Stream Recovery Post Channelization: A Case Study of Low-Gradient Streams in Central Illinois, USA

Joseph P. Becker
Illinois State University

Eric W. Peterson
Illinois State University, ewpeter@ilstu.edu

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Stream Recovery Post Channelization: A Case Study of Low-Gradient Streams in Central Illinois, USA

Joseph P. Becker [1,2] and Eric W. Peterson [2,*]

[1] Tetra Tech, One S. Wacker Dr., Ste. 3700, Chicago, IL 60606, USA
[2] Department of Geography, Geology, and the Environment, Illinois State University, 101 South School Street, Campus Box 4400, Normal, IL 61790, USA
* Correspondence: ewpeter@ilstu.edu; Tel.: +1-309-438-7865

Abstract: Stream channelization, which entails reducing the sinuosity of a stream, widening, and in some cases deepening the stream channel, is a widespread practice in agricultural regions. Channelization efforts in central Illinois have significant impacts on the geomorphology, flow regime, and sediment transport both in and adjacent to modified reaches. The goal of this study was to characterize the changes in stream channels by comparing three streams that are at various stages of recovery post channelization, 5 years (1900N), 7 years (Frog), and 35 years (Bray), to an unmodified stream reach (Crooked) and estimate a recovery rate. Measured channel slopes within the modified streams were one order of magnitude larger than the measured channelized streams in Crooked. The two streams most recently channelized exhibited little geomorphic change since their channelization, while the segment modified 35 years ago experienced bank failure and immature meander development. The lack of redevelopment resulted in sinuosity values lower than that of Crooked, and the reestablishment of meanders similar to Crooked would take an estimated 11,000 years. The distributions of the sediments within all the streams comprised poorly sorted sand and pebbles. The distribution of the sediment resembles the source, the glacial diamicton that serves as the surficial sediments. Mobilization of the sediment is frequent, with recorded scour greater than sedimentation. Overall, the channelized segments experienced limited recovery. The segments are still degrading (1900N and Frog) or are transitioning into a threshold stage (Bray).

Keywords: agricultural streams; tile-drainage systems; stream modification; hyporheic zone; streambed mobilization

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1. Introduction

In the late 1800s, the settlement and cultivation of the Midwest introduced stream channelization and modification. Stream channelization was utilized to drain lands that were too saturated for agriculture use and to minimize the impacts of flooding [1–5]. Stream channelization entails the reduction in stream sinuosity through straightening, widening, and deepening a stream channel [6]. Channelization is performed in conjunction with the installation of tile drain systems, which drain agricultural land and prevent both water logging and topsoil erosion due to the low regional topographic relief [2]. Within Illinois, once a marshy wetland [7], an estimated 25% of all streams and nearly all headwater streams have undergone channelization within the last 150 years [6].

When a stream is modified, the energy regime of the channel is changed, causing the stream to readjust towards unmodified conditions. Simon [8] proposed, and Simon and Rinaldi [9] modified, six morphological stages associated with stream channelization: (1) pre modified, (2) constructed (modification), (3) degradation, (4) threshold, (5) aggradation, and (6) restabilization. Pre modified conditions represent a stream having a natural geometry where erosion and deposition will occur and there should be vegetation along the banks and possibly within the stream. Modification is the stream channelization, characterized by trapezoidal cross-sectional geometry and the removal of basal and bank vegetation.

Degradation is the morphological response to the increase in the stream gradient from channelization. During degradation, incision occurs in the modified reach resulting in an increase in sedimentation downstream. The threshold stage occurs as incision causes a loss of bank competence, eventually resulting in failure. The influx of material from bank failure reduces the stream gradient in discreet locations, causing the aggradation of coarse material on bank surfaces. Bank failure followed by aggradation will occur until the bank height and slope are sufficiently reduced for the stream to restabilize to conditions similar to pre modification. Restabilization is characterized by the further development of a meandering thalweg, deposition of point bars, and the reestablishment of vegetation. The recovered stream segment will likely not regain full pre modified bed levels but will find a new equilibrium at a lower bed level. The capacity of a stream to reach the restabilization stage is minimal. With a lack of sand- or gravel-sized materials, the duration of the degradation phase can be over 55 years [9] and the recovery of sinuosity may take multiple centuries [10]. Additionally, multiple episodes of channelization over 50 years have been documented on stream segments in response to the siltation of the channels [11].

The impacts of stream channelization have been well documented, but the rates that streams recover to pre modification are unknown. Additionally, few studies have documented the response and recovery of stream channels subjected to channelization [12,13]. Midwest streams, with low-gradient channel slopes and resistant bed material, have exhibited limited temporal rates of change, and evidence of alteration can exist for decades [11]. Simon and Rinaldi [9] found that some stream segments in the Midwest can remain in the degradation stage for more than 70 years due to the poor bank stability attributable to the loess cap present in many areas of the Midwest. The objective of this work was to assess the rate at which channelized streams recover to understand the impacts of channelization. This study reports the geomorphic responses observed in stream channels by comparing three streams at various stages of recovery with an unmodified stream reach. The implications of stream recovery on nutrient management are briefly discussed as the topic may be of particular importance to regulators in the future as watershed-based management strategies and mitigation efforts are implemented.

2. Materials and Methods

2.1. Study Area

The Mackinaw River Basin (MRB) (Figure 1) is a major watershed in central Illinois, USA, spanning 2950 km^2 [3]. Before draining into the Illinois River, the Mackinaw River and its tributaries flow through an agriculturally dependent region with 86% of the land devoted to farming corn and soybeans [14]. Mattingly, et al. [6] determined that more than 90% of all first-order streams in central Illinois are channelized, where the Mackinaw River originates as a channelized ditch [15], and Gough [16] estimated that within the MRB, all 435 km of its first-order streams have experienced channelization to some extent.

Four streams were chosen for the study based on the last documented channelization and accessibility. All four streams are low-gradient streams located in the upper MRB, McLean County, Illinois (Figure 1, Table 1). The four streams examined for the study are an unnamed tributary (1900N), modified approximately five (5) years prior to the study; Frog Creek, channelized approximately eight (8) years prior; Bray Creek, channelized approximately 35 years prior; and Crooked Creek, a segment with no documented channelization (Figure 2). The three modified segments are all second-order streams with similar sized drainage areas and represent the highly channelized headwater areas of the URB. Crooked Creek represents a third-order segment and has a larger drainage area. As an unmodified site, Crooked Creek provided data for comparison to assess the stages of restoration in the modified channels.

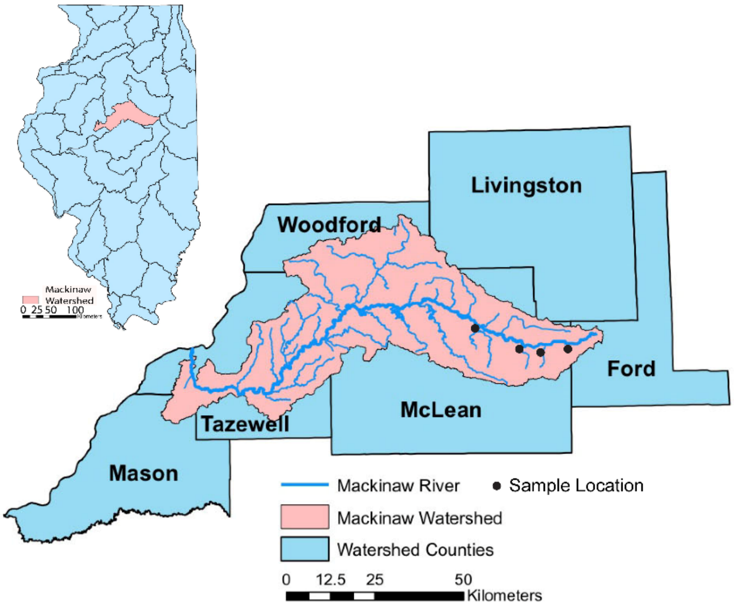

Figure 1. The Mackinaw River Basin (MRB) within Illinois, USA. The location of the four creeks identified.

Table 1. Stream characteristics.

	1900N	Frog	Bray	Crooked
Location				
Latitude	40°33′31.94″ N	40°32′36.78″ N	40°32′39.78″ N	40°36′10.68″ N
Longitude	88°28′41.72″ W	88°33′5.28″ W	88°37′36.48″ W	88°46′10.08″ W
Post Modification	5 years	7 years	~35 years	NA
Segment Length (m)	128.3	87.7	84.5	130.3
Channel Width at Average Baseflow (m)	2.7	3.6	3.3	4.6
Upstream Drainage Area (km^2)	36.4	33.7	37.7	70.8
Sinuosity	1.005	1.011	1.064	1.266
Streambed Slope (m/m)	2.26×10^{-3}	1.71×10^{-3}	1.60×10^{-3}	3.00×10^{-4}

Figure 2. Photographs of the four study reaches. (**A**) 1900N; (**B**) Frog Creek; (**C**) Bray Creek; (**D**) Crooked Creek. 2.2 Methods.

The surface geology within the watersheds of the four streams has been characterized by 30 to 120 m thick glacial deposits from the Wisconsin glaciations, 75 to 13.5 thousand years ago [15]. The glacial deposits comprise diamicton, a poorly sorted, silt-clay matrix with sand and pebbles. The diamicton forms ground and end moraine deposits of the Batestown Member of the Wedron Group [17,18]. Except for Crooked Creek, none of the channels have a developed flood plain. The channels have been cut down into the diamicton, exposing banks comprised by clay and silt.

2.1.1. Stream Profiles

At each stream, a 100-meter segment was surveyed using a Nikon total station. Data from the 2008 survey were used to generate stream profiles and cross-sections of the segments to determine the channel slope along the thalweg (*Sc*) and to calculate sinuosity. Sinuosity has been used to identify a systems response to channelization [11], and we calculated sinuosity as an indicator of restabilization post channelization using the following equation:

$$\text{Sinuosity} = \frac{\textit{Distance along the stream between } 2 \textit{ points}}{\textit{Straight line distance between } 2 \textit{ points}} \tag{1}$$

The lowest possible sinuosity is 1, which represents a stream flowing in a straight line, while a sinuosity greater than 1.5 classifies a segment as meandering [19].

2.1.2. Sediment Sampling and Analysis

Sediment was collected during two sampling events, late fall and early spring, to determine seasonal variations in grain size and size distribution. Five bulk samples were collected along the streambed of each segment, taken at approximately 20-meter intervals. The presence of large grain-size sediments required a larger sample mass to improve percentile precision between large grains and median-size grains [20]. Upon measurement of the largest streambed particles, 4 to 5 kg of sediment were collected at each location within the segments. Sediment capable of reaching threshold conditions does not typically exceed a few centimeters in depth; therefore, the samples were collected from the bed–water interface using an Eckman sampler. Each sediment sample was analyzed following the ASTM D422 [21]. Cumulative frequency curves were generated to calculate grain size and sorting. The d_{50} (the median grain size) and the d_{85} (the grain size diameter of which 85% of the distribution is finer) were ascertained from the cumulative frequency curves. The d_{50} represents the median grain size, while d_{85} represents a grain size that typically requires bankfull conditions to mobilize [22]. Sorting was quantified following Folk [23].

2.1.3. Scour

Five scour markers were installed in each stream thalweg at an interval of approximately 20 m apart. The scour markers consisted of rebar installed vertically in the surveyed portion of each stream. Washers were placed around the rebar resting against the streambed. When scouring occurred, sediment was removed underneath the washer, allowing it to slide down the rebar. The total depth of scouring after storm events was determined by measuring the distance that the washers have moved vertically on the rebar. The thickness of the sediment above the washer quantified the amount of sedimentation. The scour markers were measured monthly to record the depth of scouring and/or sedimentation.

2.1.4. Organic Matter

Sub samples were split from the sieved samples to quantify the percent of organic matter in each grab sample. The organic matter content was determined using the loss on ignition method [24]. The sub samples were limited to the six smallest Φ sieves as the larger sized grains consisted of silica. The associated Φ values were from smallest to largest; less than 4 (silts and clays), 4, 3, 2, 1, and 0 (sand).

2.1.5. Sediment Mobility

Stream sediments become entrained when the threshold conditions are exceeded [25]. Sediment mobility was evaluated by comparing critical shear stress (τ_c) with basal shear stress (τ_b) to determine the required flow depth to mobilize d_{50} and d_{85} grain size sediment following the procedures used in similar studies [22,26,27]. Following those works, the minium water depth (h) required to mobilize sediment of a given size (d) was calculated using:

$$h \geq \frac{972d}{9800S_c} \tag{2}$$

where S_c is the channel slope along the thalweg.

3. Results

3.1. Stream Profiles

Plan view profiles of the streams were generated from the survey data (Figure 3). Along the 100 m segments, the channelized streams showed nearly straight segments, with Crooked Creek possessing the most sinuous segment. The calculated sinuosity values highlight the lack of meandering within the channelized streams, with all values below 1.1 (Table 1). With a developed meander, the calculated sinuosity for Crooked Creek was 1.266. The sinuosity values of the four streams provided a relationship between the sinuosity and time since channelization (Figure 4). Three equations were fit to the data for the channelized streams: a linear equation (Equation (3)); a logarithmic equation (Equation (4)); and a power relation (Equation (4)).

$$Sinuosity = 0.9964 + 0.0019 \times years \qquad R^2 = 0.9989 \tag{3}$$

$$Sinuosity = 0.9528 + 0.0311 \times \ln(years) \quad R^2 = 0.9902 \tag{4}$$

$$Sinuosity = 0.9556 \times years^{0.0301} \qquad R^2 = 0.9914 \tag{5}$$

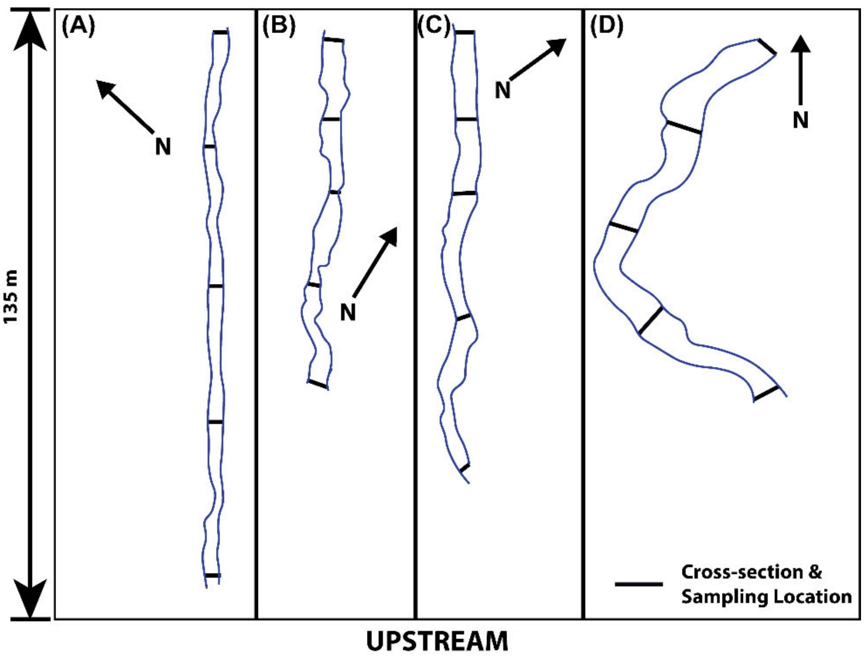

Figure 3. Plan view of the surveyed stream profiles of the four study reaches. (**A**) 1900N; (**B**) Frog Creek—7 years; (**C**) Bray Creek; (**D**) Crooked Creek. Scale along the left (y-) axis is consistent for both horizontal dimensions.

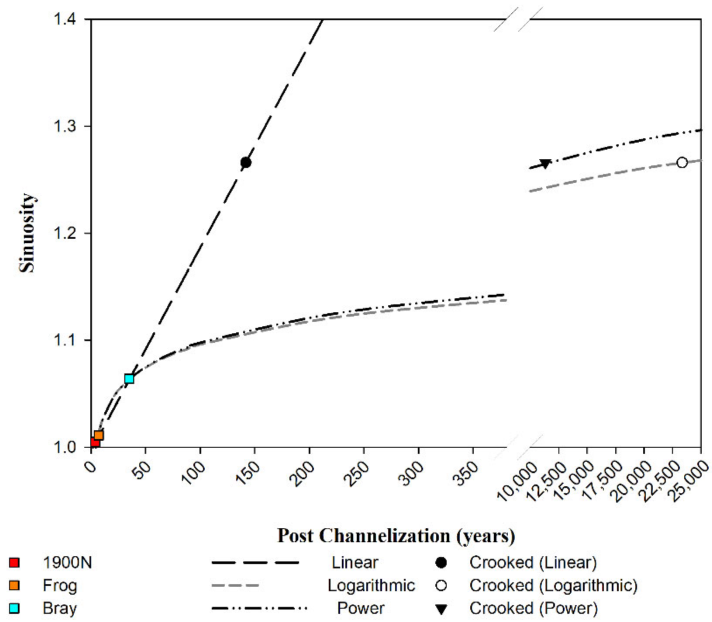

Figure 4. Sinuosity of the modified streams (1900N, Frog Creek, and Bray Creek) versus time since channelization. Crooked Creek sinuosity values are modeled using a linear (black dashed line), a logarithmic (gray dashed), and a power (black dash–dot–dot line) relationship. Note the x-axis has a break between 380 and 10,000 years.

Due to the limited number of streams in this study, all three functions represent a good fit. While the linear equation, Equation (3), possessed the best R^2 value, the relationship is unrealistic given that the sinuosity will reach an asymtope and not continually increase. The logarthhmic Equation (4) and the power Equation (5) equations also possessed strong R^2 values and identified an asymtopic value for sinuosity of ~1.3. The generated equations were used with the sinuosity of Crooked Creek to determine the number of years required to reach the sinuosity of Crooked Creek: 141 years (linear relationship—Equation (3)); 23,347 years (logarithmic relationship—Equation (4)); and 11,323 years (power relationship—Equation (5)). Meander development is a nonlinear process [28,29], and given the unrealistic time calculated, the linear model was deemed inappropriate. Assuming that Crooked Creek has never been modified, the time calcuated from the power equation aligns with the retreat of the last glaciation, suggesting it may be the most appropriate relationship.

3.2. Cross-Section Profiles

Cross-sections were surveyed along riffles in each stream segment. Representative cross-sections are presented in Figure 5. 1900N retained the trapezoidal shape associated with channelization. The right bank maintained a constant slope from the streambed to the floodplain, reflecting minimal changes since channelization. The left bank exhibits a shallow slope near the top of the bank that increases towards the streambed. The change in slope on the left bank indicates that bank failure has occurred due to incision. Frog Creek was similar in shape to 1900N, with a steep bank and a bank exhibiting failure; however, erosion in Frog Creek was more pronounced, as exhibited by the wider stream bed. Bray Creek had a steep left bank with a well-developed channel and an immature point bar was developing along the right bank following the deposition of sediment associated with bank failure. The cross-section is of a small meander where active incision is occurring (left bank), and coarse sedimentation is accruing during high flow events (right bank). Crooked Creek had a shallow profile with a well-developed point bar on the left bank and noticeable incision on the right bank. Crooked Creek had a well-developed point bar and cutbank unlike the linear profile of the modified streams.

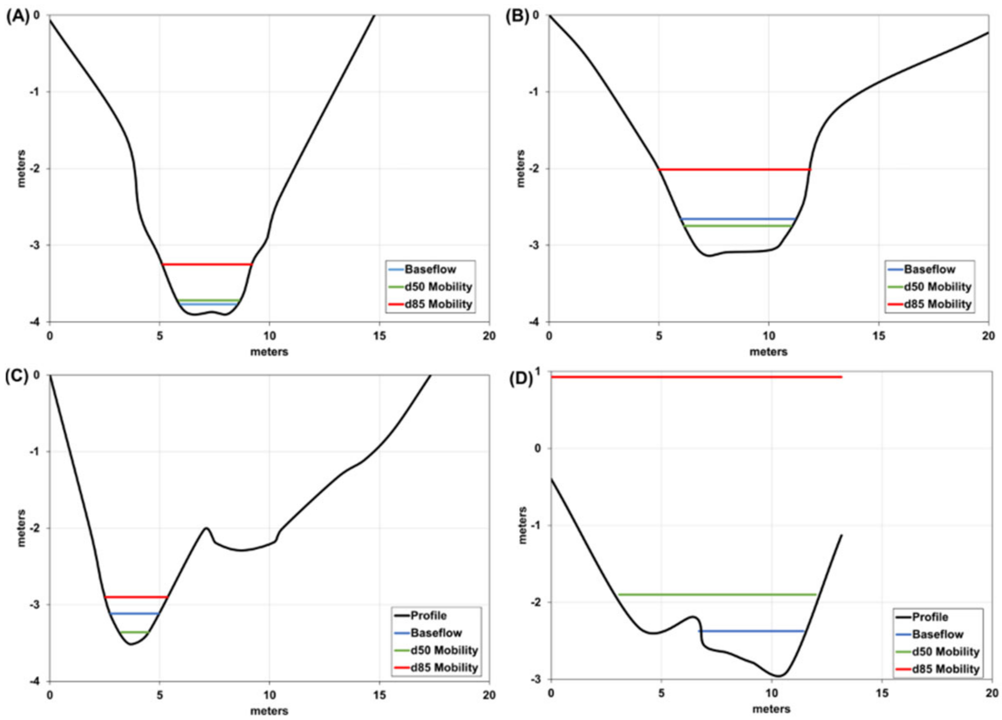

Figure 5. Representative cross-sectional for a typical riffle within each of the four streams. (**A**) 1900N; (**B**) Frog Creek; (**C**) Bray Creek; (**D**) Crooked Creek. Blue indicates baseflow gauge height; green indicates the gauge height required to mobilize d_{50} sediment; red indicates the gauge height to mobilize d_{85} sediment. Perspective is looking upstream for each cross-section. Vertical Exaggeration = 4.7.

3.3. Sediment Analysis

A total of 36 sediment grab samples, 4 to 5 kg each, were collected during sampling events in the fall and spring. Five samples were taken per stream with the exception of one location along both Frog and Bray where exposed diamicton limited sediment availability. Cumulative frequency curves were generated for each stream using the aggregate results of each sampling event (Figure 6; Table 2). Sediment grab samples taken during the fall and spring indicate the dominance of pebble and sand substrates at all four streams, resulting in similar grain size distribution. Crooked had a higher percentage of fine-grain sediment compared to the modified streams, correlating with Crooked exhibiting a slightly higher degree of sorting. However, the sediment distributions for all four streams were classified as poorly sorted. The distributions and sorting indicated that the sediment was derived from a similar source, diamicton.

3.4. Scour

All four streams experienced greater scour than sedimentation (Figure 7). The lack of observed sedimentation may also be a characteristic of the streams actively incising in the study reach. The total average scour and sedimentation documented in each stream were compared among the four study reaches (Figure 7). Frog exhibited the highest average scour (5.99 cm) followed by 1900N (4.77 cm), Crooked (3.74 cm), and Bray with the lowest average scour (3.30 cm). Similarly, Frog had the highest average sedimentation (2.09 cm) followed by Bray (1.74 cm), Crooked (1.60 cm), and 1900N with the lowest average sedimentation (1.40 cm). The ratio of scour to sedimentation among the modified streams was greatest in 1900N and decreased with time since channelization. The data support active incision immediately following channelization. However, the variability in sediment flux among the segments will control the the depth of scour as will the role of helical flow along the meander at Crooked Creek [30].

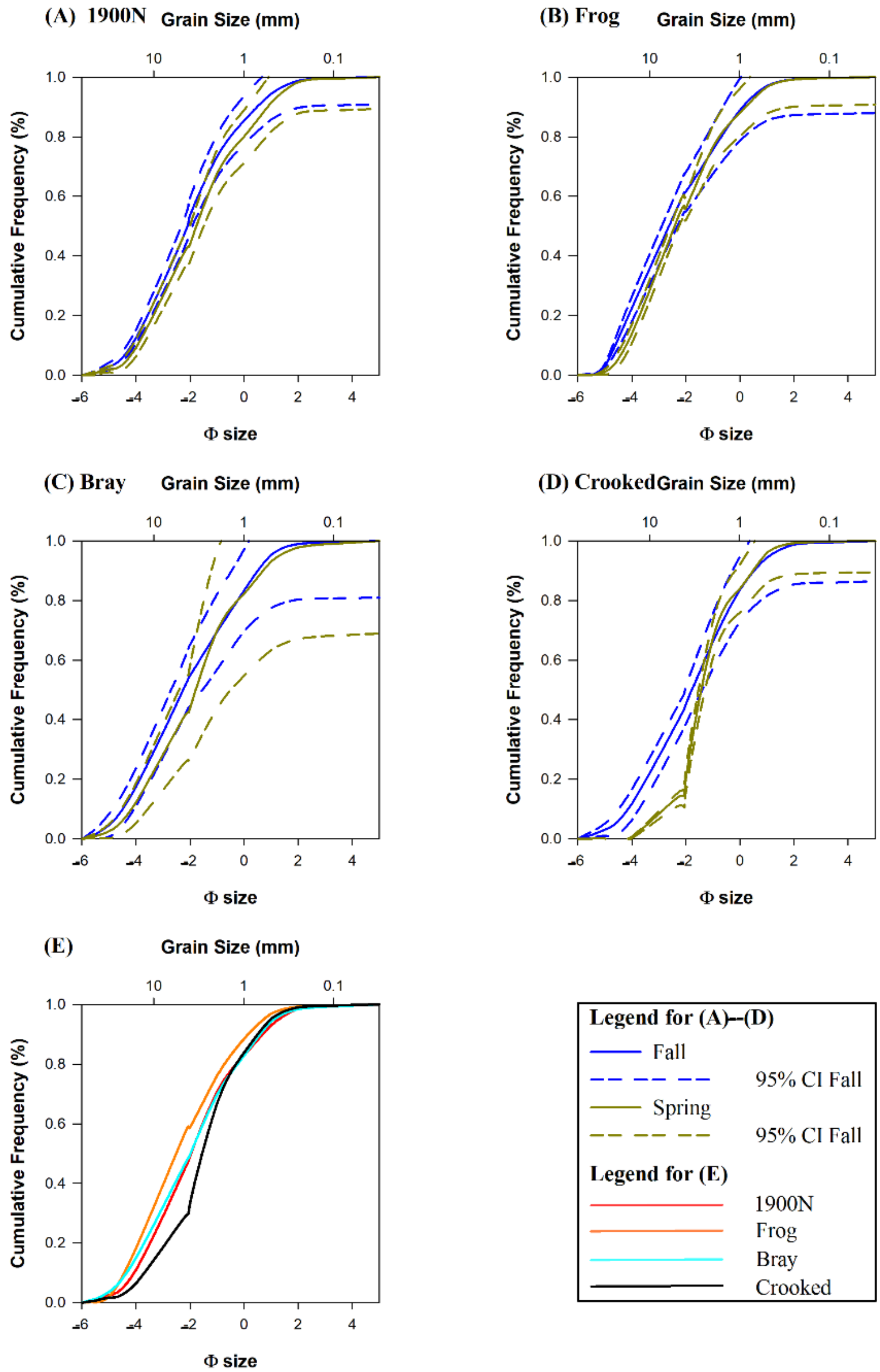

Figure 6. Cumulative frequency curve (solid) and 95% confidence interval (dashed) of each stream during the fall (blue) and spring (green). (**A**) 1900N—5 years; (**B**) Frog Creek—7 years; (**C**) Bray Creek—30 years; (**D**) Crooked Creek—unmodified; (**E**) cumulative frequency curve for the combined sediments samples for the four streams.

Table 2. Measured baseflow depths, d_{50} and d_{85} sizes, and calculated entrainment depths required to mobilize d_{50} and d_{85} sediments. Shaded cells highlight when the calculated entrainment depth was below the measured baseflow depth.

			1900N	Frog	Bray	Crooked
Baseflow (m)			0.12	0.46	0.39	0.52
Fall	d_{50} (mm)		4.38	6.11	4.77	3.53
	d_{85} (mm)		15.16	22.04	18.96	14.71
	Sorting		Poorly sorted			
	Water depth for Entrainment (m)	d_{50}	0.19	0.35	0.18	1.17
		d_{85}	0.67	1.28	0.72	4.86
Spring	d_{50} (mm)		3.48	5.83	3.52	2.73
	d_{85} (mm)		13.92	15.68	14.88	4.65
	Sorting		Poorly sorted			
	Water depth for Entrainment (m)	d_{50}	0.15	0.34	0.13	0.90
		d_{85}	0.61	0.91	0.57	1.54
Cumulative	d_{50} (mm)		3.92	6.45	3.96	3.00
	d_{85} (mm)		14.61	19.10	15.98	11.54
	Sorting		Poorly sorted			
	Water depth for Entrainment (m)	d_{50}	0.17	0.37	0.15	0.99
		d_{85}	0.64	1.11	0.61	3.82

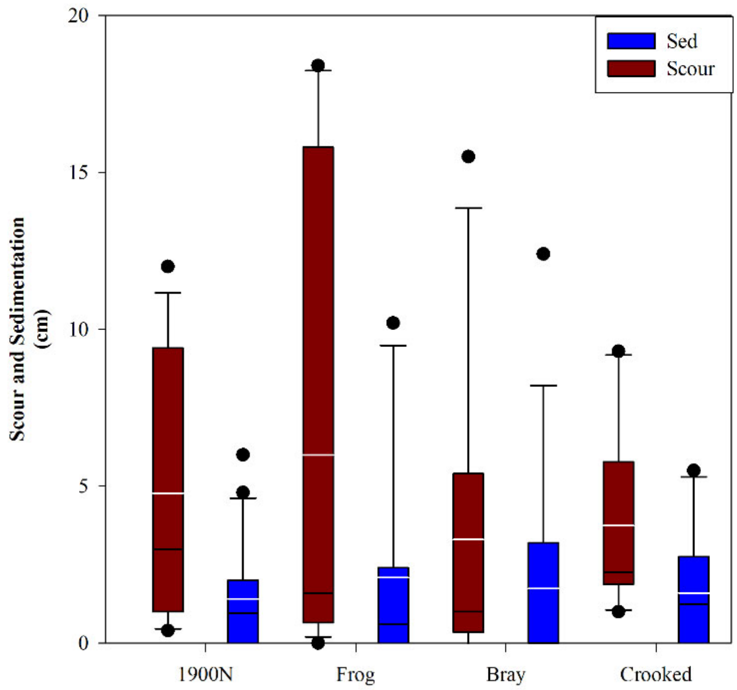

Figure 7. Scour and sedimentation in each stream. The ends of the boxes represent the 25th and 75th percentiles with the solid black line at the median and the solid white line at the mean; the error bars depict the 10th and 90th percentiles and the points represent the 5th and 95th percentiles.

3.5. Organic Matter

Organic matter ranged from 1% to 3% for sediment between 1 mm and 0.125 mm in diameter and was between 4% to 5.5% for sediment less than 0.125 mm in diameter (Figure 8). The cumulative organic matter content appeared to be inversely related to sediment diameter. All four streams exhibited similar organic matter content with no clear relationship with time since channelization.

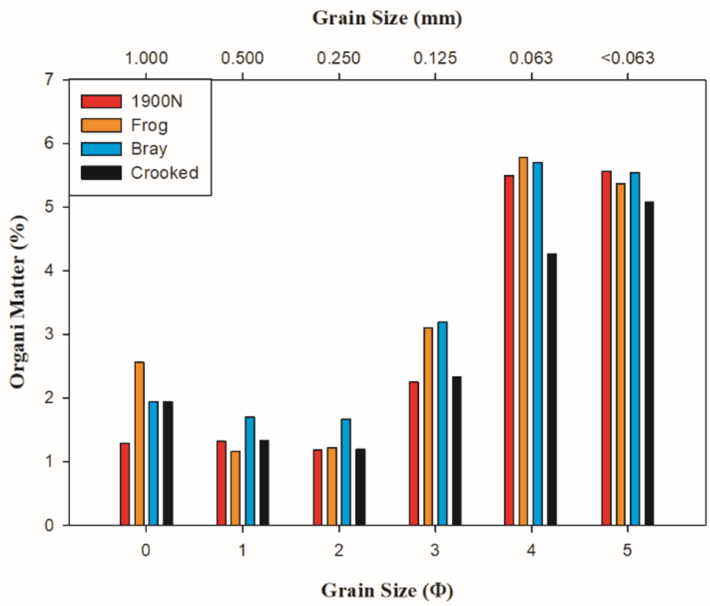

Figure 8. Cumulative percent organic matter in sediment less than 1 mm in diameter collected during the fall and spring.

3.6. Sediment Entrainment Threshold

Water depths required for the entrainment of the d_{50} and d_{85} sediments were calculated using Equation (2) (Table 2) and were plotted on the stream cross-sections along with the baseflow depths (Figure 5). The baseflow conditions were measured during the stream survey in a riffle of each stream. 1900N has a very shallow baseflow, slightly less than that required to mobilize d_{50} sediment. Conversly, Frog has a baseflow slightly greather than that required to mobilize d_{50} sediment. Bray exhibits a baseflow that falls between 1900N and Frog but is anomalous in that the baseflow conditions are nearly capable of mobilizing d_{85} sediment. Crooked had a baseflow that was positioned below the surface of the point bar. Mobilization of the d_{50} sediment would not occur until the water column depth was slightly above the point bar. The modified streams all require a similar water column depth to mobilize d_{85} sediment and the depth does not appear to correspond to a morphological feature such as a point bar. Crooked requires a flow depth that is in excess of bankfull conditions to mobilize d_{85} sediment.

4. Discussion

In terms of lateral and longitudinal morphology, the three modified streams, 1900N, Frog, and Bray, exhibited similar shapes created with the channelization. 1900N and Frog maintained the flat streambed with steep banks, while Bray had evidence of recovery. Channelization increased the streambed slope along 1900N, Frog, and Bray. Each channelized stream retained a streambed slope (*Sc*) an order of magnitude higher than the slope measured at Crooked. The higher *Sc* values provided greater opportunity for bank incision. After 5 years, no evidence of bank failure was observed along 1900N, while incision and bank failure were noted along both Frog and Bray. Frog showed evidence of channel widening after 7 years, and the lateral migration and development of immature meanders were present in Bray. Along Bray, a point bar was actively forming on the right bank, while a cutbank on the left bank was migrating horizontally. The baseflow wetted perimeter in Bray had also developed into a narrow channel compared to both 1900N and Frog, a result of sedimentation along the point bar. As Bray continues to meander, the baseflow wetted perimeter will begin to develop an asymmetrical shape similar to the one observed along Crooked, the unmodified stream.

The modified streams sinuosity indices were significantly less than that of Crooked. Although the morphology is redeveloping, meandering and mobilization are slow processes within the channelized stream despite 35 years of recovery. The lack of significant recovery aligned with the period of 10 to 15 years of degradation was reported by Simon and Rinaldi [9] for streams in western Illinois.

Channelization in conjunction with the installation of tile drains is an effective design to quickly drain runoff within the watersheds, resulting in higher incision rates. Observations of all four streams showed that scour was more significant than sedimentation. Average scour was found to be highest in Frog, which was consistent with active incision due to a reduction in sinuosity. Bray exhibited scour similar to Crooked, suggesting that the immature meanders that had formed in the 35 years may be beginning to replicate more natural conditions. The consistent and high degree of scour observed in 1900N and Frog was a result of uniform flow regimes throughout the reaches, whereas the variability observed in Bray and Crooked were indicative of riffle/pool sequences where the flow regime energy required to entrain sediment was more variable.

The modified streams sinuosity indices were significantly less than that of Crooked, indicating that although the morphology is developing, recovery is a slow process. While Bray possessed morphological features suggesting a transition to the threshold stage, the stream did not resemble natural conditions despite 35 years of recovery. The three channelized streams maintained low-gradient, low-sinuosity values, and at times, limited sediment, as indicated by the presence of exposed diamicton along the streambed. Streams with low gradients, low sinuosity, and bedrock outcrops can have areas of limited mobility [31], resulting in the limited reestablishment of natural features in channelized streams [11,32].

The ability of a stream to restore itself requires sediment [9,33]. Loose sediment was present along each channel, but exposed diamicton could be seen in some segments. Among the streams, the distributions of the sediment sizes were similar (Figure 6), supporting the weathering diamicton as the source of the sediment. While fines are present, the sediments at all sites are poorly sorted and dominated by sand and pebble particles. The lack of finer sediment low-energy systems should enhance meander development [34]; however, the high rate of scour, as compared to sedimentation, may be contributing to the lack of recovery. Sediments within the modified streams were mobile at or near baseflow conditions (Figure 5), consistent with the stage of degradation. The degradation of 1900N and Frog will continue until sufficient coarse-grained materials are introduced into the stream allowing for aggradation. Once aggradation occurs, the stream will begin to recover with the deposition of alternate point bars and the establishment of a new floodplain. Bray exhibited signs of bank failure, which provided sediments point bar development.

Lorang and Hauer [26] found that disturbances to the streambed often have a substantial impact on flow competence. A storm event capable of mobilizing d_{85} sediment causes the most significant erosion, and the process of streams in the region returning to natural conditions is dependent on the occurrence of these events. The water depth required to mobilize d_{85} sediment was highest in Frog compared to both 1900N and Bray. Bray is in a transient state in that baseflow is capable of moving d_{50} sediment although not capable of mobilizing d_{85} sediment. This scenario could not be sustained for a substantial period of time without sedimentation occurring. Crooked entrains d_{50} sediment at a water depth that closely corresponds to a point bar that has an asymmetrical shape of a small levee present in a major riffle. The water depth required to mobilize d_{85} sediment in Crooked is greater than bankfull discharge and only occurs infrequently during high flow events where significant flooding is occurring. All three modified streams appear to be in a complex and fluid state that was not observed in the developed morphology of more natural conditions. In a low-order, low-gradient (3×10^{-3} m/m) watershed similar to those investigated in this study, high flow events capable of entraining the d_{85} grainsize (11 to 39 mm) occur every 2.1 months [27]. Despite the lack of frequency data, the recorded scour along the segments confirmed the recurrent entrainment of the sediment.

Typically, the formation of bar units in modified streams leads to the development of a secondary "meandering" stream within the straightened stream channel [2,35]. In areas such as central Illinois, the stream power is inadequate to incise into to the glacial till present beneath the stream [2]. Sediments are derived from bank failure. In the absence of bank failure producing sand and gravel, recovery is limited [2,11]. 1900N and Frog appeared to be in the degradation stage, while Bray had transitioned to the threshold stage. Using Crooked as the reference and employing the power Equation (5), the streams will require over 11,000 years to return to their natural state. It is doubtful that the three modified systems will show significant recovery in the near future.

The impact of channelization goes beyond geomorphic considerations. Within the Midwest, channelization coupled with the installation of tile-drainage networks are performed to improve productivity by draining water from agricultural soils to streams [36,37]. These practices have accelerated nutrient export from fields to streams, exacerbating the growth of the hypoxic zone in the Gulf of Mexico [36,38–43]. Headwater streams play an integral role in nutrient removal in agricultural systems [44]. Established streambeds and meanders serve as areas of nitrate removal within streams systems [45–54]; however, channelization results in a more mobile streambed and the removal of meanders. Subsequently, the ability of the channelized streams studied here to remove nitrate has been reduced [55]. Landowners employ routine maintenance practices to ensure the efficiency of agricultural drainage practices; thus, any geomorphic recovery is reset, which further impairs the ability of streams to remove nutrients.

5. Conclusions

The results of this study suggest the following:

Channelization results in an increase in the streambed slope. The recovery of the stream, based on the stream's sinuosity, would require over 10,000 years to replicate the conditions in an unmodified segment. However, practices of continued maintenance negate the recovery processes and reset the recovery period.

1900N and Frog Creek are still in the degradation stage. Both exhibit greater scour than sedimentation but have not experienced bank failure.

After over 35 years, Bray Creek is in the threshold stage. Bray experienced more scour than sedimentation; however, the two values were closer. Bray has experienced bank failure, from which a meander system is developing. However, the stream segment has not reached the aggradation or restabilization stage.

In agricultural areas where stream modification is a common, reoccurring practice, streams will never recover to their natural state. Recovery of the stream, especially the redevelopment of the streambed, is critical to the cycling of nutrients and the microbial process [47,56–58], which are needed to reduce nutrient concentrations in headwater streams [44].

Further research into the potential cause–effect relationship between stream modification and sediment transport and the effects that stream modification have on sediment availability should be undertaken. A detailed examination of the channelization history, an examination of aerial imagery, would provide insight into how variable maintenance schedules influence recovery rates. Looking at stream segments upstream from the study sites to determine whether there are changes in sediment transport along a stream would be useful in determining the source of the sediment.

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