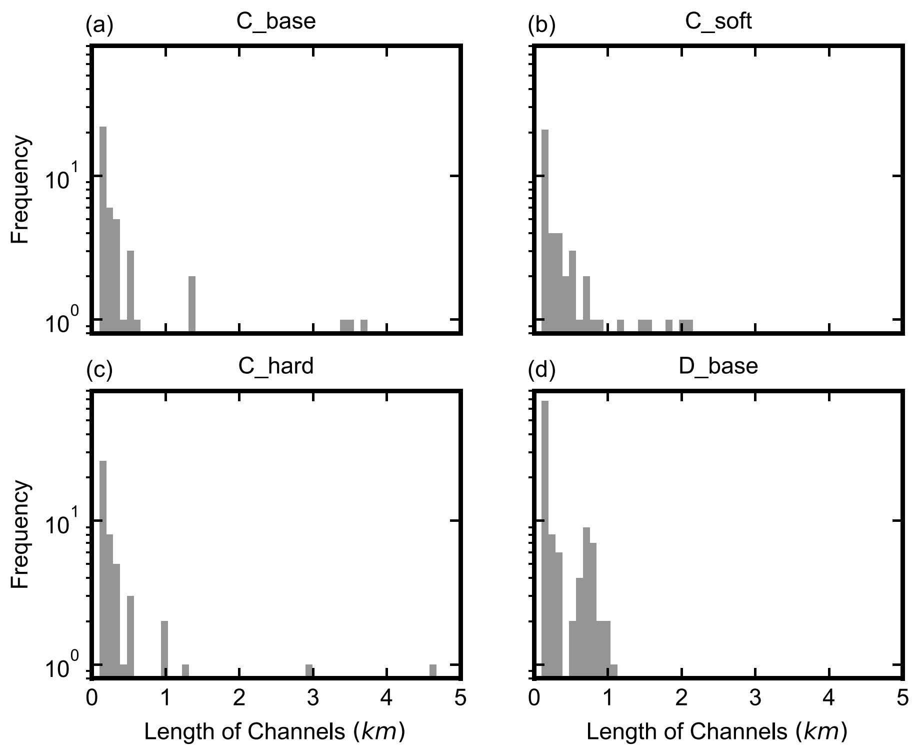

Figure 7. Histograms of channel lengths for channels above 100 m in length when 15% of the upland is integrated. (a–c) Results of connected case with different fluvial erosion coefficient values. (d) The result of the disconnected case. The diffusivity value is 0.001 in all four simulations. Note that the vertical axis is in log scale.

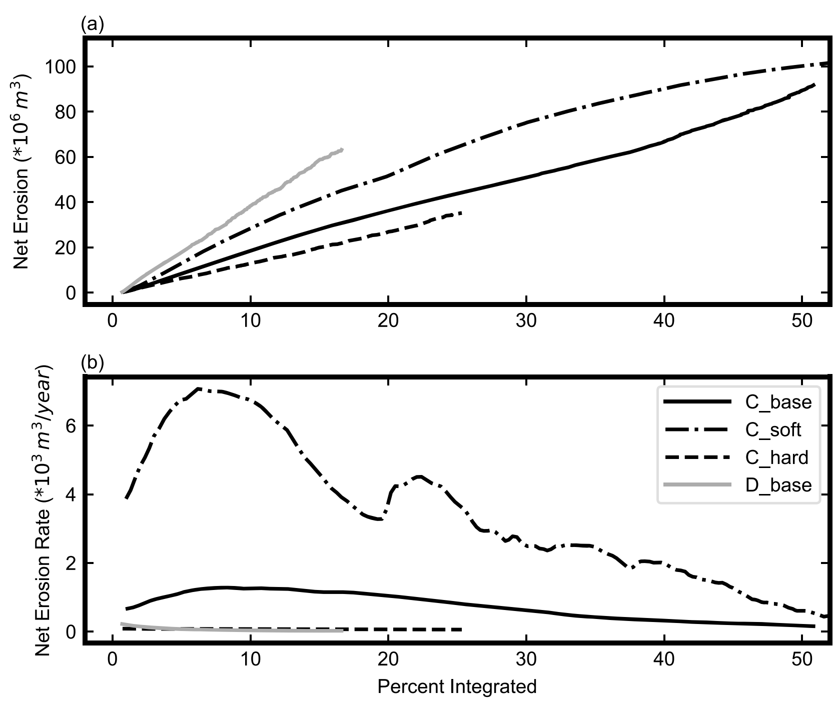

Figure 8. The evolution of net erosion (a) and its rate (b) as a function of percent integrated. Black lines are results of connected cases with different fluvial erosion coefficient values, and the result of the disconnected case is shown as gray line. The diffusivity value is 0.001 in all four simulations.

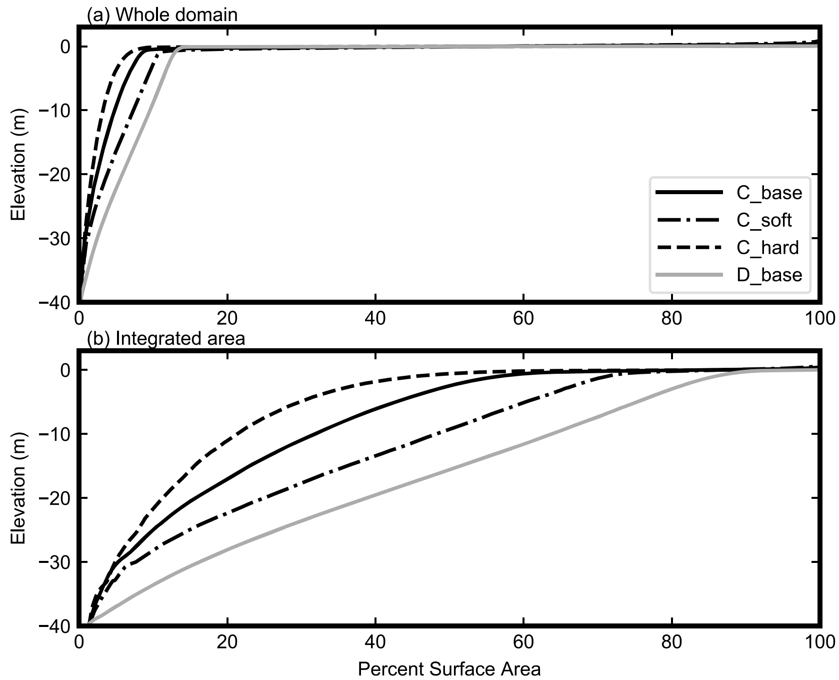

Figure 9. The hypsometric curves of the whole domain (a) and only the integrated area (b) when 15% of the upland becomes integrated. Black lines are results of connected cases with different fluvial erosion coefficient values, and gray line shows the result of the disconnected case.

efficient at erosion than the connected case when the accumulated water volume is less than ~800 km^3 (black and gray solid lines in Figure 10a). Similarly, the disconnected case results in higher fraction of integrated area when the accumulated water volume is less than ~300 km^3 (black and gray solid lines in

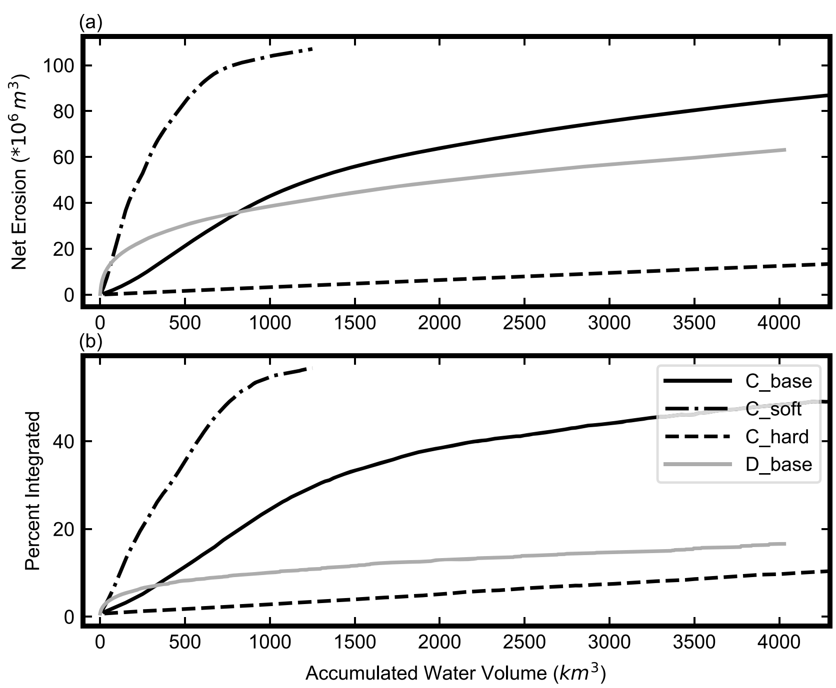

Figure 10. The evolution of net erosion (a) and percent integrated (b) as a function of accumulated water volume. The precipitation rate is assumed to be 1 m/year. Black lines are results of connected cases with different fluvial erosion coefficient values, and gray line shows the result of the disconnected case.

Figure 10b). However, at higher accumulated discharges, the connected case saw more total erosion and greater amounts of integration than the disconnected case, indicating that the efficiency of integration and erosion increases relative to the disconnected case as greater volumes of water act on the landscape.

In summary, when the depressions on the upland are hydrologically connected, the growth of channel network is faster than when the depressions are disconnected. The channel network in the connected case has longer and more sinuous channels than the disconnected case. The same degree of integration in the disconnected case requires more erosion and produces a landscape with much more low-elevation area relative to the connected case. Holding the volumes of water constant shows that the disconnected case is more efficient than the connected case at eroding and integrating the drainage network only for limited volumes of accumulated discharge.

4.2. Sensitivity to Fluvial Erosion Coefficient

We tested the sensitivity of our results to variation in the fluvial erosion constant and the hillslope diffusivity in the connected and disconnected cases. Changing the value of diffusivity to 0.01 and to 0.0001 has minimal impact on the evolution and morphology of landscapes, although higher diffusivity values do result in fewer tributary channels. However, the fluvial erosion coefficient, K, does significantly impact the rate of landscape evolution and also influences morphology to a lesser extent.

A high value of the fluvial erosion coefficient results in faster growth of channel network. After 50,000-year evolution, Experiment C_soft has longer and wider channels and larger integrated area than cases with lower K values (Figure 4). Over 50% of the whole domain becomes integrated after 50,000 years in Experiment C_soft (black dash-dotted line in Figure 5a). In contrast, less than 5% is integrated after 50,000 years in Experiment C_hard (black dashed line in Figure 5a). High values of K also create high total erosion rates (Figure 5b). This is not surprising, since K is defined to scale the erosion rates (equation (3)).

The fluvial erosion coefficient also has control on the landforms when the percent of integrated area is the same. When K is higher, the fluvial network has shorter channels (Figure 7), but there are more tributary channels (Figure 6). However, fewer tributaries in the low K cases might be a result of the competition between diffusion and fluvial processes (Perron et al., 2008). The low K cases need more time to accomplish the same degree of channel integration than high K cases, allowing more time for diffusion in the low K cases. When the same percent of integration is accomplished, the cases with higher values of K cause more overall erosion (Figure 8), and in consequence, there are more areas with high elevations preserved in the low K cases.

The connected case with a low value of K (Experiment C_hard) has the highest efficiency of integration (black dashed line in Figure 8a). Although Experiment C_hard has a very slow erosion rate, more parts of the upland are integrated than in other connected cases when the same amount of material is eroded (Figure 8). In other words, when K is higher, the fluvial network is more efficient at erosion but less efficient at integration. Thus, the efficiency of integration is not equivalent to the efficiency of erosion. In the case with the low value of K, channels are shallowly incised and erosion of tributary valley walls is very limited, meaning that network integration occurs with minimal mass removal. In contrast, when the value of K is larger, channels are wider and more deeply incised into the upland and more material is removed for the same degree of network integration.

5. Discussion—Fundamental Importance of Hydrologic Connection

In our numerical model the connection or disconnection of NCA on the uplands to growing channels has profound implications for both the rate and style of drainage network growth. The fundamental importance of connection to the modeled evolution motivates careful consideration of the potential role of hydrological connection of the uplands in driving evolution of the landscapes of the glaciated Central Lowland of the United States.

The majority of the landscape in central North America has been extensively modified to allow for intensive agriculture. Channel networks have been artificially extended by ~300% in the Upper Sangamon River Basin of east central Illinois, for example (Rhoads et al., 2016). This postsettlement modification of landscapes means that there are very few opportunities to observe hydrologic processes as they would have been before intensive agriculture. Prior to agricultural development, ponds, lakes, wetlands, and sloughs were common in the wet prairies of central Illinois (Winsor, 1987). The western Canadian Prairies are similar to the Central

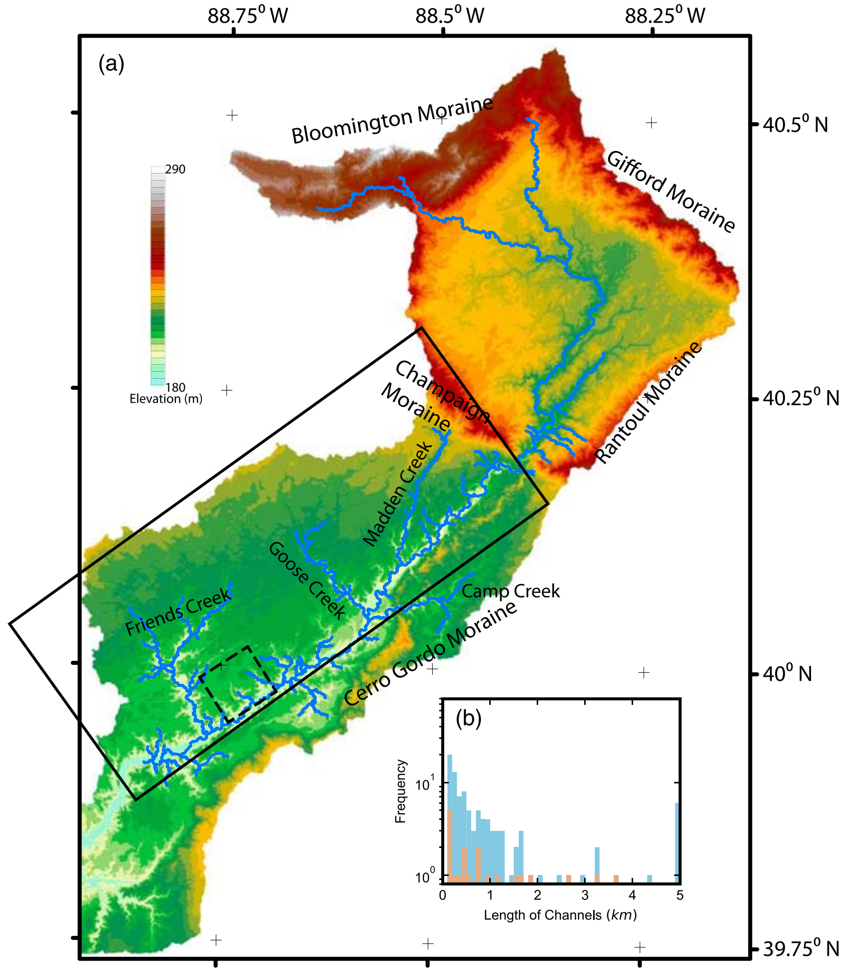

Figure 11. Digital elevation map of the Upper Sangamon River basin in east central Illinois (a). The presettlement channel network as estimated by Rhoads et al. (2016) is shown by the blue lines. In the area defined by the black rectangle we measure the lengths of channels extending from the northeast side of the Sangamon Valley and show the distribution of these lengths as blue color in the inset histogram (b), which can be compared to Figure 7. The area shown in Figure 2 is indicated by the dashed line box and the distribution of channel lengths in this area is shown as light orange color in the histogram (b).

Lowland in their glacial history and the lack of a well-defined, externally draining fluvial network. Instead, much of the land drains to seasonal or persistent wetlands or sloughs (Stichling & Blackwell, 1957). In this environment, wetland closed depressions have variable connection to streams over time, acting as NCA when water levels are low and episodically connecting and discharging into stream networks when full (Shook & Pomeroy, 2011). It is reasonable to assume that these wetlands also contributed episodically to streamflow via filling and spilling. Therefore, we believe that the connection of NCA in the glaciated Central Lowland may have occurred in these landscapes prior to anthropogenic modification and extension of the drainage networks.

The pace of network growth in our numerical model as well as the form of the modeled channel networks can be qualitatively compared to landscapes of the Central Lowland. However, we emphasize that our numerical model is not meant as a simulation of the evolution of a particular place but as an idealization of processes contributing to postglacial evolution. Therefore, we qualitatively compare characteristics of a channel network developed on late Wisconsin episode low-relief till plains adjacent to the Sangamon River Valley incised during the end of this most recent glaciation (Figure 11) to our modeled landscapes.

The Upper Sangamon Valley, in east central Illinois, carried meltwater of the Lake Michigan Lobe during its retreat following glaciation approximately 20,000 years ago (Grimley, Anders, & Stumpf, 2016; Grimley,

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Wang, & Oien, 2016). Moraines define the drainage divide around most of the basin except the northeast boundary below the Champaign Moraine. South of the Champaign Moraine, the Sangamon Valley incised ~15 m and tributaries developed on both sides of the valley (Figure 11). On the southern side of the lower valley, short tributaries incise into the Cerro Gordo Moraine and Camp Creek breaches the moraine. The high relief of the moraine likely contributed to active channel incision here. In contrast, on the northern side of the valley the drainage divide is not defined by a glacial moraine, but a broad low-relief plain separates the Sangamon basin from the Salt Creek watershed to the north. Prior to agricultural drainage, the area between the Sangamon River and Salt Creek included significant areas without incised streams. Three longer tributaries of the Sangamon (Friends Creek, Goose Creek, and Madden Creek) were likely connected to the main stem of the Sangamon River prior to incision (Rhoads et al., 2016). Broad convexities in the long profiles of these streams suggest that knick zones generated by incision of the Sangamon have propagated upstream, though typical slopes of ~10^{-3} make these features difficult to measure (Rhoads et al., 2016). Smaller tributaries on the north side of the basin have a distribution of lengths including many channels with lengths of several kilometers (Figure 11). We mapped these channels using a 1-m resolution DEM derived from light detection and ranging (Illinois State Geological Survey) along with georeferenced digital raster graphic maps of the original U.S. Geological Survey paper topographic quadrangle maps. The location of the preagricultural channel head was estimated for these channels by eye using valley morphology and channel straightness to assess channelized reaches. We assume that ditching extended from the preagricultural channel head and that straightening of natural streams was limited, making our length estimates minimum values. Channel lengths were measured by digitizing stream segments from the channel heads down slope to meet the incised Sangamon Valley. Over the ~45-km length of the reach, we measure ~100 channels on the northern side of the valley with lengths $>$100 m (Figure 11). Within the area shown in Figure 2, a domain the same size as our model domain, we measure 20 channels longer than 100 m, including 7 longer than 1 km. Our numerical model with disconnected flow routing is unable to produce channels of this length or variety of lengths. In contrast, our model with connected flow routing does produce channels with a range of lengths, including lengths of more than a kilometer, over timescales of ~25,000 years (Figure 7). We stress that our model is not meant as a simulation of evolution channels in the Sangamon Basin, and we cannot be certain of the postglacial topography or geometry of the channel network at the time of incision of the Sangamon. We simply compare the channel network to our model to suggest that connection of NCA to external drainage networks may have influenced their evolution, motivating future work aimed at reconstructing the history of fluvial network growth and hydrological connection in the Central Lowland of the United States.

Having established that the pace of evolution and morphology of modeled channel networks formed via connected drainage regimes is plausibly similar to that observed in real systems, we consider what the qualitative impact of temporal variability in climate and connection of NCA may have been. First, we recognize that the end-member scenarios of disconnected and connected drainage are unlikely to be realized in the real system—an intermediate case with connection occurring in some places for a fraction of the time is more likely. The modeled integration rate is much faster in the connected case than in the disconnected case, suggesting that even if the connection of NCA is intermittent and only occurs during a small fraction of the time, it may still dominate the expansion of channel networks. The climate of the Central Lowland during the Holocene was very dynamic. Holocene pollen data document broad-scale migration of the forest/prairie border, suggesting that precipitation decreased in the early Holocene and increased again in the late Holocene (Bartlein et al., 1984). Changes in vegetation and precipitation are both likely to have significantly influenced landscape evolution. Changes from forest to prairie vegetation are likely to have strongly influenced the resistance to erosion at the channel head. Therefore, we expect that values of the fluvial incision constant, K, should change with vegetation type. An increase in precipitation can accelerate erosion by increasing surface runoff. Moreover, the connection of NCA via filling and spilling is more likely to happen under wet conditions. Thus, intervals of connection were likely limited to or more frequent during wet periods, and the channel networks present may dominantly have evolved under wetter than average conditions.

In our model, the connection of NCA is via flow paths that would be expected for unchannelized surface flow spilling out of closed depressions. Groundwater flow is another potential way to add water from NCA on uplands to external drainage networks. The presence of strong permeability contrasts in the subsurface due to layering of glacial till, outwash, and loess favor lateral flow of water. The existence of a shallow water table near the surface, especially in wet conditions, also supports lateral flow at shallow depths. Observations from North Dakota within the prairie potholes region document reversals in the direction of water movement between wetlands and groundwater accompanying cycles of drought and wetter conditions (Winter & Rosenberry, 1998). We have not attempted here to model the paths of subsurface flow but suggest that groundwater routing in the wet and low-relief postglacial setting of the preagriculture Central Lowlands is an interesting target for future research. We predict that connection through subsurface flow would result in a similar rate of drainage integration as in the case of connected surface flow, but anticipate a different planform evolution channel network because surface topography would not control flow routing. We note that the planform channel network in our current model is strongly dependent on the initial conditions because the initial allocation of water to the edge of the main valley depends on the initial topography. Depending on the routing scheme developed to model groundwater routing, surficial initial conditions would likely become less important to the planform evolutions.

In conclusion, in our numerical model the connection and disconnection of NCA in uplands have significant impacts on both evolution and morphology of postglacial landscape. When upland closed depressions are connected to external drainage, much faster rates of erosion and integration, and longer, more sinuous channels occur than when upland NCA remain disconnected. The connected case accomplishes the same degree of integration with lower total erosion than the disconnected case. Although it is difficult to observe such hydrologic connection in today's landscape due to extensive agricultural activities, a simple comparison between real landscapes and model results suggests that hydrologic connection of NCA could have had a profound importance in the evolution of postglacial landscapes in Central Lowland of the United States.

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