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Logistic analysis of channel pattern thresholds: meandering, braiding, and incising

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Abstract

A large and geographically diverse data set consisting of meandering, braiding, incising, and post-incision equilibrium streams was used in conjunction with logistic regression analysis to develop a probabilistic approach to predicting thresholds of channel pattern and instability. An energy-based index was developed for estimating the risk of channel instability associated with specific stream power relative to sedimentary characteristics. The strong significance of the 74 statistical models examined suggests that logistic regression analysis is an appropriate and effective technique for associating basic hydraulic data with various channel forms. The probabilistic diagrams resulting from these analyses depict a more realistic assessment of the uncertainty associated with previously identified thresholds of channel form and instability and provide a means of gauging channel sensitivity to changes in controlling variables.

Keywords: Channel stability; Braiding; Incision; Stream power; Logistic regression

1. Introduction

Excess stream power may result in a transition from a meandering channel to a braiding or incising channel that is characteristically unstable (Schumm, 1977; Werritty, 1997). Changes in the magnitude, relative proportions, and timing of sediment and water delivery in these channels may affect water quality via a wide variety of mechanisms. These mechanisms include changes in channel morphology, planform, bed material, and suspended sediment loads, loss of riparian habitat because of stream bank erosion, and changes in the predictability and variability of flow and sediment transport characteristics relative to aquatic life cycles (Waters, 1995). In addition, braiding and incising channels frequently threaten human infrastructure.

Alluvial channel patterns form a continuum rather than discrete types and distinctions between morphologic types are fuzzy and complex (Ferguson, 1987; Knighton and Nanson, 1993). Process and historical studies of individual streams suggest that switches between channel patterns may be historically contingent on how intrinsic variables have 'primed' a reach for instability and on the state of the channel at the time of an impact (Brewer and Lewin, 1998). Because channel patterns are frequently transitional and shaped by complex sequences of disturbance

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events, stochastic alternatives to deterministic thresholds may be more useful and realistic for predictive and postdictive work on the effects of geomorphic change (Graf, 1981; Tung, 1985; Ferguson, 1987). Probabilistic discrimination of relatively stable and unstable channel types using basic sedimentary and hydraulic variables offers improved predictions of environmental impacts. Such predictions of risk help establish priorities for management, planning, and policy.

1.1. Discriminators of braiding and meandering

In the latter half of the twentieth century, geomorphologists and engineers attempted to predict the planform of rivers based on the slope and some measure of discharge or drainage area. The concept of a threshold discharge–slope (Q–S) combination that discriminates braiding rivers from meandering ones has become firmly embedded in the doctrine of fluvial geomorphology (Carson, 1984). The Q–S discriminator was first suggested by Lane (1957) and Leopold and Wolman (1957). Many other investigators have provided support for the notion of a threshold between meandering and braiding types and have used this approach to interpret a variety of field and flume data (Schumm and Khan, 1972; Chitale, 1973; Osterkamp, 1978; Begin, 1981; van den Berg, 1995).

Critical examination of the early work on meandering to braiding thresholds has subsequently revealed several limitations of the original approach. Critical stream power for braiding appears to vary with bed material size; i.e., the critical slope for braiding at a given discharge is higher for gravel than for sand bed channels (Carson, 1984; Ferguson, 1987). The threshold suggested by Leopold and Wolman (1957) is too high for sand bed channels and too low for gravel bed channels because it is based on a combination of the two channel types. Other concerns with the original stream power approach arise from bias associated with using channel slope and bankfull discharge parameters (van den Berg, 1995). Channel slope and bankfull discharge are not necessarily independent of planform. Braided channels are inherently steeper than meandering channels for a given valley slope because of generally low sinuosity. Braided channels may also have larger bankfull cross-sections as a consequence of braiding. Some investigators have also suggested that bank resistance is a confounding factor in the analysis of channel planform (Carson, 1984; Ferguson, 1987; Bridge, 1993).

Several theoretical approaches to defining the transition from meandering to braiding have also been developed (e.g., Parker, 1976; Fredsøe, 1978; Fukuoka, 1989). These techniques have limited predictive value, however, because the techniques rely on parameters such as width, depth, and Froude number that are usually not available for a priori predictions of channel form. The theoretical approaches do seem to suggest that braiding generally occurs at channel width-to-depth ratios in excess of 50 (Fredsøe, 1978). Bridge (1993) provides an excellent review and summary of the various empirical and theoretical thresholds that have been proposed for the transition from braiding to meandering.

In an attempt to reconcile some of the issues associated with the original empirical approaches, van den Berg (1995) devised a simple parameter representing potential specific stream power that enables discrimination of braiding and meandering rivers (sinuosity ≥ 1.3) in unconfined alluvium. Using a data set of 126 streams and rivers, he arrived at a discriminant function of the form:

$$\omega \cong \frac{\gamma}{\alpha} S_v Q_{\mathrm{bf}}^{0.5} = 900\, D_{50}^{0.42} \tag{1}$$

where specific stream power (ω) is a function of valley slope, estimated bankfull discharge (m^3/s), and a regression coefficient (α) computed for a particular collection of streams that varies between sand bed and gravel bed rivers. The discriminate function applies to both sand and gravel bed rivers with median bed material ranging from 0.1 to 100 mm. Potential specific stream power and median particle size (D_{50}) are expressed in Watts per square meter (W/m^2) and meters, respectively. The resulting specific stream power represents the maximum potential specific stream power for a particular valley slope.

1.2. Stream power and evolution of incising sand bed streams

Channel incision, or bed lowering by erosion, results from an imbalance in the power *available* to move a sediment load and the power *needed* to move the sediment load (Bull, 1979; Galay, 1983). Where banks are cohesive and resistant to hydraulic forces, bed erosion is initially dominant over channel widening. As an incising channel deepens, flow events of increasingly greater magnitudes are contained within the channel banks. This process may create a positive feedback wherein shear stress on the bed and toe of the banks during large events is magnified through incision. If bed degradation continues until banks reach a critical height for geotechnical failure, radical channel widening may be initiated. Such widening can proceed at a staggering rate, with tenfold increases in cross-sectional areas reported in some instances (Harvey and Watson, 1986).

Conceptual models of the temporal response or evolutionary sequence of incised channels have been described by various investigators (Schumm et al., 1984; Harvey and Watson, 1986; Watson et al., 1988a,b; Simon, 1989; Simon and Hupp, 1992). The models generally describe the same process: excess specific stream power initially results in bed degradation followed by a period of widening and bank failure and further bed adjustment until the channel eventually establishes a new flood plain and quasi-equilibrium channel form within newly deposited alluvium.

When compared with work on the meandering to braiding threshold, incised channel forms have received relatively little attention from researchers. Even less common are investigations of thresholds of stream power associated with the development of incised channel forms.

1.3. Objectives

Water resources engineers and fluvial geomorphologists sometimes need to relate qualitative dependent variables to one or more independent variables, which may or may not be quantitative. In the case of channel instability and ecosystem changes because of excess stream power, the dependent variable might be the occurrence or nonoccurrence of a rapid and significant geomorphic response in the form of widening and/or incision. Thus, the dependent variable is binary and qualitative and the independent variable may be quantitative and continuous, such as specific stream power, the size of bed material, sediment load, and bank resistance. Logistic regression (Menard, 1995; Christensen, 1997) is a statistical technique that allows comparison of binary and continuous parameters. The research described below is targeted at developing a risk-based approach for predicting the occurrence of stable meandering, braiding, and incising channel forms as a function of simple hydraulic and sedimentary attributes. The specific objectives of the proposed research were the following.

(i) To use a very large data set from actual streams with logistic regression methodology to identify probabilities of occurrence of braiding or incising channels versus meandering channels using simple indices of specific stream power and characteristics of bed material.

(ii) To contrast the logistic regression results with van den Berg's (1995) previously defined geomorphic threshold between meandering and braiding forms.

2. Methods

2.1. Logistic regression analysis—basic concepts

Commonly applied regression techniques are appropriate only when the dependent variable and the explanatory variables are quantitative and continuous. To analyze a binary qualitative variable (0 or 1) as a function of a number of explanatory variables, special techniques must be used if the analysis is to be performed adequately. The regression problem may be revised so that, rather than predicting a binary variable, the regression model predicts a continuous variable that stays within the 0–1 bounds. One of the most common regression models that accomplishes this is the logit or logistic regression model (Menard, 1995; Christensen, 1997). Although logistic regression is most frequently applied in the social and health sciences, Tung (1985) presented a logistic regression methodology to evaluate the potential of channel scouring as a function of quantitative data taken from flume studies.

In the logistic regression model, the predicted values for the dependent variable are never ≤ 0 or ≥ 1 regardless of the values of the independent variables. This is accomplished by applying the following regression model:

$$y = \frac{\exp(\beta_0 + \beta_1 x_1 + \ldots + B_n x_n)}{1 + \exp(\beta_0 + \beta_1 x_1 + \ldots + \beta_n x_n)} \quad (2)$$

Regardless of the regression coefficients or the magnitude of the x values, this model will always produce predicted values in the range of 0 to 1. Suppose the binary dependent variable y represents an underlying continuous probability p, ranging from 0 to 1. The probability p may be transformed as:

$$p' = \ln\left(\frac{p}{1-p}\right) \quad (3)$$

This transformation is referred to as the logit or logistic transformation. Note that p' can theoretically assume any value between minus and plus infinity. Since the logit transform solves the issue of the 0–1 boundaries for the original dependent variable (probability), the logit transformed values could be used in an ordinary linear regression equation. If Eq. (3) is applied to both sides of the logistic regression equation stated in Eq. (2), the standard linear regression model is obtained:

$$p' = \beta_0 + \beta_1 x_1 + \ldots + \beta_n x_n \quad (4)$$

In logistic regression analysis, maximum likelihood techniques may be used to maximize the value of a function, the log-likelihood function, which indicates how likely it is to obtain the observed values of the dependent variable given the values of the independent variables and parameters, $\beta_0, \ldots, \beta_n$. Unlike ordinary least squares regression, which is able to solve directly for parameters, the solution to the logistic regression model is found through an iterative process that maximizes the likelihood function until the solution converges within tolerance. Maximum likelihood estimation was used for all logistic regression analyses described in this study. A quasi-Newton method provided in the statistical analysis software Statistica® (StatSoft®, 1999) was used to optimize the maximum likelihood function. Model results from Statistica® were verified using the SAS software package (SAS Institute, 1990).

2.2. Regression interpretation and diagnostics

In ordinary regression analysis, the coefficient of determination (R^2) is frequently used as a measure of model performance. In logistic regression, it is common to be more concerned with whether the predictions are correct or incorrect than with how close the predicted values are to the observed (0 or 1) values of the dependent variables. Therefore, R^2 has little meaning in logistic regression analysis (Tung, 1985; Christensen, 1997). One of the most meaningful ways of interpreting a logistic regression model is to examine the number of incidences of misclassification (Tung, 1985). The number of correct and incorrect classifications may be used to calculate an 'odds ratio' (Neter et al., 1988) from a 2×2 classification table which displays the predicted and observed classification of cases for a binary dependent variable. Although the odds ratio provides a useful measure of predictive accuracy, it is quite sensitive to sample size. Care must be taken in comparing across models that have differing numbers and proportions of dependent variable cases. In this study, the percentages of streams and rivers correctly classified by the various logistic regression models was used as a primary measure of model performance.

Goodness-of-fit tests may also aid in the interpretation of the results of logistic regression. The likelihood L_0 for the null model, where all slope parameters are zero, may be directly compared with the likelihood L_1 of the fitted model. Specifically, one can compute the χ^2 statistic for this comparison as:

$$\chi^2 = -2(\log(L_0) - \log(L_1)) \quad (5)$$

The degrees of freedom for this χ^2 value are equal to the number of independent variables in the logistic regression. If the p-level associated with this χ^2 is significant, the estimated model yields a significantly better fit to the data than the null model and the regression parameters are statistically significant. This statistic is equivalent to the F statistic in ordinary least squares regression.

Logistic regression diagnostics, like using linear regression diagnostics, may seem more art than science (Menard, 1995). Diagnostic statistics hint at potential problems, but whether remedial action is required is a matter of judgement after close inspection of the data. In a sample of 200–250, random sampling variation alone will produce 10–12 cases of residuals with absolute values > 2 on standardized, normally distributed variables such as the deviance residual or the Studentized residual. Very large residuals do not necessarily indicate problems in the model (Menard, 1995). As described below, only a few independent variables were considered for inclusion in the logistic regression models of channel response. Measures of flow energy and sedimentary characteristics were either combined as a single parameter or used as two separate, independent variables. Therefore, issues associated with model mis-specification and multi-collinearity of independent variables were kept to a minimum. The residuals of each regression model were examined for outliers, influential cases, and non-normality. As might be expected with a large and diverse data set on river characteristics, some rivers were consistently misclassified. Such cases were examined for potential errors, but all cases were retained in the data set because no compelling reasons existed to suspect that mistakes in reporting or measurement had occurred.

2.3. Field data used in analyses of channel pattern and stability

A primary objective of this study was to develop an extensive data set on slope, discharge, characteristics of bed material, planform, and morphology of alluvial rivers from various regions of the world. Data chosen for the analysis were selected from several scholarly publications including peer-reviewed articles from scientific journals and government reports and documents. Streams and rivers included in the data set ranged from live bed channels with beds of very fine sand to threshold channels composed of cobble-sized materials. The data were limited to self-formed channels in alluvial material that are free from constraints such as bedrock outcrops and stabilization structures that restrict the evolution of braided rivers. The resulting data set of 270 streams and rivers from around the world along with sources can be obtained from the corresponding author.

Five categories of channels were delineated for the analyses: stable meandering, braiding, incising, braiding or incising, and quasi-equilibrium channels. Stable meandering channels were defined as single-thread channels that have maintained a sinuosity greater than or equal to 1.3 without progressive aggradation, degradation, or changes of width for a period of years. Streams exhibiting dynamic stability, such as lateral migration without significant changes in width and depth, were deemed acceptable for inclusion. Like meandering, braiding has been defined in numerous ways by various investigators. In this analysis, braiding referred to multiple-thread channels with generally unvegetated bars and islands that were not significantly wider than the adjacent channels. Unfortunately, insufficient data precluded attempts to distinguish between actively braiding and relatively inactive braided streams.

By contrast, only streams that were actively and progressively incising over periods of 1–10 years were included in the analysis. Channels identified as incising were all classified as CEM Type 2 according to the Watson et al. (1988a,b) model of incised channel evolution. Type 2 channels are in the early stages of rapid incision and have yet to initiate the dramatic widening that occurs in subsequent stages of evolution. Quasi-equilibrium channels were defined as channels that have a stable slope after a full cycle of incision (CEM Types 4 and 5) according to the Watson et al. (1988a,b) model of channel evolution.

To facilitate the separation of channels with sand beds from the rest of the data set during statistical analyses, the data were also tagged as having one of three categories of bed material: sand, mixed, or gravel. Sand was defined as a D_{50} from 0.0625–2 mm, mixed was defined as >2–10 mm, and gravel was defined as >10 mm. These distinctions are admittedly arbitrary, but such a separation allows a rough discrimination between live bed channels that are very sensitive to sediment supply and threshold channels that are somewhat less sensitive (Montgomery and Buffington, 1997). van den Berg (1995) reported that relatively few streams occur with a D_{50} between 2 and 10 mm. The mixed channels were only included in collective analyses of all size fractions.

2.4. Variables used in the analyses

The parameters considered for inclusion in the logistic regression models were limited to the basic variables of slope, discharge, and some representation of bed material. Sinuosity was used to relate bed slope to valley slope where valley slope data were not available. In cases where sinuosity data were not available for braided rivers, valley slope was assumed to be 10% steeper than bed slope. Bed slope was assumed to be representative of energy slope for all streams with the exception of incising and quasi-equilibrium streams in the Yazoo River watershed of northern Mississippi. For these streams, energy slopes were estimated using surveyed cross-sections (Watson et al., 1998a, 1999) in the hydraulic model HEC-RAS (USACE, 1997).

Unfortunately, limiting the analysis to streams with detailed descriptions of the characteristics of bed materials would have drastically reduced the size of the data set. For a great number of streams, only the median particle size (D_{50}) was reported. As a result, only the diameter of the median particle size was utilized to maximize sample size. Estimates of the median size of bed materials were the result of sieve analyses for sand fractions and Wolman counts (Wolman, 1954) for gravel and coarser materials. Sediment information was not available for some streams in the Yalobusha River watershed in Mississippi. Median size of sediment in the basin, however, is extremely uniform within a range of 0.3–0.5 mm (Watson et al., 1998b). The median size of particles in unsampled streams was assumed to equal the median size of 0.36 mm for streams that have been sampled in the Yalobusha watershed.

2.5. Development of model parameters

In developing parameters for the logistic regression models, emphasis was placed on maintaining independent variables in forms that clearly represent physical processes having a theoretical foundation. Specifically, slope (S) and discharge (Q) were combined into one variable representing a surrogate for specific stream power. A preliminary logistic regression analysis was performed using combinations of this parameter in conjunction with D_{50} and fall velocity. The results of this analysis suggested that

$$S\sqrt{\frac{Q}{D_{50}}} \tag{6}$$

is a simple but robust predictor of channel planform and stability. In some cases, this single parameter had explanatory power equaling that of models containing slope, discharge, and D_{50} as separate independent variables. This was especially true for channels with sand beds. The inclusion of D_{50} in the denominator simply scales flow energy relative to the size of bed material. The form of this parameter is also consistent with the theoretical relationships developed by Chang (1985) and the empirical relationship of van den Berg (1995). This parameter is approximately proportional to unit stream power, VS (Yang, 1976), multiplied by a relative submergence term:

$$S\sqrt{\frac{Q}{D_{50}}} \propto \frac{S\,Re}{\sqrt{D_{50}}} \propto \mathrm{VS}\left(\frac{h}{D_{50}^{0.5}}\right) \tag{7}$$

The ratio of forces represented by this parameter suggests that it is an index of erosive power or mobility. Henceforth, it will be referred to as a "mobility index." It is worth noting that Eq. (6) may be made dimensionless by adding kinematic viscosity (υ) to the denominator under the radical:

$$S\sqrt{\frac{Q}{D_{50}\upsilon}} \tag{8}$$

If one assumes a value of 10^{-6} m^2/s for clear water at 20°C, then the value of Eq. (8) is simply the value of Eq. (6) multiplied by a factor of 10^3 in SI units. The dimensionless value of this parameter is not reported in this study because potential differences in kinematic viscosity make application and interpretation more difficult.

The mobility index represented in Eq. (6) was used extensively in the logistic regression analyses. In addition, models containing $SQ^{0.5}$ with D_{50} as separate independent variables were employed. Analyses were performed using bedslope and valley slope. Annual flood and bankfull discharges were utilized in combination and separately to allow a comparison of accuracy. The $\log_{10}$ transforms of all data were utilized in the logistic regression models. Two-parameter logistic regression models were of the form:

$$p(\text{instability}) = \frac{\exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2)}{1 + \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2)} \tag{9}$$

where x_1 is the specific stream power term; x_2 is the median bed material term; and p(instability) is the probability of braided, incising, or unstable channel types when regressed against stable meandering or quasi-equilibrium channels. The single parameter models were equivalent to Eq. (9) without the $\beta_2 x_2$ terms. In the single parameter models, the mobility index (Eq. (6)) was used exclusively as the independent variable. Over 200 logistic regression models were tested using one- and two-parameter approaches. The logistic regression results provided explicit probabilistic statements that were attached to diagrams of channel stability to clearly associate the risk of a particular channel form with varying levels of excess stream power.

2.6. Relating logistic regression results to other thresholds

The logistic regression results were compared with thresholds of channel form and stability reported by van den Berg (1995). An interesting feature of logistic regression is the potential for transforming a relationship like Eq. (9) into a function representing the combination of independent variables corresponding to a 50% chance of the binary-dependent variable occurring in either category. For example, assume that a two-parameter logistic regression model has been fit to $\log_{10}$ transformed data on meandering and braiding streams. The combination of independent variables resulting in a probability of braiding of 0.5 represents the circumstances under which it is most uncertain whether a stream will be braiding or meandering. Recalling that for a two-parameter logistic model:

$$\ln\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 \tag{10}$$

it follows that the combination of independent variables corresponding to $p = 0.5$ chance of meandering or braiding may be written as:

$$x_1 = -\frac{\beta_0}{\beta_1} - \frac{\beta_2}{\beta_1} x_2 \tag{11}$$

Assuming that x_1 and x_2 happen to be $\log_{10} SQ^{0.5}$ and $\log_{10} D_{50}$, respectively, then a power function approximately corresponding to $p = 0.5$ is:

$$S\sqrt{Q} = 10^{-\frac{\beta 0}{\beta 1}} D_{50}^{-\frac{\beta 2}{\beta 1}} \tag{12}$$

This approach was used in comparisons with the discrete threshold proposed by van den Berg (1995). In addition, the original data of van den Berg (1995) were re-analyzed using a two-parameter logistic regression model. This allows a risk-based interpretation of the discriminant function presented in Eq. (1).

3. Results and discussion

A comprehensive summary of logistic regression results for 74 models is presented in Table 1. Each logistic regression model was assigned a number in Table 1 that is used in referring to specific models throughout this discussion. The excellent fit of these models underscores the predictive power of the simple indices used to represent the balance of erosive and resistant forces. All log-likelihood χ^2 statistics of the models were significant at the $p < 10^{-5}$ to $p < 10^{-29}$ levels.

In general, the most accurate results for the greatest number of cases of all stream types were obtained by using bedslope in conjunction with annual flood discharge as first priority with bankfull discharge substituted for those streams without annual flood data. Overall, differences in predictive accuracy, resulting from using combinations of annual flood and bankfull discharge data versus using annual flood or bankfull alone, were generally less than 10%. The most notable exceptions were detected when using valley slope instead of bedslope to represent specific stream power. The predictive accuracy of the logistic regression models was reduced in all cases when bedslope was replaced with valley slope.

The one- and two-parameter models varied in explanatory power depending on the type of channels examined. For example, the single parameter model using the mobility index $S(Q/D_{50})^{0.5}$ was extremely robust in analyses of channels with sand beds using bedslope. In contrast, two-parameter

Table 1
Summary of the results of logistic regression

Model no.	Independent variable(s)	Bed[a]	% Classified correctly[b]					β_0	β_1	β_2	χ^2	Odds ratio	n	Flow used[c]
			M	B	I	BI	Q							
1	$\log_{10}(S(Q/D_{50})^{0.5})$	s/m/g	92.6	73.7				2.01	5.06	–	109.25	35.13	206	$Q_{af}+Q_{bf}$
2		sand	97.9	84.2				2.33	10.97	–	55.08	250.67	67	$Q_{af}+Q_{bf}$
3		gravel	94.6	73.5				3.75	6.50	–	76.38	48.89	127	$Q_{af}+Q_{bf}$
4	$\log_{10}(S_v(Q/D_{50})^{0.5})$	s/m/g	89.9	56.7				0.84	3.78	–	70.85	11.68	206	$Q_{af}+Q_{bf}$
5		sand	89.6	59.1				0.24	5.44	–	30.52	12.42	67	$Q_{af}+Q_{bf}$
6		gravel	93.5	64.7				2.45	5.69	–	58.26	26.58	127	$Q_{af}+Q_{bf}$
7		sand	95.8	63.6				−0.47	160.97	−57.85	33.30	40.25	67	$Q_{af}+Q_{bf}$
8		gravel	96.8	58.8				−2.06	39.91	−2.10	56.89	42.86	127	$Q_{af}+Q_{bf}$
9	$\log_{10}(SQ^{0.5})$ and $\log_{10}(D_{50})$	s/m/g	94	75				11.87	6.54	−2.22	131.05	46.67	206	$Q_{af}+Q_{bf}$
10		sand	97.9	84.2				18.12	10.75	−6.06	55.11	250.67	67	$Q_{af}+Q_{bf}$
11		gravel	94.6	76.5				12.53	6.52	−2.65	79.58	57.2	127	$Q_{af}+Q_{bf}$
12	$\log_{10}(S_vQ^{0.5})$ and $\log_{10}(D_{50})$	s/m/g	92.6	61.7				8.34	5.1	−1.69	86.04	20.18	206	$Q_{af}+Q_{bf}$
13		sand	95.8	68.4				8.53	6.48	−6.15	37.35	49.83	67	$Q_{af}+Q_{bf}$
14		gravel	93.5	67.6				10.35	5.71	−2.45	58.39	30.32	127	$Q_{af}+Q_{bf}$
15	$\log_{10}(S(Q/D_{50})^{0.5})$	sand	89.6		92.9			4.63	14.39	–	82.45	111.80	90	$Q_{af}+Q_{bf}$
16	$\log_{10}(S_v(Q/D_{50})^{0.5})$	sand	72.9		71.4			1.38	6.29	–	35.40	6.73	90	$Q_{af}+Q_{bf}$
17	$\log_{10}(SQ^{0.5})$ and $\log_{10}(D_{50})$	sand	87.5		90.5			24.08	14.34	−12.12	84.43	66.50	90	$Q_{af}+Q_{bf}$
18	$\log_{10}(S_vQ^{0.5})$ and $\log_{10}(D_{50})$	sand	77.1		73.8			9.55	6.44	−6.97	39.59	9.48	90	$Q_{af}+Q_{bf}$
19	$\log_{10}(S(Q/D_{50})^{0.5})$	sand	85.4			91.8		4.51	13.15	–	100.06	65.60	109	$Q_{af}+Q_{bf}$
20	$\log_{10}(S_v(Q/D_{50})^{0.5})$	sand	68.8			82		1.63	6.35	–	49.68	10.00	109	$Q_{af}+Q_{bf}$
21	$\log_{10}(SQ^{0.5})$ and $\log_{10}(D_{50})$	sand	87.5			93.8		19.94	11.40	−8.83	98.39	105.00	109	$Q_{af}+Q_{bf}$
22	$\log_{10}(S_vQ^{0.5})$ and $\log_{10}(D_{50})$	sand	70.8			85.2		9.57	6.18	−6.23	53.36	14.03	109	$Q_{af}+Q_{bf}$
23	$\log_{10}(S(Q/D_{50})^{0.5})$	sand			88.1		68	4.28	13.95	–	43.18	15.73	67	$Q_{af}+Q_{bf}$
24	$\log_{10}(SQ^{0.5})$ and $\log_{10}(D_{50})$	sand			90.5		68	25.38	13.87	6.18	43.01	20.19	67	$Q_{af}+Q_{bf}$
25	$\log_{10}(S(Q/D_{50})^{0.5})$	s/m/g	92.6	70.2				1.87	4.95	–	108.53	29.52	206	$Q_{bf}+Q_{af}$
26		sand	97.8	84.2				2.07	10.94	–	54.45	250.67	67	$Q_{bf}+Q_{af}$
27		gravel	94.6	79.4				4.13	7.01	–	83.20	67.89	127	$Q_{bf}+Q_{af}$
28	$\log_{10}(S_v(Q/D_{50})^{0.5})$	s/m/g	90.6	59.6				0.68	3.73	–	68.65	14.26	206	$Q_{bf}+Q_{af}$
29		sand	93.8	73.7				0.01	7.46	–	35.19	42.00	67	$Q_{bf}+Q_{af}$
30		gravel	95.7	67.6				2.54	5.93	–	61.10	46.52	127	$Q_{bf}+Q_{af}$
31	$\log_{10}(SQ^{0.5})$ and $\log_{10}(D_{50})$	s/m/g	95.3	77.2				12.64	7.14	−2.18	134.99	68.66	206	$Q_{bf}+Q_{af}$
32		sand	97.9	84.2				17.61	10.66	−6.19	54.49	250.67	67	$Q_{bf}+Q_{af}$
33		gravel	95.7	76.5				13.81	7.01	−3.01	83.33	72.31	127	$Q_{bf}+Q_{af}$
34	$\log_{10}(S_vQ^{0.5})$ and $\log_{10}(D_{50})$	s/m/g	94.6	64.9				8.96	5.64	−1.70	91.42	32.61	206	$Q_{bf}+Q_{af}$
35		sand	97.9	73.7				9.03	7	−6.71	37.15	131.6	67	$Q_{bf}+Q_{af}$
36		gravel	95.7	64.7				11.00	5.93	−2.70	61.15	40.79	127	$Q_{bf}+Q_{af}$
37	$\log_{10}(S(Q/D_{50})^{0.5})$	sand	87.5		90.5			4.35	14.07	–	78.41	66.50	90	$Q_{bf}+Q_{af}$
38	$\log_{10}(S_v(Q/D_{50})^{0.5})$	sand	70.8		69			1.22	5.96	–	30.37	5.42	90	$Q_{bf}+Q_{af}$
39	$\log_{10}(SQ^{0.5})$ and $\log_{10}(D_{50})$	sand	83.3		90.5			23.93	13.9	−9.79	79	47.5	90	$Q_{bf}+Q_{af}$

40	$\log_{10}(S_v Q^{0.5})$ and $\log_{10}(D_{50})$	sand	70.8		69			8.72	5.81	−5.81	33.04	5.42	90	$Q_{bf}+Q_{af}$
41	$\log_{10}(S(Q/D_{50})^{0.5})$	sand	85.4			91.8		4.21	12.77	–	95.62	65.60	109	$Q_{bf}+Q_{af}$
42	$\log_{10}(S_v(Q/D_{50})^{0.5})$	sand	66.7			80.3		1.46	6.07	–	44.41	8.17	109	$Q_{bf}+Q_{af}$
43	$\log_{10}(SQ^{0.5})$ and $\log_{10}(D_{50})$	sand	85.4			91.8		22.93	12.64	−6.81	95.65	65.6	109	$Q_{bf}+Q_{af}$
44	$\log_{10}(S_v Q^{0.5})$ and $\log_{10}(D_{50})$	sand	70.8			83.6		8.90	5.77	−5.57	47.25	12.39	109	$Q_{bf}+Q_{af}$
45	$\log_{10}(S(Q/D_{50})^{0.5})$	sand	88.6		95.2			7.89	22.11	–	82.61	155.00	77	Q_{af}
46	$\log_{10}(S_v(Q/D_{50})^{0.5})$	sand	71.4		81			2.09	7.81	–	36.16	10.63	77	Q_{af}
47	$\log_{10}(SQ^{0.5})$ and $\log_{10}(D_{50})$	sand	94.3		95.2			37.5	21.43	−16.5	84.54	330	77	Q_{af}
48	$\log_{10}(S_v Q^{0.5})$ and $\log_{10}(D_{50})$	sand	74.3		85.7			13.16	8.47	−8.62	40.69	17.33	77	Q_{af}
49	$\log_{10}(S(Q/D_{50})^{0.5})$	sand			88.1		68	4.28	13.95	–	43.18	15.73	67	Q_{af}
50	$\log_{10}(SQ^{0.5})$ and $\log_{10}(D_{50})$	sand			88.1		68	25.61	13.99	−6.22	43.20	15.73	67	Q_{af}
51	$\log_{10}(S(Q/D_{50})^{0.5})$	s/m/g	91.7	77.4				2.10	4.98	–	105.28	37.93	174	Q_{bf}
52		sand	96.2	88.9				2.50	13.40	–	42.97	200.00	44	Q_{bf}
53		gravel	97.8	77.4				3.93	6.91	–	78.36	150.86	121	Q_{bf}
54	$\log_{10}(S_v(Q/D_{50})^{0.5})$	s/m/g	90.1	66				1.06	4.09	–	74.61	17.66	174	Q_{bf}
55		sand	84.6	77.8				0.34	8.00	–	28.56	19.25	44	Q_{bf}
56		gravel	96.7	67.7				2.47	6.02	–	58.73	60.90	121	Q_{bf}
57	$\log_{10}(SQ^{0.5})$and $\log_{10}(D_{50})$	s/m/g	95	81.1				12.03	6.72	−2.23	119.07	82.42	174	Q_{bf}
58		sand	96.2	88.9				17.35	13.42	−17.98	45.46	200.00	44	Q_{bf}
59		gravel	97.8	77.4				13.94	6.91	−3.24	78.38	150.86	121	Q_{bf}
60	$\log_{10}(S_v Q^{0.5})$ and $\log_{10}(D_{50})$	s/m/g	95	67.9				8.98	5.47	−1.89	84.69	40.59	174	Q_{bf}
61		sand	84.6	88.9				8.96	8.31	−12.57	33.15	44.00	44	Q_{bf}
62		gravel	96.7	67.7				11.42	6.02	−2.97	56.73	60.90	121	Q_{bf}
63	$\log_{10}(S_v Q^{0.5})$ and $\log_{10}(D_{50})$	s/m/g	93.1	76.9				16.21	10.06	−3.25	94.60	45.00	126	VDB Q_{bf}
64		sand	94.4	80				12.80	10.42	−11.43	23.52	68.00	28	VDB Q_{bf}
65		gravel	95.3	77.8				14.10	10.33	−1.82	66.91	71.17	91	VDB Q_{bf}
66	$\log_{10}(S_v Q^{0.5})$ and $\log_{10}(D_{50})$	s/m/g	89.8	80				10.46	6.83	−1.54	57.03	35.33	89	VDB Q_{af}
67		sand	100	50				8.89	6.38	−3.47	7.02	–	39	VDB Q_{af}
68		gravel	71.4	84.6				9.48	6.86	−0.91	27.55	13.75	47	VDB Q_{af}
69	$\log_{10}(S_v Q^{0.5})$ and $\log_{10}(D_{50})$	s/m/g	94.8	73.8				13.79	8.78	−2.54	98.3	51.20	157	VDB $Q_{bf}+Q_{af}$
70		sand	100	72.7				9.34	7.13	−5.66	25.77	–	52	VDB $Q_{bf}+Q_{af}$
71		gravel	93.9	79.3				12.04	9.19	−1.21	64.87	59.42	95	VDB $Q_{bf}+Q_{af}$
72	$\log_{10}(S_v Q^{0.5})$ and $\log_{10}(D_{50})$	s/m/g	92.2	71.4				12.78	8.08	−2.40	92.68	29.44	157	VDB $Q_{af}+Q_{bf}$
73		sand	97.6	63.6				8.52	6.36	−4.93	25.23	70.00	52	VDB $Q_{af}+Q_{bf}$
74		gravel	90.9	79.3				11.46	8.38	−1.38	59.47	38.33	95	VDB $Q_{af}+Q_{bf}$

[a] s/m/g refers to sand, mixed, and gravel channels modeled collectively.

[b] M, B, I, BI, and Q refer to meandering, braided, incising, braided or incising, and quasi-equilibrium channels (CEM Types 4 and 5), respectively. Model parameters are defined as in Eq. (12). In single-parameter models, D_{50} is in meters. In two-parameter models, D_{50} is in millimeters. Discharges are in units of m^3/s, and slopes are dimensionless.

[c] $Q_{af}+Q_{bf}$ refers to combining Q_{af} and Q_{bf} with Q_{af} used as first priority. $Q_{bf}+Q_{af}$ refers to combining Q_{bf} and Q_{af} with Q_{bf} used as first priority. VDB refers to the exclusive use of van den Berg's (1995) data set.

models were most appropriate for rivers with gravel beds.

3.1. Channels with sand beds

Diagrams based on the single parameter logistic regression models provide a convenient means for envisioning the risk associated with varying levels of specific stream power relative to sediment size (Fig. 1). In general, systems that are particularly susceptible to abrupt shifts between the specified channel patterns produce steep logistic curves. Transitions in channel type were particularly abrupt in the comparison of stable meandering and incising channels with sand beds (Fig. 1). The logistic curve, representing the transition from meandering to incising (model 15, $n = 90$), classified stable meandering and incising channels with sand beds with 89.6% and 92.9% accuracy, respectively. The accuracy of predicting an incising channel was improved to over 95% in the model using only annual flood discharges (Table 1).

In channels with sand beds, a greater level of flow energy relative to the caliber of bed materials is associated with a fully braided form when compared to an incised form (Fig. 1). This seems logical because a greater shear stress is typically exerted on the bed of the channel than on the banks, and one would suspect that erosion of the bed would often precede bank erosion in noncohesive sand. Moreover, incision is a process typically occurring at the initiation of channel adjustment as opposed to braiding that, at least in the case of a formerly meandering channel, is a channel form that results *after* significant adjustment. The greater magnitude of $S(Q/D_{50})^{0.5}$ in a braided channel may, in many situations, reflect increases in slope associated with bank erosion and straightening as well as possible decreases in the median size of bed material. These processes could increase the value of $S(Q/D_{50})^{0.5}$ as a channel adjusts to the form of a braided channel.

The mobility index was also effective in predicting the transition from a stable meandering form to an incising *or* braiding form of a channel with a

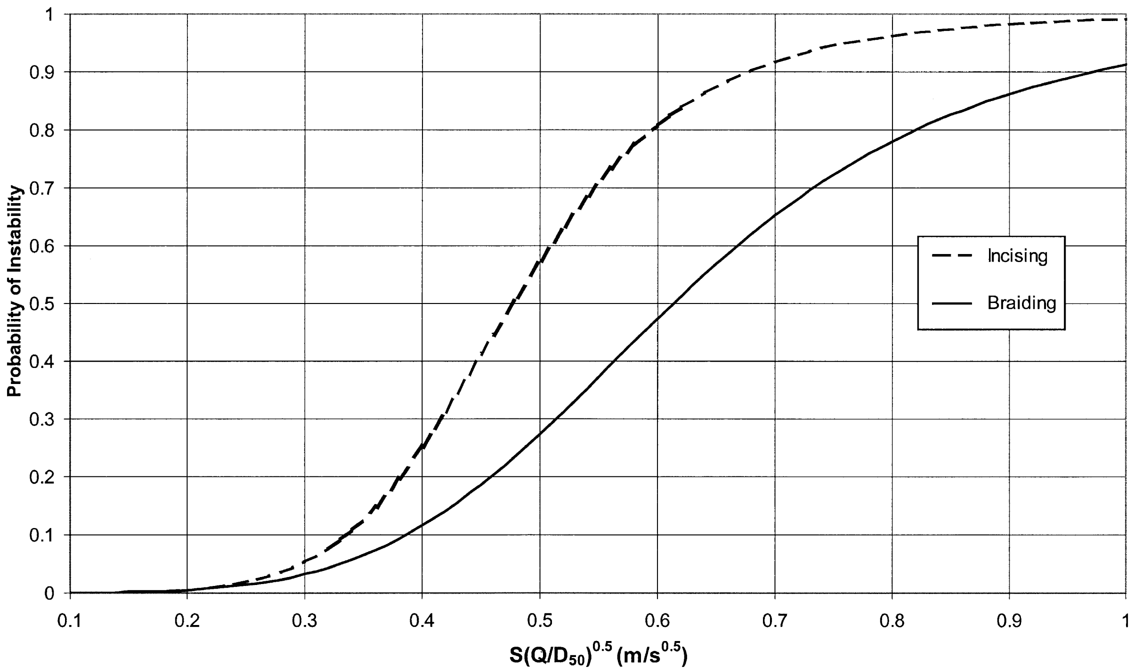

Fig. 1. Results of regression models 2 and 15 comparing stable meandering with braiding and incising streams with sand beds. Discharge is represented by annual flood as first priority then bankfull.

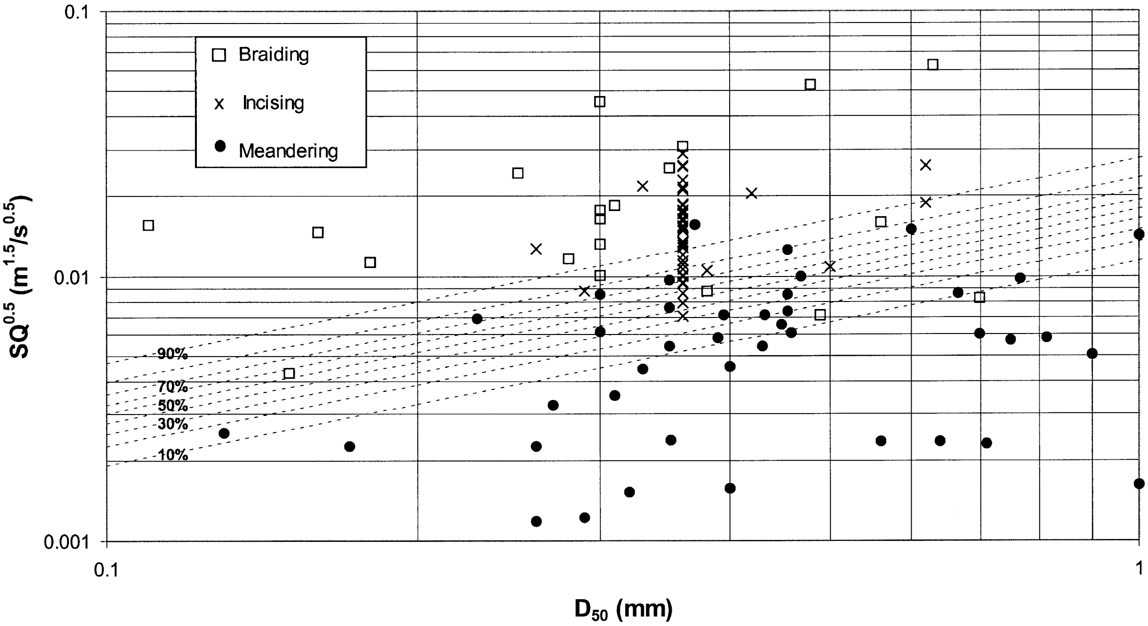

Fig. 2. Probability of incising or braiding as a function of $SQ^{0.5}$ and D_{50} for streams with sand beds (model 21, $n = 109$). Discharge is represented by annual flood as first priority then bankfull.

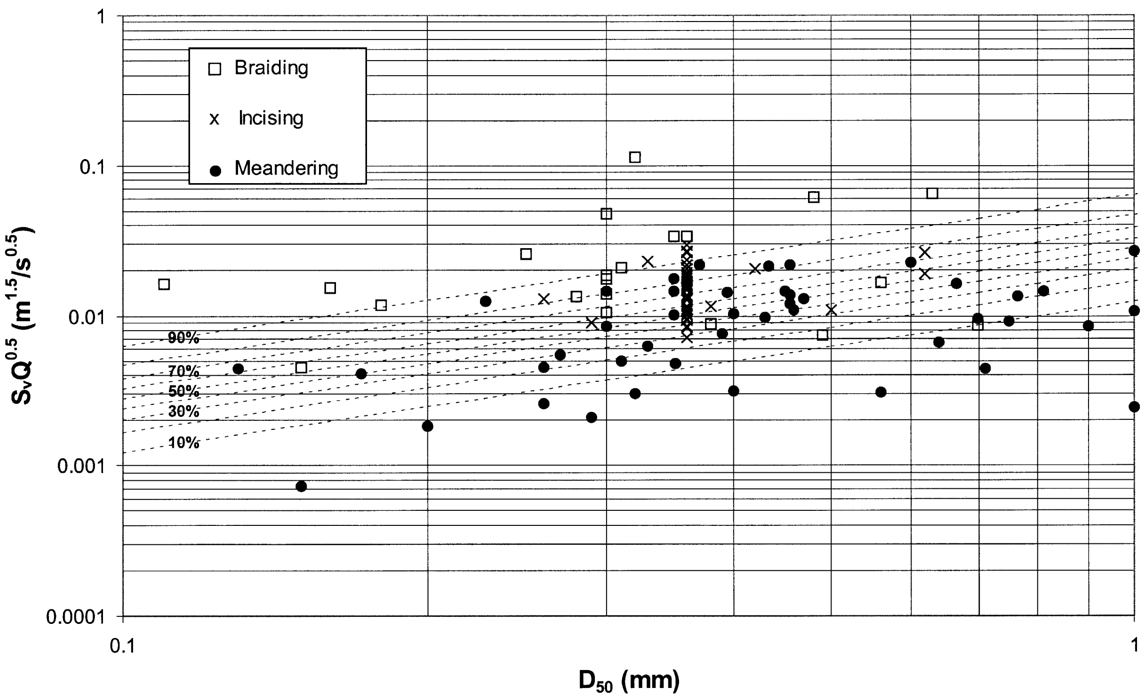

Fig. 3. Probability of incising or braiding as a function of $S_vQ^{0.5}$ and D_{50} for streams with sand beds (model 22, $n = 109$). Discharge is represented by annual flood as first priority then bankfull.

sand bed. The relationship resulting from model 19 is:

$$p=\frac{\exp\left[4.51+13.15\log_{10}\left(S\sqrt{\dfrac{Q}{D_{50}}}\right)\right]}{1+\exp\left[4.51+13.15\log_{10}\left(S\sqrt{\dfrac{Q}{D_{50}}}\right)\right]} \quad (13)$$

where S is the dimensionless bedslope; Q is the annual flood or bankfull discharge in m^3/s; and D_{50} is the median size of particle in meters. Eq. (13) classified stable meandering versus incising or braiding streams with sand beds with 85.4% and 91.8% accuracy, respectively ($n=109$). The logistic curve represented by Eq. (13) is essentially equivalent to the incision curve presented in Fig. 1, with a 50% risk corresponding to a mobility index of 0.45 $m/s^{0.5}$. Again, this indicates that the incision data define the lower limit of $S(Q/D_{50})^{0.5}$ values associated with instability of sand bed channels. The results of the two-parameter models for predicting an incising or braiding channel form in sand bed channels are also presented in Figs. 2 and 3. The predictive accuracies of the two-parameter models using bedslope are essentially equal to the accuracies of the single parameter models. This reflects the fact that even in the two-parameter models channel pattern varied with $D_{50}^{0.5}$. When using valley slope, however, the accuracies of the two-parameter models are superior when compared to the mobility index models.

Exclusive use of bankfull discharges in conjunction with bedslopes resulted in the most accurate predictions of braiding in channels with sand beds. Unfortunately, the limited number of annual flood data from braiding channels precluded any meaningful analysis based solely on annual flood data. Models utilizing annual flood data in conjunction with bankfull discharge data for missing values ($n=67$) were 96% accurate for classifying meandering channels, but only managed to classify braiding channels with 82% and 68% accuracy using bedslope and valley slope data, respectively. Accuracy for classification of braiding channels increased to 89% for bedslope and valley slope models when only bankfull values were used ($n=44$). In contrast, the ex-

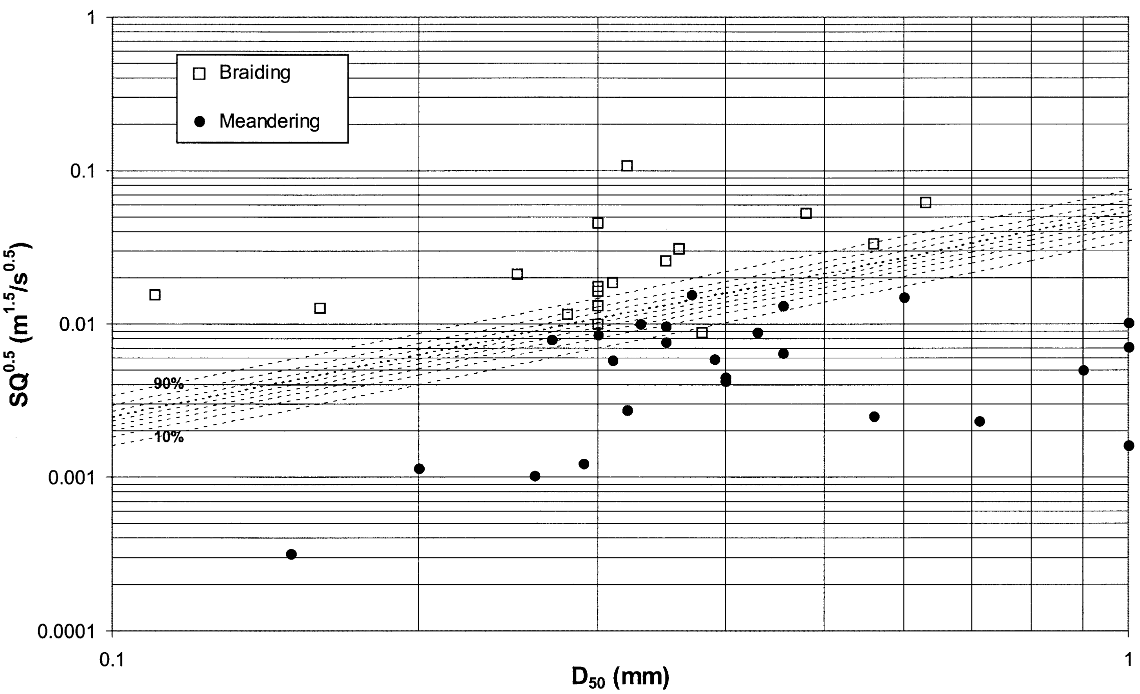

Fig. 4. Probability of braiding as a function of $SQ^{0.5}$ and D_{50} for streams with sand beds (model 10, $n=67$). Discharge is represented by annual flood as first priority then bankfull.

clusive use of bankfull data reduced accuracy for prediction of meandering channels. The models developed with only bankfull discharge data were more strongly influenced by the D_{50} term and suggested that very high values of stream power were necessary to achieve braiding in coarse sand. These results were strongly influenced by a few meandering channels in coarse sand occurring on relatively steep valleys. The models using annual flood as first priority were based on 23 more samples and were less influenced by these extreme values as evidenced by higher χ^2 values (Figs. 4 and 5).

3.2. Channels with gravel beds

Braiding in channels with gravel beds apparently is more difficult to predict accurately than incising or braiding in channels with sand beds, given the models examined. Bank resistance, flood plain resistance to the development of chute cutoffs, the rate of sediment delivery from eroding banks, and other factors may be more influential in controlling the form of gravel bed channels. In many instances, D_{50} exerted much less influence over the transition from meandering to braiding in gravel channels as compared to sand channels. This is evidenced by the relatively low values of β_2 in some of the two-parameter logistic regression models for gravel (Table 1). These low values indicate that holding the exponent of the D_{50} term at a constant value of 0.5, as in the mobility index, reduces the accuracy of some models. The best-fitting two-parameter models suggest that the stream power associated with a certain risk of a braided channel varies with D_{50} to the exponent 0.40 to 0.49. In general, regression relationships for stable rivers with gravel beds reported by other investigators suggest that bed materials in the range of D_{65} to D_{90} exert more control on channel slope than D_{50} (Knighton, 1998). Unfortunately, data regarding coarser fractions of bed materials were not available for a large number of streams used in this study.

The two-parameter models developed using a mix of 127 annual flood and bankfull data classified stable meandering channels with over 93% accuracy when using either bedslope or valley slope. By con-

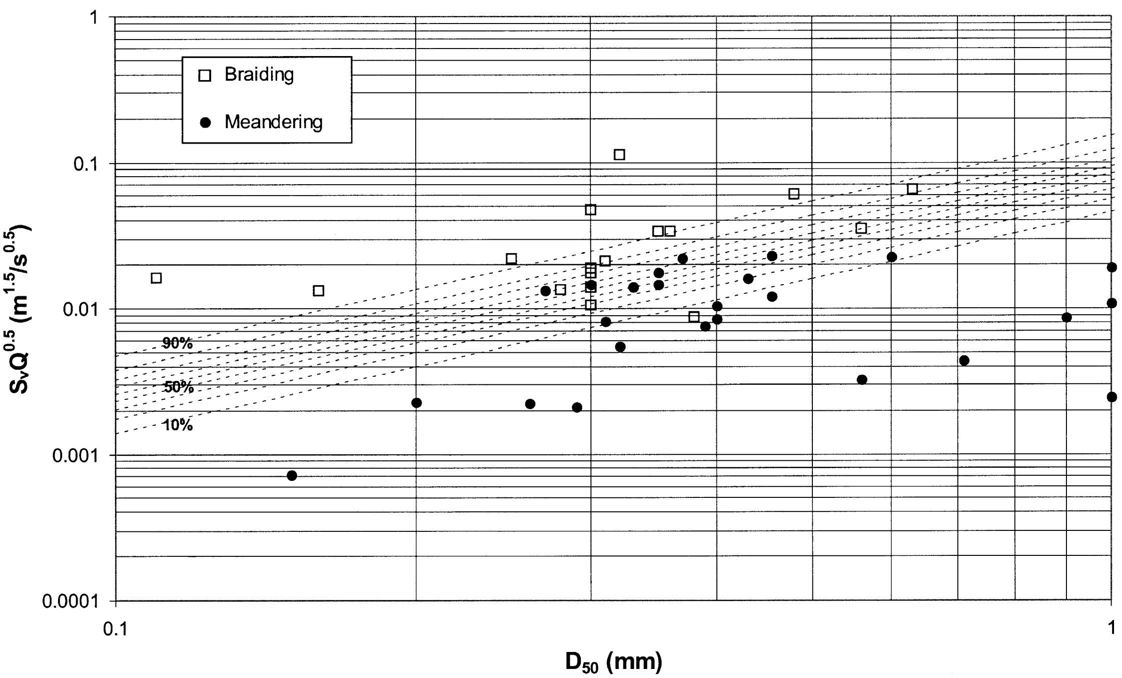

Fig. 5. Probability of braiding as a function of $S_v Q^{0.5}$ and D_{50} for streams with sand beds (model 13, $n = 67$). Discharge is represented by annual flood as first priority then bankfull.

trast, the same models classified braiding channels with only 77% and 68% accuracy when using bedslope and valley slope, respectively. Diagrams depicting these models for gravel streams are presented in Figs. 6 and 7. Exclusive use of bankfull discharge data did not substantially improve the accuracy of the two-parameter models.

3.3. Comparisons with the meandering–braiding thresholds of van den Berg (1995)

When compared to the data set compiled by van den Berg (1995), the expanded data set developed for this study resulted in a 1–10% lower rate of correct classification in the logistic models when using valley slope as an independent variable (Table 1). Nonetheless, the logistic models extend van den Berg's original data set and assign risks of braiding as opposed to a discrete threshold. In contrast to van den Berg's combined analysis of streams with D_{50} between 0.1 and 100 mm, these results suggest that separating sand and gravel streams yields more accurate predictions of channel form for each type. Attempts to develop a robust predictor of braiding for sand and gravel streams, taken collectively, produced a relatively high percentage of misclassified streams. Re-analysis of the data used to develop van den Berg's discriminant function also indicated that separating sand and gravel yielded slightly more accurate results (Table 1).

Part of van den Berg's success in developing a single discriminator for the transition from meandering to braiding in streams with a D_{50} of 0.1–100 mm may be attributed to the regime widths assumed for estimating specific stream power. By selecting a regime equation from the design of an irrigation canal, streams with sand beds were assumed to be 57% wider than streams with gravel beds in van den Berg's analysis. It follows that estimates of specific stream power for sand bed streams were biased 57% lower than the estimates for streams with gravel beds. In reality, streams with sand beds transporting substantial sediment loads may require more specific stream power than threshold channels composed of fine to medium gravel (Howard, 1980). van den

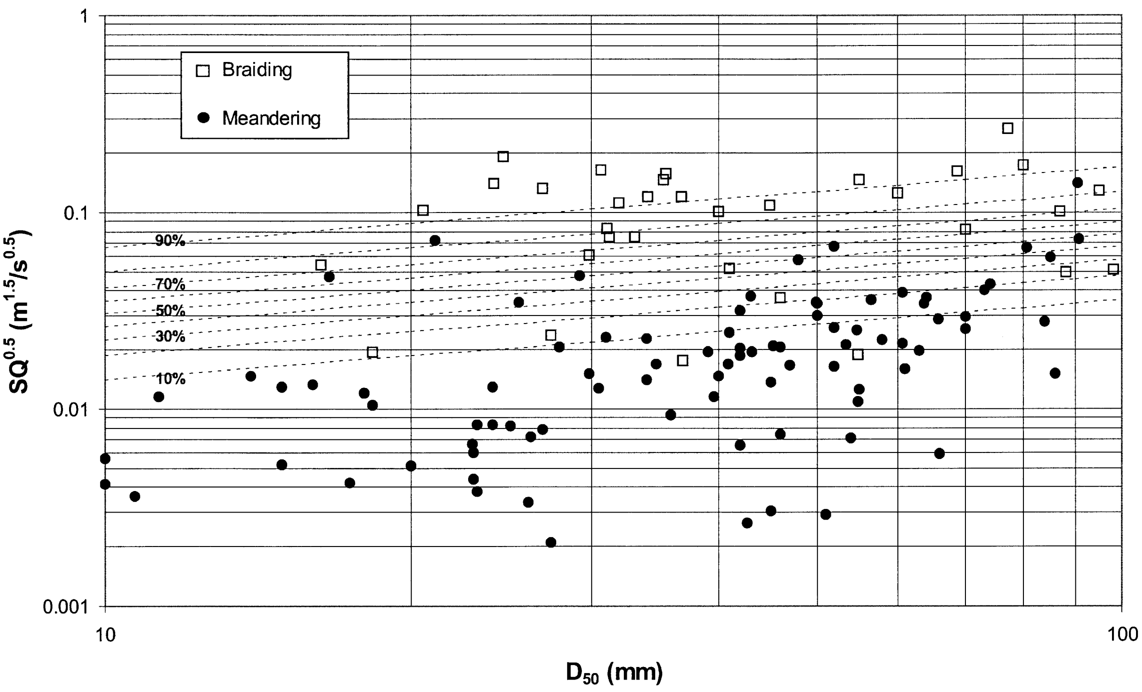

Fig. 6. Probability of braiding as a function of $SQ^{0.5}$ and D_{50} for streams with gravel beds (model 11, $n = 127$). Discharge is represented by annual flood as first priority then bankfull.

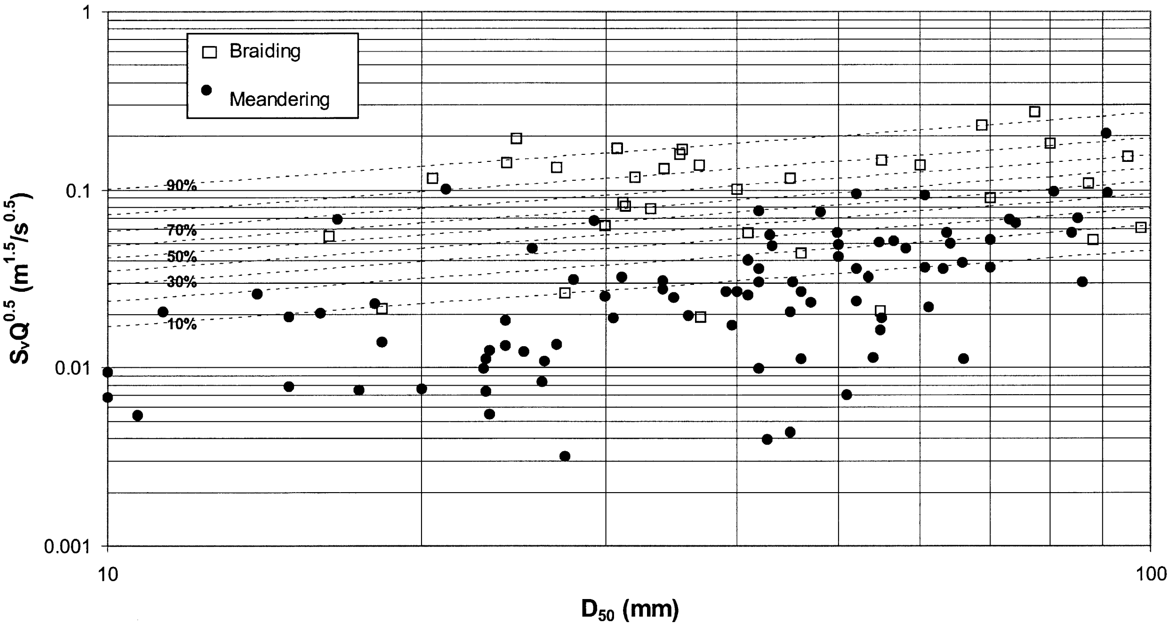

Fig. 7. Probability of braiding as a function of $S_v Q^{0.5}$ and D_{50} for streams with gravel beds (model 14, $n=127$). Discharge is represented by annual flood as first priority then bankfull.

Berg's selection of $w = 4.7Q^{0.5}$ and $w = 3Q^{0.5}$ for the regime width of sand and gravel channels, respectively, would tend to remove this offset in the estimated stream power and facilitate fitting a single function for sand and gravel.

By applying the regime width that van den Berg assumed for gravel channels, his original discriminator based on 28 sand and 98 gravel bed streams (Eq. (1)) may be restated as:

$$S_v\sqrt{Q} = 0.0151 D_{50}^{0.42} \tag{14}$$

where valley slope is dimensionless; Q is the bankfull discharge in m^3/s; and D_{50} is the median size of particle in millimeters. For comparison, the logistic regression results for 127 gravel streams utilizing annual flood data in combination with bankfull discharge (model 14, Fig. 7) may be reduced to:

$$S_v\sqrt{Q} = 0.0153 D_{50}^{0.43} \tag{15}$$

with units corresponding to Eq. (14). This equation represents a 50% probability of braiding and is almost exactly the same result that van den Berg proposed for D_{50} between 0.1 and 100 mm. The similarity of these relationships indicates that despite the inclusion of more data, the 50% risk level for gravel is essentially equivalent to van den Berg's original discriminator. If van den Berg's data on sand channels are combined with the gravel data without assuming a 57% difference in width, the results are significantly different. In this case, the 50% risk of braiding for sand and gravel corresponds to:

$$S_v\sqrt{Q} = 0.0245 D_{50}^{0.32} \tag{16}$$

This constant of 0.0245 indicates a value of $S_v Q^{0.5}$ required for a 50% risk of braiding in 1 mm sand that is substantially higher than the value 0.0151 suggested by Eq. (14) (van den Berg's original discriminator), which is biased toward lower powers for the occurrence of braiding in channels with sand beds.

In general, logistic models of the transition to braiding in streams with sand beds differed substantially from van den Berg's original discriminant function. This resulted from a few influential data on braiding channels with D_{50} between 1 and 2 mm, despite logistic models being developed in this study being based on 67 streams with sand beds as opposed to the 28 used by van den Berg. Meandering channels in coarse sand exhibited very steep valley slopes and strongly influenced the nature of the regression relationship. As a result, the predicted level of $S_v Q^{0.5}$ that is associated with a certain risk of braiding is extremely sensitive to D_{50}. Until further data on streams with beds of coarse sand are obtained, the relationship between $S_v Q^{0.5}$ and D_{50} will remain unclear. The logistic regression models resulting from van den Berg's original data set are presented in Figs. 8–10.

3.4. Some limitations of the approach

Statistical analysis is a tool for associating observations with measurements of variables that are thought to represent underlying controls. But the associations between favored variables and observed outcomes do not necessarily imply causation. Specifically, these analyses do not demonstrate *how* channels develop an incising or braiding form. Instead, the logistic regression models indicate that certain channel forms are clearly associated with specific combinations of slope, discharge, and characteristics of bed materials. Inferences may be drawn from these associations, but the models do not reveal the trajectories of specific stream power, size of bed material, and roughness characteristics as streams respond to erosive forces. Coarsening and/or armoring of beds may be particularly confounding. In addition, gravel bed channels with mobility indices suggesting a low risk of braiding may still be laterally unstable.

Another limitation of the logistic regression models is the absence of variables representing sediment supply and the ratio of bank resistance to bed resistance. Channels with sand beds are extremely sensitive to the inflowing sediment load delivered from upstream reaches. Even if a meandering channel with a sand bed has a low risk of incision according to the results of the logistic regression analysis, it might still incise if the inflowing sediment load is substantially reduced. The limits of stability presented in this study might be more accurately portrayed as thresholds of catastrophic channel change. The results should not be interpreted to suggest that inci-

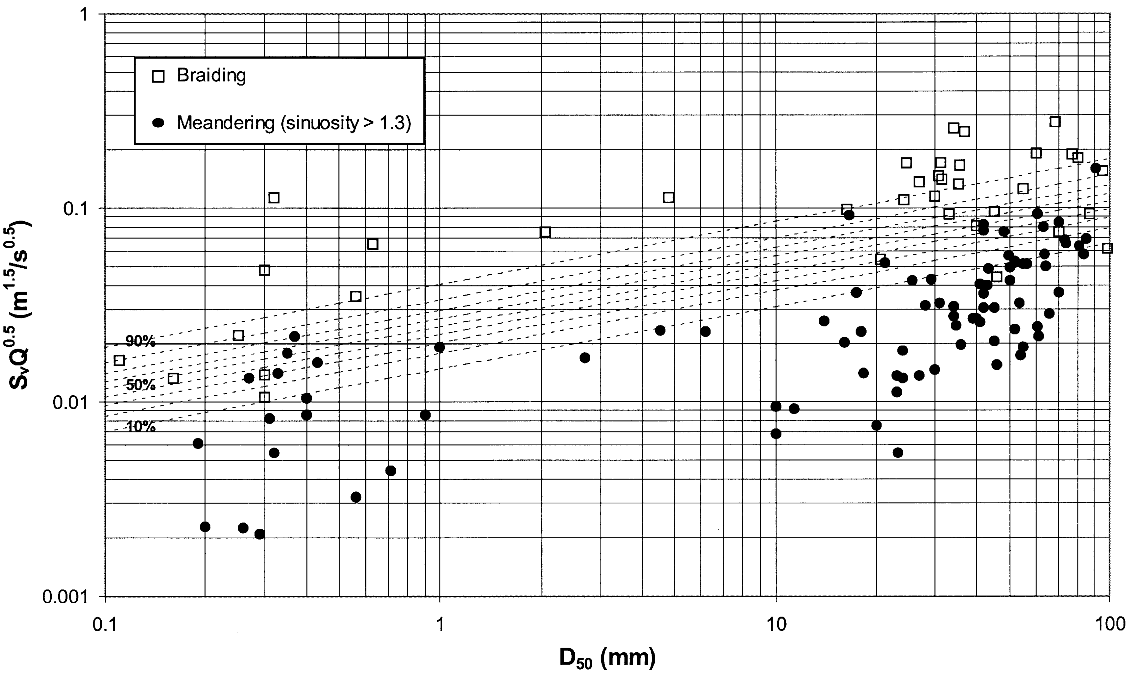

Fig. 8. Logistic regression analysis of van den Berg's original data set using bankfull discharge and D_{50} between 0.1 and 100 mm.

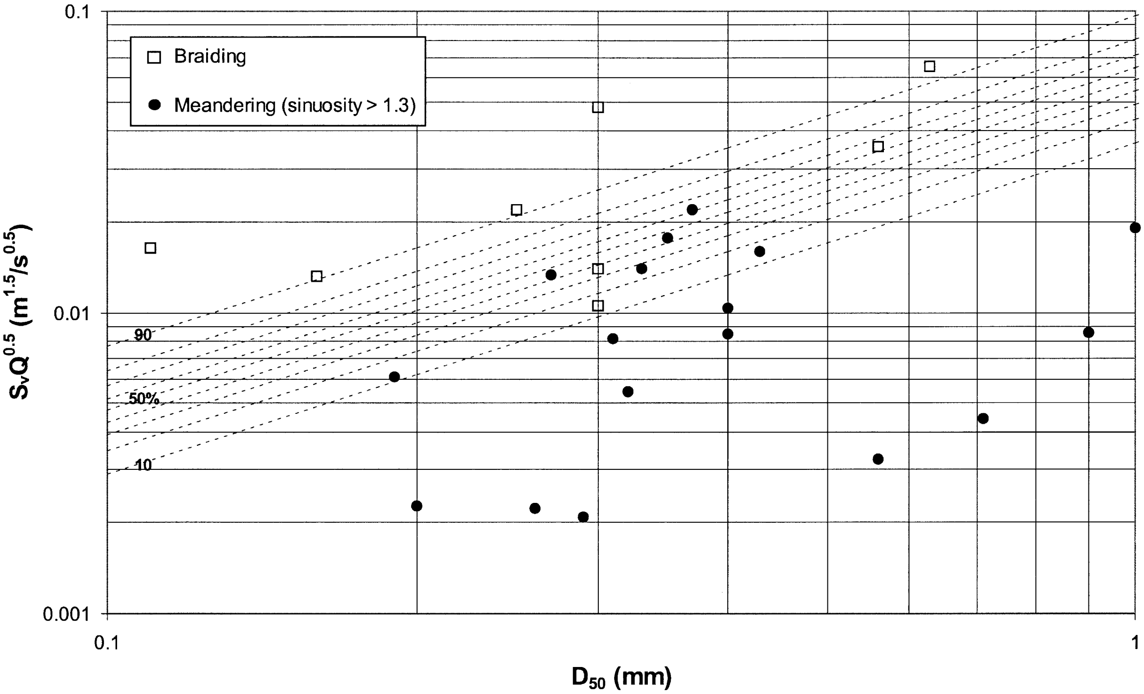

Fig. 9. Logistic regression analysis of van den Berg's original data for streams with sand beds using bankfull discharge.

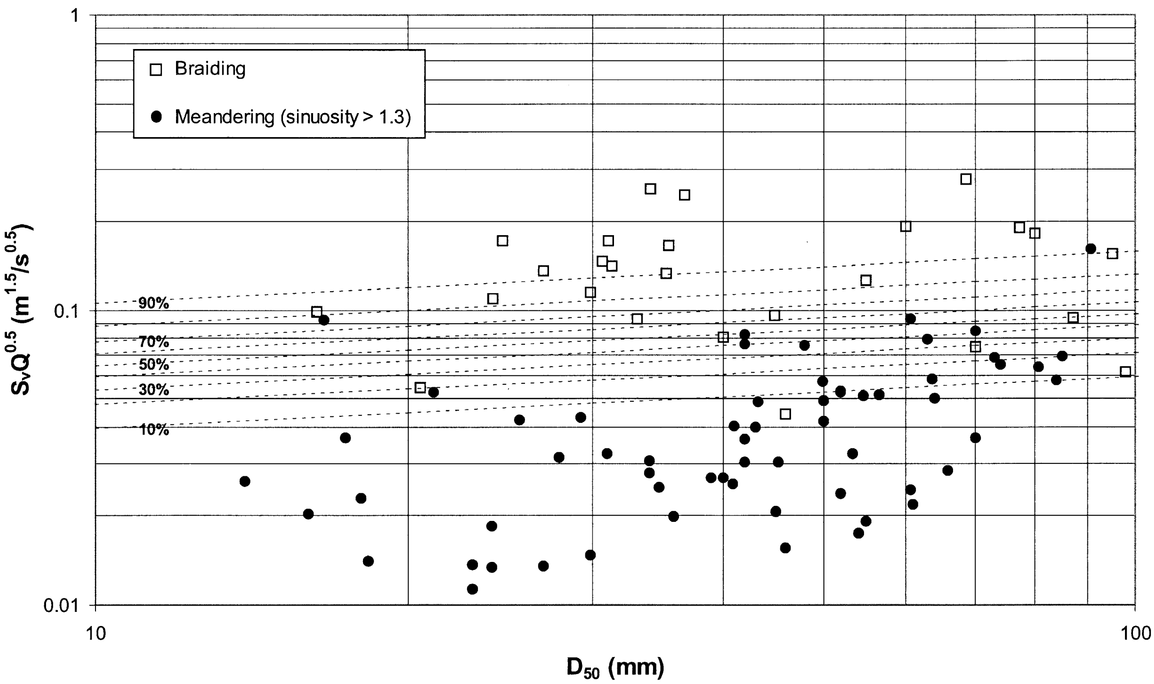

Fig. 10. Logistic regression analysis of van den Berg's original data for streams with gravel beds using bankfull discharge.

sion or widening will not occur in channels with sand beds at values of $S(Q/D_{50})^{0.5}$ less than about 0.3 $m/s^{0.5}$.

The logistic regression models presented herein should be considered a starting point. The models should be refined for general and regional application as more data on unstable channels become available. In particular, regional relationships for channels with sand beds should be developed in an effort to include the effects of sediment supply and differing bank conditions. Because data on incision by the stage of channel evolution are rare for areas outside the Yazoo River watershed of northern Mississippi, the incision data used in this analysis were necessarily limited to that region. These streams are quite similar and generally have highly cohesive banks and medium sand beds. Inclusion of other incision data could have biased estimates of incipient incision because many observations of instability are recorded after a channel response has resulted in a decrease in stream power (i.e., slope). An incising stream that is in CEM stage 3 or 4, for example, typically looks severely unstable. But the process of channel incision, having exceeded the critical height for bank failure, may have already resulted in a significant decrease in channel slope. It is likely that some streams, that are assumed to be rapidly incising, could have previously lowered values of $S(Q/D_{50})^{0.5}$ if slope is measured after incision has progressed for an adequate period of time. Thus, it will be necessary to identify streams with sand beds by the stage of channel evolution if regional analyses are to accurately reflect levels of stream power that result in incision.

4. Conclusions

The high predictive accuracies of the resulting statistical models suggest that logistic regression analysis is an appropriate technique for associating basic hydraulic data with various stable and unstable channel forms. The utility of this approach for identifying streams that are particularly susceptible to changes in the controlling variables is also clear. Traditional discriminators of channel pattern do not adequately portray the fuzziness of these transitions. In particular, the relative flatness of logistic curves produced by the meandering–braiding transition reflects the omission of key factors that control lateral adjustment processes and the preponderance of intermediate channel patterns. The probabilistic diagrams resulting from these analyses provide users with a more realistic assessment of the uncertainty associated with previously identified thresholds of channel instability. In addition, the mobility index $S(Q/D_{50})^{0.5}$ proved highly effective in predicting the form of channels with sand beds with limited information. This parameter is also quite useful for predicting the form of streams with gravel beds and in scaling stream slopes across a broad range of watershed scales and geologic conditions.

The logistic regression models suggest that channels with sand beds with cohesive banks may be particularly susceptible to modest increases in specific stream power. Although incising and braiding, streams with sand beds exhibit similarly high levels of specific stream power relative to stable meandering streams, incision apparently initiates at levels of specific stream power that are less than those found in fully braided channels. For channels with gravel beds, the logistic regression results provide a probabilistic version of van den Berg's (1995) threshold for the transition from meandering to braiding. Although data on certain size fractions remain sparse, the logistic models suggest that the transition to braiding in channels with sand beds may be more dependent on the caliber of bed material than in channels with gravel beds.

In general, methods for systematic evaluation of potential instability in alluvial channels at the watershed scale are still primitive. Such an evaluation might be performed in a particular basin by estimating available stream power using relations of regional flow and a geographic information system to determine whether excess stream power is available to initiate channel instability. Booth (1991) and Simon and Downs (1995) suggest that the likelihood of channel instability can be assessed in a general manner for study sites in a given drainage basin and that such an approach should be pursued. The logistic regression approach developed in this study provides an alternative tool for risk-based management of fluvial systems in the context of channel modifications and watershed disturbances.

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