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Big Pine Creek Ditch revisited: Planform recovery to channelization and the timescale of river meandering

Chelsy R. Salas, Bruce L. Rhoads *

Department of Geography and Geographic Information Science, University of Illinois at Urbana-Champaign, Urbana, IL 61801, United States of America

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ABSTRACT

Channelization has changed the form and dynamics of rivers on a global scale. In the midwestern United States, widespread straightening of meandering headwater streams has been undertaken for the purpose of improving land drainage. Few studies have examined in detail how meandering streams respond to straightening, especially over timescales of nearly a century following straightening. This study uses historical aerial imagery and contemporary lidar data to examine how a small headwater stream that was straightened nearly a century ago, Big Pine Creek Ditch (BPCD) in Indiana, USA, has adjusted to straightening and to relate observed changes to stream power. The evolution of this fluvial system was examined in the late 1970s and this study updates that previous work using additional imagery and GIS-based methods, extending the timeline of analysis from 1932 to 2018. Results reveal that recovery varies spatially along the length of BPCD with some reaches not adjusting at all, some reaches increasing in sinuosity but then being artificially restraightened, and other reaches evolving continuously in response to channelization. For reaches that have evolved continuously, the rate of increase in sinuosity over time is directly related to bankfull stream power per unit length. Rates of increase in sinuosity per logarithmic unit of power per unit length have been linear and should attain the prechannelized relation between sinuosity and stream power over a timescale of about 100 years. Reaches with estimated bankfull stream power per unit area below 25 W m^{-2} exhibit no recovery of sinuosity, whereas those with power per unit area greater than 50 W m^{-2} have progressively increased in sinuosity. Between these thresholds, straightened reaches may or may not increase in sinuosity. Not all aspects of channel planform recovery are captured by changes in sinuosity; the prechannelized meandering stream exhibited greater lateral shifts in the position of the meander belt than do current meandering reaches. Overall, the study provides insight into spatial and temporal variability of recovery to channelization, the long-term recovery of meandering streams to straightening, as well as the timescale of meander development in straight channels.

1. Introduction

Human impacts on the geomorphological characteristics of rivers and streams are a global hallmark of the Anthropocene. These impacts include indirect effects associated with changes in climate and land use as well as direct effects involving physical modification of river form or implementation of barriers, such as dams (Rhoads, 2020). Channelization, the widening, deepening, and straightening of river channels for flood control, to form property boundaries, or to improve land drainage, is an especially prominent type of direct impact (Brookes, 1988). Enlargement and straightening of meandering rivers through channelization increases the power of bankfull flows, enhancing bed-material transport capacity and the potential for subsequent channel change. It also leads to well-documented detrimental impacts on the ecological quality of streams (Schlosser, 1982; Frothingham et al., 2001; Sullivan et al., 2004; Lau et al., 2006; Kairo et al., 2017; Blake and Rhanor, 2020). Morphological adjustments of meandering rivers to channelization vary (Brookes, 1987a), but include incision and widening (Parker and Andres, 1976; Simon, 1989; Simon and Rinaldi, 2006), recovery of sinuosity (Noble and Palmquist, 1968; Barnard and Melhorn, 1982), and the development of a sinuous low-flow channel following net deposition within a straight, enlarged channel (Landwehr and Rhoads, 2003). How any particular river will respond to channelization often is difficult to predict, but factors influencing the response include the magnitude of increase in stream power, the erodibility of bed and bank materials, and the extent of channel widening.

* Corresponding author.
E-mail address: brhoads@illinois.edu (B.L. Rhoads).

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Throughout the midwestern United States many headwater streams have been and continue to be channelized for the purpose of land drainage (Rhoads and Herricks, 1996; Frothingham et al., 2002; Urban and Rhoads, 2003; Rhoads et al., 2016). Only a few studies have examined responses to channelization in this region, but incision, recovery of sinuosity, and development of a sinuous low-flow channel have all been documented (Noble and Palmquist, 1968; Barnard and Melhorn, 1982; Simon and Rinaldi, 2000; Landwehr and Rhoads, 2003). Recovery of sinuosity and development of a sinuous thalweg are most common in low-relief landscapes of the Midwest shaped by late Wisconsin glaciation; however, many channelized reaches in such landscapes do not exhibit any noticeable changes in channel planform decades after initial channelization (Urban and Rhoads, 2003; Rhoads et al., 2016). To some extent, lack of recovery may be related to repeated maintenance of straightened channels, but natural factors, such as the low power of channelized streams and resistant bed and bank materials, also limit the capacity for adjustment. Adjustment is slow when bankfull stream power per unit area is less than 35 W m^{-2} (Brookes, 1987a), a condition met by some channelized streams in the region (Rhoads and Herricks, 1996). Although past work has documented responses to channelization or lack thereof in a few cases in Wisconsin-glaciated landscapes of the Midwest, spatial variability in response to channelization and the timescale over which reaches that do respond adjust to channelization remain poorly understood. Such understanding is important for assessing the degree to which humans act as geomorphic agents in this setting. Widespread modification of stream channels resulting from channelization implies that human action can be viewed as having a catastrophic impact on the form of headwater streams in the sense that changes in form caused by channelization are not readily undone and persist for many decades (Urban and Rhoads, 2003).

The purpose of this study is to evaluate spatial and temporal variation in the planform response of an artificially straightened meandering river to channelization and to relate this variation to the potential controlling factor of stream power. The work builds on and extends findings of previous research examining the timescale of planform recovery of this same river to channelization (Barnard and Melhorn, 1982). Previous analysis used rather rudimentary methods of assessing change in channel position over time and examined planform change using only three sets of aerial images over a period of 39 years. The present study employs GIS-based analysis of planform change using ten sets of aerial images over a period of 86 years. The results not only inform how the response of meandering rivers to channelization can vary spatially, but provide insight into the timescale of this response and the extent to which human actions produce long-lasting, catastrophic change in channel form. The findings also contribute to the understanding of how straight rivers evolve into meandering forms by

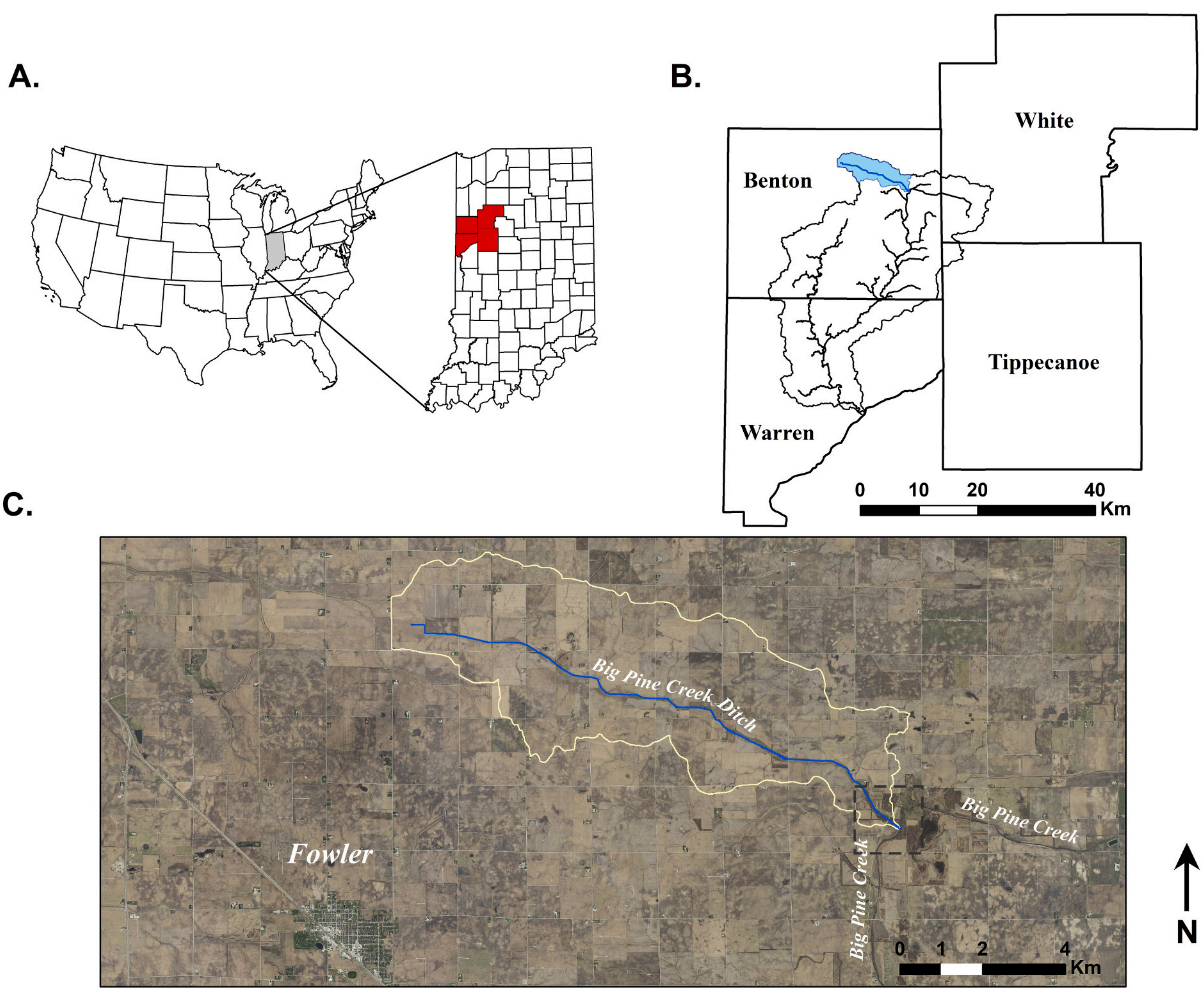

Fig. 1. (a) location of Indiana counties containing Big Pine Creek watershed (red) (b) drainage basin and stream network of Big Pine Creek (black lines) and location of Big Pine Creek Ditch (blue line) and its watershed (blue shading) (c) aerial image showing Big Pine Creek Ditch (blue line, watershed boundary in yellow) and Big Pine Creek (black dotted square is section 1 T25N R7E). Upstream of the confluence with Big Pine Creek Ditch, Big Pine Creek consists of a drainage ditch that extends eastward into White County (see panel b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

documenting the timescale over which meandering develops, spatial variability of this timescale, patterns of meander development, and rates of increase in channel sinuosity over time.

2. Study Area

Big Pine Creek Ditch (BPCD) is a small headwater stream located in Benton County, Indiana; it represents one of two major headwater branches of Big Pine Creek, a tributary to the Wabash River (Fig. 1). BPCD extends about 13 km headward in a northwesterly direction from where it joins Big Pine Creek and has a drainage area of 40 km^2. The morphology of BPCD varies considerably. Along much of its length it has the form of a straight trapezoidal ditch with top widths of about 15 to 20 m, bottom widths of about 6 to 8 m, and depths of 2 to 4 m. These reaches generally lack riparian vegetation. Other reaches consist of a meandering or relatively straight channel lined by riparian trees with a bottom width of about 5 to 6 m and channel banks 3 to 4 m high.

The watershed of BPCD is located on the Iroquois Till Plain physiographic division of Indiana, which consists mainly of glacial till of Wisconsinan age with pockets of sand and gravel outwash deposits (Gray, 2000, 2001). The thickness of this material varies from 5 to 25 m and underlying bedrock consists mainly of limestone and shale (Yeh, 1969). Wet, poorly drained silt-loam and silty clay loam soils have formed in thin loess and underlying glacial till (Barnard, 1977; Franzmeier et al., 2004). Surface elevations range from a high of 248 m. a.s.l. on Mt. Gilboa, a glacial kame situated along the Nebo-Gilboa morainal ridge at the northern boundary of the watershed (Yeh, 1969), to 216 m.a.s.l. at the mouth of BPCD. Average basin slope is 1.7%.

European settlement of the region began in the early 1830s with organization of Benton County occurring in 1840 (Gorby, 1886; Barnard, 1977; http://genealogytrails.com/ind/benton/county-history.html). Much of the land was originally wet prairie (Franzmeier et al., 2004), which when suitably drained and managed, became productive farmland for growing crops. Today, 96% of the land in Benton County is farmed (USDA, 2017) and the BPCD watershed is almost entirely farmland. General Land Office (GLO) maps produced from surveys in 1834 show that what is now BPCD existed at that time as a small meandering stream at the upstream end of Big Pine Creek (Fig. 2). Although today Big Pine Creek upstream from the confluence with BPCD consists of a drainage ditch extending eastward (Fig. 1b and c), this headwater branch is not documented on the GLO maps; instead, the maps indicate that what is now BPCD was originally the headwater portion of Big Pine Creek. The small tributary where Big Pine Creek turns abruptly to the northwest in the 1830s (labelled as A on Fig. 2) is today a tributary of BPCD and is distinct from the modern eastern branch of Big Pine Creek.

The origin of the creek on the GLO maps is in section 30 T26N R7W –

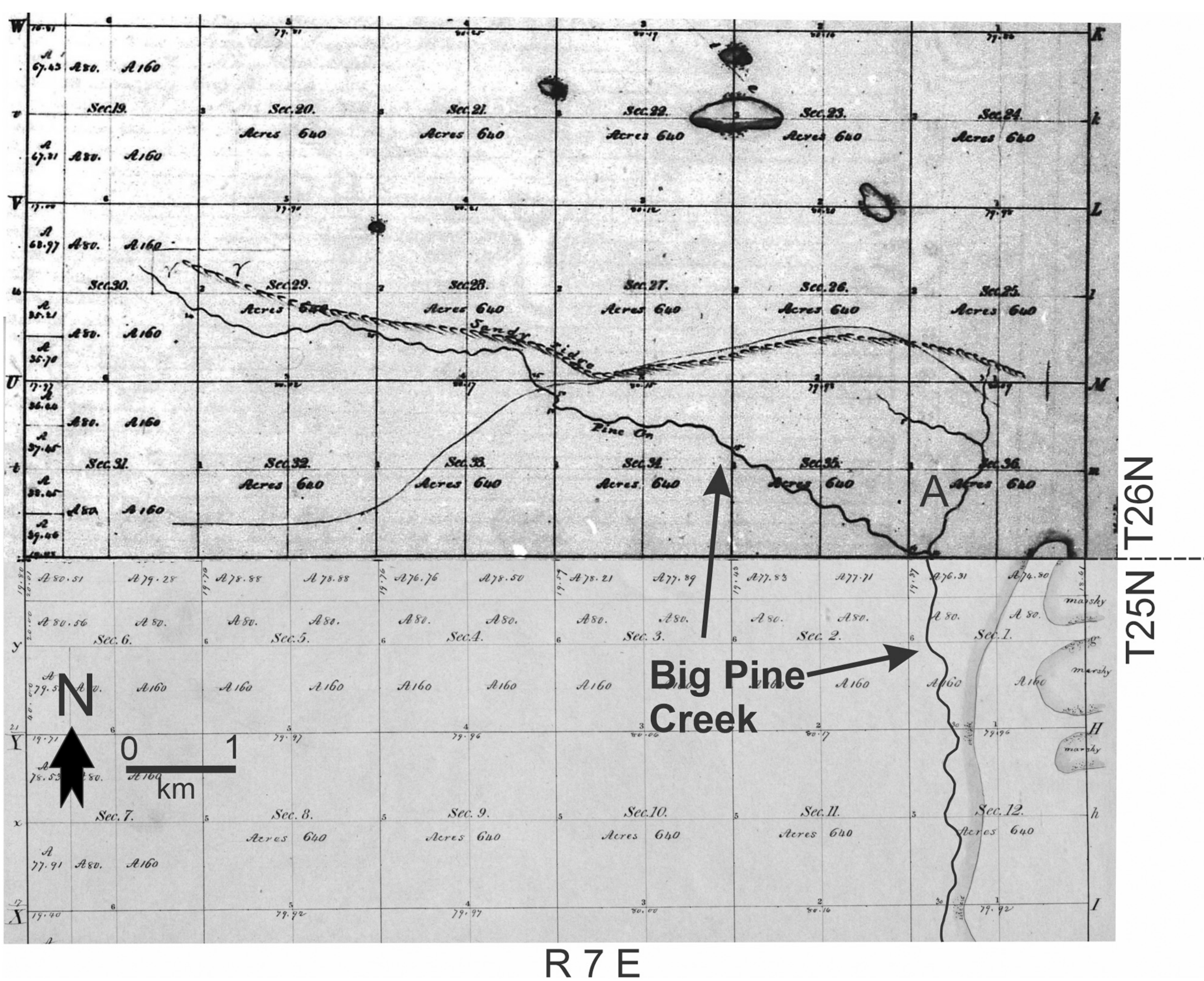

Fig. 2. General Land Office survey maps from 1834 for portions of T25N R7E and T26N R7E showing location of Big Pine Creek (labelled Pine Ck. on map). Tributary at A is today a tributary of Big Pine Creek Ditch, which now extends into section 1 T25N R7E. Note absence of a branch of Big Pine Creek extending eastward from section 1 T25N R7E (see Fig. 1b and c).

a location about 3.9 km downstream from the current origin of BPCD in section 23 T26N R8W. A county map from 1876 (Indiana Historical Society, n.d.) indicates that the eastern headwater branch of Big Pine Creek did not exist at that time and depicts the origin of the creek in section 24 T26N R8W, 1.75 km from its current origin and near the location of its origin in the earliest aerial photos from 1939. Whether the creek was lengthened artificially between the 1830s and 1870s is not known, but many stream channels have been extended headward in wet prairie regions of the Midwest to provide outlets for tile drainage systems (Rhoads and Herricks, 1996; Rhoads et al., 2016). Clearly, the excavation of the eastern headward branch of what is now Big Pine Creek sometime after 1876 is an example of channel extension. Marshy areas are noted on the GLO maps to the east of Big Pine Creek in section 1 T25N R7E, but not in the headwaters of the creek (Fig. 2). Nevertheless, as early as the late 1800s, wet conditions throughout much of the county led to installation of drainage tiles under farm fields to facilitate land drainage (Gorby, 1886; Barnard, 1977). Installation of these tiles would have generated a demand for outlet ditches into which subsurface tiles could drain.

In an effort to improve land drainage along what is now BPCD, a major channelization project was undertaken in 1932. Details of this project are described by Barnard and Melhorn (1982) and the original project plans were recovered from the drainage records archive, Ditch Docket #137, at the Benson County Courthouse. The project involved straightening and enlarging the channel of BPCD over a distance of 11.4 km upstream from its mouth at Big Pine Creek. By this time, the eastern headwater branch of Big Pine Creek had been excavated and the confluence between BPCD and Big Pine Creek had formed at its current location (section 1 T25N R7E) (Fig. 1). The channel of BPCD was shaped into a trapezoidal cross-sectional form along its length with bottom width increasing systematically in the downstream direction. Most important for the present study, meandering portions of the channel were straightened along its entire length. The project as designed involved the excavation of 121,748 m^3 of earth material (Barnard, 1977).

Change in channel planform subsequent to the 1932 channelization project was examined by Barnard (1977) and Barnard and Melhorn (1982) using sets of aerial imagery for 1938, 1963, and 1971. The path of the channel for each set of imagery was determined by manual tracing using unrectified aerial images at different scales (≈1:21,000 for 1938 and ≈1:16,000 for 1963 and 1971). A map of the prechannelized path of the stream was also produced based on interpretation of remnant meander scars visible on the 1938 images. No attempt was made to superimpose channel paths from different years to directly compare changes through time. Based on the tracings, changes in channel sinuosity over time were determined for reaches corresponding to 1.6 km in length and reaches over which the channel bed elevation changes vertically by 1.5 m. Although the lengths of these two types of reaches could differ, the report is not clear regarding which reach lengths were actually used to determine sinuosities. Slopes for each reach were estimated from elevation information for the original design plans and from 1962 topographic maps. In addition, values of discharge for the two-year flood for each reach were derived using a flood estimation procedure for streams in Indiana (Davis, 1974). The slope-discharge data were used to compute stream power per unit length for each reach for each year of aerial imagery as well as for the prechannelized state of the stream.

Plots of sinuosity (linear axis) versus stream power (logarithmic axis) were produced for each case (Fig. 3a) and the slopes of best-fit linear regression relations for these plots (λ) were then plotted versus time to infer the temporal trajectory of recovery (Fig. 3b). The results suggested that the rate of increase in sinuosity for the artificially straightened creek increases with increasing steam power and that the overall recovery trajectory of increasing sinuosity per logarithmic unit of stream power is nonlinear with a progressively declining rate of increase over time. Based on projection of the nonlinear trend in λ to the value associated with the pre-channelized planform of BPCD, Barnard and Melhorn (1982) concluded that full recovery would be reached about 165 years after the initial channelization (Fig. 3b).

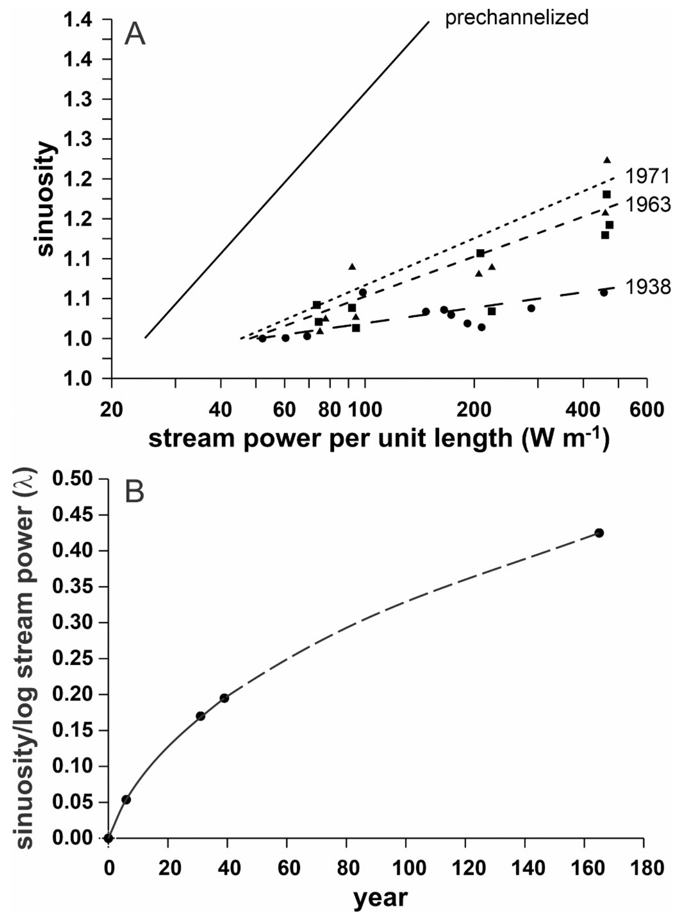

Fig. 3. Plots adapted from Barnard and Melhorn (1982) showing (a) sinuosity versus stream power per unit length (W/ m) for three different years of aerial imagery and for the prechannelized planform of Big Pine Creek Ditch (b) trend in adjustment over time of the relation between sinuosity/ log of stream power per unit length.

The work by Barnard (1977) and Barnard and Melhorn (1982) is one of the few studies to systematically examine the planform response of a meandering stream in the agricultural Midwest to straightening associated with channelization. It provides the basis for re-analysis of planform change for BPCD using rigorous geospatial methods and additional aerial imagery for periods before and after 1971. The present analysis updates the story of recovery to channelization for this headwater fluvial system and also allows the inferred response (Fig. 3b) to be evaluated in relation to change over an additional four decades since the initial study.

3. Methods

Aerial images of BPCD for the years 1938, 1951, 1957, 1963, 1971, 1983, 1998, 2005, 2013, and 2018 were obtained from a variety of sources and processed using ArcGIS (Table 1). Aerial images from 1938 to 1998 lacked spatial control and were georeferenced in ArcMap. Georeferencing was based on spatial coordinates of control points for the orthorectified 2018 imagery. Spatial coordinates for this imagery were transformed in ArcMap from the state plane system to the universal transverse Mercator (UTM) system. On each unrectified image, 10 control points were identified and linked to corresponding locations on the 2018 orthorectified imagery. Control points were intentionally located within the vicinity of BPCD and spaced along its length on each image to enhance rectification accuracy (Hughes et al., 2006). Cubic

Table 1
Aerial photography used in analysis of planform change.

Year	Source	Project ID	Rectified
1938	USDA	BEV	No
1951	USDA	BEV	No
1957	USDA	BEV	No
1963	USDA	BEV	No
1971	USDA	BEV	No
1983	USDA	18007	No
1998	USGS -NAPP	10845	No
2005	State of Indiana	N/A	Yes
2013	State of Indiana	N/A	Yes
2018	State of Indiana	N/A	Yes

spline transformation, a true rubber sheeting approach that fits the source control points exactly to the target control points, was used for georeferencing. A drawback of this method is that it does not produce an error metric, such as root mean square error, because the fit has no error. The average RMSE of transformations obtained using 2nd-order polynomial functions were generally less than 1 m and never exceeded 1.5 m. Any error inherent in the cubic spline method at locations other than the control points should be at most equal to these values and presumably is less than these values. To further evaluate rectification accuracy of the images, the Swipe Layer tool in ArcMap was used to assess how well the positions of BPCD at fixed locations not used as control points, such as bridge crossings, matched on the georeferenced images and the orthorectified 2018 image at a viewing scale of 1:1000. In all cases, no visible differences could be observed in channel positions between the orthorectified and georeferenced images.

Once all of the images were georeferenced, the centerline of the channel path on each image was digitized in ArcMap. The centerline rather than each channel bank was digitized because the small width of the channel, along with banks obscured by vegetation cover on some images, only allowed the general path of the channel to be identified consistently on all images. For georeferenced images, all of which had some overlap with adjacent images, digitization was restricted to the center part of the images where any potential error not completely corrected for by georeferencing is minimized. The spacing of digitized points varied depending on planform complexity with a minimum spacing of about one channel width (5 m) for reaches with curving or irregular channel paths. The planform of BPCD prior to channelization in 1932 was in some locations clearly visible as remnant meander scars produced by channelization (Fig. 4). The extent of visibility of the prechannelized stream was discontinuous so that only portions of the prechannelized planform could be captured through digitization of these meander scars.

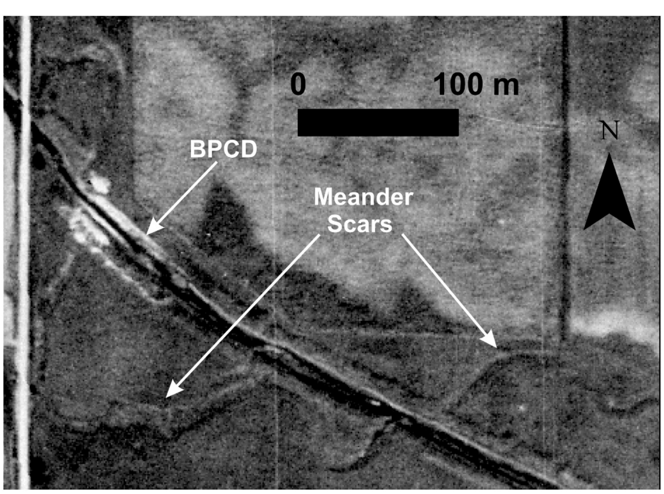

Fig. 4. Scene from 1938 aerial imagery showing straight planform of Big Pine Creek Ditch (BPCD) following channelization and remnant meander scars of meandering planform prior to channelization.

The digitized centerlines for each image year were superimposed to identify where along BPCD detectable change in channel planform has occurred and where channel planform has not changed over time. This process led to the classification of the total length of BPCD into distinct reaches based on whether or not planform over the length of the reach did or did not exhibit change. For each reach, sinuosity for each year was determined as the length of the channel centerline divided by the straightened path of the channel. The design plans did not include a map of channelization, but the straightened path of BPCD was apparent on the 1938 aerial imagery, even though at that time some reaches of the channelized stream exhibited minor planform adjustment in response to the channelization. To determine the valley slopes (S_v) of the study reaches, elevations at the upstream and downstream ends of the reaches were identified using Lidar data obtained in 2018 by the state of Indiana (Table 2). Valley slopes were calculated by dividing the difference in these elevations by the straightened length of the reach. Discharges of the two-year flood (Q_2) for each reach, assumed to be similar to bankfull discharge (Rhoads, 2020), were estimated from a regional general least squares regression relation based on drainage area for Region 1 of Indiana – the region containing Benton County (Rao, 2006):

$$Q_2 = 146.884A^{0.64} \quad R^2 = 0.99 \tag{1}$$

where A is the drainage area at the downstream end of the reach (Table 2). Stream power per unit length (Ω) is:

$$\Omega = \gamma Q_2 S_v \tag{2}$$

where γ, the specific weight of water, is assumed to be 9810 N m^{-3} (Table 2). This metric of power per unit length, because it is based on valley slope, defines the potential stream power of straightened reaches of BPCD. It represents the human-imposed energy regime to which the channelized stream adjusts.

4. Results

Overlay analysis of channel centerlines indicates that adjustment to channelization has varied spatially along the length of Big Pine Creek Ditch. To characterize this variability, the total length of the creek is divided into three types of reaches: (1) those exhibiting little or no increase in channel sinuosity (S_I) since initial channelization, (2) those exhibiting increases in sinuosity after channelization, but that were subsequently artificially restraightened, and (3) those exhibiting continuous development of meandering through increases in sinuosity over the period of analysis (1932–2018) (Fig. 5). Determinations of changes in channel sinuosity were restricted to changes substantial enough to exceed the bounds of the original straight drainage ditch. For

Table 2
Valley slope, drainage area, discharge, and stream power measurements.

Reach	Valley slope	Drainage area (km^2)	Estimated discharge of 2-year flood (m^3/s)	Stream power per unit length (W/m)	Stream power per unit area (W/m^2)
A	0.0009	39.52	23.79	209	29.8
B	0.0017	39.42	23.75	404	57.8
C	0.0013	38.81	23.56	311	44.4
D	0.0013	35.97	22.40	286	40.9
E	0.0022	31.98	20.77	447	63.8
F	0.0007	29.43	19.70	140	20.0
G	0.0010	29.42	19.70	200	28.7
H	0.0044	28.08	19.12	822	117.5
I	0.0013	27.84	19.01	246	35.2
J	0.0021	23.29	16.96	342	48.9
K	0.0010	23.06	16.85	173	24.7
L	0.0017	9.17	9.34	153	21.8

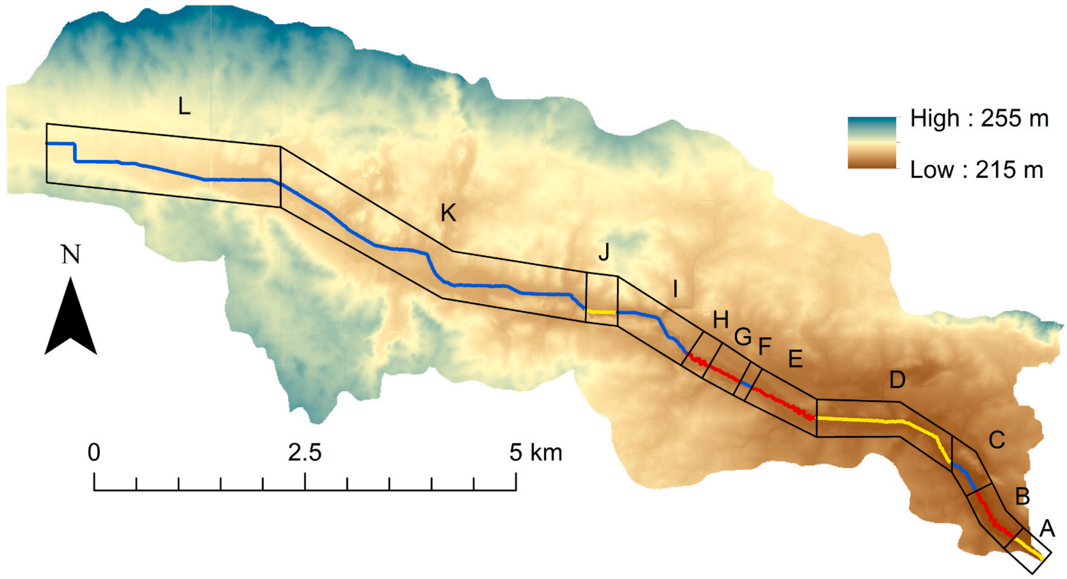

Fig. 5. Classification of the total length of Big Pine Creek Ditch into reaches displaying no change in planform over time (blue), initial increase in sinuosity but artificially restraightened (yellow) and continuous increase in sinuosity over time (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

some portions of Type 1 reaches, an irregularly sinuous thalweg on the bottom of an otherwise straight ditch could be discerned, particularly on recent high-resolution aerial images (2013–2018). The development of meandering thalwegs within ditches through accumulation of sediment on the ditch bottom has been documented elsewhere in tile-drained portions of the Midwest (Rhoads and Herricks, 1996; Landwehr and Rhoads, 2003; Rhoads and Massey, 2012). The focus of attention here is on adjustment leading to erosion of the ditch banks and the recovery of channel sinuosity, rather than on the development of a sinuous thalweg within an otherwise straight ditch. Contiguous reaches of the same type were delineated either by dividing long uniform sections of BPCD into segments to explore spatial changes in possible control variables over distance (e.g., reaches K and L) or by identifying abrupt spatial changes in the amount of recovery of channel sinuosity over time (e.g., reaches G and H).

Notably, the vast majority of the total length of BPCD (69%) exhibits no change in channel planform, i.e., the ditch as originally constructed has remained straight. The lack of recovery is particularly prominent in the most headward portion of BPCD. The upper 8.1 km, except for a short 350 m reach, does not display any recovery of a sinuous planform since 1932. Despite some minor adjustments of morphology within the ditch, reaches C, F, I, K, and L still mainly exist in channelized form (Fig. 6).

Three reaches (A, D, and J), constituting 15% of the total length of BPCD, increased in channel sinuosity following initial channelization in 1932, but were subsequently artificially restraightened. In Reach A, the downstream-most portion of BPCD, a large bend that developed between 1932 and 1971 was eliminated by restraightening of the channel between 1971 and 1983 (Fig. 7). The reach has remained relatively straight since that time. Barnard (1977) reported restraightening of the channel in section 35 T26N R7E sometime between 1971 and 1977. By 1971, channel sinuosity in this portion of Reach D had increased slightly to 1.03 (Fig. 8). Restraightening during the 1970s reduced sinuosity to 1.0 in 1983. In 2018 the channel planform exhibited some adjustment to restraightening, but sinuosity remained slightly less than in 1971 ($S_I =$ 1.02) (Fig. 8). In the downstream portion of reach D, channel sinuosity in 1971 had increased to 1.07 relative to the 1932 channel path (Fig. 9). Restraightening, presumably during the 1970s, reduced the sinuosity to 1.01. Subsequent adjustments have increased channel sinuosity to 1.03 by 2018 (Fig. 9). On the 1938 imagery, reach J in section 28 T26N R7W

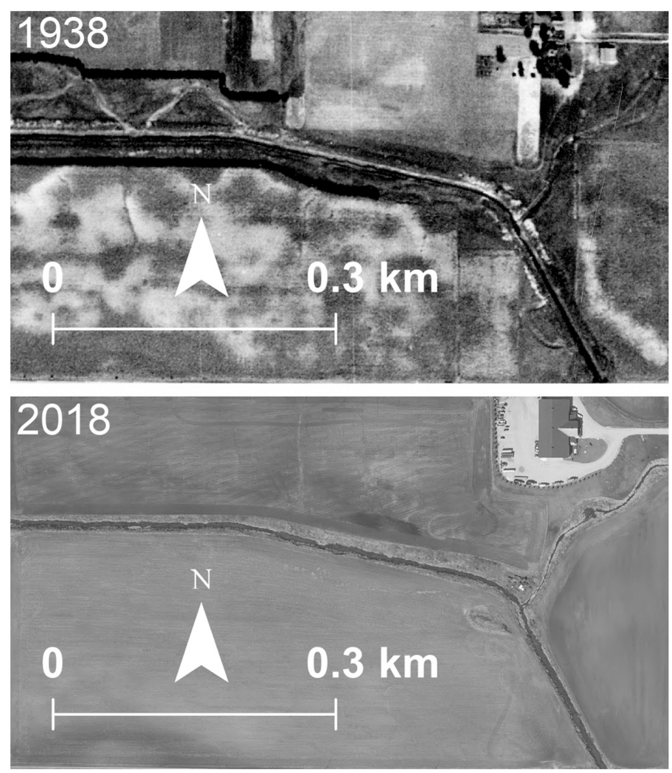

Fig. 6. An example from reach I showing unchanged alignment of BPCD in 1938 and 2018.

shows evidence of pronounced meandering only six years following the channelization project (Fig. 10). Barnard (1977) noted this location and speculated that construction methods here inadequately filled the pre-existing channel, which was quickly re-occupied. Another possibility is that the reach was not channelized for some reason during the 1932 project. Close inspection of the 1938 aerial image reveals no evidence of channelization; the creek seems to flow across a natural floodplain and terminates in what appears to be a small wetland or pond at the

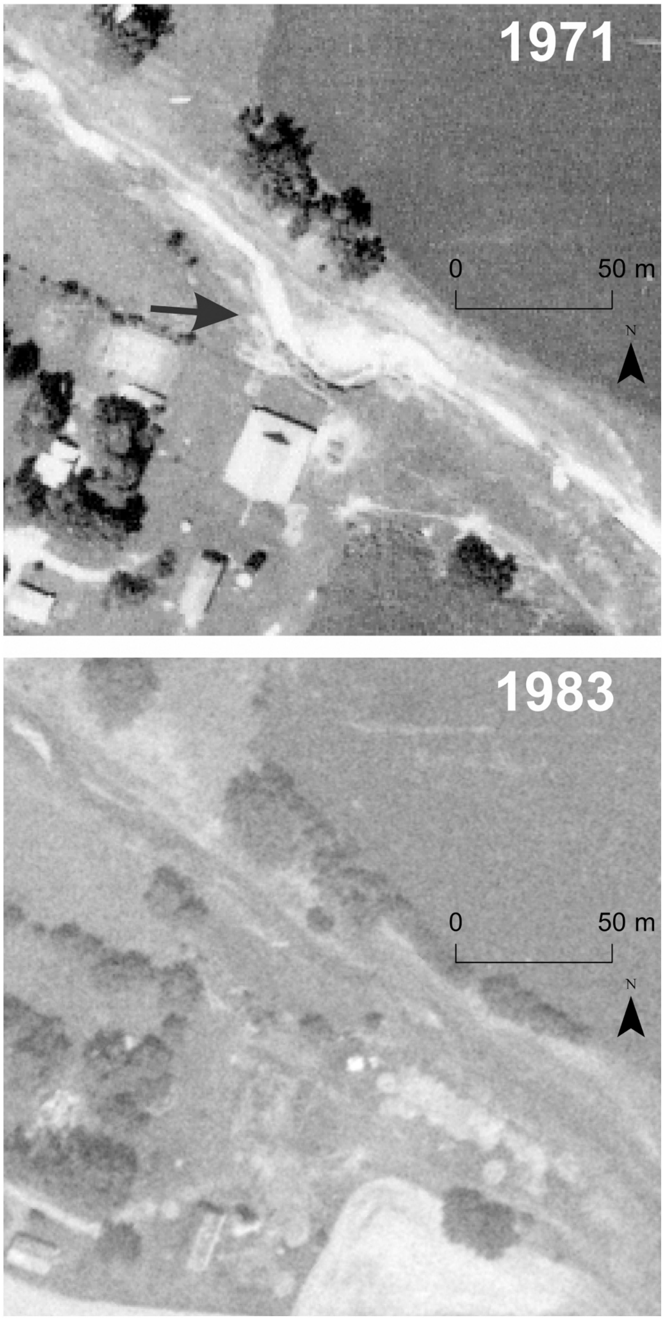

Fig. 7. Reach A showing large bend in 1971 in the middle of the reach (black arrow) and the elimination of this bend by 1983.

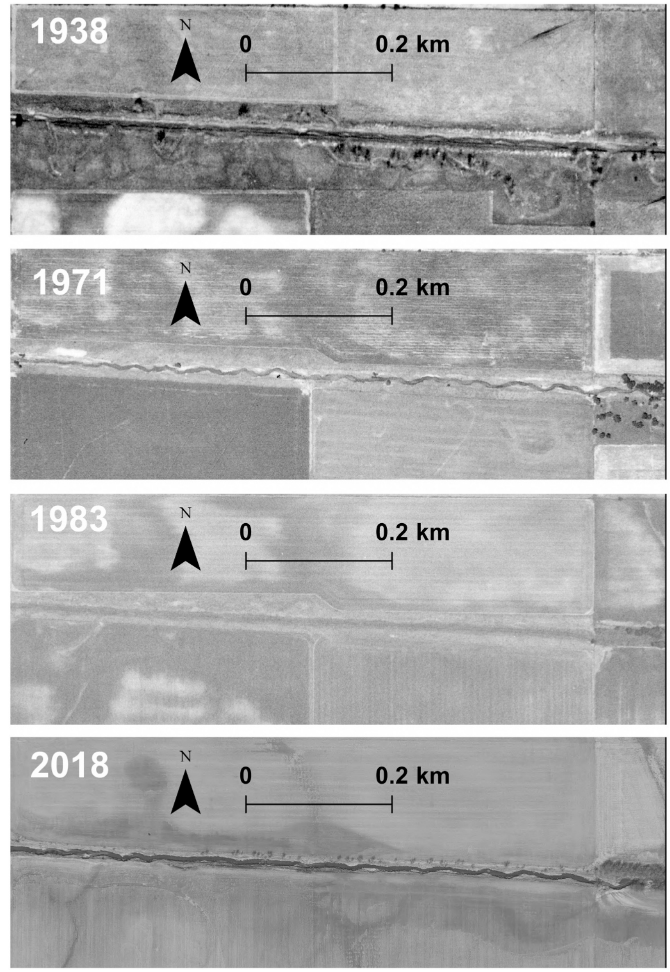

Fig. 8. Upstream portion of reach D within section 35 T26E R7N in 1938, 1971, 1983, and 2018.

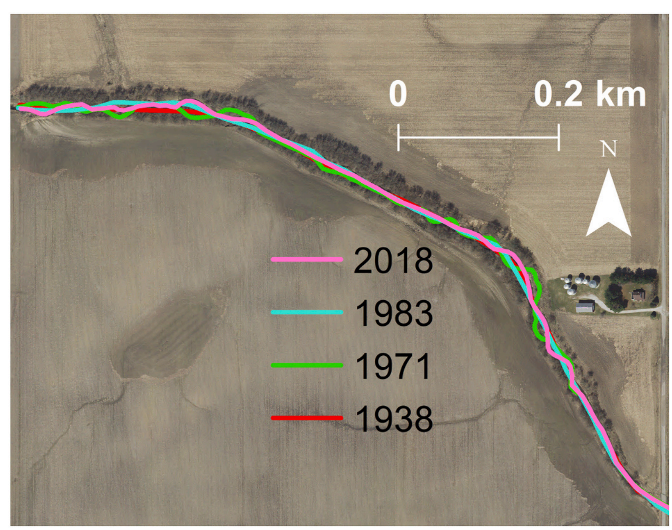

Fig. 9. Channel positions in the lower portion of reach D in 1938, 1971, 1983, and 2018. Sinuosity increased between 1938 and 1971 following channelization in 1932. Restraightening in 1983 reduced sinuosity, which has increased somewhat by 2018.

downstream end of this reach (Fig. 10). The channel still visibly meanders on the 1951 imagery with marked bend evolution occurring over the intervening 13-year period (Fig. 10). The clarity of the 1951 image confirms that no pond or wetland existed along the reach at that time. In 1957 the reach is straight (Fig. 10), indicating that either initial straightening or restraightening occurred between 1951 and 1957. The reach has remained straight from 1957 to 2018.

In four reaches (B, E, G and H) that collectively constitute 15% of the total length of Big Pine Creek Ditch, sinuosity has systematically increased since 1932 (Table 3; Fig. 11). The increase in sinuosity has varied over time in the reaches, with the fastest rate of adjustment occurring in reach H, which corresponds to the location of a knickpoint in the longitudinal profile (Barnard, 1977), and the slowest rate occurring in reach G, which occurs immediately downstream of reach H

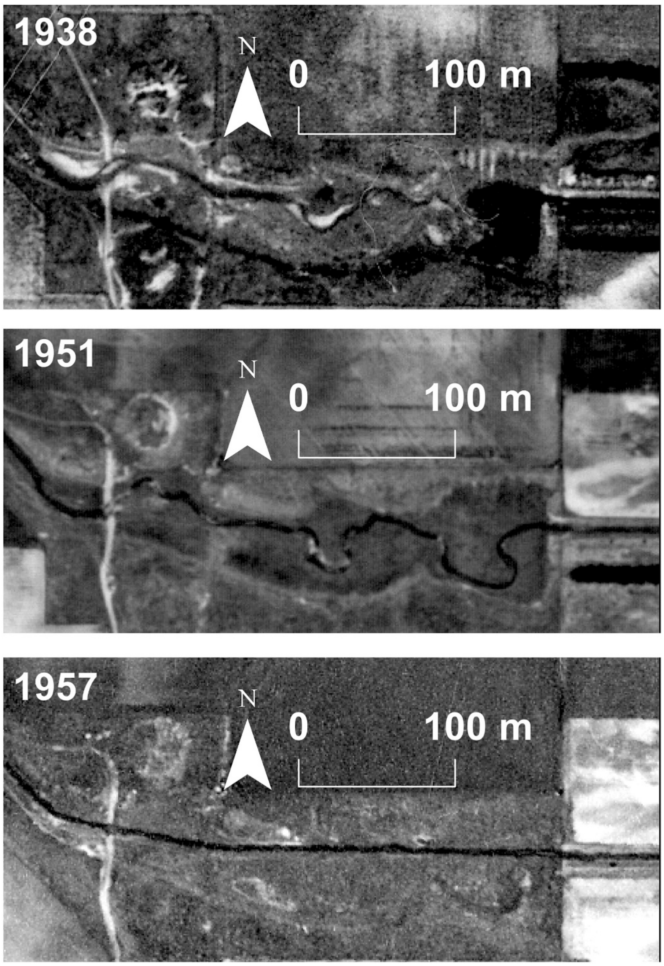

Fig. 10. Sequence of aerial images for reach J showing meandering channel in 1938 and 1951 and straight channel in 1957.

Table 3
Sinuosity measurements for the four reaches with uninterrupted recovery.

Year	B	E	G	H
2018	1.20	1.31	1.07	1.54
2013	1.22	1.29	1.06	1.52
2005	1.15	1.24	1.06	1.42
1998	1.15	1.20	1.02	1.41
1983	1.10	1.17	1.01	1.35
1971	1.08	1.10	1.05	1.21
1963	1.07	1.05	1.02	1.19
1957	1.05	1.04	1.01	1.10
1951	1.03	1.06	1.00	1.05
1938	1.02	1.02	1.01	1.02

(Fig. 12a). Linear regression analysis of the sinuosity data versus the logarithm of stream power per unit length of the estimated 2-year flood for each year of aerial photography, in the manner conducted by Barnard and Melhorn (1982) (see Fig. 3), reveals that sinuosity is strongly related to stream power for each year and that generally the strength of this relation increases over time (Fig. 12b). The increasing spread in the data toward high values of stream power reflects the higher rate of increase in sinuosity as the stream power of a reach increases – a relation revealed by plotting the rate of increase in sinuosity versus stream power for the four reaches (Fig. 13a). Barnard and Melhorn (1982) did not show plotted data for the prechannelized relation between sinuosity and stream power (Fig. 3), but data for four reaches of the prechannelized path of the creek visible on the 1938 imagery indicate only a weak relation between sinuosity and stream power (Fig. 12b). Plotting the slope of the regression lines for each year of imagery versus time illustrates the rate of recovery of sinuosity per unit stream power over time (Fig. 13b). Clearly, this relationship is linear, not curvilinear as inferred by Barnard and Melhorn (1982) (Fig. 3). Moreover, if it is assumed that full recovery occurs when λ equals the value associated with the prechannelized creek, this condition should be achieved in 2033, about 100 years after initial straightening and about 65 years less than the time period for full recovery predicted by Barnard and Melhorn (1982).

5. Discussion

The results of the GIS-based analysis of planform adjustment to channel straightening along Big Pine Creek Ditch reveals that adjustment has been spatially uneven. The majority of the total length of the ditch has not adjusted at all (i.e., has remained straight) over a period of 80 years. Channels in three reaches began to adjust, but were subsequently artificially restraightened and have since remained straight. Only four reaches have adjusted continuously. These results are more specific than those reported by Barnard (1977) and Barnard and Melhorn (1982), who did not indicate that some reaches of BPCD remained straight between 1938 and 1971 – the period over which they analyzed channel change. The impression provided by their analysis is that adjustment occurred along most of the length of the channelized stream. Maps of channel planform for three years of aerial imagery (1938, 1963, and 1971), included as plates in Barnard (1977), are at too small of a scale to determine where specific adjustments did or did not occur.

The lack of adjustment along most of BPCD is consistent with results of other work analyzing planform change following channelization of meandering headwater streams in midwestern landscapes affected by Wisconsin glaciation (Urban and Rhoads, 2003). Two factors may account for this lack of evidence for planform adjustment. First, repeated maintenance of some reaches of the ditch through removal of accumulated sediment may have reset the recovery process. Unfortunately, the extent and frequency of maintenance along BPCD is difficult to ascertain. Maintenance activities are rarely reported and a search of drainage records at the Benton County Courthouse did not yield any information on such activities. Obvious restraightening of the ditch did occur in the Type 2 reaches, but dredging of relatively straight reaches could have occurred without this activity being apparent on aerial images. Second, differences in recovery of sinuosity may reflect differences in erosional energy among the reaches. Brookes (1987a, 1987b) found that channelized lowland meandering streams in glaciated landscapes of Denmark, England and Wales exhibited evidence of adjustment to channelization when the estimated bankfull stream power per unit area exceeds 35 W m^{-2}. Although channel slope was used in his analysis, estimates of bankfull stream power per unit area (ω) for BPCD can be computed by dividing power per unit length (Ω) derived from Eq. (2) by channel width. Plots of valley slope versus discharge per unit width depict relations of stream power per unit area among the reaches for $\gamma = 9810$ N m^{-3} (Fig. 14). Some overlap occurs among the three types of reaches, but three of the four reaches that have adjusted continuously to channelization (Type 3) plot above 35 W m^{-2}. Moreover, these three reaches (B, E, H) also exhibit the greatest rates of increase in sinuosity (Fig. 12a). Reach G, where $\omega = 28.7$ W m^{-2}, has the lowest relative rate of increase in sinuosity following channelization. Two of the three Type 2 reaches that have recovered sinuosity, but were subsequently artificially restraightened (D, J) have values of ω greater than 35 W m^{-2}, whereas the third reach (A) has a value slightly less than this value (29.8 W m^{-2}). As noted previously, Reach J, which has the highest power per unit area of the three reaches (48.9 W m^{-2}) may not have been channelized in 1932 and thus may not represent restraightening after initial channelization. It has, however, remained straight since being straightened sometime between 1957 and 1963. Of the five reaches that have not exhibited recovery since straightening in 1932, three of the five (F, K, L) plot well below 35 W m^{-2}, whereas two plot near (I) or above (C)

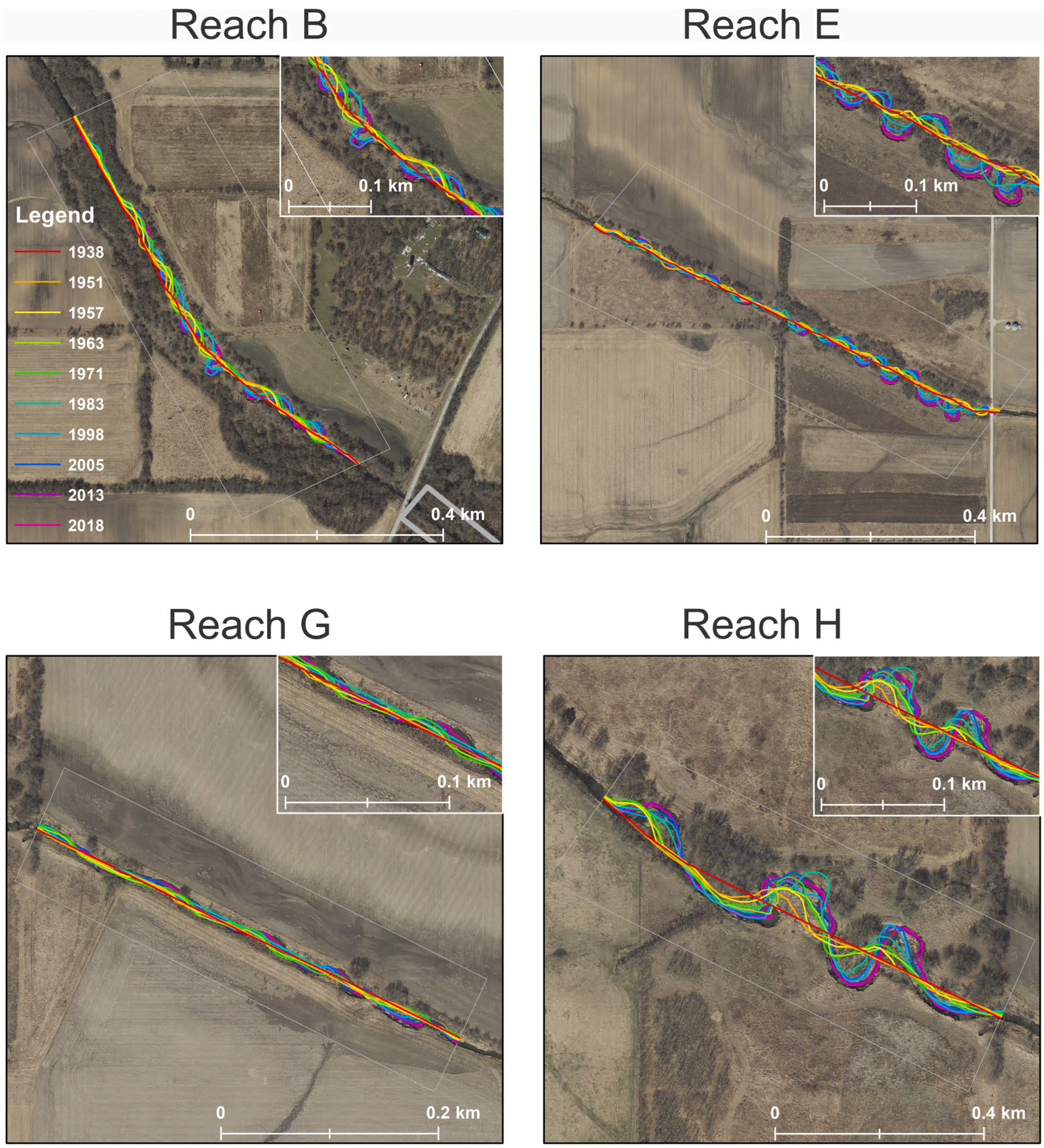

Fig. 11. Systematic recovery of sinuosity following channel straightening in 1932 in reaches B, E, G and H along Big Pine Creek Ditch as determined from GIS-based analysis of historical aerial imagery (insets in upper corners show detail of channel change in part of the reach).

this value. All of reach L and the upper half of reach K correspond to portions of the modern ditch that extend beyond the upstream limit of the Big Pine Creek as depicted on the GLO maps (Fig. 2) and therefore likely represent excavated channels. Overall, this comparison of stream power per unit area among reaches suggests that those with values of $\omega > 50$ W m^{-2} are highly likely to recover sinuosity following straightening, whereas those with $\omega < 25$ W m^{-2} are likely to remain straight, assuming that channel maintenance is not an important factor influencing the low-power channels. Channels with values of stream power per unit area between 25 and 50 W m^{-2} may begin to recover sinuosity following straightening or remain straight, indicating that stream power alone is not the sole determinant for these channels of whether straightening will lead to subsequent recovery through increases in sinuosity. In particular, local spatial variation in the resistive properties of bed and bank materials may be important locally for determining the type of post-channelization response – a factor not considered in this study. Soil maps from the Web Soil Survey (https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm) show that soils along BPCD are relatively homogenous. All reaches except reach L consist of Comfrey silty clay loam with a sandy substratum. Soils in reach L include Selma silty clay loam and Free clay loam.

The results here confirm the findings of Barnard and Melhorn (1982) that reaches of BPCD that do adjust to straightening do so mainly through an increase in sinuosity. Past work on channelization has indicated that types of adjustment can also include incision and widening, armoring of the bed, and development of a sinuous thalweg (Brookes, 1987a). Incision and widening has been prominently documented in regions of the midwestern United States with loess cover that lie beyond the boundary of Wisconsin glaciation (Simon and Rinaldi, 2000). Incision may accompany an increase in sinuosity, but further work based on detailed field surveys of channel form would be required to ascertain whether or not incision has occurred.

Recovery of sinuosity has been documented as the primary response to channelization of headwater agricultural streams in parts of Illinois

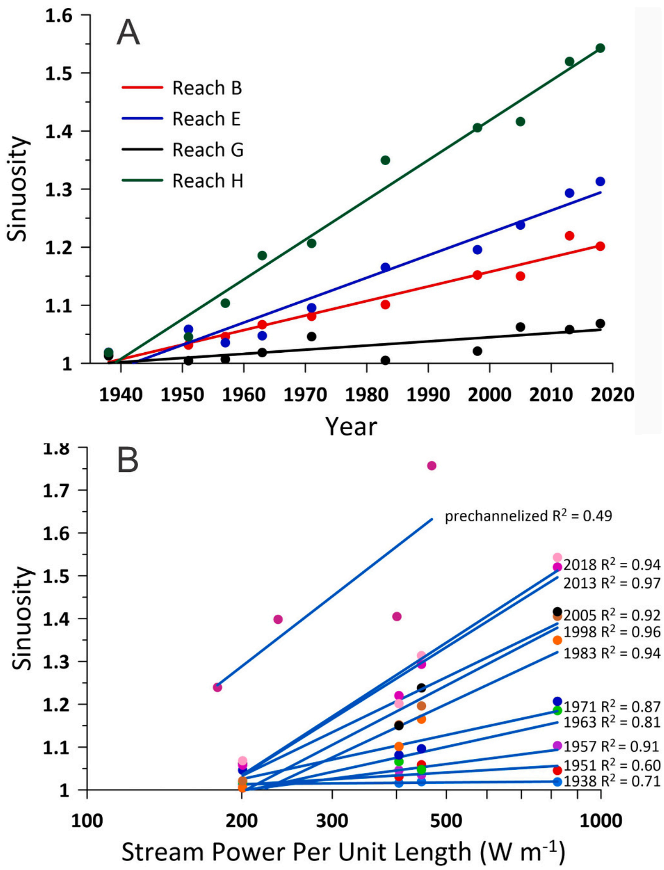

Fig. 12. (a) Increase in sinuosity over time for the four reaches of Big Pine Creek Ditch with uninterrupted recovery to channelization (b) best-fit regression lines between data for stream power per unit length and sinuosity for each year of imagery following channelization and for the prechannelized creek.

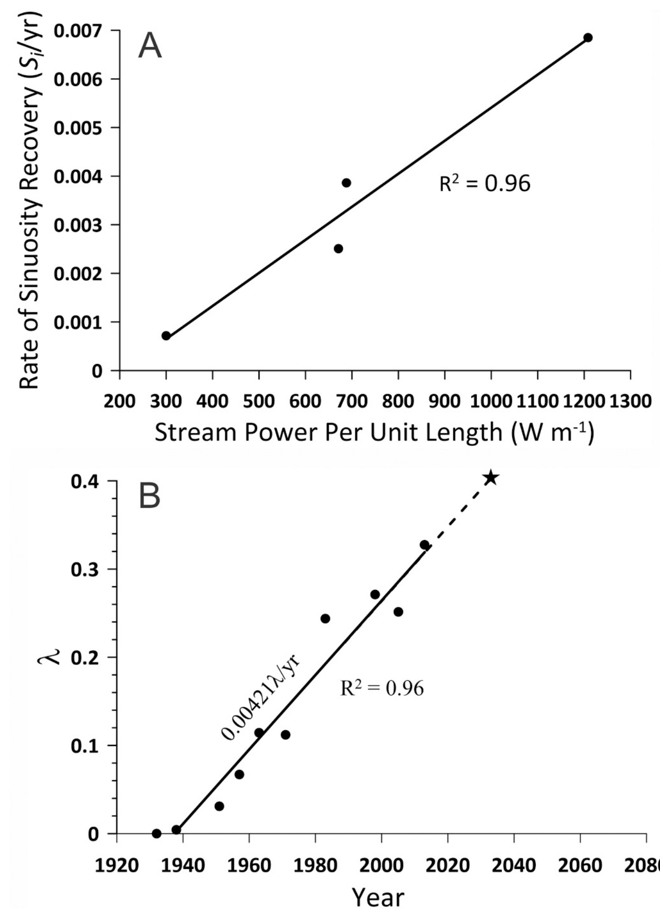

Fig. 13. (a) rate of increase in sinuosity versus stream power per unit length for the four reaches of BPCD exhibiting uninterrupted recovery (b) λ versus time for reaches with uninterrupted recovery.

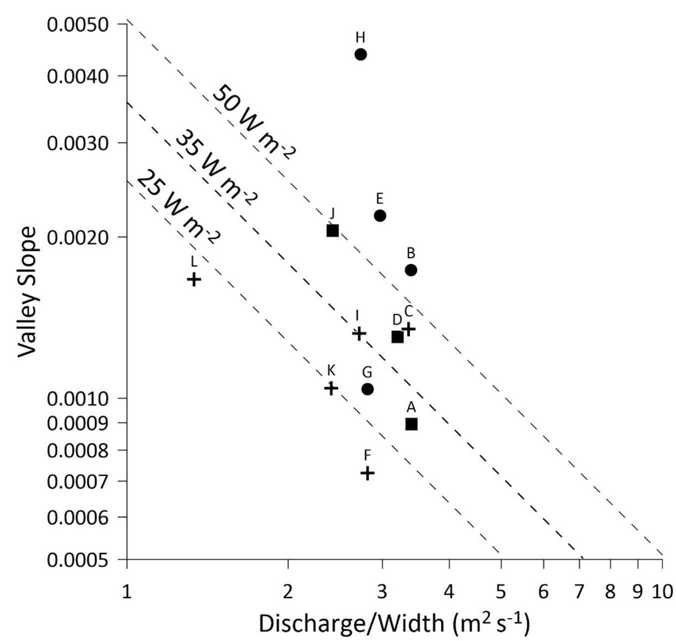

Fig. 14. Discharge per unit width versus valley slope for the different reaches along Big Pine Creek Ditch (letters indicate reaches, plus symbol is type 1 reach, filled square is type 2 reach, and filled circle is type 3 reach).

affected by Wisconsin glaciation (Urban and Rhoads, 2003; Guneralp and Rhoads, 2009; Rhoads et al., 2016). In Illinois streams, the process of remeandering can occur within wide ditches through the development of bars on the ditch bottom, which over time grow in height and become vegetated (Landwehr and Rhoads, 2003). Once stabilized, the bars deflect flow within the meandering thalweg laterally into the ditch banks, initiating systematic erosion of these banks. Initiation of meandering through the formation of steady alternate bars within a straight channel is consistent with bar-bend theories of meandering initiation (Rhoads and Welford, 1991; Rhoads, 2020). The mechanism of bar formation is also consistent with experimental work and numerical simulations suggesting that lateral oscillation of the incoming flow is necessary to initiate meandering within a straight channel (van Dijk et al., 2012; Schuurman et al., 2016). Such oscillation results in the formation of a steady bar at the upstream end of the straight channel that triggers local bank erosion opposite the bar. A sequence of bars and bank erosion then propagates downstream.

Bar forms are visible on the aerial images as meandering begins to develop in reaches that have adjusted continuously to initial straightening. Whether or not these bar forms initiated meandering cannot be ascertained from aerial image analysis given that the earliest images are not of high enough resolution to determine whether bars developed within the ditch prior to meandering. The development of vegetated bars flanking a sinuous thalweg is evident in some headwater reaches of the ditch (Fig. 15a), suggesting that bar formation may play a role in the initiation of meandering where the ditch bottom is sufficiently wide to promote deposition (e.g., Landwehr and Rhoads, 2003). Bar formation as a trigger for meandering is not immediately obvious in the upstream portion of Reach D that displays incipient sinuosity in 2018 (Figs. 8 and

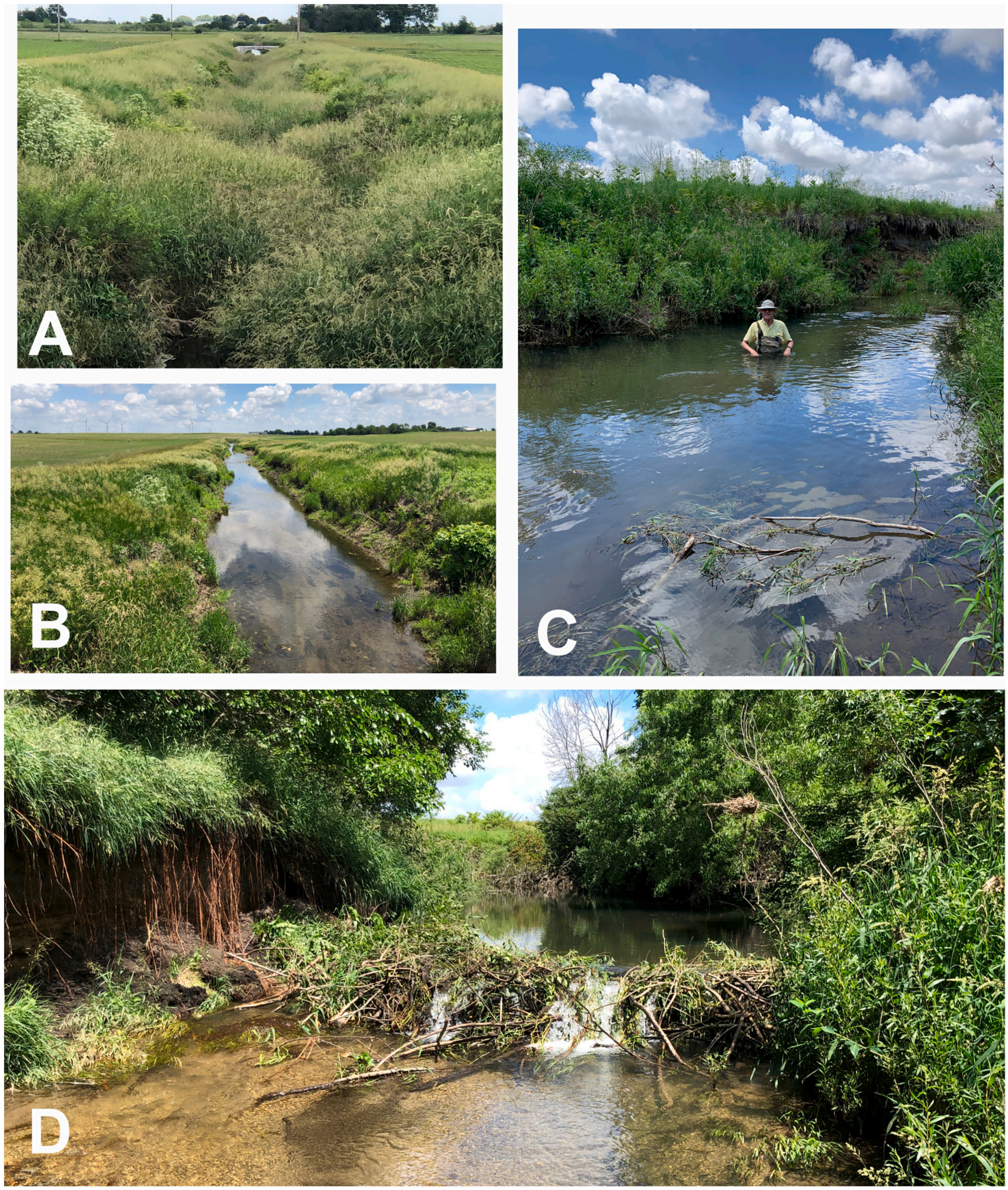

Fig. 15. (a) vegetated bars flanking a sinuous thalweg within reach K of Big Pine Creek ditch (b) looking downstream through the upstream portion of reach D where systematic erosion of the channel banks on alternate sides of the channel has produced slight sinuosity of the channel (see Fig. 8, 2018 image). (c) Pool in a meander bend in reach E. (d) Beaver dam about 100 m upstream of pool (note shallow flow depth downstream of dam). Photos taken in June 2021.

15b). Instead, the incipient sinuosity mainly reflects systematic erosion of the channel banks in offset longitudinal positions on the two sides of an otherwise relatively straight channel with a flat bed. This mode of adjustment suggests that the development of bars on the bottom of the ditch may not necessarily be a precursor of meander initiation in straight reaches of BPCD. If meandering does begin to develop without bar formation, the process would differ from that postulated by bar-bend theory, which attributes the initiation of meandering to flow-sediment interactions that promote bar formation and subsequent bend development (Rhoads and Welford, 1991; Rhoads, 2020). Moreover, the relatively straight alignment of the channel upstream of the three reaches that have had the greatest continuous increases in sinuosity (B, E, H) is difficult to reconcile with experimental and numerical studies indicating that lateral oscillation of the flow is necessary to initiate meandering (van Dijk et al., 2012; Schuurman et al., 2016). Whether or not flow could conceivably oscillate laterally in a straight upstream channel is uncertain. On the other hand, the considerable meandering of reach H immediately upstream of reach G, which has the lowest power per unit area and the least increase in sinuosity of the recovering reaches, may help to trigger mild meandering downstream.

Overall, the results here support conclusions of previous work indicating that widespread channelization of meandering headwater streams in low-relief landscapes of the midwestern United States shaped by late Wisconsin glaciation has had a catastrophic effect on these fluvial systems (Frothingham et al., 2002; Urban and Rhoads, 2003). Most of the length of BPCD ditch has either remained straight since initial channelization or has been artificially restraightened in some places where planform began to adjust. Moreover, the length of this fluvial system has been extended headward artificially, a common practice when creating ditches for the purpose of land drainage (Rhoads et al., 2016). Where adjustment has been allowed to occur, the time rate of adjustment is slow with both the absolute rate of increase in sinuosity and the level of sinuosity corresponding to complete recovery being dependent on the available stream power. Although the estimated recovery time revealed by this study is shorter than that estimated by Barnard and Melhorn (1982), it is still quite long – on the order of a century. Thus, change produced by channelization is long-lasting, even when the system has the necessary stream power to recover its sinuosity and is left undisturbed to achieve recovery.

The analysis of stream power-sinuosity relations for the continuously adjusting reaches for the extended period of the present study confirm the findings of Barnard and Melhorn (1982) that the rate of increase in sinuosity as well as the total sinuosity following complete recovery are highly dependent on stream power per unit length of the reaches. However, the updated analysis in the present study also shows that the increase in sinuosity per logarithmic unit of stream power per unit length exhibits a linear rate of recovery rather than a diminishing curvilinear rate. The time for complete recovery of sinuosity is also about 60 years shorter than that predicted by Barnard and Melhorn (1982). The linear rate of increase in sinuosity per logarithmic unit of stream power has continued despite a gradual increase in the density of trees along reaches B, E, G, and H since initial channelization. All of these reaches now include at least some tree cover (Fig. 11); the riparian corridor along reach E has become protected habitat for game birds and this reach includes well-developed pools (Fig. 15C) and signs of beaver activity (Fig. 15 D). The increasing presence of trees does not appear to be slowing the rate of erosional adjustment.

The extent to which increases in sinuosity alone can be viewed as an indicator of complete recovery of channel planform must also be considered within the context of fluvial responses to channel straightening. In all four reaches where recovery of sinuosity has occurred continuously since initial channelization, the change in channel planform has involved the development of bends centered around the initial straightened channel path (Fig. 11). In other words, the width of the meander belt is defined by bends that have developed along the axis of the straightened channel path. By contrast, the path of the meandering channel of BPCD prior to channel straightening, as derived from visible channel traces on the 1938 imagery, is much more varied, extending laterally across a wider swath of the valley bottom than the relatively narrow meander belt of the recovering reaches (Fig. 16). Whereas general recovery to date mainly consists of the development of bends that are relatively small in wavelength and amplitude, and clustered narrowly around a straight axis, bends prior to channelization tended to be relatively large in wavelength and amplitude, and included lateral

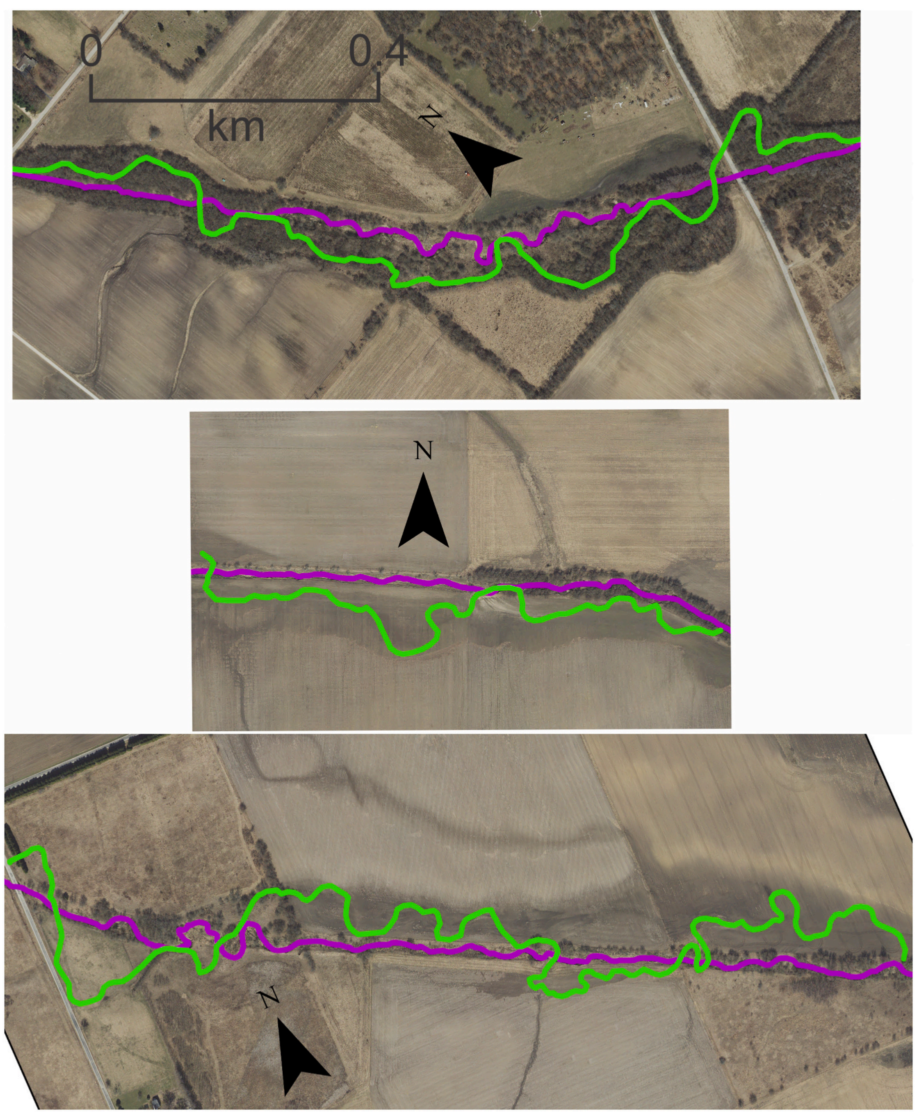

Fig. 16. Differences between the prechannelized planform of Big Pine Creek Ditch (green) for three reaches where this planform could be determined from the 1938 aerial imagery and the 2018 planform of the ditch (purple). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

displacements that extended across much of the valley bottom. Differences in such characteristics of planform cannot be captured through a simple metric like sinuosity. Instead, multiple scales of planform variability must be considered, including differences between lengthening of the channel path associated with the development of discrete meander bends and lengthening associated of the channel path associated with large-scale "meandering" of the mean center of the meander belt (Gutierrez and Abad, 2014). Such large-scale lateral variation in the path of the meander belt often develops when an evolving meandering river reaches the stage when cascades of bend cutoffs begin to occur (Stolum, 1996). Only a few minor cutoffs are evident in meandering reaches of BPCD; moreover, even if cutoffs begin to increase in frequency, local farmers are unlikely to allow meandering reaches to extend laterally to any great extent given that land adjacent to these reaches is used to grow crops. Spectral (Guneralp and Rhoads, 2011), wavelet (Zolezzi and Guneralp, 2016; Ruben et al., 2021), or Hilbert-Huang (Konsoer and Rhoads, 2018) analysis of curvature series might be appropriate tools for unraveling different scales of channel change relevant to planform recovery in human-modified streams.

6. Conclusion

A reanalysis of the response of Big Pine Creek Ditch to channelization shows that the primary mode of recovery is an increase in sinuosity to re-establish a meandering channel. The recovery of a meandering planform varies spatially with some reaches remaining straight and others systematically increasing in sinuosity when left undisturbed. The vast majority of the total length of the channelized ditch has remained straight over a period of 86 years. These reaches tend to have relatively low estimated bankfull stream power per unit area (< 25 W m^{-2}). Where stream power per unit area is locally high (> 50 W m^{-2}), channels have been left undisturbed and sinuosity has increased systematically over time. Systematic recovery of sinuosity also occurred in an undisturbed reach with stream power per unit area less than 50 W m^{-2} located directly downstream from a recovering reach with stream power per unit area greater than 50 W m^{-2}. Rates of increase in sinuosity over time in reaches that have recovered systematically increase with increasing bankfull stream power per unit length. The rate of recovery of sinuosity per logarithmic unit of stream power is linear and the time required for complete recovery of prechannelized relations between sinuosity and stream power is on the order of a century. The long time scale for recovery of sinuosity in reaches capable of recovering, the resetting of recovery in some reaches through restraightening of channels that begin to re-meander, and the lack of recovery over much of the total length of headwater agricultural streams such as Big Pine Creek Ditch confirms that humans are now catastrophic agents of channel change in tile-drained landscapes of the midwestern United States (Frothingham et al., 2002; Urban and Rhoads, 2003; Rhoads et al., 2016). The study also suggests that incipient meandering of straight channels can occur, at least in some instances, without the precursory development of bars on the channel bottom. Further work is needed to document in detail how re-meandering of straightened channels actually ensues in different contexts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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