Bank erosion as a source of sediment and phosphorus delivery to small Danish streams

ANKER R. LAUBEL, BRIAN KRONVANG, SØREN E. LARSEN, MORTEN L. PEDERSEN & LARS M. SVENDSEN

Department of Streams and Riparian Areas, National Environmental Research Institute, Vejlsøvej 25, DK-8600 Silkeborg, Denmark

e-mail: arl@dmu.dk

Abstract Bank erosion was measured at 33 study sites situated along 15 small Danish lowland streams over an 11-month period. Soil erosion (rill erosion) was measured from adjacent agricultural fields. The geometric mean bank erosion rate over the 11-month period was 2.7 mm. The spatial variation in bank erosion was considerable. Bank erosion was higher at sandy sites than at loamy sites (3.4 *vs* 2.3 mm), and highest from the lower 50 cm of the banks. Optimal strategies for applying erosion pins for representing entire stream reaches or catchments are discussed. The mean soil volume delivered to the streams by bank erosion at agricultural sites was 0.023 m^3 per m stream reach (one streamside only, median 0.010). In comparison, the mean soil volume of soil delivered to the streams by rill erosion from overland flow was 0.0025 m^3 per m stream reach (one streamside only), corresponding to 1.9 g P per m stream reach.

INTRODUCTION

Bank erosion is a major source of sediment and sediment-associated substances such as phosphorus (P) in lowland streams (e.g. Foster *et al.*, 1988; Svendsen *et al.*, 1995). Other pathways such as soil erosion/surface runoff and subsurface drainage are also significant for sediment and P delivery to streams (Steegen *et al.*, 1998; Kronvang *et al.*, 1997). Eutrophication of many shallow surface waters is controlled by diffuse loss of P (European Environment Agency, 1994). Moreover, excess input of soil materials can have a harmful impact on freshwater ecology (e.g. on the success of trout spawning: Madsen, 1995), particularly in lowland streams with a normally low capacity to transport sediment. Channelized streams in poor physical shape often suffer from excessive sediment delivery (Vanoni, 1977). Of the Danish streams that fail to meet their quality objectives, 25% fail to do so because of poor physical conditions (Skriver *et al.*, 1997). When considering measures to improve water and habitat quality it is therefore important to quantify the different sources of sediment delivery to the streams—primarily bank erosion and rill erosion by overland flow.

The present study examined bank erosion rates and spatial variation in bank erosion as a basis for discussing methodological problems associated with the use of erosion pins and for comparing estimated bank erosion volumes with observed soil erosion volumes at a large number of study sites. The site-specific factors controlling bank erosion will be examined in a forthcoming paper.

STUDY SITES

The investigation was undertaken at 33 slope units representative of the landscape types, climate gradients, dominant soil types and buffer zone types found in Denmark. Twenty-six of the slope units are on agricultural land while the remaining seven slope units are on uncultivated areas, i.e. forest and fenced meadow. The dominant soils are alfisols and spodosols, with textural composition ranging from sand to sandy loam. The average slope of the 33 slope units studied is 5.6% (range 2.5–10%), which is somewhat greater than the typical slope of areas bordering small Danish streams. The length of the slope units ranges from 70 to 630 m. The 15 streams below the slope units are first- and second-order lowland streams (Strahler, 1957), most of which have been physically modified and channelized. Average bankfull width was 3.3 m (range 1.0–7.2 m). Average annual precipitation and temperature in Denmark during the study period, i.e. the hydrological year 1998/99, were 871 mm and 7.8°C, respectively, compared to 712 mm and 7.7°C, respectively, for the period 1961–1990.

METHODS

Erosion pins (60 cm long, 0.6 cm diameter) were inserted into the bank face of a 75-m-long stream reach below each of the 33 slope units in June 1998 (Fig. 1). Bank retreat was measured twice during the 11 month study period (November and May). At each site, erosion pins were arranged in three groups spaced 25 m apart to represent the bank face of the 75-m site. The number of pins in each group varied depending on the height of the bank. Each group of pins was arranged in three columns spaced 50 cm apart, with 25 cm between the pins in the vertical direction (Fig. 1). A total of 1500 erosion pins was used. To ensure a reference point when measuring bank retreat, a hard plastic square (4.5 × 4.5 cm, 0.3 cm thick) with a hole in the centre was slid along each erosion pin until it was flush with the stream bank. The squares were held in place by metal clips and realigned with the bank after each measurement. The measurements

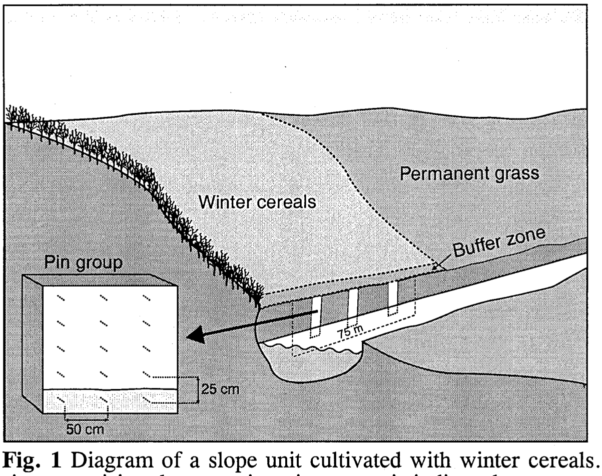

Fig. 1 Diagram of a slope unit cultivated with winter cereals. The 75-m-long study site comprising three erosion pin groups is indicated.

were made as "topside readings" before and after moving the square, i.e. readings along the upper side of the erosion pin from the free end to the plastic square.

Bank retreat over the two periods (June–November and November–May) was summed to represent the bank erosion rate for the entire 11-month study period (mm per 11 months). The geometric mean of all the 1500 bank erosion rate measurements made during the study period was used as a typical bank erosion rate for the investigated streams:

$$\text{geometric mean} = \exp\left[1/n\sum_{i=1}^{n}\log(xi+1)\right]-1 \tag{1}$$

where *xi* is the bank erosion rate of each erosion pin. Geometric mean bank erosion rate was also calculated for pin groups, for sites, and for sandy *vs* loamy sites. The volume of material eroded was calculated for each pin group, each erosion pin being assumed to represent half the distance to adjacent erosion pins.

Soil erosion by overland flow was measured as the volume of significant rill erosion within each of the 33 slope units in early March 1999 following the winter period. Inter-rill erosion was not measured. Delivery of soil by rill erosion to buffer zones and streams was surveyed and if present estimated by subtracting the deposited soil volume from the eroded soil volume at the slope unit in question. Soil erosion volumes and bank erosion volumes are reported in the units m^3 per metre stream reach (one streamside only). Total soil P content in topsoil samples from slope units and buffer zones was analysed using the analytical method described by Svendsen *et al.* (1993). Potential P loss from bank and soil erosion was compared based on an unmeasured bulk density estimate. Bulk density of bank and parent rill material were estimated to be 1.3 g cm^{-3}, based on national soil data (Sundberg *et al.*, 1999).

Coefficients of variation were calculated on non log-transformed bank erosion rates. A variance component model (Snedecor & Cochran, 1989) was applied on log-transformed bank erosion rates allowing total variance in bank erosion rate to be subdivided into three sources of variation, i.e. variance from within pin groups, between pin groups, and between sites. The estimated variance of the mean log-transformed erosion rates can be expressed in terms of the estimated components of variation $\hat{\sigma}_A^2$, $\hat{\sigma}_B^2$ and $\hat{\sigma}^2$ by:

$$\text{var}(\bar{y}) = \frac{\hat{\sigma}^2}{n} + \frac{\hat{\sigma}_B^2}{g} + \frac{\hat{\sigma}_A^2}{s} = V_1 + V_2 + V_3 \tag{2}$$

where $\bar{y}$ is the mean log-transformed erosion rate, *n* the total number of pins, *g* the total number of pin groups, and *s* the number of sites; V_1 is the variance within pin groups, V_2 the variance between pin groups, and V_3 the variance between sites.

RESULTS AND DISCUSSION

Spatial variation in bank erosion rates

The geometric mean bank erosion at all erosion pins was 2.7 mm over the 11-month period. Bank erosion rates were significantly lower for the seven sites adjacent to

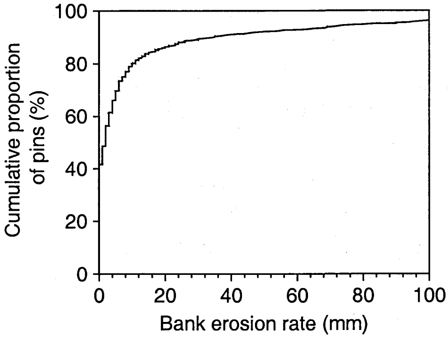

Fig. 2 Cumulative curve of bank erosion measured at 1500 erosion pins at 33 sites during the study period, June 1998–May 1999.

uncultivated areas (geometric mean 1.8 mm) than for those adjacent to agricultural fields (geometric mean 3.0) (Student *t*-test: $p = 0.01\%$). The variation in bank erosion among the 1500 erosion pins was considerable, however (Fig. 2). The coefficient of variation for all erosion pins was 340%. Bank erosion was ≤1 mm at 49% of the erosion pins and less than 90 mm at 95% of the erosion pins.

Bank erosion rates not only varied considerably between sites, but also within sites and even within pin groups. The median coefficient of variation was 206% for all erosion pins within a site and 156% for erosion pins within a pin group. These high coefficients of variation reflect a high degree of spatial variation in bank erosion and are to be expected for bank erosion, for which the coefficient of variation often exceeds 100% (Lawler, 1993).

The variance component analysis revealed that the variation between the 33 sites was greater than that within the sites (Table 1). Furthermore, the variation between pin groups was generally greater than that within pin groups. The three-fold greater variance component found between the 33 sites (75% contribution) than within the sites (19 + 6% contribution) indicates that site-specific factors have a marked influence on the observed bank erosion rates. Important site specific factors could be soil type, bank vegetation, bank angle, bank height, stream power, stream form, buffer zone width, and land use on the adjacent fields.

Table 1 Geometric mean bank erosion rate, variance of the mean, *VAR* (log-transformed data), and components of variation from different spatial levels of variation: within pin groups (V_1), between pin groups (V_2), and between sites (V_3). The relative contribution of each component of variation to the total variance is indicated in percentage.

	No. of sites	No. of pins	Geometric mean bank erosion rate (mm)	*VAR*	Component of variation from:		
					Within pin groups (V_1)	Between pin groups (V_2)	Between sites (V_3)
All sites	33	1496	2.7	0.0173	0.0011 (6%)	0.0033 (19%)	0.0129 (75%)
Sandy sites	17	680	3.4	0.0518	0.0025 (5%)	0.0112 (22%)	0.0381 (73%)
Loamy sites	16	816	2.3	0.0159	0.0019 (12%)	0.0023 (14%)	0.0117 (74%)
Sparrebæk catchment (loamy)	4	151	3.8	0.0613	0.0169 (27%)	0.0102 (17%)	0.0342 (56%)
Haustrup catchment (sandy)	8	397	3.1	0.0721	0.0044 (6%)	0.0150 (21%)	0.0527 (73%)

Sandy *vs* loamy sites

The geometric mean bank erosion rate for sites on sandy soil (3.4 mm) was significantly higher (Student *t*-test: $p = 0.02\%$) than that for loamy sites (2.3 mm). The inter-site variation in bank erosion rate was greater than the intra-site variation for both sandy and loamy sites (Table 1). The sandy sites differed from the loamy sites in that the variance of the mean was higher ($VAR_{sandy} = 0.0518$, $n = 680$ *vs* $VAR_{loamy} = 0.0159$, $n = 816$). Part but not all of this difference is attributable to very high bank erosion rates on one specific sandy site influenced by cattle grazing. At the loamy Sparrebæk catchment, bank erosion rates were higher and more variable than is normal for loamy sites, probably due to high erosion rates at the lower portion of the bank at two sites in the catchment.

Lower *vs* upper bank erosion

The variation in bank erosion rate within erosion pin groups was higher perpendicular to the bank (vertically) than parallel to the bank (horizontally). The mean variance in bank erosion perpendicular to the bank was 1.7-fold greater than that parallel to the bank (log-transformed data).

Erosion was significantly higher from the lower 50 cm section of the banks (geometric mean 6.9 mm) than from the section 50 cm and above (geometric mean 1.6 mm) (Student *t*-test: $p < 0.01$). This finding suggests that water erosion is a very important process in bank erosion since the water level is rarely higher than 50 cm in most of the streams studied. This may indicate that the banks are slowly being undercut, and that they can be subject to bank failure, a process described by several workers (e.g. Hey *et al.*, 1991). We believe that sudden bank collapse at our sites is unlikely to occur more frequently than once every five years, and hence is unlikely to be measured during a single study year. Bank erosion rates measured during a single study year clearly do not represent long-term average rates. Slow mass movement of soil is also likely to occur from banks of streams of this type under the influence of gravity, freeze–thaw action and solifluction processes. Although not systematically measured, at several sites we observed that erosion pins on banks changed position in a downward direction, probably due to slow soil mass movement.

As the variation in bank erosion was higher perpendicular to the banks than horizontal to them, a better measuring strategy for small streams of this type could be to reduce the number of pin columns in each group, to increase the distance between pin columns in a group, or simply to evenly distribute the columns along the bank face of the entire stream reach. The erosion pins should be spaced much more closely in the direction perpendicular to the bank than in the direction horizontal to the bank.

Optimal monitoring strategy when applying erosion pins

A variance component analysis was performed assuming that only two erosion pin columns spaced 1 m apart were present in each erosion pin group, i.e. only analysing two thirds of the data set. In this scenario, the component of variation between pin groups (19%) was generally greater than within pin groups (10%). In a second scenario it was assumed that each pin group contained only one pin column, i.e. the analysis only encompassed one third of the data set. The component of variation between pin groups (14%) was slightly smaller than within pin groups (19%). On sites in this type of small stream it therefore seems preferable to distribute the columns evenly—or randomly—along the bank in order to represent the entire reach in the most optimal manner, i.e. to give up the "pin group" concept and simply space the "pin columns" randomly or at fixed intervals along the bank. If the aim is to study bank erosion from the stream reach as such, erosion should be studied on both banks simultaneously. For bank erosion studies at the stream reach scale, Thorne (1981) recommends the use of pin columns with a fixed spacing along the stream between 1 and 5 m.

In order to be representative of erosion from entire catchments—even small ones such as the Sparrebæk and Haustrup catchments—a relatively high number of erosion pins is required. A total number of 400–500 erosion pins is required to determine the mean log-transformed erosion rate within a ±10% limit (based on a 95% confidence interval), and the corresponding mean non log-transformed erosion rate within a ±20% limit in the Sparrebæk and in the Haustrup catchment. This is based on the erosion pin strategy applied in this study. In our opinion, 250–500 erosion pins can be recommended for such small lowland streams when estimating bank erosion rates at the catchment level, for instance as part of a sediment budget investigation. For this purpose, the pins can preferably be placed in pin columns at fixed spacing either at a relatively high number of sites or along the entire stream system. Curr (1984), for example, used 30 sites in a 4.1 km^2 catchment. Stott *et al.* (1986) used more than 500 erosion pins placed in columns spaced 50 m apart in a small catchment (<7.7 km^2).

In on-going studies we are currently classifying our banks to determine whether bank erosion rate varies as a function of slope, vegetation cover, stream form, etc. In this context the strategy applied in the present study, i.e. three pin groups per site, has proven very suitable. If bank erosion rate proves to correlate to bank type, an alternative erosion pin strategy could be to place erosion pins strategically in different types of bank and to classify all the banks in a catchment so as to be able to scale up the erosion rates for each bank type.

The strategy applied in the present study, i.e. three erosion pin groups per site, also proved useful when performing the above-mentioned scenario analyses. Although it is not the optimal strategy for quantifying bank erosion rates and erosion volumes from entire stream reaches, the results obtained are useful for comparing with another important pathway for sediment and P delivery to streams, namely rill erosion by overland flow.

Comparing stream bank erosion and rill erosion volumes

The soil volume lost from the banks at all study sites ranged from 0.000 03 to 0.140 m^3 per m stream reach (mean 0.020, median 0.009). Less was lost from banks adjacent to uncultivated areas (mean 0.009 m^3 per m stream reach, median 0.006) than from banks adjacent to agricultural fields (mean 0.023 m^3 per m stream reach, median 0.010).

Soil erosion (rill erosion) was significant on four of the 26 agricultural slope units after the winter of 1998/99. Rill erosion was only a source of sediment delivery to the stream at a single slope unit. Mean rill erosion on the 26 slope units was 0.22 m^3 ha^{-1}, corresponding to 0.0042 m^3 per m stream reach; soil loss to the streams from rill erosion was 0.0025 m^3 per m stream reach (total stream length of the 26 sites). During the present study period, bank erosion alongside the slope units delivered *c.* 4–9 times more soil to the streams than rill erosion from the slope units. Inter-rill erosion was not measured; its contribution is variable. In most studies, however, soil loss from rill erosion (rilling) is more important than that from inter-rill erosion (cf. Govers & Poesen, 1988).

In the present study, soil was only delivered to the stream by rill erosion at a single slope unit, where the soil was sandy with a P content of 0.35 mg TP g DW^{-1} (0.35 mg total P per gramme dry weight). Twenty-one cubic metres of soil were transported by rill erosion, two thirds of which entered the stream. Thus up to 11 kg TP (1.9 g TP per m stream reach over the total stream length of the 26 sites) may have entered the stream. In comparison, the mean TP content of the buffer zone topsoil potentially eroded by bank erosion at the sites was 0.71 mg TP g DW^{-1}. If the TP content of the bank soil was equally high, delivery to the stream by bank erosion (median 0.010, mean 0.023 m^3 per m stream reach) would correspond to 9–21 g TP per m stream reach. Even if the P content of the bank soil was actually considerably lower, bank erosion would still have been more important for P loss to the stream in the study year than soil erosion.

This relative importance of bank erosion compared to other delivery sources is in concert with the finding of other lowland catchment studies (Foster *et al.*, 1988; Svendsen *et al.*, 1995; Laubel *et al.*, 1999). However, soil erosion by overland flow is subject to very high temporal variation, possibly much more than is the case of bank erosion. Soil erosion in the study year 1998/99 was neither particularly low nor particularly high as compared with the six-year period from 1993/94 to 1997/98 (Kronvang *et al.*, 2000). Simultaneous measurements of both soil and bank erosion over a longer time period are needed in order to confirm whether bank erosion is the dominant pathway for soil and P delivery to streams in the Danish landscape.

Acknowledgements This study was supported by the Danish Ministry of Food, Agriculture and Fisheries under the research programme "Land use—the farmer as land manager". We also thank our technical staff for assistance.

REFERENCES

Curr, R. H. (1984) The sediment dynamics of Corston Brook. Unpublished PhD Thesis, University of Exeter, UK.

European Environment Agency (1994) *European Rivers and Lakes. Assessment of their Environmental State.* EEA Environmental Monographs 1, European Environment Agency, Copenhagen, Denmark.

Foster, I. D. L., Dearing, J. A. & Grew, R. (1988) Lake-catchments: an evaluation of their contribution to studies of sediment yield and delivery processes. In: *Sediment Budgets* (ed. by M. P. Bordas & D. E. Walling) (Proc. Porto Alegre Symp., December 1988), 413–424. IAHS Publ. no. 174.

Govers, G. & Poesen, J. (1988) Assessment of the interrill and rill contributions to total soil loss from an upland field plot. *Geomorphology* **1**, 343–354.

Hey, R. D., Heritage, G. L., Tovey, N. K., Boar, R. R. Grant, N. & Turner, R. K. (1991) *Streambank Protection in England and Wales.* R&D Note 22, National Rivers Authority, London.

Kronvang, B., Grant, R. & Laubel, A. (1997) Sediment and phosphorus export from a lowland catchment: quantification of sources. *Wat., Air and Soil Pollut.* **99**, 465–476.

Kronvang, B., Laubel, A., Larsen, S. E. & Iversen, H. L. (2000) Soil erosion and sediment delivery through buffer zones in Danish slope units. In: *The Role of Erosion and Sediment Transport in Nutrient and Contaminant Transfer* (ed. by M. Stone) Proc. Waterloo Symp., July 2000). IAHS Publ. 263 (this volume).

Laubel, A., Svendsen, L. M., Kronvang, B. & Larsen, S. E. (1999) Bank erosion in a Danish lowland stream system. *Hydrobiologia* **410**, 279–285.

Lawler, D. M. (1993) The measurement of river bank erosion and lateral channel change: a review. *Earth Surf. Processes and Landforms* **18**, 777–821.

Madsen, B. L. (1995) *Danish Watercourses—Ten Years with the New Watercourse Act.* Danish Environmental Protection Agency, Copenhagen, Denmark.

Skriver, J., Baattrup-Pedersen, A. & Larsen, S. E. (1997) State of the streams (in Danish). In: *Ferske Vandområder—Vandløb og Kilder*, 29–45. Report no. 214, National Environmental Research Institute, Denmark.

Snedecor, G. W. & Cochran, W. G. (1989) *Statistical Methods*, eighth edition. Iowa State University Press.

Steegen, A., Govers, G., Beuselinck, L. & Merckx, R. (1998) Sediment and phosphorus delivery from agricultural catchments in central Belgium. In: *Practical and Innovative Measures for the Control of Agricultural Phosphorus Losses to Water* (ed. by R. H. Foy & R. Dils) (Proc. Belfast Workshop, June 1998), 170–171. Dept of Agriculture for Northern Ireland.

Stott, T. A., Ferguson, R. I., Johnson, R. C. & Newson, M. D. (1986) Sediment budgets in forested and unforested basins in upland Scotland. In: *Drainage Basin Sediment Delivery* (ed. by R. F. Hadley) (Proc. Abuquerque Symp., August 1986), 57–68. IAHS Publ. no. 159.

Strahler, A. N. (1957) Quantitative analysis of watershed geomorphology. *Trans Am. Geophys. U.* **38**, 913–920.

Sundberg, P. S., Callesen, I., Greve, M. H. & Raulund-Rasmussen, K. (1999) *Danish Soil Profiles* (in Danish). Danish Institute of Agricultural Sciences.

Svendsen, L. M., Rebsdorf, Aa. & Nørnberg, P. (1993) Comparison of methods for analysis of organic and inorganic phosphorus in river sediment. *Wat. Res.* **27**, 77–83.

Svendsen, L. M., Kronvang, B., Kristensen, P. & Græsbøll, P. (1995) Dynamics of phosphorus compounds in a lowland river system: importance of retention and non-point sources. *Hydrol. Processes* **9**, 119–142.

Thorne, C. R. (1981) Field measurements of rates of bank erosion and bank material strength. In: *Erosion and Sediment Transport Measurement* (Proc. Florence Symp., June 1981), 503–512. IAHS Publ. no. 133.

Vanoni, V. A. (1977) *Sedimentation Engineering.* ASCE Manuals and Reports on Engineering Practice, 54, Am. Soc. Civ. Engrs, New York.