WIDTH OF STREAMS AND RIVERS IN RESPONSE TO VEGETATION, BANK MATERIAL, AND OTHER FACTORS[1]

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ABSTRACT: An extensive group of datasets was analyzed to examine factors affecting widths of streams and rivers. Results indicate that vegetative controls on channel size are scale dependent. In channels with watersheds greater than 10 to 100 km^2, widths are narrower in channels with thick woody bank vegetation than in grass lined or nonforested banks. The converse is true in smaller streams apparently due to interactions between woody debris, shading, understory vegetation, rooting characteristics, and channel size. A tree based statistical method (regression tree) is introduced and tested as a tool for identifying thresholds of response and interpreting interactions between variables. The implications of scale dependent controls on channel width are discussed in the context of stable channel design methods and development of regional hydraulic geometry curves.
(KEY TERMS: river restoration; river engineering; stable channel design; fluvial geomorphology; hydraulics; watershed management.)

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INTRODUCTION

Given the recent emphasis on rehabilitation and restoration of altered stream and river channels, there is a need to improve understanding and predictive models of stable channel width in fluvial systems. The lateral dimensions of self-formed alluvial channels are controlled by stochastic interactions between driving forces such as the magnitude, frequency, duration, rate of change, timing and sequence of flows, and a host of other factors including the relative erodibility of bed materials and bank strata, the type and density of reinforcing vegetation along channel margins, large woody debris (LWD), bank drainage and geotechnical characteristics, and the inherent recovery time of the system (Wolman and Gerson, 1978; Thorne, 1990; Knighton, 1998).

Despite the complexity of these processes, the downstream hydraulic geometry (DHG) relationship for width is typically represented by a simple power-law function,

$$w = \alpha Q^{\beta} \tag{1}$$

where w is width (m), Q is a geomorphically significant discharge (m^3/s) that varies between sites (such as bankfull or with a known recurrence interval), and α and β are the regression coefficient and exponent, respectively. Many studies over the last half century have established that the parameters in Equation (1) vary widely. The regression coefficient α and exponent β (in parentheses) vary from 1.85 to 15.96 (0.23 to 0.84) in sand bed rivers and 1.59 to 5.68 (0.36 to 0.66) in gravel bed rivers (Knighton, 1998; Soar, 2000). In fitting DHG models, several researchers have discovered that stratification by bank vegetative conditions (above ground) often improves univariate DHG models based on a representative discharge (Table 1).

Although exponent β does exhibit variability, past research has demonstrated that β is consistently near 0.50, and is often not statistically different from 0.50 (Soar, 2000). Other researchers have recognized that

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TABLE 1. List of Regression Coefficients and Exponents for Equation (1) With Q in Units of m^3/s.

Data Set	Bank Vegetation Conditions	Regression Parameters α	Regression Parameters β
Andrews (1984), Gravel Bed (dimensionless form)	Thin (grass or light woody vegetation)	4.94	0.48
	Thick (trees and brush)	3.91	0.48
Hey and Thorne (1986), Gravel Bed	Grassy Bank (Type I)	4.33	0.50
	1 to 5 Percent Tree/Shrub (Type II)	3.33	0.50
	5 to 50 Percent Tree/Shrub (Type III)	2.73	0.50
	>50 Percent Tree/Shrub (Type IV)	2.34	0.50
Charlton *et al.* (1978), Gravel Bed, Negligible Sediment Load	Grass Lined	4.11	0.45
	Tree Lined	3.37	0.45
Huang and Nanson (1997), Gravel Bed	Lower Tree Frequency (< 5 trees/10 m of bank length)	2.90	0.50
	Higher Tree Frequency (> 5 trees/10 m of bank length)	1.80	0.50
Soar (2000), Gravel Bed (utilizing data from Andrews (1984), Hey and Thorne (1986), and Charlton *et al.* (1978))	Grass Lined (< 5 percent tree/shrub cover)	3.75	0.50
	Tree Lined (≥ 5 percent tree/shrub cover)	2.48	0.50
Soar (2000), Sand Bed	Tree Cover < 50 percent	5.32	0.50
	Tree Cover ≥ 50 percent	3.38	0.50

model fit can be improved by adding sedimentary characteristics (e.g., Schumm, 1971; Ferguson, 1973) or variables from flow resistance equations (e.g., Huang and Nanson, 1997). However, few research efforts have investigated the issue of scale dependency of DHG relationships and the interactions that may exist between controlling variables.

Although more sophisticated multivariate models of channel width have been developed for selected regions and channel types, univariate DHG models of width as a function of discharge or watershed area as presented by Dunne and Leopold (1978), Rosgen (1996), and many others continue to be widely applied and cited. These "regional curves" are based on data from broadly defined regions (e.g., eastern U.S.) and provide an estimate of channel width as a function of bankfull flow or watershed area within that region. A large degree of scatter is typically present in plots of this nature, as attempts to describe channel width over a large geographic area do not adequately capture the wide range of processes and intrinsic controls responsible for channel width (Hession, 2001). State agencies and organizations have recognized the shortcomings of large scale regional curves and have taken the next logical step of generating curves by state or physiographic region, such as the Vermont Department of Environmental Conservation (VDEC, 2001) and the North Carolina Stream Restoration Institute (NCSRI, 2002). However, even curves developed for a particular state or smaller region often exhibit a large degree of variability that reduces confidence in design applications and may not be valid if area specific channel forming flows and hydroclimatic conditions are not too variable.

Objectives

Design approaches for channel width in river engineering and stream restoration or rehabilitation that utilize a DHG equation or regional curve involve substantial uncertainty. The objective of this paper is to assist engineers, hydrologists, geomorphologists, and aquatic scientists in making better decisions as they select an appropriate design width by: (1) performing a meta-analysis of existing datasets to identify response patterns of single-thread stream and river channels width to factors across a broad range of scales; (2) investigating interactions between channel size, bank vegetation, and bank sedimentary characteristics; and (3) discussing the implications that the results have for development of regional curves and restoration or rehabilitation of degraded streams and rivers.

METHODS

The meta-analysis used data collected by 39 different researchers at over 1,100 locations with more than 65 measured or descriptive variables. These datasets represent low gradient, alluvial channels spanning a wide range of geologic settings, rainfall and runoff patterns, scales, vegetative conditions, bed and bank conditions, and sediment transport characteristics. Criteria for inclusion of datasets in the meta-analysis were: (1) width at bankfull or annual high flow was one of the measured parameters; (2) drainage area or discharge (bankfull, mean annual, or with a known recurrence interval) could be determined for the location; and (3) one or more potentially controlling variables were documented, particularly vegetation type, coverage or density, substrate characteristics, and LWD loading. Any channels that were noted by the researchers to exhibit a tendency towards vertical or lateral adjustment at the decadal time scale were excluded.

The description of vegetative conditions presented herein is complicated by the lack of a common reporting method among the researchers whose datasets were used in this analysis. Some researchers quantified bank vegetation conditions typed by percent coverage (Hey and Thorne, 1986; Soar, 2000), density index (Coon, 1998), maturity index (Diez *et al.,* 2001), or tree frequency (Huang and Nanson, 1997). Others qualitatively described bank conditions as grass, forested, thick, thin, heavy, moderate, or light (Simons and Albertson, 1960; Charlton *et al.,* 1978; Andrews, 1984; Rowntree and Dollar, 1999; Hession *et al.,* 2003). Throughout this text and in the analyses, bank vegetative conditions are referred to as "thick" or "thin." If percent coverage data were available, "thick" vegetation refers to bank vegetation qualitatively described by the researchers as forested, heavy, or thick vegetated bank conditions with greater than 5 percent tree/shrub cover. Thin vegetation refers to grass covered banks, nonforested channels, or channels where tree/shrub coverage is less than 5 percent (see Table 1). Where bank conditions were not specified by the researcher(s) but photographs were available, percent coverage was estimated for the purpose of this study from photographs (Barnes, 1967; Annable, 1996). Note that thick does not equate to density, as grasses may be much denser than woody vegetation on a stem per area basis. Thus, the term thick is best described as a qualitative index of woody vegetation dominance (density, basal area, and coverage) that is directly related to the stiffness and length scale of bank roughness elements. The descriptions provided in the literature do not yield information on rooting characteristics such as depth and density per volume, although underground rooting characteristics may relate broadly to aboveground characteristics.

Unavoidably, the selected datasets were also inconsistent in the number, type, and descriptive power of the variables each contained. Combining the individual datasets into a larger, single dataset for use in the meta-analysis required various degrees of augmentation with information collected from other sources such as geographic information systems (GIS), precipitation maps, agency databases, and other supporting documentation.

Comparisons between factors and issues of scale were performed graphically, using linear regression methods, and performing statistical tests (Ott and Longnecker, 2001). The role of vegetation and bank material and scale influences were described using least squares methods in linear regression. The linear models presented in this part of the analysis were performed without forcing a particular value on a coefficient or exponent. Hydraulic geometry relationships were used as the basis for meta-analysis using a statistical method for regression trees (Breiman *et al.,* 1984; Venables and Ripley, 1999). Features that make regression trees appropriate for this analysis include efficacy in identifying interactions between explanatory variables, handling missing and categorical data, and meaningful description of nonlinear relationships. Regression tree analysis was performed with the width coefficient, α, as the dependent variable. Where drainage area data were available, analyses were performed with drainage area as a surrogate for discharge. Thus, the regression coefficient and exponent have a subscript to denote whether they represent discharge or drainage area (i.e. α_Q and α_D correspond to the width coefficient using discharge or drainage area, respectively, as the independent variable). The exponents were assumed constant, 0.50 for discharge and 0.45 for drainage area (Soar, 2000; Castro and Jackson, 2001).

$$\alpha_Q = \frac{w}{Q^{0.5}} \tag{2}$$

$$\alpha_D = \frac{w}{D^{0.45}} \tag{3}$$

where w is channel width (m), Q is discharge (m^3/s), α_Q is the regression coefficient for discharge (dimensionless), D is the drainage area of the contributing watershed (km^2), and α_D is the regression coefficient for drainage area.

The coefficients α_Q and α_D were log transformed and used as dependent variables in the regression tree models. As used in the power law functions, variability in the coefficient reflects variability in channel width. In many cases, drainage area and discharge were available, and these data were included in both the analysis for α_Q and α_D. The regression tree analysis was performed using the statistical package

S-PLUS 6 for Windows (Insightful Corp., 2001) and recursive partitioning (RPART) routines developed by Therneau and Atkinson (1997).

To build a tree, RPART determines the single variable that best splits the data into two groups using a method that utilizes a measure of impurity such as the Gini index (Therneau and Atkinson, 1997) or difference in the sum of squares between the initial group and the two subgroups as the basis for splitting. The process is repeated separately on the two subgroups of data formed from the initial split and then subsequently on the individual groups of data formed by the next split. This process is repeated until no improvement can be made or a predetermined minimum number of observations is reached for a split. The RPART routine was also used to perform cross validation to select the "best" tree. Cross validation was performed by dividing the data into groups with an equal number of observations and averaging the results of trees grown for all the combinations where one of the groups is withheld.

Once the tree has been developed, it is often oversized, and requires "pruning," to reduce the complexity of the tree and remove portions of the tree that do not explain much variability. Pruning methods can be based on a complexity parameter (*cp*), or a standard error (*SE*) term that is a function of the relative error and standard deviation of the last split. A bootstrapping procedure was used to determine the prediction error associated with the model. A mean degree of optimism was computed for the model using the bootstrap method and added to the model Mean Squared Error (*MSE*) to determine the estimated *Prediction MSE* for the model. More information on regression tree analysis can be found in Breiman *et al.* (1984), Venables and Ripley (1999), and De'ath and Fabricius (2000).

RESULTS

The overall processes that dominate channel width are different in small streams and rivers than those in the larger rivers. The difference in the least squares regression lines in Figure 1a indicates that for the same bankfull discharge conditions, channels with thick bank vegetation, Types 3 and 4 in Hey and Thorne (1986) or trees in Charlton *et al.* (1978), are narrower. The solid lines in Figure 1a are the least squares regression lines for the combined thick bank vegetation data ($r^2 = 0.93$) and combined thin bank vegetation data ($r^2 = 0.93$) where the Hey and Thorne (1986) and Charlton *et al.* (1978) data were aggregated. The dashed lines are the 95 percent confidence interval for the regression lines. The slope of the regression lines for thick vegetation is steeper than the slope for thin vegetation and as channel width approaches 50 m (Q_{bf} is approximately 300 m^3/s), the vegetative effects on width become less discernable and the regression line confidence intervals begin to overlap, suggesting an upper bound on channel narrowing effects of vegetation. Very few of the width data in Figure 1a are less than 10 m.

Davies-Colley (1997) and Hession *et al.* (2003) provide data where the least squares regression line indicates that nonforested channels are *narrower* than channels with forested (thick) bank vegetation (Figure 1b). The data from Davies-Colley (1997) and Hession *et al.* (2003) forested channels were combined to generate one regression line ($r^2 = 0.80$) and the nonforested data were combined to generate the other ($r^2 = 0.85$). The regression lines in Figure 1b indicate that the narrower, nonforested channels increase width in the downstream direction faster than the forested reaches. A key difference between the data presented in Figures 1a and 1b is the size of the watersheds from which the data were collected. Nearly all the channels in the data collected by Davies-Colley (1997) and Hession *et al.* (2003) are less than 10 m wide, while the Hey and Thorne (1986) and Charlton *et al.* (1978) data are from channels that are mostly wider than 10 m. The mean drainage area of the Hey and Thorne (1986) and Charlton *et al.* (1978) data is 218 km^2, while the Davies-Colley (1997) and Hession *et al.* (2003) watersheds average 9 km^2. Figures 1a and 1b are presented in log-log space, indicating that the width response to increasing channel size is nonlinear.

In addition to the vegetation effects described above, the sedimentary characteristics in the channel boundary also influence width. Data from Schumm (1960), Simons and Albertson (1960), and Soar (2000), indicate that as the percentage of silt and clay (adding cohesive strength) in the bank material increases, channel width tends to decrease. Vegetative effects coexist with bank sediment controls; woody vegetation covering a greater portion of the banks tends to result in narrower channels as before (Figure 2a). Note that these channels have fine grained bed material and are about the same size as the gravel and cobble bed Charlton *et al.* (1978) and Hey and Thorne (1986) channels. The U.S. Army Corps of Engineers (USACE, 1994) design recommendations (curves superimposed on Figure 2a) indicate that as clay content of the bank material is greatest (USACE Curve 1), channel width is narrowest, and cohesionless channel boundaries result in the widest channels (USACE Curve 3). When the data are stratified according to bank vegetative conditions (Figure 2b),

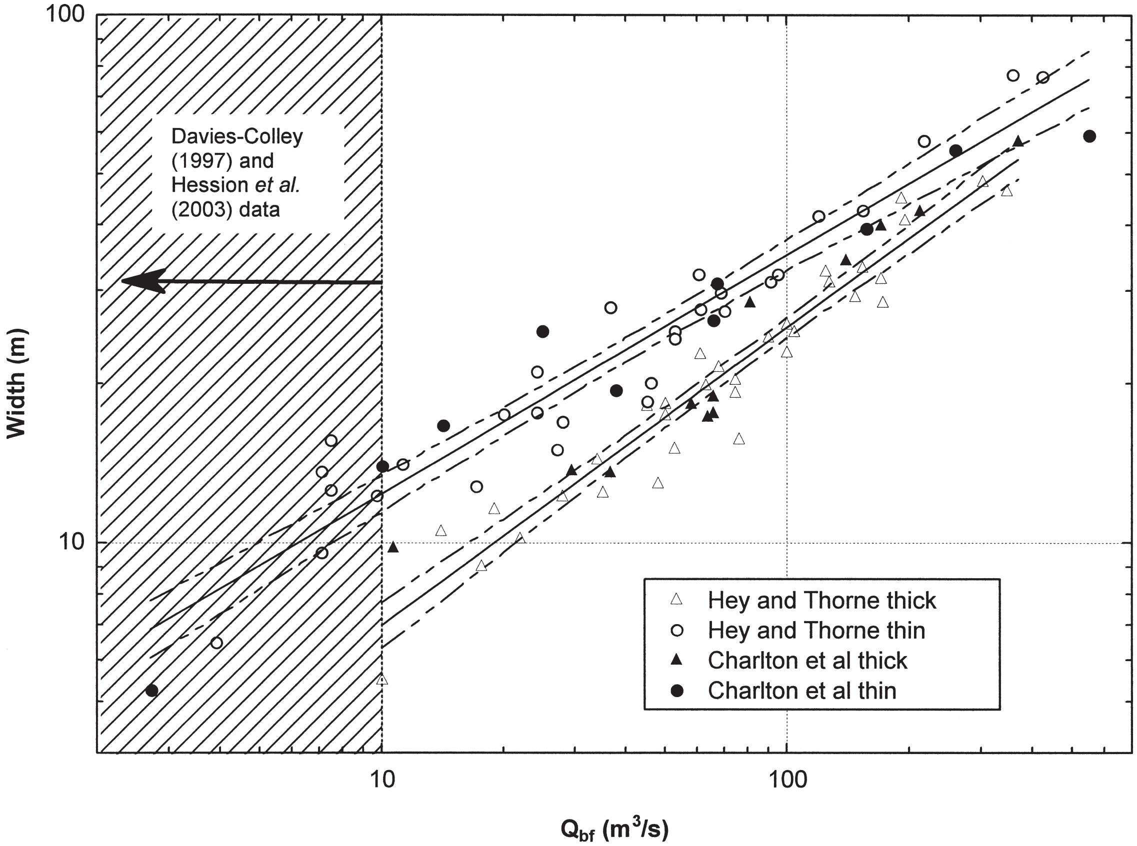

Figure 1a. Width Discharge Relationships by Vegetation Type (Charlton *et al.*, 1978; Hey and Thorne, 1986). Regression lines are presented with the 95 percent confidence interval.

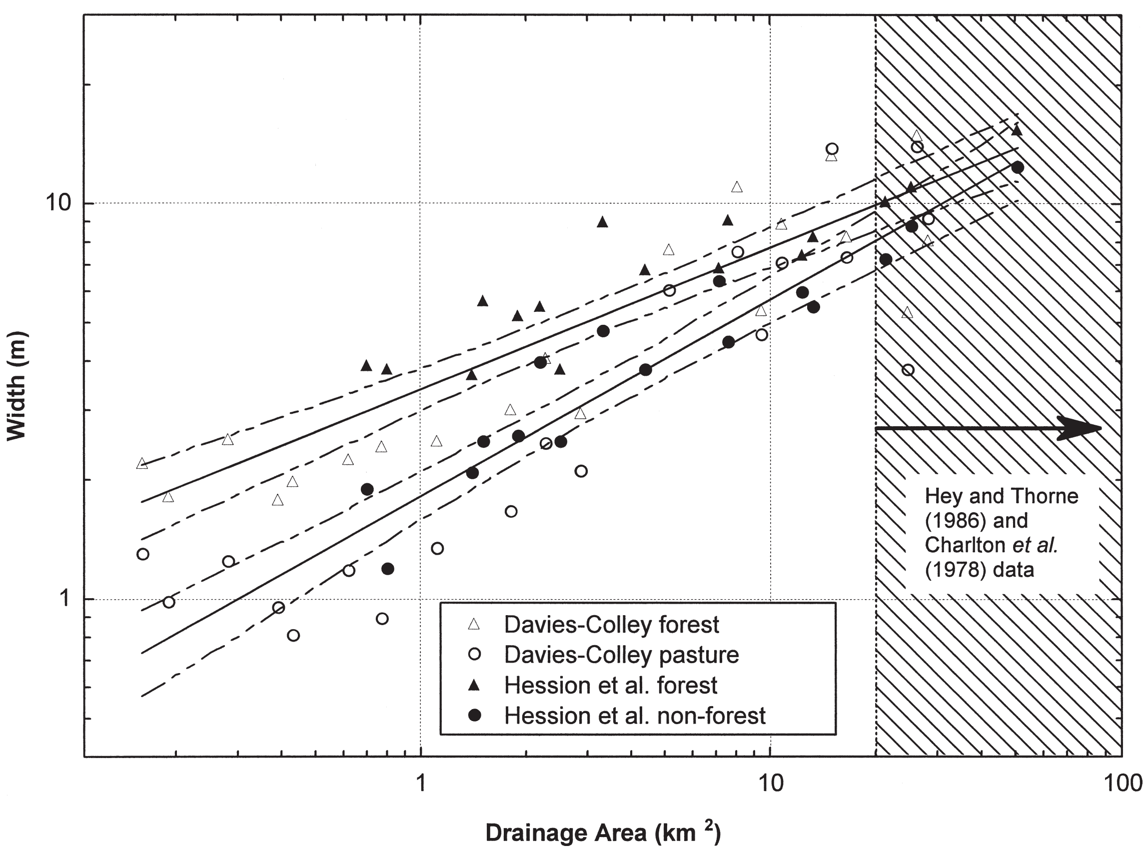

Figure 1b. Width Drainage Area Relationship by Bank Vegetation (Davies-Colley, 1997; Hession *et al.*, 2003). Regression lines are presented with the 95 percent confidence interval. Note the opposite trend where thick bank vegetation is associated with wider channels.

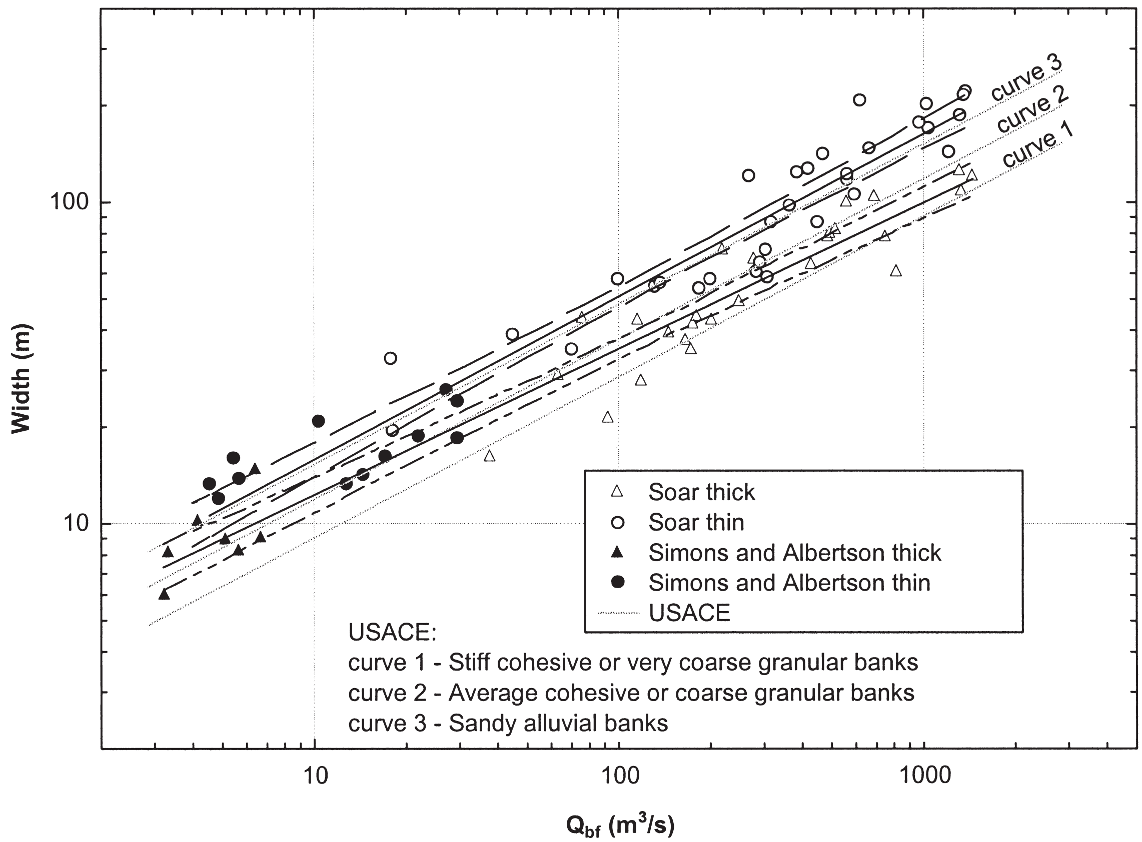

Figure 2a. Width Discharge Relationships Illustrating Vegetation Effects (Simons and Albertson 1960; USACE, 1994; Soar, 2000). Regression lines are presented with the 95 percent confidence interval and superimposed on USACE design recommendations.

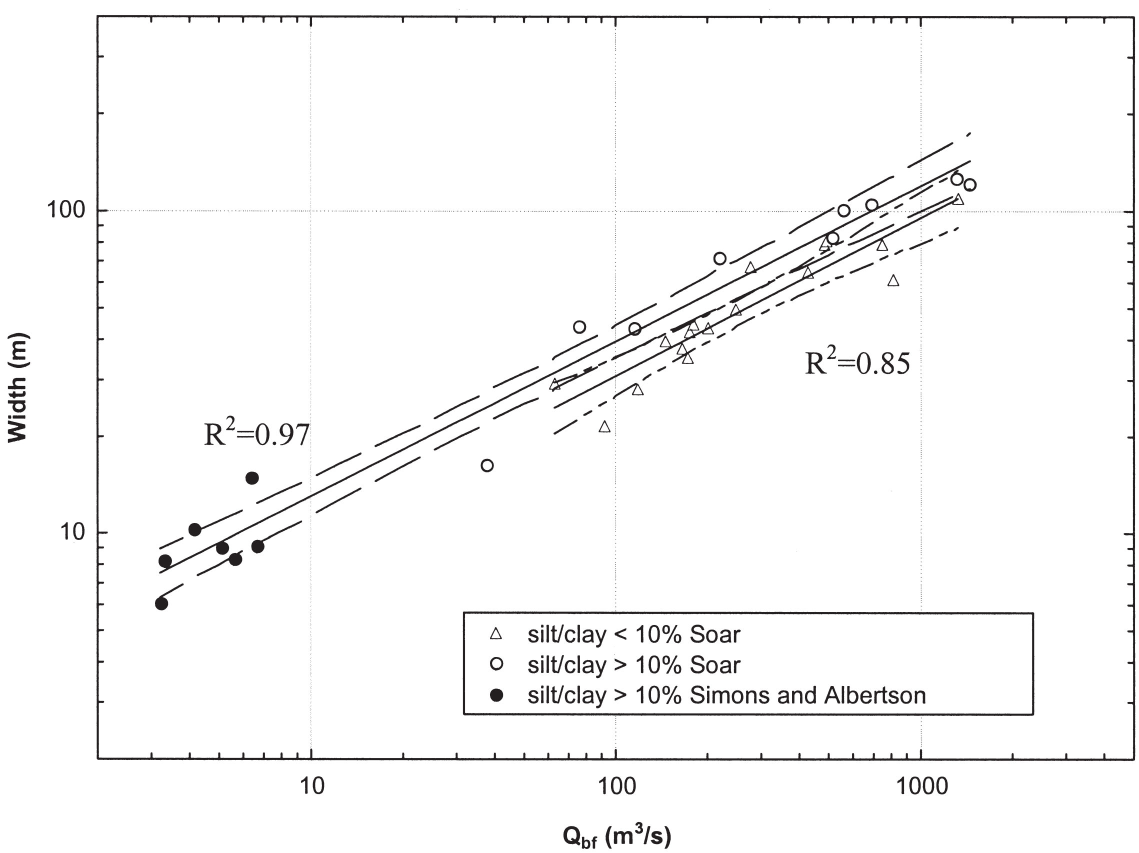

Figure 2b. Width Discharge Relationships for Channels With Thick Bank Vegetation (Simons and Albertson, 1960; Soar, 2000). Regression lines are presented with the 95 percent confidence interval. Note that the 95 percent confidence intervals are for regression equations for silt/clay < 10 percent and silt/clay > 10 percent.

the channels with vegetation covering a greater extent of the bank are narrowest with *lower* percent silt and clay in the channel margins.

Over 50 regression trees were generated in the course of the analysis. Two representative trees are presented in Figures 3a and 3b to highlight some of the typical response patterns. Figure 3a was developed from gravel bed river datasets shown by least squares regression methods to have strong vegetation controls (Charlton *et al.,* 1978; Andrews, 1984; Hey and Thorne, 1986; Davies-Colley, 1997; Hession *et al.,* 2003). Figure 3b was developed from the entire dataset. The drainage area coefficient, α_D, was log transformed and is the response variable for both trees.

The results from Figure 3a indicate that mean annual precipitation was the variable explaining the most variability, with the split occurring at 870 mm/year. Channels in regions where precipitation was above 1,463 mm/year were placed into a terminal node without further splits. The average width coefficient for channels with mean annual precipitation above 1,463 mm/year was the second largest in the analysis. Only the channels with more woody bank vegetation in small watersheds (with mean annual precipitation less than 1,463 mm/year) had a higher width coefficient. Results from regression tree analysis of the entire dataset (Figure 3b) indicate similar responses as in Figure 3a, with precipitation (791 mm/year) partitioning most variability, widest channels associated with highest precipitation (≥ 1,575 mm/year), and scale dependent channel widths in areas with higher relative precipitation. Channels with silt and clay content greater than or equal to 90 percent are the narrowest, while bank material effects are only observed in channels with relatively low precipitation (< 791 mm/year) and smaller bed material size (d_{50} < 12 mm). Not only are these results consistent with the results of Figures 1 and 2, but the regression tree results present interactions in the context of multiple explanatory variables (particle size and mean annual precipitation) to suggest the conditions in which vegetative or bank sedimentary characteristics are most likely to be significant.

DISCUSSION

Meta-analysis of hydraulic geometry data from single-thread alluvial channels underscores the complexity and non-linearity of factors influencing channel width adjustment. Table 2 describes key factors controlling channel width and probable trends suggested by this analysis and observed by other researchers studying other factors such as LWD loading, land use, canopy closure, freeze/thaw cycles, rooting density and depth. Scale dependent width responses to bank vegetative conditions observed in this analysis have been inferred by other researchers. Trimble (1997) reported a similar response in channels less than 12 m wide and found that the baseflow widths of forested sections of his study site were wider than grass lined reaches in pastures, even where cattle had a considerable negative effect on bank stability. The findings from smaller watersheds also support the work presented by Zimmerman *et al.* (1967) and Murgatroyd and Ternan (1983). Zimmerman *et al.* (1967) report that vegetative characteristics greatly influenced mean width of the channels when the drainage area was less than 13 km^2, with forested channels wider than grass lined channels. Murgatroyd and Ternan (1983) measured widths and erosion rates of a channel draining a watershed of about 5 km^2 where pastures had been converted to plantation forests. Channels in the plantation forests had greater widths and erosion rates as compared to channels in pastures. Bank vegetation also has scale-dependent effects on Manning's roughness coefficient and affects near bank flow fields. Coon (1998) reported that measurable effects of bank vegetation on Manning's roughness coefficient were most discernable in narrow channels (less than 19 m) with small, but measurable, effects on channels up to 30 m.

Differences in scale may allow a forested canopy to completely cover the entire channel in a small stream. Davies-Colley (1997) and Stott (1997) point out that shading suppresses understory growth, reducing bank armoring by grasses. Furthermore, smaller streams are likely to be more susceptible to LWD effects such as locally increasing erosion rates (Keller and Swanson, 1979) or creating chute cutoffs and channel avulsion (Rowntree and Dollar, 1999). Higher LWD loading (number of pieces/m^2 streambed) has been observed in headwater streams in Spain (Diez *et al.,* 2001), and the input/output process model suggested by Keller and Swanson (1979) suggests that LWD removal processes occur at much longer time scales in smaller streams than larger streams. An analysis of first-order to third-order stream data from Diez *et al.* (2001) indicates that as LWD loading increased, the width coefficient for drainage area, α_D, increased. Wood loading decreased as stream order increased, suggesting that removal by flotation is an infrequent process in smaller streams and supports scale dependence in LWD effects.

Channel width response due to vegetation or forest type may also be a result of differences in rooting depth conditions (Stott, 1997; Simon and Collison, 2001). Although rooting depth was not considered in the analysis because this information was not reported in the datasets, research by Simon and Collison

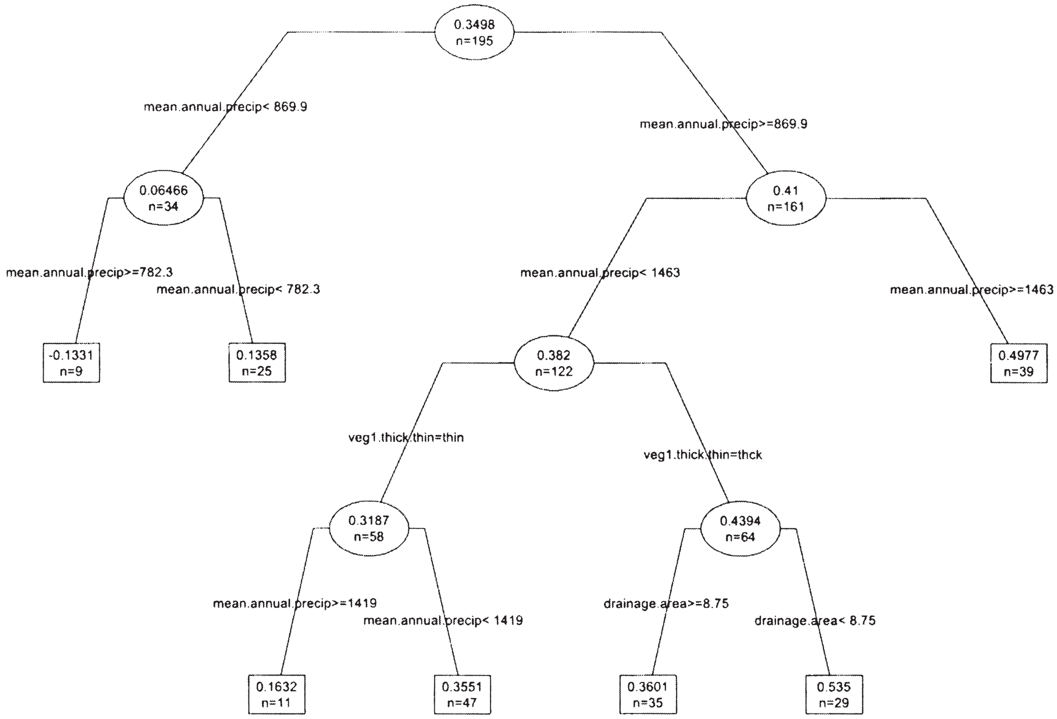

Figure 3a. Regression Tree Results for α_D (log-transformed values and number of observations are provided in ovals) Using Gravel Bed River Data From Selected Researchers (Charlton *et al.,* 1978; Andrews, 1984; Hey and Thorne, 1986; Davies-Colley, 1997; Hession *et al.,* 2003) (prediction *MSE* = 0.0235, *cp* = 0.025).

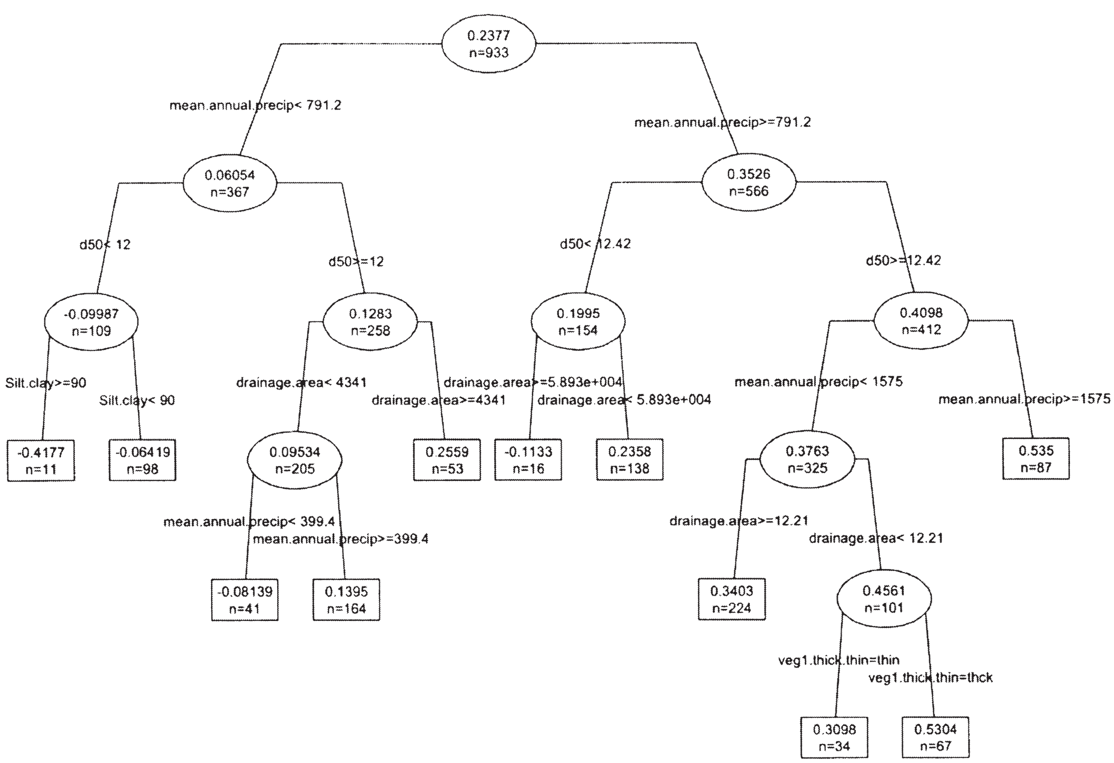

Figure 3b. Regression Tree Results for α_D (log-transformed values and number of observations are provided in ovals) Using the Entire Data Set (prediction MSE = 0.0439, cp = 0.013).

TABLE 2. Key Processes and Probable Trends in Channel Width.

Factor	Probable Trend	Description	Source
Silt Clay	Narrower	Higher silt/clay content when little or no vegetation present.	Simons and Albertson (1960); Schumm (1971); Ferguson (1973); USACE (1994)
Vegetation	Narrower	Thicker woody bank vegetation along larger channels (channel width >10 to 15 m or drainage areas >10 to 100 km^2).	Charlton *et al.* (1978); Graf (1978); Andrews (1984); Hey and Thorne (1986); McKenney *et al.* (1995); Friedman *et al.* (1996); Hupp and Osterkamp (1996); Davies-Colley (1997); Huang and Nanson (1997); Trimble (1997); Rowntree and Dollar (1999); Diez *et al.* (2001); Hession *et al.* (2003)
	Wider	Thicker woody bank vegetation along smaller channels (channel width <10 to 15 m or drainage areas < 10 to 100 km^2).	
	Wider	Less woody bank vegetation along larger channels (channel width >10 to 15 m or drainage areas > 10 to 100 km^2).	
	Narrower	Deep rooted grasses along smaller channels (channel width <10 to 15 m or drainage areas < 10 to 100 km^2).	
LWD	Wider?	LWD loading is high and/or LWD lengths greater than or equal to channel width. Note that LWD removal may result in channel enlargement as a result of reduced energy dissipation.	Beschta (1990); Thorne (1990); Robison and Beschta (1990); Dose and Roper (1994); Buffington and Montgomery (1999b); Diez *et al.* (2001)
	Narrower	LWD loading is low to moderate and/or LWD oriented parallel to flow direction or in a manner that stabilizes/armors bank.	Robison and Beschta (1990); McKenney *et al.* (1995)
	Wider	Debris jams in low gradient streams tend to widen channels upstream; higher gradient streams have more variable width when debris jams are present.	Keller and Swanson (1979); Hickin (1984); Church (1992)
Land Use	Wider?	LWD removal can lead to channel widening in Pacific Northwest streams. Possible narrowing if LWD is source of channel bank erosion.	Robison and Beschta (1990); Dose and Roper (1994); Buffington and Montgomery (1999b);
	Wider	Changes associated with urbanization often reflect changes in the flow regime and sediment supply.	Pizzuto *et al.* (2000); Bledsoe and Watson (2001); Hession *et al.* (2003)
	?	Afforestation may stabilize or destabilize banks depending on channel size, susceptibility to freeze/thaw bank erosion, LWD input and removal, rooting characteristics, and historical context.	Zimmerman *et al.* (1967); Murgatroyd and Ternan (1983); Davies-Colley (1997); Stott (1997); Trimble (1997)
Canopy Closure	Wider	Considerable shading reduces light availability to understory, potentially diminishing the establishment and growth of stabilizing vegetation.	Murgatroyd and Ternan (1983); Davies-Colley (1997)
Freeze/Thaw	Wider	Higher incidents of freeze/thaw cycles have been associated with higher erosion rates.	Zimmerman *et al.* (1967); Stott (1997)
Root Density	Narrower	High root density has been associated with lower erosion rates. Root density decreases as silt and clay content increases. Effect is lessened as bank height exceeds rooting depth.	Murgatroyd and Ternan (1983); Dunaway *et al.* (1994); Simon and Collison (2001)
Rooting Depth	Narrower	Relative to bank height, deeper rooted vegetation can reduce bank erosion	Abernethy and Rutherford (1998); Simon and Collison (2001)

(2001) demonstrates that rooting depth and tensile strength varies by plant species. Furthermore, rooting depth and scale may interact based on bank height. Small streams may have bank heights allowing the roots of both grasses and woody vegetation to extend to the saturated soil zone of the banks. In this case, the denser roots of the grasses can increase the strength of the soil and minimize erosion through fluvial processes (grain by grain detachment), and mass wasting or rotational failure potentials are small due to small bank height. Acknowledging that the specific erosional and depositional processes are still poorly understood and warrant further investigation, it is inferred that the small streams studied by Davies-Colley (1997), Hession *et al.* (2003), Trimble (1997), and others likely reflect this process. Although these grassy channels are narrower, researchers have documented higher rates of lateral migration in small channels with grassy reaches (Allmendinger *et al.,* 1999). Channels with bank heights on the order of 1 m may have toe elevations well below the rooting depth of many grass species but within the range of woody plant species (Simon and Collison, 2001). Under these conditions, the high strength root matrix of grass species is well above the bank toe and, thus, unable to protect the bank from fluvial or mass wasting erosional processes. However, woody plant species (and some grasses) have roots that can extend 1 m or deeper and reinforce the soil structure and resist bank erosion. As channel size increases such that bank height is much greater than the rooting depths of both woody and nonwoody vegetation, protection against erosional processes by fluvial, mass wasting, or rotation failures is reduced. Moreover, mass wasting or rotational failure potential due to the surcharge of woody vegetation increases. Owing to the size of the channels studied by Hey and Thorne (1986), Charlton *et al.* (1978), Andrews (1984), Soar (2000), and Huang and Nanson (1997), most are likely to have widths that reflect adjustment to erosion through fluvial processes, mass wasting, and rotational failure. Abernethy and Rutherford (1998) report that mass failure was the dominant erosional process in the lower reaches of the Latrobe River in southeast Australia where channel depths were on the order of several meters. The erosion in the mid reaches (depths about 1 m) of the Latrobe River was dominated by fluvial entrainment, while the headwater reaches (depths less than 1 m) exhibited localized erosional process dominated by LWD effects (wind throw of streamside trees and concentrated flow into banks due to debris dams).

Investigating vegetative influences where cohesive bank conditions exist suggests the potential for vegetation bank material interactions. When stratified solely by percent silt/clay in the bank material, data from Simons and Albertson (1960) and Soar (2000) indicate that channels with higher silt and clay content are narrower. However, when data are stratified by the amount of bank vegetation, channels with more bank vegetation are narrower when the bank silt and clay content is *lowest*, in direct contrast to the design recommendations proposed by the USACE (1994). Although the 95 percent confidence intervals for the regression lines for channels with different silt/clay contents overlapped, the trend supports a bank material/vegetation interaction reported by Dunaway *et al.* (1994) based on flume experiments on soil samples taken from the banks of rivers in eastern California and central Nevada. Higher erosion rates were positively correlated with clay content of the bank material. Differences in erosion rates were attributed to lower root densities found in bank materials with highest silt or clay content. This suggests that high silt/clay content inhibits root growth in some instances. Sandier soils had highest root densities and lowest erosion rates. These results suggest that a complex set of interactions between channel width, bank strength due to soil cohesion, bank strength due to rooting effects, root volume, and silt/clay content occur.

Regression Trees

The regression tree analysis generated many models with complex tree structures. Although interpretation was often problematic given the complexity of the trees, patterns emerged and thresholds were identified in controlling variables. Using the width coefficient (α_Q and α_D) as the dependent variable is particularly useful in that it permits the result of a regression tree analysis to be used for stratifying relationships for channel width as a function of bankfull discharge or drainage area. Using the width coefficients (after back transforming) of the regression tree output in Figure 3a, estimated widths of channels with thick vegetation are approximately 50 percent greater for channels in smaller watersheds (< 8.75 km^2) as compared to channels with a larger watershed and thick vegetation (width coefficients of 3.43 and 2.29, respectively). These values are reasonable based on the data and confidence limits presented in Figure 1b.

The following summarizes the general responses observed in the trees analyzed across geographic regions, precipitation patterns, and bank sedimentary and vegetative characteristics. (1) Vegetation-scale interactions are apparent only in regions that are relatively humid. (2) These vegetation-scale interactions seem to reverse the controlling processes at drainage areas on the order of 10 to 20 km^2, with thick vegetation associated with wider channels than thin vegetation in the smaller watersheds. The opposite trend is observed for larger watersheds. (3) Bed material splits occur at particle sizes in the 1 to 12 mm range. In dryer regions, the split occurs at about 1 mm, whereas coarser splits tend to occur in regions that are more humid. (4) Silt/clay interactions are associated with drier regions and finer bed material. (5) There is a paucity of flow data in the smaller watersheds, often confounding comparisons between the α_Q and α_D trees.

Tree based models are relatively new tools for data analysis (Venables and Ripley, 1999; De'ath and Fabricius, 2000). The features that make regression trees attractive for this type of analysis include efficacy in identifying interactions between explanatory variables, handling missing and categorical data, and straightforward description of nonlinear relationships. Given the growing emphasis on developing regional curves relating channel dimensions to drainage area or discharge, regression trees can be used as an aid in determining appropriate factors and process thresholds for stratification when developing hydraulic geometry models. These factors could include bank vegetation characteristics, such as vegetation type, height, stiffness, root density, rooting depth, and the ratio of rooting depth to bank height. Other candidate stratification variables are bed and bank material texture, channel size (e.g., < 20 m wide) or contributing watershed area, and flow regime attributes (magnitude, frequency, duration, timing, and rate of change of flow). Additionally, mode of sediment transport, stream and valley type, geology, and land use (e.g., agricultural, forested, or urbanizing watersheds) may be useful descriptors for regression tree analysis. Regression trees readily reveal interactions and a hierarchical stratification of controlling factors beyond discharge and drainage area. Regression trees provide a suitable platform for analysis of a changing and growing dataset, as they can continually be refined as datasets are improved, enlarged, or developed.

Design Considerations

Channel designs based on DHG relationships or regional curves may not adequately reflect controlling variables. Even when stratified by vegetation type, scale dependent effects are missing. The recent work of Huang and Nanson (1998), Julien and Wargadalam (1995), and others have advanced the empirical foundation of DHG relationships. However, these advances utilize terms for roughness in either an exponent or coefficient that is expressed in traditional terms of Manning's roughness coefficient, Shields parameter, or grain size. These approaches may indirectly reflect interactions between bed and bank roughness but fail to capture the scale-vegetation interactions.

Approaches other than DHG are also utilized in stream channel design. However, analytic methods (deterministic or quasi-empirical) based on extremal hypotheses have been criticized for their lack of a physical basis (Hey, 1997). Yet others argue that principles of thermodynamics are appropriately applied to the open system setting of the fluvial system (e.g., Leopold and Langbein, 1962; Chang, 1988). Extremal approaches have been incorporated into design models, such as the hydraulic design package SAM (Copeland, 1991, 1994) and HEC-RAS Version 3.1 (USACE, 2002). In applying extremal approaches, these packages use a channel partitioning scheme proposed by Einstein (1950) to provide a means for accounting for the differences between the effects of bed and bank roughness. The Einstein method, when coupled with the SAM or HEC-RAS computational processes, provides stable channel dimensions (no net aggradation or degradation) based on a simultaneous solution of a set of equations for each of the bed and bank zones. Although seemingly an advancement by considering the bed and bank effects separately, the extremal solution based on the Einstein partitioning method often predicts wider channels as bank roughness is increased, a response opposite to that documented by Hey and Thorne (1986), Charlton *et al.* (1978), and Andrews (1984). Other researchers have recognized the limitations of analytical and quasi-empirical approaches and have endeavored to improve these methods through quantification of the diverse factors which influence widths of natural channels (Houjou *et al.,* 1990; Ikeda and Izumi, 1990; Millar and Quick, 1993; Julien and Wargadalam, 1995; Cao and Knight, 1996; Buffington and Montgomery, 1999a; Cribb and Darby, 2002; Simon and Collison, 2002). However, these approaches generally neglect the interaction between increased boundary strength or roughness and channel size. Thus, selecting a single channel width for restoration design given currently available methods is an arduous task, with apparent ambiguities in the results achieved by the different methods. However, recognizing potential influences (such as vegetation, cohesion, scale, etc.) and how these factors interact permits a more informed assessment of design methods and results in the context of expected processes. Although a discussion of acceptable margins of error in design is beyond the scope of this work, this investigation suggests that coupling an understanding of scale-dependent processes with statistical methods that better reveal complex interactions among factors has the potential to reduce uncertainty in DHG relationships and prediction of stable channel widths.

CONCLUSIONS

The processes controlling channel widths are many, varied, and complexly interactive. This investigation has revealed numerous trends in channel width response to vegetative influences and interactions between controlling variables. Most variability in channel width is explained by the amount of water flowing through the channel (in the simplest sense – duration, frequency, and rate of change are implied, but not examined here). Drainage area may be used as a surrogate for discharge, although this practice increases the risk of spurious inference and generally reduces explanatory power.

Bank vegetative conditions strongly influence the width of a channel. In relatively humid climates, vegetative influences tend to override sedimentary influences but interactions between bank vegetation and bank material exist. Moreover, the effect of vegetation on the stable width of natural channels is clearly scale dependent and nonlinear, with trend reversal at widths of approximately 20 m and watershed areas on the order of 10 to 100 km^2.

Appropriate classification or stratification using factors such as channel size is very important when considering the role of vegetation. However, stratifying on scale alone may not fully capture the processes controlling width. Bed and bank material can vary considerably within a small spatial extent and LWD loading and recruitment may be key stratifying variables. Geologic type, land use, valley type, or floodplain extent may also be powerful stratifying attributes. Incorporating the information from the meta-analysis and summary table (Table 2) into channel analysis and design is likely to improve the success of restoration activities.

Although there are many factors potentially affecting stable channel widths that have not been adequately considered in this meta-analysis, these findings reveal specific knowledge gaps and lead to the following recommendations. First, more data describing stream bank conditions are needed to address the factors that control the resistance of channel boundaries to fluvial erosion. While more data would be helpful, consistency in measurement and reporting is essential to allow direct comparisons between different datasets. Vegetative effects on channel hydraulics and resistance may be better understood by measures of stiffness, density, and diameter of streamside vegetation (Masterman and Thorne, 1994). When describing bank vegetation, inferences are made about the root structure based on above ground observations. Direct measures of rooting density, depth, and strength, although difficult, would increase understanding of how vegetation increases the erosion resistance of stream banks. In addition to rooting depth, rooting depth relative to bank height may be a robust variable to assess the extent that bank vegetation controls channel width. Recent research efforts (Cribb and Darby, 2002; Simon and Collison, 2002) directed towards understanding the processes of rooting effects on bank erosion rates are a positive step forward in understanding how bank vegetation effects stream channel width. These approaches should be tempered with an awareness of scale dependent processes.

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