The impact of scale on the processes of channel-side sediment supply: a conceptual model

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Abstract A conceptual model of downstream change in river bank erosion is presented that indicates scale to be an important control of the many dominant retreat processes. The model predicts that in upstream reaches, where banks are small and stream power is low, sub-aerial preparation processes are most effective. In mid-basin areas, combining individual functions for spatial change in discharge and slope suggests that stream power peaks and fluid entrainment mechanisms prevail. In the lowest reaches, where materials are cohesive and resistant to fluid shear, bank heights exceed critical geotechnical instability thresholds and the most important bank process is mass failure. Experiments and literature suggest that the modeling approach helps rationalize the variety of process conclusions reached by other workers, which has implications for understanding the nature, rate and timing of sediment transfer from channel sides to rivers.

INTRODUCTION

There is increasing recognition of the role of river banks as suppliers of sediment to fluvial systems (Church & Slaymaker, 1989; Lapointe & Carson, 1986; Prestegaard, 1988). Uncertainty remains concerning the influence of (a) fluid entrainment, (b) sub-aerial preparation processes, and (c) mass failure mechanisms. At present, bank sediment delivery processes are weakly represented in most models of river water quality, sediment transport and fluvial evolution. Goals here are to (a) outline an important source of uncertainty, (b) present a conceptual model of scale control on bank erosion domains, and (c) test the model with numerical experiments and a literature survey.

A MODEL OF DOWNSTREAM CHANGE IN BANK EROSION PROCESSES

Some workers have found a systematic tendency for bank erosion to increase downstream (Hooke, 1980; Hasegawa, 1989). Others identified peak lateral mobility in middle reaches (Lewin 1987; Prestegaard, 1988). Downstream change may be explained by scaling up in magnitude, frequency and/or duration of erosion processes. An alternative is that new, more dynamic processes occur at points downstream as scale and system thresholds are crossed; the effect may account for increasing erosion downstream (Lawler, 1992). These ideas are formalized here in a conceptual model based on hypothesized downstream change in relative efficacy of three bank process groups: sub-aerial preparation processes, fluid entrainment and mass failure.

Sub-aerial preparation processes

Many sub-aerial weathering processes cause transfer of bank sediment to the flow or condition bank material for fluvial removal (Twidale, 1964; Lawler, 1993a). Freeze-thaw activity is a bank material weathering process in humid temperate and sub-arctic environments (Wolman, 1959; Lawler, 1987; 1993a). As frost frequencies decrease with decreasing altitude (Lawler, 1988), freeze-thaw effects on banks also decline downstream.

Desiccation processes, however, which are significant at some sites (Bello *et al.*, 1978; Lawler, 1992), are inversely related to rainfall, and positively related to riparian summer air temperatures and bank evapotranspiration rates, and may increase in significance with declining altitude downstream. Opposing tendencies in freeze-thaw and desiccation efficacy suggest that downstream change in effectiveness of preparation processes is conservative. Theory too suggests that sub-aerial processes largely operate externally to the river, and are related more to microclimatic and moisture balance of the "perifluvial corridor" than to hydraulic feedbacks. If the absolute contribution from preparation processes is stable downstream, with an increase in erosion downstream, preparation processes should weaken down valley.

Direct fluid entrainment processes

Entrainment of bank particles closely relates to the boundary shear stresses, which can be loosely approximated by stream power variations. Bankfull stream power, Ω (W m^{-1}), is:

$$\Omega = pgQS \tag{1}$$

in which p is fluid density (1000 kg m^{-3}), g is gravitational acceleration (9.81 m s^{-2}), Q is bankfull discharge (m^3 s^{-1}) and S is energy slope (m m^{-1}). If p and g are constant downstream, combining the functions for change in Q and S yields an equation for downstream change in Ω. In the following numerical experiments, discharge is a power function of channel length, L (km) and:

$$Q = kL^m \tag{2}$$

and slope is made a negative exponential function of L (Rana *et al.*, 1973):

$$S = S_o e^{-rL} \tag{3}$$

in which S is channel slope and r is the coefficient of slope reduction. Multiplying gives:

$$QS = (kL^m)\,(S_o e^{-rL}) \tag{4}$$

which, when differentiated, yields the downstream rate of change of the stream power index:

$$\delta(QS)/\delta L = (mkL^{m-1})(S_o e^{-rL}) + (kL^m)(-rS_o e^{-rL}) \quad (5)$$

or:

$$\delta(QS)/\delta L = kL^m S_o e^{-rL}[(m/L) - r] \quad (6)$$

Equation (4) describes an inverted "U", suggesting low stream power in headwater reaches, peaks in mid-basin and small values further downstream. We can also determine critical channel length, L_c, at which stream power peaks, where $\delta(QS)/\delta L = 0$. As only the bracketed expression in equation (6) can be zero, this is the only term set to zero. Thus:

$$L_c = m/r \quad (7)$$

which is simply the ratio of the two rates of change of the component relations (equations (2) and (3)).

Figure 1A shows the profile and exponential slope function, using an initial slope value for S_o of 0.1 and an r of 0.085 (equation (3)). Discharge, increasing downstream logarithmically, uses k and m values of 0.1 and 1.5 (equation (2)). The resultant pattern shows that stream power peaks in mid-basin (Fig. 1A). Gross stream power is low in the headwaters owing to low discharge, but increases to a peak 17.65 km downstream (equation (8)). A hypothetical channel width series of the form $w = xL^y$ ($x = 1.8$, $y = 0.7$) was added (Fig. 1B) to allow derivation of specific stream power (Ω/w), in W m^{-2}, which also peaks a few km downstream. Further experiments indicated that peak stream power in the middle reach is of a more general case (Knighton, 1987) unless Q and S are both mode power functions of L.

Results provide a framework in which previous evidence of mid-basin stream energy maxima can be placed (Lewin, 1982; 1983; 1987; Graf, 1982; 1983). Baker and Costa (1987) showed that shear stress is maximized in moderately sized basins (10-100 km^2), and Magilligan's (1992) data show that shear stress and unit stream power peak at drainage areas of 200-300 km^2. Possibly reinforcing the dominance of fluid entrainment processes in middle reaches is the effect of a progressive downstream decrease in bank sediment size. Headwater bank sediment can be coarse, whereas lower reaches may have bank material high in clay; both of these size populations offer greater entrainment resistance than do the fine sand and coarse silt of mid-basin. Only a small and variable portion of this energy is likely available for bank erosion (Lewin, 1983).

Mass failure processes

Bank retreat often occurs by mass failure of unstable blocks (Kesel & Baumann, 1981). At the bank foot, blocks can break up catastrophically to release slugs of fine sediment, or simply "leak" material over longer periods. Slope stability models have been applied to bank failures quite successfully (Little *et al.*, 1982), and many feature strong scale control whereby maximum height beyond which instability becomes likely is defined. If the critical height is exceeded, soil above a potential failure surface is too great to be

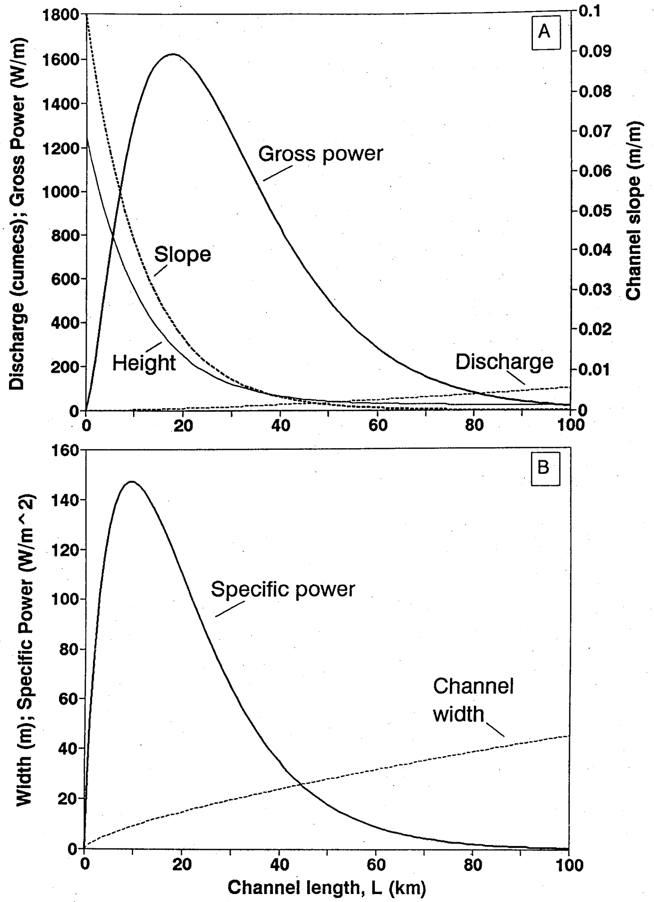

Fig. 1 Theoretical downstream stream power distributions derived from combining a negative exponential slope function with power functions for discharge and channel width: (A) gross stream power distribution for given long profile, slope and discharge changes; (B) specific stream power for given width function.

supported by the shearing resistance of the material.

A simple stability equation is the Culmann formula (in Selby, 1982), which is based on total, rather than effective, stress principles and assumes a planar shear surface of slab or wedge failure. Thorne (1978) notes weaknesses in a Culmann analysis and presents an equation for critical height of a vertical bank, H_c' (m), in which tension cracks, extending to around one-half of total bank height, are included (Thorne, 1982):

$$H_c' = (2c/\gamma)\tan(45 + \phi/2) \tag{8}$$

where c is cohesion (kPa), γ is unit weight of material (kN m^{-3}) and ϕ is friction angle (°). Equation (8) is used in Fig. 2 to yield stability curves, assuming ϕ of 16°, a range of cohesion values and saturated (worst case) unit weights. The curves can predict, for a given material, the critical bank height for wedge/slab failure to occur. The denser the material, the smaller is critical height, but critical height increases with material cohesion (Fig. 2).

Applied to river systems, as channel depth/bank size increases downstream (Leopold & Maddock, 1953; Prestegaard, 1988), a zone in which bank height exceeds critical value, leading to mass failure, begins. Upstream, where banks are low, other processes supply sediment from banks, whereas downstream bank retreat is increasingly a problem of slope stability. By combining downstream distributions of bank height with bank material properties, reaches can be identified where height first exceeds critical value for bank failure. To calculate the area "required" for this to happen, H_c' is inserted in a bank height/downstream distance relation of power function form:

$$H = gA^h \tag{9}$$

in which A_t is minimum drainage area "required" before slab failure can occur. Substituting H_c' from equation (8) for H in equation (10) yields an expression for A_t directly in terms of material properties:

$$A_t = \{[(2c/\gamma)\tan(45 + \phi/2)]/g\}^{1/h} \tag{11}$$

As an example (Fig. 3), if $g = 0.15$, $h = 0.55$, $\phi = 16°$, $c = 12$ kPa and $\gamma = 16$ kN m^{-3}, use of equations (8) and (11) suggests that vertical banks are stable to 1.99 m ($H_c' = 1.99$) and a drainage area, A_t, of 110 km^2; this is the area at which mass failure becomes significant.

Recalculating equation (11) for ranges of cohesions and bulk weights provides predictive curves for basin area thresholds (Fig. 4). For bank material of high unit weight and/or low cohesion, the failure threshold is reached higher in the basin and bank failure is widespread. Because many failures are suspected to occur on hydrograph

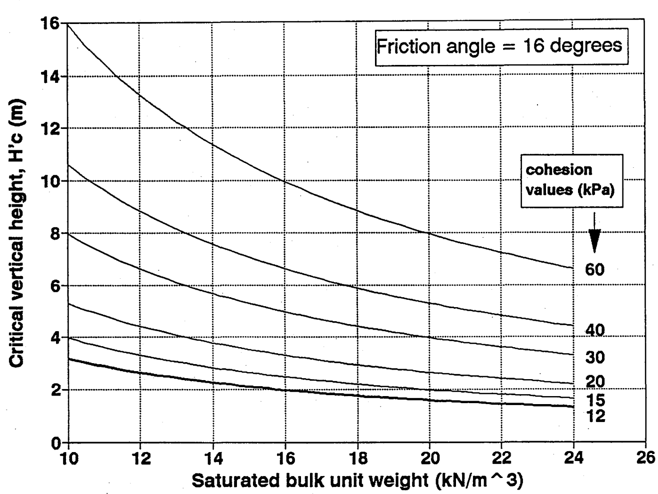

Fig. 2 Culmann-type bank stability curves, predicting critical stable height for vertical banks cut in material of friction angle 16°, for given cohesion values and saturated bulk unit weights.

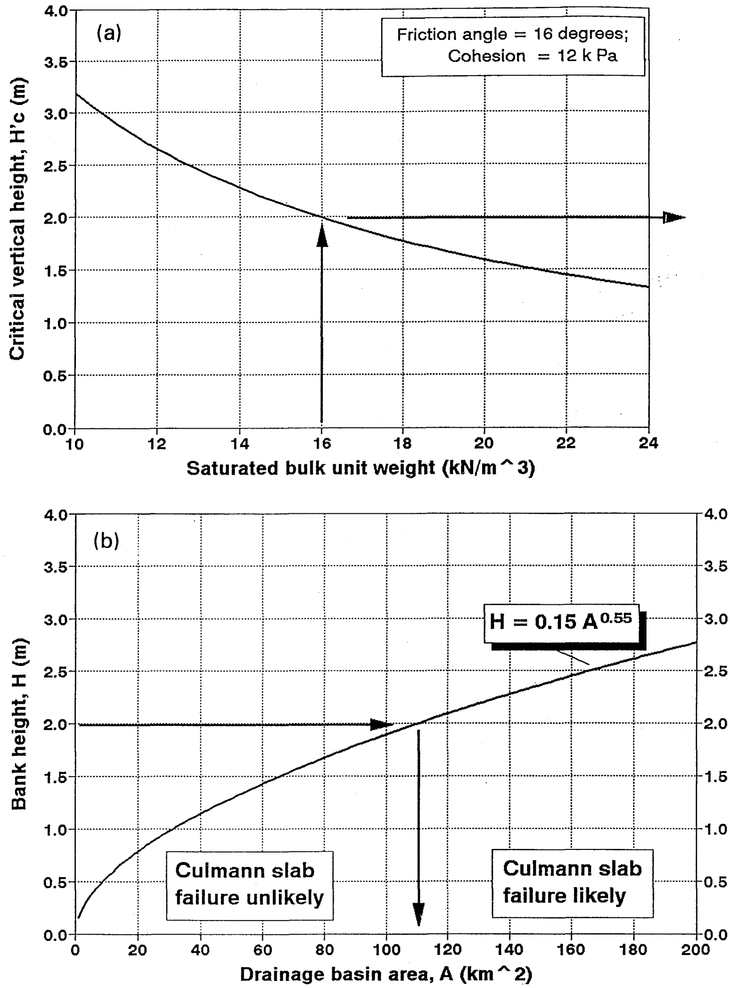

Fig. 3 Prediction of spatial zoning of slab failure processes in river basins derived from combining (a) critical bank height distribution for given material properties with (b) a relation for hypothetical downstream change in bank height. In this example, vertical banks cut in material of 16 kN m^{-3} saturated bulk unit weight are stable up to 1.99 m: this height is reached at a drainage area of 110 km^2.

recessions (Lawler & Leeks, 1992), identification of likely mass failure zones may have implications for the timing of sediment into streamflow, hence explanations of basin dynamics. Other variables relevant to the model also change downstream but the approach appears promising and may be extended to other stability analyses that incorporate non-linear slip surfaces and effective stresses.

DOMINANCE DOMAINS FOR BANK PROCESSES

Figure 5 combines spatial zonings of the three process groups; overlapping illustrates

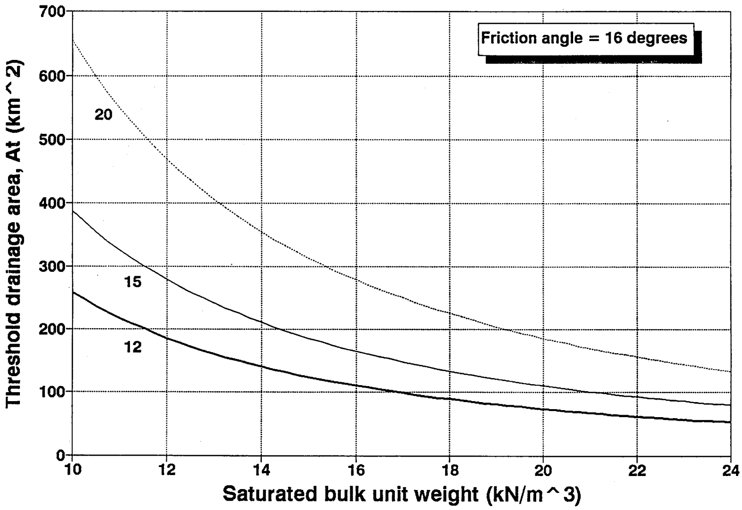

Fig. 4 Relation between saturated bulk unit weight of bank material and threshold drainage area for mass failure, for given friction angle (16°) and cohesion values (12, 15 and 20 kPa).

the importance of process combinations (Hooke, 1979; Thorne, 1982; Lawler, 1992). Summarizing, in upstream reaches of low stream power and low banks, sub-aerial preparation processes are most effective; in the middle courses, stream power peaks and fluid entrainment prevails; in low reaches, bank heights achieve critical values and mass failure dominates. The conceptual model is represented as a series of overlapping dominance domains (Kirkby, 1980).

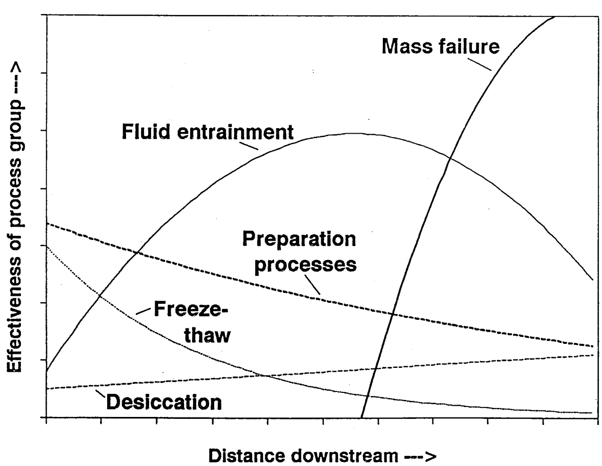

Fig. 5 Summary of the conceptual model of downstream change in bank erosion process groups. The overlapping dominance domains indicate the role of process combinations in affecting bank retreat and sediment delivery to streams.

Supportive evidence

Lawler (1992; 1993b) shows that all studies in which freeze-thaw is a strong bank erosion influence were conducted in basins of less than 85 km^2 (Table 1); this tendency holds for other preparation processes too (Twidale, 1964; Bello *et al.*, 1978). Studies demonstrating dominance of fluid entrainment processes have been conducted in "middle-order" basins (Table 2). Mass failure has been identified as dominant for bank retreat along large streams such as the Mississippi River (Turnbull *et al.*, 1966; Kesel & Baumann, 1981), the Brahmaputra River (Coleman, 1969) and the Yazoo River (Little *et al.*, 1982). Grissinger (1982) stressed that "gravity forces are relatively more significant than hydraulic forces" on the high steep banks of the northern Mississippi. Scott (1978) concluded that "there are definite differences in stream behavior related to size". He found that for Arctic rivers bank failure was nonexistent at the smallest sites; a few instances of collapse were found in moderately-sized basins (132-450 km^2), although most failures occurred in the largest basins (4680-4830 km^2).

Table 1 Bank erosion studies demonstrating the importance of freeze-thaw processes.

Reference	River	Area (km^2)
Hill (1973)	Clady & Crawfordsburn, N. Ireland, UK	3.4
Curr (1984)	Corston Brook, Avon, England, UK	4.1
Lawler (1986; 1987)	Ilston, Gower, S. Wales, UK	6.8-13.2
Stott *et al.* (1986)	Kirkton Glen, Balquhidder, Scotland, UK	<7.7
Wolman (1959)	Watts Branch, Maryland, USA	9.6
Blacknell (1981)	Afon Crewi, Mid-Wales, UK	35.5
Gardiner (1983)	Lagan, N. Ireland, UK	85

Table 2 Selected studies demonstrating the importance of flow variables on bank erosion rates.

Reference	River	Scale variable	Dominant control
Twidale (1964)	Torrens, S.Australia	$A = 78$ km^2	"late winter floods"
Knighton (1973)	Bollin-Dean, UK	$w = 3\text{-}13$ m; $d < 1.5$ m	discharge magnitude & variability
Hooke (1979)	Exe & Axe, UK	$A = 288\text{-}620$ km^2	corrasion
Pizzuto & Meckelnberg (1989)	Brandywine Creek, PA, USA	$w = 42.0$ m; $d = 2.6$ m	near-bank velocity
Lewin (1982; 1983; 1987)	Severn & Wye, UK	$w \approx 10\text{-}40+$ m	stream power

w = channel width; d = depth; A = drainage basin area.

CONCLUSIONS

The conceptual model, simple numerical experiments and literature evidence suggest that system scale has profound influence on which processes are dominant. In headwater reaches, where banks are too low to be susceptible to mass failure and stream power is limited by small discharges, weathering/preparation processes may be most effective. In middle reaches, fluid entrainment mechanisms prevail, in line with model results that demonstrate stream power peaks. In large basins, where banks are fine-grained, cohesive and resistant to shear, and where stream power is reduced by gentle channel slopes, fluid entrainment may be limited. High banks in these reaches may exceed critical heights and may be subject to mass failure processes. These predictions have implications for systematic downstream changes over varying time scales in the nature, timing, rate and patterns of channel side sediment delivery to rivers.

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