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OBJECTIVE IDENTIFICATION OF POOLS AND RIFFLES IN A HUMAN-MODIFIED STREAM SYSTEM

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ABSTRACT: *Pools have been defined as topographic lows along a longitudinal stream profile and riffles are topographic highs. Past research has shown pools and riffles are the fundamental bed forms in meandering streams and that channel cross sections in meandering channels exhibit varying degrees of asymmetry that coincide with these bed form features. Two indices that identify pool and riffle bed forms are the bed differencing technique (bdt) developed by O'Neill and Abrahams (1984) and the areal difference asymmetry index (A^*) (Knighton, 1981). The purpose of this research was to use these indices to objectively identify pools and riffles in three reaches of a human-modified stream. Geomorphological data were collected in two meandering reaches and one straight reach of the East Branch of Cazenovia Creek, NY. Between 16 and 19 cross sections were surveyed in each reach during summer low flow conditions. The bdt identified more bed forms in the meandering reaches versus the straight channelized reach (six and two bed forms, respectively). Results from the asymmetry analysis indicated that more cross sections in the two meandering reaches were asymmetrical (71 and 73% of the cross sections) versus 47% of the cross sections being asymmetrical in the straight reach. Moreover, asymmetrical cross sections generally corresponded with pool bed forms identified by the bdt and symmetrical cross sections corresponded with riffle bed forms identified by the bdt. This research has provided a practical field-based test of the accuracy of the bdt and the A^* and agreement between the two indices also was evaluated. These results also support previous research that has found that channel planform and cross-sectional shape are linked and that as channels progress from straight to meandering cross-sectional asymmetry increases.*

INTRODUCTION

Geomorphological research on pools and riffles has shown that these bed forms are fundamental elements of meandering streams (Bhowmik and Demissie, 1982; Dietrich, 1987; Clifford, 1993; Sear, 1996). Moreover, there has been in interest in geomorphology to objectively define pools and riffles based on their physical characteristics. Therefore, the identification of pool and riffle features has focused on the morphology, spacing and sedimentology of these features (Leopold et al., 1964, p. 203; Richards, 1976; Keller and Melhorn, 1978; Hirsch and Abrahams, 1981; Bhowmik and Demissie, 1982; Knighton, 1981; O'Neill and Abrahams, 1984; Wohl et al., 1993; Thompson et al., 1996). Pools have been defined morphologically as topographic lows along a longitudinal stream profile (O'Neill and Abrahams, 1984) and research has shown that they generally have asymmetrical cross section shape (Knighton, 1981). Conversely, riffles are topographic highs (O'Neill and Abrahams, 1984) that have symmetrical cross section shapes (Knighton, 1981). Previous field studies have also shown that pools and riffles are generally spaced five to seven channel widths apart (Leopold et al., 1964; Keller and Melhorn, 1978) and bed sediment in pools is finer than bed sediment found in riffles (Hirsh and Abrahams, 1981; Bhowmik and Demissie, 1982; Clifford, 1993).

Two indices based on stream morphology were developed in the 1980's to objectively define pools and riffles. O'Neill and Abrahams (1984) developed the bed differencing technique (bdt) to define pools and riffles based on bed topography and Knighton (1981) developed the areal difference asymmetry index (A^*), which provided a quantitative measure of cross section shape. The purpose of this research was to objectively identify pools and riffles in a human-modified stream system using these two indices. The bed differencing technique and the areal difference asymmetry index were used to quantify stream morphology in three stream reaches with different channel planforms (i.e., meandering versus straight). This research has provided a practical field-based test of the accuracy of the bdt and the A^* and agreement between the two indices also was evaluated. Additionally, this research allowed for the linkages between pool and riffle location and channel planform to be investigated in reaches with natural meandering and channelized straight planforms.

METHODOLOGY

Study Area

Cazenovia Creek is one of three tributaries to the Buffalo River, Buffalo, NY (Figure 1 inset). The International Joint Commission (IJC) has designated the Buffalo River as one of 43 Areas of Concern (AOC). The designation was based, in part, on factors like degradation of fish and wildlife habitat and contaminated bed sediment in the river (New York State Department of Environmental Conservation, 1989). Cazenovia Creek is 48 km long and has a drainage area of 350 km^2. Fourteen and one half kilometers of Cazenovia Creek were part of a Natural Resources Conservation Service (NRCS;

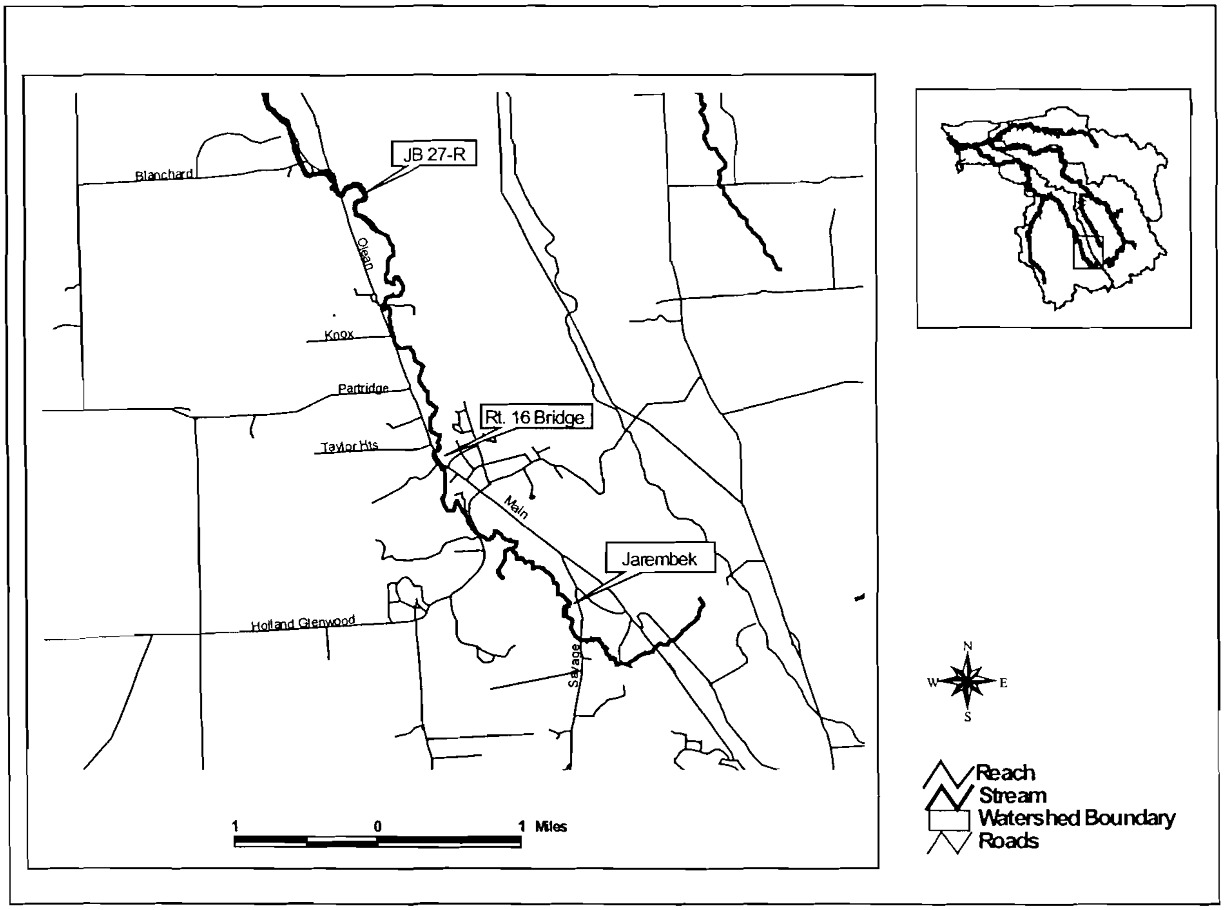

Figure 1. Map of the East Branch of Cazenovia Creek with study sites identified. Buffalo River watershed in inset.

Table 1 Summary data from each reach

	JB 27-R site	Rt. 16 bridge site	Jarembek site
Length of Reach (m)	167.9	187.3	155.4
Number of cross sections surveyed	16	19	16
Sinuosity	1.21	1.05	1.29

Table 2 Results of the bed differencing technique

	JB 27-R site	Rt. 16 bridge site	Jarembek site
$S_d(T)$	0.24	0.14	0.38
Number of bed forms identified	6	2	6

formerly the Soil Conservation Service) bank stabilization program that began in 1953 (Parsons et al., 1963). Moreover, the creek has been the target of recent stream bank stabilization projects to address the issue of in-stream sediment sources (Mark Gaston, Erie County Soil and Water Conservation District, personal communication). When channels are stabilized, they are often straightened and lined with rock rip-rap, which prevents re-meandering.

Field Methods

Geomorphological data were collected in three reaches of the East Branch of Cazenovia Creek, NY (Figure 1) using a total station. Site set-up at each reach began with obtaining an easting, northing, and elevation (x,y,z) reading at an initial benchmark point (BM100) using a Trimbal® hand-held GPS unit. A second benchmark was installed due north (i.e., zero azimuth) of the BM100 to provide horizontal and vertical control for the surveys. Easting, northing, and elevation data were then obtained along cross sections using a Sokkia® total station. Approximately twenty cross sections were surveyed in each reach. Cross sections were spaced roughly 10 meters apart (i.e., approximately one channel width). The number of points surveyed in each cross section ranged from seven to 11 depending on the geomorphological complexity of the cross sections. At each cross section, points on the banks, gravel bars, and edges of water (EOW) were surveyed.

Table 3 Summary results of the Areal Difference Asymmetry Index

Reach	A^* range	Symmetrical cross sections	Asymmetrical cross sections
JB 27-R	-0.88-0.46	27% (4)	73% (11)
Rt. 16 bridge	-0.42-0.31	53% (10)	47% (9)
Jarembek	-0.08-0.74	29% (5)	71% (12)

Table 4 JB 27-R site A^* vs. bdt Comparison

Cross-section	A^*	bdt	match
2	0.13	riffle	no
5	0.41	pool	yes
6	-0.88	riffle	no
10	0.28	pool	yes
11	-0.04	riffle	yes
16	0.46	pool	yes

Bed Differencing Technique

The bed differencing technique followed the methodology described in O'Neill and Abrahams (1984). The channel thalweg (i.e., the deepest part of the channel) location from each cross section was used to calculate the bdt. First, the bed elevation difference series was calculated from upstream to downstream for each reach:

[1] $B_1 - B_2, B_2 - B_3, \ldots$

where $B_{1,2,3,n}$ is equal to the bed elevation of the thalweg of each cross section. Second, the standard deviation (S_d) of the bed elevation difference series was calculated and a tolerance (T) was calculated based on the standard deviation of the difference series values. T is defined as the absolute minimum value needed to identify a pool or riffle bed form. Several values of T were investigated for this study ($0.5S_d$, $0.75S_d$, $1.0S_d$, $1.25S_d$, $2.0S_d$). Finally, the bed elevation difference at each point or series of points from the last identified bed form were compared to T to identify absolute minimum and maximum bed elevations (i.e., locations of pools and riffles).

Areal Difference Asymmetry Index

The areal difference asymmetry index compares cross-sectional area on either side of the channel centerline (Knighton, 1981) and is calculated as follows:

[2] $A^* = (A_r - A_l)/A$

where A^*= areal difference asymmetry index, A_r= area to the right of channel centerline, A_l= area to the left of channel centerline, and A = total cross-sectional area. Knighton (1981) did not indicate where the boundary between symmetrical and asymmetrical cross section shape was; however, the transition from symmetrical to asymmetrical cross section shape for his artificially-constructed cross sections was $A^* = 0.08$ to 0.13. In this study, therefore, cross sections with A^* values between -0.10 and 0.10 were considered symmetrical (i.e., riffles) and all other cross sections were considered asymmetrical (i.e., pools).

RESULTS AND DISCUSSION

Three reaches were investigated in this study: the JB 27-R site, the Route 16 bridge site, and the Jarembek site (Figure 1). The JB 27-R and Jarembek sites are meandering (Table 1) and the banks have not been stabilized, while the Rt. 16 bridge site is a straight reach immediately downstream of a bridge and the entire east bank has been stabilized with rock rip-rap. Reaches ranged from 155.4 meters to 187.3 meters in length and the number of cross sections surveyed in each reach ranged from 16 to 19 (Table 1).

Bed Differencing Technique

A T of $1.0S_d$ was determined to be most accurate for the three reaches based on the longitudinal profiles of the reaches (Figure 2) and the five to seven channel width spacing of pools and riffles (Leopold et al., 1964; Keller and Melhorn, 1978). Results from the bdt indicate that more bed forms were identified at the JB 27-R and Jarembek sites than the Rt. 16 bridge site (Table 2; Figure 2). Three pools and three riffles were identified in the JB 27-R and Jarembek sites (Figure 2). The location of these bed forms corresponded with the meandering planform of the reaches. In other words, for the most part, pools in these two reaches were located at and along bend apexes and riffles were located between bends. One pool and one riffle were identified in the Rt. 16 bridge site (Figure 2). The pool that was identified in the Rt. 16 bridge site (Table 2; Figure 2) was located immediately downstream of a block of concrete in the stream and was not linked to overall channel planform in the reach. Lastly, the S_d in the three reaches ranged from 0.14 to 0.38 (Table 2) and was higher in the two more sinuous reaches versus the straight reach, indicating more variability in bed elevation at the two meandering sites.

Areal Difference Asymmetry Index

Results of A^* indicate that more cross sections in the meandering reaches are asymmetrical versus those in the straight stabilized reach (Table 3; Figure 3). Seventy-three and 71% of the cross sections in the JB 27-R and Jarembek sites were

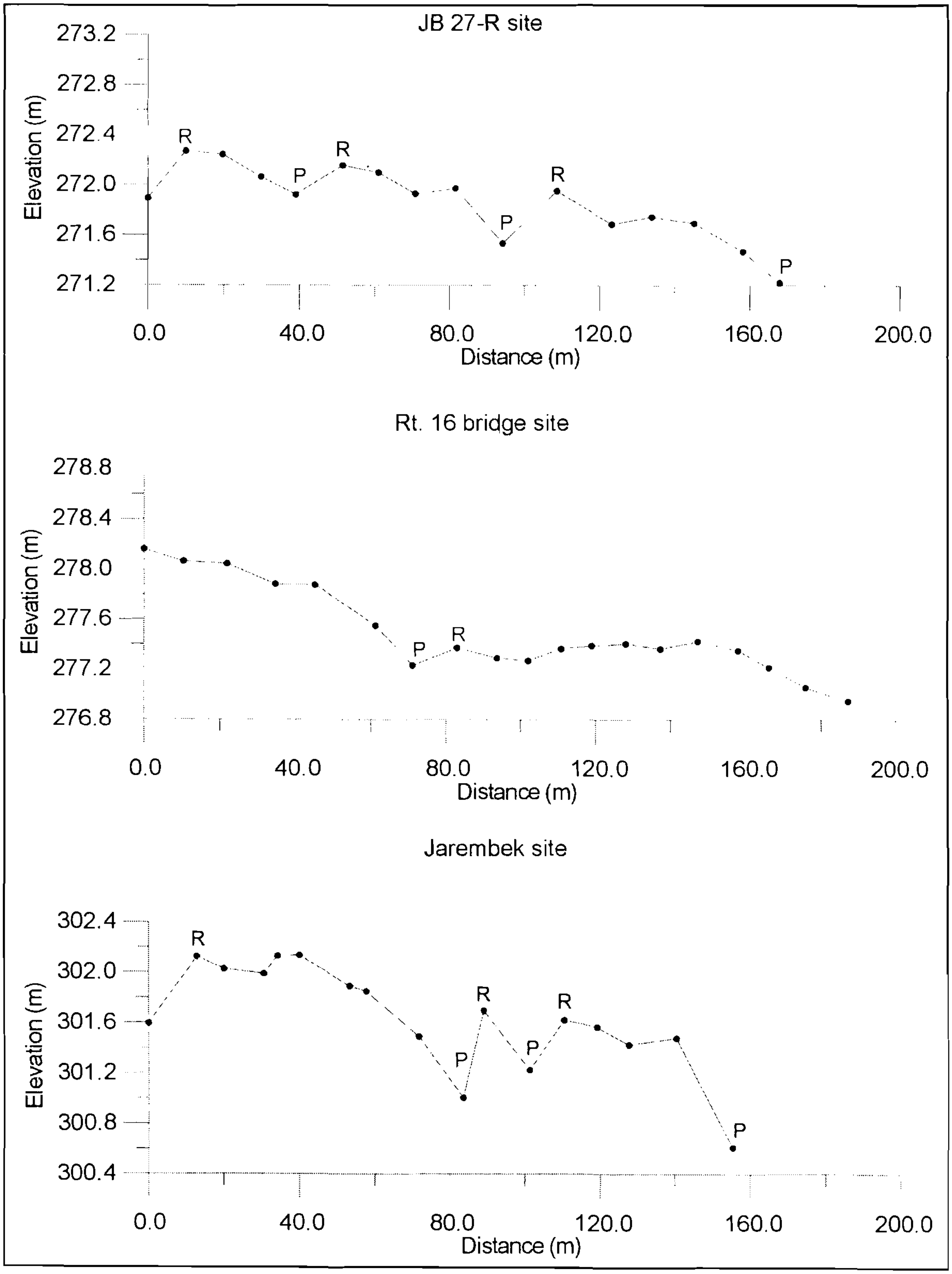

Figure 2. Longitudinal profiles of study reaches and results of the bdt; P = pool bed forms and R = riffle bed forms as defined by the bdt.

Table 5 Rt. 16 bridge site A^* vs. bdt Comparison

Cross-section	A^*	bdt	match
7	-0.42	pool	yes
8	0.02	riffle	yes

Table 6 Jarembek site A^* vs. bdt Comparison

Cross-section	A^*	bdt	match
2	0.22	riffle	no
10	0.74	pool	yes
11	0.34	riffle	no
12	0.39	pool	yes
13	0.04	riffle	yes
17	0.51	pool	yes

asymmetrical, while only 47% were asymmetrical in the Rt. 16 bridge reach. The A^* range was also greater in the two meandering reaches versus the straight reach, again indicating more variability in cross section shape in the JB 27-R and Jarembek reaches (Table 3; Figure 3). These results support previous research that has shown that as channel planform changes from straight to meandering, the number of asymmetrical cross sections increases (Leopold and Wolman, 1960; Einstein and Shen, 1964).

Comparison of the A^* vs. bdt Results

Generally there was good agreement between the bdt and A^* in all three study reaches (Tables 4-6). Both bed forms in the Rt. 16 bridge site matched in their identification of pool and riffle (Table 5). However, two of the six bed forms identified in the JB 27-R and the Jarembek reaches (Table 6) did not match.

Cross-section two at the JB 27-R site was defined as a pool using A^* and as a riffle using the bdt (Table 4). The A^* value of 0.13 at cross-section two was only slightly greater than the 0.10 symmetrical to asymmetrical transition boundary chosen for this study and it was within Knighton's (1981) classification of a symmetrical (e.g., riffle) cross section. Given that the bed form at cross-section two was close to the pool/riffle transition boundary and the fact that bed sediment in the cross section was relatively coarse, the authors would agree with the bdt classification of the bed form as a riffle. Cross-section six at the JB 27-R site was defined as a pool using A^* and as a riffle using the bdt (Table 4). This discrepancy between the indices was due to the location of the cross section in the reach and a noticeable change in channel form upstream and downstream of cross-section six. Cross-section six was located immediately downstream of a large (approximately 20 m tall) fallen tree adjacent to the east bank. Upstream of cross-section six the channel (EOW-EOW) was approximately 10 m wide through the area with the fallen tree. Downstream of the fallen tree, the channel narrowed to approximately 5 m wide because of the deposition of a large gravel bar along the west bank of the stream. Despite the asymmetrical shape of cross-section six (Figure 3), the authors would classify the cross section as a riffle because: 1) this area was a topographic high (Figure 2) coming out of a pool caused by the fallen tree, 2) bed sediment in the cross section was coarser (e.g., gravel with some cobbles) here than in other areas of the reach, and 3) velocity increased as the channel narrowed at this cross section.

There was disagreement between the bdt and A^* at cross-sections two and 11 in the Jarembek reach (Table 6). Cross-section two did have a slightly asymmetrical shape ($A^* = 0.22$) (Figure 3) and the bed sediment at this cross section was relatively fine (e.g., silt and sand); however, it is also apparent from the longitudinal profile (Figure 2) that it was a topographic high and the location of cross-section two was not at or near the meander bend apex. Given this mix of pool/riffle characteristics it is difficult to say whether this bed form should be classified as a

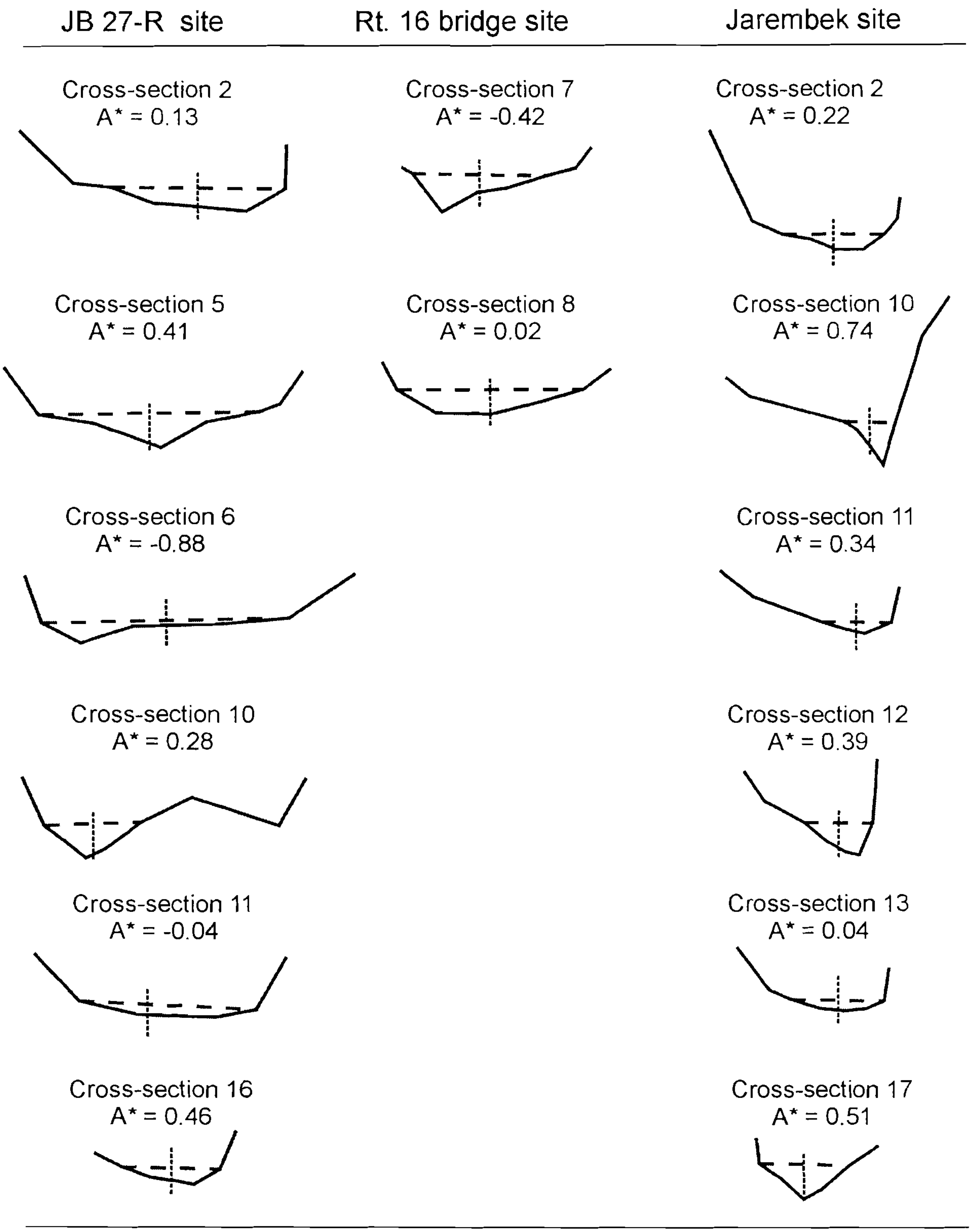

Figure 3. Examples of cross section profiles and A^* values from study reaches. Large dashes indicate water surface and small dashes show the location of the channel centerline.

pool or riffle, but it is clear that its form is not associated with planform meandering. In the case of cross-section 11, however, the authors favor the A^* index and would classify this bed form as a pool. Cross-sections eight through 12 are at and immediately downstream of the meander bend apex and an extended pool was located along the west bank of this section of the reach. There was considerable erosion along the west bank, which has caused bank failure of large chunk of cohesive clay, rock, and tree stumps. It is the opinion of the authors that the topographic high (i.e., riffle) identified here using the bdt may have resulted from survey points on top of this failed bank debris; however, cross-section 11 is more accurately identified as a pool because of the morphology of this section of the reach.

CONCLUSIONS

In conclusion, both the bdt and the A^* indices identify pools and riffles based on stream morphology. This study attempted to identify bed forms in a human-modified stream using these indices. Overall the identification of pool and riffles in the three reaches agreed and the location of the bed forms corresponded with meandering planform shape (e.g., most pools were found at bend apexes and riffles were identified between bends) or the presence of obstacles in the stream. These results also support previous research that has found that channel planform and cross-sectional shape are linked and that as channels progress from straight to meandering cross-sectional asymmetry increases (Leopold and Wolman, 1960; Knighton, 1981). This research, therefore, provided a much needed field-based verification of the bdt and the A^* indices and it allowed for conclusions to be made regarding the link between channel planform and pool/riffle development.

In cases where there was not agreement between the bdt and the A^*, the discrepancies can be explained by examining stream morphology in the field. This is a noteworthy point and, the authors believe, does not take away from the objectivity or accuracy of the indices. There is some subjectivity inherent in both indices; for example, picking the T value for the bdt and determining the transition point from symmetrical to asymmetrical for A^*. Additional subjectivity and knowledge of field sites has to be incorporated into results analysis to explain differences between pool and riffle identification using the two indices; this additional information may include bed sediment distribution, velocity, and location of the bed form within a bend. For the most part, using the indices together provides corroboration of results and strengthens the analysis. This is especially important in human-modified stream systems because these are not "textbook" meandering streams, so the location of the bed forms associated with stream meandering may or may not be located exactly where one might expect them.

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