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Stream bank erosion: a review of processes of bank failure, measurement and assessment techniques, and modelling approaches

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Stream bank erosion: a review of processes of bank failure, measurement and assessment techniques, and modelling approaches

Motueka Integrated Catchment Management
(Motueka ICM) Programme Report Series

by

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Cover Photo: Severe bank erosion in the Kahuhuru River near Raglan.

PREFACE

An ongoing report series, covering components of the Motueka Integrated Catchment Management (ICM) Programme, has been initiated in order to present preliminary research findings directly to key stakeholders. The intention is that the data, with brief interpretation, can be used by managers, environmental groups and users of resources to address specific questions that may require urgent attention or may fall outside the scope of ICM research objectives.

We anticipate that providing access to environmental data will foster a collaborative problem-solving approach through the sharing of both ICM and privately collected information. Where appropriate, the information will also be presented to stakeholders through follow-up meetings designed to encourage feedback, discussion and coordination of research objectives.

We acknowledge the funding received from NIWA as part of the Raglan Fine Sediment Study for preparation of this report.

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Summary

Stream bank erosion is a natural geomorphic process which occurs in all channels as adjustments of channel size and shape are made to convey the discharge and sediment supplied from the stream catchment. However, increases in sediment supply due to accelerated stream bank erosion are often linked to land-use change and are a major contributor to sediment yield in rivers. In New Zealand there is little data on the contribution of bank erosion to measured river sediment yields and it has been a poorly studied process.

Bank erosion includes two main groups of processes:

- hydraulic processes at or below the water surface entrain sediment and directly contribute to erosion, particularly of non-cohesive banks, by processes of bank undercutting, bed degradation, and basal cleanout.
- gravitational mass failure processes (including shallow and rotational slides, slab and cantilever failures, earthflows and dry granular flows) detach sediment primarily from cohesive banks and make it available for fluvial transport.

The two process groups are frequently linked, with hydraulic processes often a precursor to gravitational failures. Two major factors contribute to bank erosion: bank characteristics (erodibility potential) and hydraulic/gravitational forces. Processes of surface erosion, liquefaction, development of positive pore water pressure, freeze/thaw, soil piping, and soil cracking can also contribute to bank erosion.

A wide range of techniques can be used to characterise bank erosion with some suited to high precision, short time-scale estimates while others are suited to low precision, long time-scale estimates. The main techniques that have been used to measure bank erosion are: erosion pins (metal or electronic), bank profilers, photogrammetry, topographic survey (planimetric or cross section), historic sources (maps and photos), sedimentological and botanical evidence.

Bank erosion assessment provides an alternative to detailed measurements, which can only be carried out in a small number of places. Bank erosion assessment can be used to select representative measurement sites, provide a basis for extrapolation of site-specific measurements, and provide a rapid overview of bank erosion problems. It is more commonly used to guide mitigation measures than quantitative measurements. It provides a rapid field survey of key attributes relevant to bank erosion including: location (GPS; toe, slope or bank top; left or right bank), extent (length of feature, height of bank), type of sediment (cohesive or non-cohesive, particle size, stratification), type of failure and contributing processes (e.g., freeze/thaw, water drawdown), toe sediment accumulation, general evidence (e.g., exposed roots, undercut banks), severity of erosion/bank stability, geometry of the bank (height, slope, profile shape), evidence of cracking, vegetation, channel geomorphic unit, and protection status.

Bank erosion modeling approaches range from empirical to process-based. Many catchment erosion models have sophisticated routines for predicting in-stream sediment transport, sediment routing and bed degradation, but often neglect the contribution of bank erosion to sediment load. Most models with some process basis deal only with specific forms of gravitational failure (using some form of factor-of-safety analysis to predict bank failure) or hydraulic erosion (calculating sediment transport capacity from hydraulic shear stress/bank material strength analysis). However, given the complexity of processes that can contribute to bank erosion a comprehensive process-based model of bank erosion would be difficult to implement.

1 Introduction

Stream bank erosion is a natural geomorphic process which occurs in all channels. It is one of the mechanisms by which a channel adjusts its size and shape to convey the discharge and sediment supplied to it from the surrounding land. As a natural process, bank erosion is generally beneficial to the ecology of waterways, since erosion and deposition create a variety of habitats for flora and fauna which contributes to ecological diversity (Environment Agency 1999). Conversely, an increase in sediment supply due to accelerated stream bank erosion, which can often be linked to land-use change, is a major cause of non-point source pollution within river systems.

Bank erosion occurs by a wide variety of processes and is driven by two major factors: bank characteristics (erodibility potential) and hydraulic/gravitational forces. Two main groups of processes contribute to bank erosion:

- hydraulic processes at or below the water surface entrain sediment and directly contribute to erosion, primarily of non-cohesive banks,
- mass failure processes, including planar and rotational failures, detach sediment from cohesive banks making it available for fluvial transport.

In addition, surface erosion, liquefaction, development of positive pore water pressure, soil piping, and soil cracking can contribute to bank erosion. Hydraulic and gravitational forces occur within the bank material as well as within the water column of the stream. The velocity, velocity gradients, boundary shear stress, strong down-welling and up-welling currents in the near-bank region, back-eddy circulation and other flow mechanisms affect the overall rate of stream bank erosion (Rosgen 1996). Understanding the processes contributing to bank erosion is important in determining appropriate techniques for bank erosion measurement and for identifying mitigation techniques.

In many countries, including New Zealand, quantitative measurements of bank erosion have lagged behind measurements of most other processes and there is little information on the contribution of bank erosion to measured river sediment yields. However, it is likely bank erosion is a major contributing process as it delivers sediment directly into rivers and streams. This contrasts with many mass movement and surface erosion processes which are poorly connected to rivers.

Quantitative measurement and prediction of stream bank erosion can provide a tool to apportion the contribution of stream bank sediment sources to the total sediment load from a catchment. Reid and Dunne (1996) note that bank erosion is one of the most difficult sediment production processes to evaluate in sediment budgets and provide few techniques to quantify bank erosion.

This report updates Lawler's (1993) review of techniques for measuring bank erosion. It identifies techniques suitable for identifying the processes contributing to bank erosion and measuring the supply of sediment from bank erosion that could be used in the Raglan Fine Sediment study and the Motueka Integrated Catchment Management programme. The report briefly reviews:

- processes of bank erosion,
- major factors influencing bank erosion,
- techniques for both semi-quantitative assessment and quantitative measurement of bank erosion,
- approaches to modelling bank erosion.

2 Processes of Stream Bank Erosion

Bank erosion process can be classified into two basic groups, those dominated by gravitational or mechanical failures (mass movement) and those where hydraulic-induced failure mechanisms (fluvial erosion) dominate. Gravitational failures include both mass movement failures and individual grain failures. The two process groups are often linked (e.g., a hydraulic-induced mechanism, such as bank undercutting, can cause a gravitationally-induced collapse such as a cantilever failure). Identification of bank erosion processes is important for determining suitable measurement techniques and for choosing appropriate remedial options.

The conditions under which different processes occur are determined by bank material characteristics and local soil moisture conditions (O'Neill and Kuhns 1994). Table 1 summarises twelve main bank erosion mechanisms and lists typical sediment and moisture conditions associated with each of these processes. Fig. 1 provides a key for recognition of many of the different types of gravitational bank failures.

Mechanisms	Classification	Typical flow conditions	Sediment characteristics	Bank moisture	Description
Shallow slides	Gravitational	Low	Fine grained, low cohesion	Saturated	Layer of bank material displaced along a plane parallel to bank surface
Rotational slip	Gravitational	Low	Fine grained, cohesive	Saturated	Deep seated movement along curved slip surface
Slab failure	Gravitational	Low	Fine-grained cohesive	Varies	Block of bank falls forward into channel
Cantilever failure	Gravitational	Low	Composite fine/coarse	Varies	Collapse of overhanging block of sediment
Wet earth flow	Gravitational	Low	Fine-grained cohesive	Saturated	Saturated flow, often on low angled banks
Popout failure	Hydraulic/ gravitational	Low	Fine-grained cohesive	Saturated	Small blocks forced out of bank due to excessive pore pressure and overburden
Dry granular flow	Gravitational	Low	Non-cohesive	Dry	Movement of individual grains in banks close to angle of repose
Soil/rock fall	Gravitational	Low	Weakly cohesive	Dry	Individual grains or blocks fall into channel from very steep banks
Piping failure	Hydraulic/ gravitational	Low	Interbedded fine/coarse	Saturated	Loss of strength due to preferential flow in areas of high porewater pressure
Bank undercutting	Hydraulic	High	Generally non-cohesive	N/A	Removal of cohesive material from toe of bank, causing bank to overhang.
Bed degradation	Hydraulic	High	Relatively erodible bed	N/A	Removal of material from bed of stream.
Basal cleanout	Hydraulic	Varies	All types	N/A	Removal of (often) non-cohesive material at base of bank.

Table 1 Bank erosion mechanisms (after O'Neill and Kuhns 1994, Thorne 1998, Environment Agency 1999)

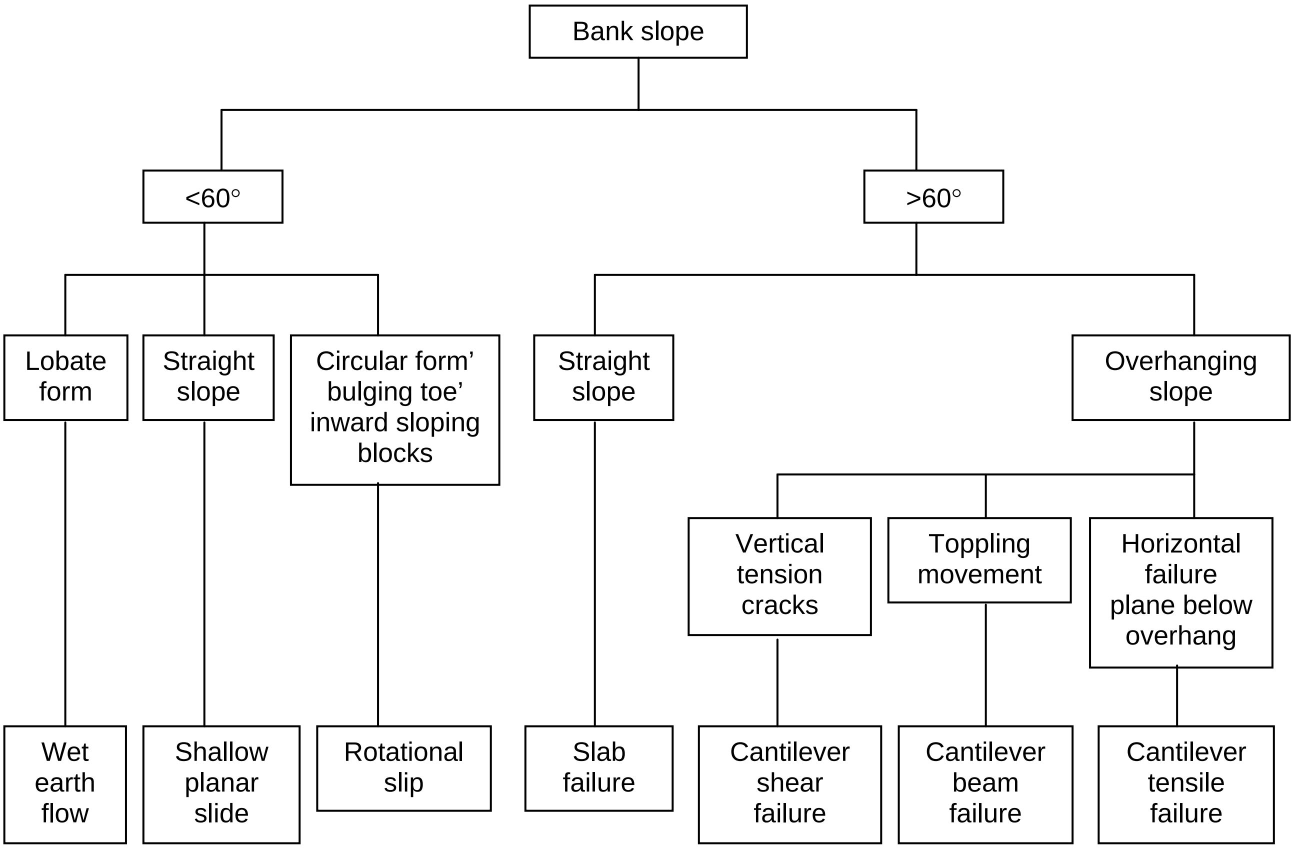


Fig. 1 Key to recognition of different types of mass movement bank failure (after Environment Agency 1999)

2.1 Gravitational failure mechanisms

2.1.1 Shallow slides

These are shallow failures where a layer of material moves along a plane parallel to the bank surface (Fig. 2). They are typical of soils with low cohesion, and occur when the angle of the bank exceeds the angle of internal friction of the bank material. Typically they occur where banks are moderately steep. Shallow slides often occur as secondary failures following rotational and/or slab failures (Thorne 1998). These failures contribute large amounts of loose sediment to the base of the bank where it can be easily removed by medium flow events (Environment Agency 1999).

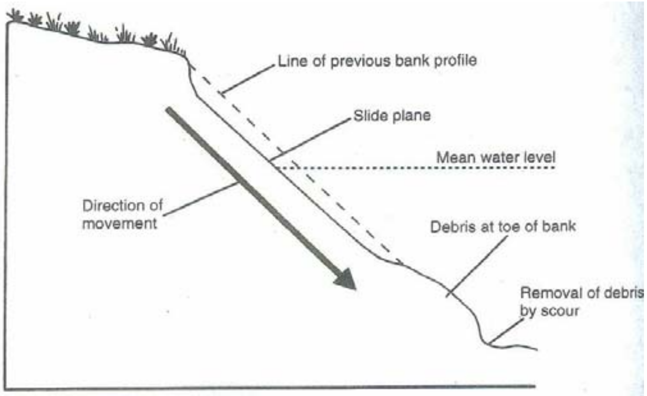


Fig. 2 Shallow slide (from Environment Agency 1999)

2.1.2 Rotational failures

Rotational failures are deep-seated movements of material both downward and outward along a curved slip surface (Fig. 3), and are common on cohesive banks with slopes less than 60°. After failure the upper slope of the slipped block is typically tilted inward toward the bank. They can often be linked to the formation of vertical tension cracks within the bank structure. Rotational failures tend to be of greater volume than slab failures (Dapporto *et al.* 2003) and are commonly a result of scour at the base of the bank and/or high pore water pressure within the bank material. Often they will occur during rapid drawdown following high flow events.

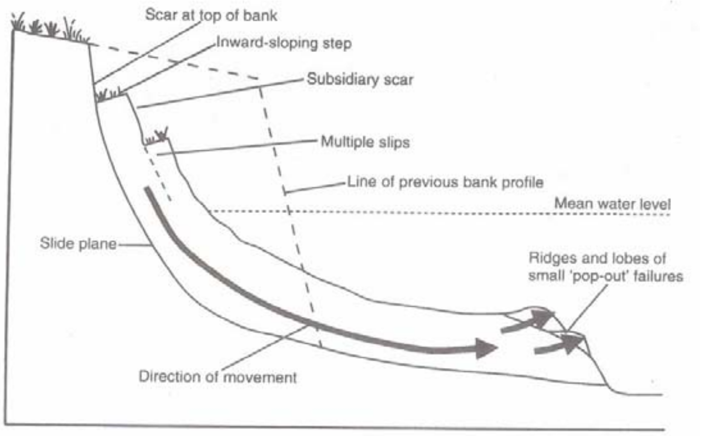


Fig. 3 Rotational slip (from Environment Agency 1999)

2.1.3 Slab failure

Slab failures are the sliding and forward toppling of a deep-seated mass into the channel (Fig. 4.). They are associated with steep, low height, fine-grained cohesive banks and tend to occur during lower flow conditions. They result from the combination of scour at the bank toe, high pore water pressure in the bank material and the development of tension cracks at the top of the bank. Under these conditions the stability of the bank depends on the tensile strength of the bank material (Environment Agency 1999). An accumulation of failed blocks can offer temporary protection to the lower section of the bank.

Potential slab failures are characterised by cracks that form at some distance back from the river bank. Desiccation and tension can develop rapidly and cracks often develop due to stress release. Tension cracks reduce the effective length of the potential failure surface and hence decrease bank stability. In low river banks (less than 3 m) tension cracks may occupy a significant portion of the bank height. Crack development can allow surface and subsurface flows to drain into the bank, increasing seepage forces and subsequently reducing stability, causing blocks of effected bank material to slide downward and outward into the channel as a mass failure (Simons and Li 1982).

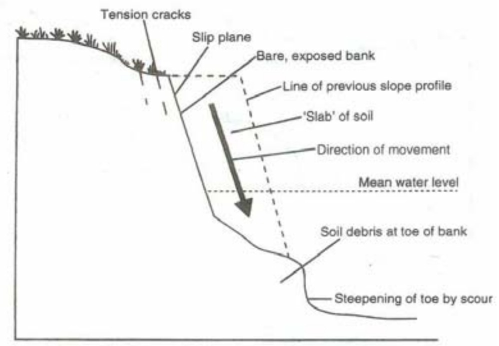


Fig. 4 Slab failure (from Environment Agency 1999)

2.1.4 Cantilever failure

Cantilever failures are the collapse of an overhanging block into the channel (Fig. 5), often occurring after the bank has been undercut. They tend to occur in a composite of fine/coarse grained materials, and to be active during low flow conditions. There are three principle modes of cantilever failure (shown in Fig. 6.).

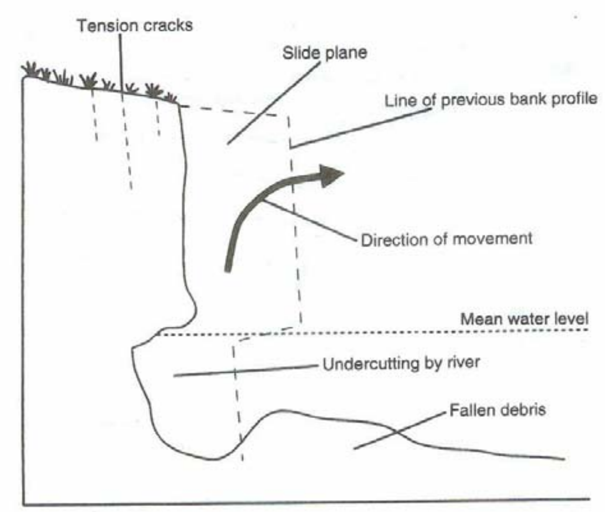


Fig. 5 Cantilever failure (from Environment Agency 1999)

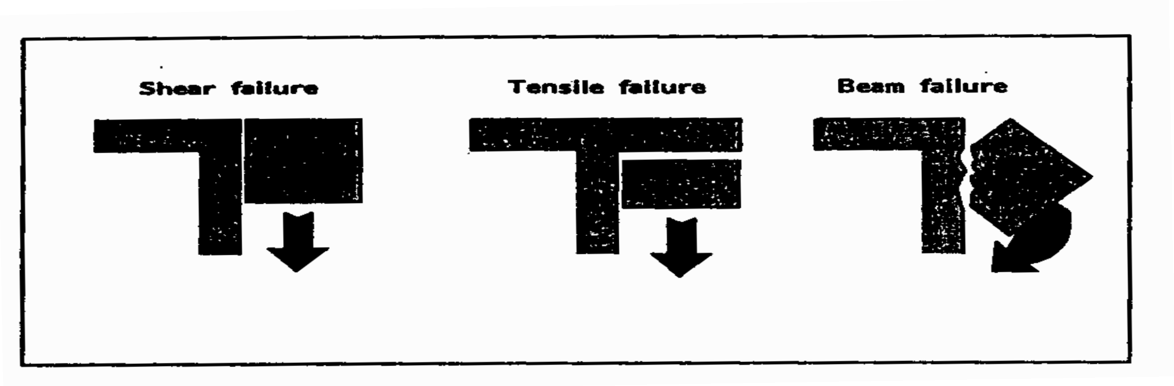


Fig. 6 Mechanisms of cantilever failure (Ashbridge 1995)

Shear failures occur by downward displacement of an overhanging block initiated by tension cracks that form at some distance back from the river bank. Failure comes about because the shear stress due to the weight of the block overcomes the shear strength of the soil (Thorne and Tovey 1981).

In tension failures the lower part of the block is already detached from the bank because of the development of a vertical crack upwards from the base of the overhang. Failure occurs when the tensile stress due to the weight of the lower part of the block overcomes the tensile strength of the soil. Tension failures often leave root bound remnant blocks as overhangs which eventually fail by the beam mechanism (Thorne and Tovey 1981).

In a beam failure, the block rotates forward about a horizontal axis somewhere in the block. Above the axis, failure is in tension and below it, in compression. Failure occurs because the moment of the weight of the block about the neutral axis overcomes the resistive moments of the soil’s tension and compressive strengths (Thorne and Tovey 1981). Generally beam failures are the most common mechanism of cantilever collapse.

A cantilever overhang can be enhanced where the roots of the bank vegetation help bind the soil to the top of the bank to give it additional cohesion. The collapsed blocks produced by these failures may break-up on impact and be removed or may, particularly if root bound, remain intact to be removed by future hydraulic action (basal cleanout, see later), but in the meantime protect the lower bank from further erosion (Knighton 1998; Ashbridge 1995).

2.1.5 Wet earthflow

This type of failure occurs where the loss of strength of a section of bank due to saturation increases bank weight and decreases bank material strength to a point where the soil flows as a highly viscous liquid. Failures typically occur on low angle banks and the affected material flows down the bank to form lobes of material at the toe (Fig. 7). Such material is extremely weak and is easily removed by scour, even at lower flows (Thorne 1998). Earthflows occur in banks subject to strong seepage and poor drainage. Typically they are caused by waterlogging due to high rainfall, snowmelt, or rapid drawdown of water in the channel.

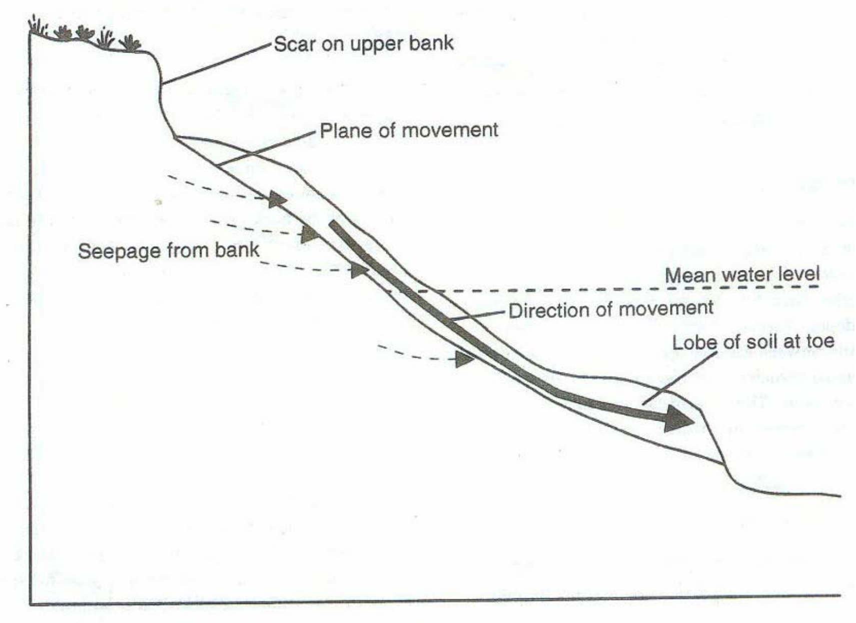


Fig. 7 Earth flow (from Environment Agency 1999)

2.1.6 Popout failure

Popout failure is a term used to describe failures where small to medium sized blocks are forced out at or near the base of the river bank due to excessive pore-water pressure and overburden. A slab of material in the lower half of the bank will fall out, leaving an alcove-shaped cavity (Fig. 8). This mode of failure is usually associated with steep banks and saturated finer-grained cohesive bank materials that allow the build up of positive pore-water pressure and/or strong seepage within its structure. The overhanging roof of the alcove may subsequently collapse as a cantilever failure. Evidence of popout failures includes: cohesive materials, steep bank face with seepage areas low in the bank, and alcove-shaped cavities in the bank face (Thorne 1998).

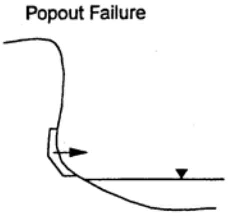


Fig. 8 Popout failure (from O’Neill and Kuhns 1994)

2.1.7 Dry granular flow

This type of failure typically occurs on non-cohesive banks at, or close to, the angle of repose, which are undercut, thereby increasing the local bank angle above the friction angle. Individual grains roll, slide and bounce down the bank in a layer, a few grains thick. Usually there is a toe accumulation of loose grains in cones and fans.

2.1.8 Soil/rockfall

This only occurs on weakly-cohesive steep eroding banks where individual grains or blocks of soil fall directly into the channel (Thorne 1998). They often occur when a stream undercuts the toe of a sand, gravel, or deeply weathered rock bank.

2.1.9 Piping failure

This is the collapse of part of the bank due to high groundwater seepage pressures and rates of flow causing selective removal of sections of the bank. It is usually due to preferential ground water flow along interbedded saturated layers contained within stratified river banks, with lenses of sand and coarser material sandwiched between layers of finer cohesive material. Flow is induced in the more permeable layers by changes in river stage and/or ground water seepage. If the flow magnitude through the permeable lenses is capable of dislodging and transporting particles, material is slowly removed. This can lead to undermining of portions of the cohesive upper bank leading to slab or cantilever-type failures (Thorne 1998).

2.2 Hydraulically-induced failure mechanisms (fluvial erosion)

Direct fluvial erosion results from the change in balance between hydraulic shear stress and bank material strength. Where the shear stress exceeds bank material strength sediment transport will be initiated. This occurs because shear stress increases as flow increases, while bank material strength typically reduces (e.g., when the bank becomes saturated). There are three main types of hydraulically induced failures (Fig. 9). Fluvial erosion is often a precursor to gravitational failures, and is also responsible for transport of the debris produced by gravitational failures.

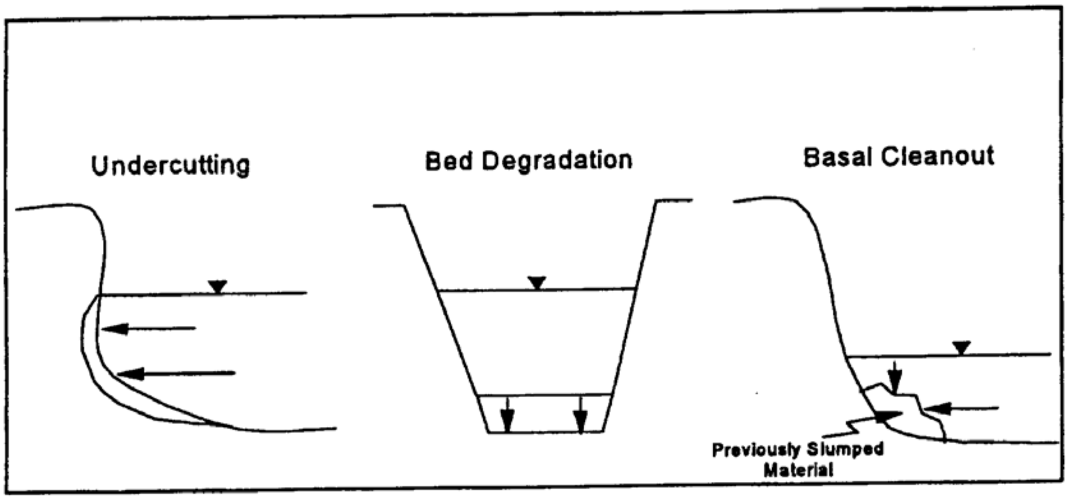


Fig. 9 Hydraulic failure mechanisms (from O’Neill and Kuhns 1994)

2.2.1 Undercutting

Undercutting, or scouring, is the direct removal of bank material at or below water level by the physical action of flowing water and the sediment it carries. As flow increases the erosive power of flowing water also increases until the fluid-derived shear stresses exceed the cohesive strength of the bank material. Undercutting can be the result of the redirection and acceleration of flow around obstructions such as debris and vegetation within the channel, or bank soil characteristics such as poor drainage and/or seams of readily erodible non-cohesive material within the bank profile. It is also common on the outside of meander bends where flow velocity and shear stress is typically higher. In cohesive bank material, undercutting is the forerunner of mass movement failures and in non-cohesive bank material to dry granular flow.

2.2.2 Bed Degradation

Bed degradation occurs when the erosive power of flowing water increases to a point where the applied fluid-generated shear stresses overcome the relatively erodible (compared to the bank material) channel bed. This process effectively increases the bank height and steepness making the bank more susceptible to undercutting and mass failure.

2.2.3 Basal cleanout

River banks can be made unstable by the removal during high flows of supportive or protective material at their base. The removal of collapsed bank material will leave lower-bank material prone to a continuing cycle of undercutting, collapse and removal, and the subsequent processes of river bank retreat.

The cyclic process of basal erosion, upper bank failure, lower bank accumulation, and removal of failed blocks, plays an important part in controlling the form, stability and retreat rates of all types of stream banks.

3 Factors Affecting Stream Bank Erosion

The stability of a bank primarily depends on channel and flow characteristics, and the strength of the bank materials (Table 2). Instability can be inherent in some channel systems as a result of the nature of the river system (e.g., high-energy braided rivers) and historic or geomorphic factors (e.g., tectonic uplift). While the size and shape of a river channel reflects the development of a “stable” condition in which the channel can transmit the water and sediment supplied to it, in reality most channels continuously adjust their form as flow conditions, bank stability and sediment supply fluctuate through time. Rivers also tend to evolve over long time periods to both natural (e.g., changes in runoff due to climatic variability, increased sediment supply from earthquakes or storms) or induced change (e.g., forest clearance, channel narrowing for flood control). Understanding the evolutionary tendencies of rivers is essential for interpreting channel and bank stability (Rosgen 1996).

3.1 Storm frequency

The amount of precipitation in a storm, a measure of flood duration, is not necessarily an important factor when considering bank erosion (Simons and Li 1982). Although bank erosion caused by hydraulic action (fluvial erosion) is closely related to the magnitude and duration of a

Factor	Relative Characteristics
Storm frequency	Rainfall intensity and duration
Flow properties	Magnitude-frequency, duration and variability of stream discharge Magnitude and distribution of stream velocity and shear stress Degree of turbulence Sediment load
Bank material composition	Size, gradation, cohesively and stratification of bank material
Bank geometry	Height, slope, length, profile shape
Bank moisture conditions	Soil moisture levels, seepage, pore water pressures, piping
Channel geometry	Width, depth, slope of channel, stream curvature (concave, convex, straight)
Vegetation	Type, % cover, age, rooting depth, exposed roots, stability
Man-induced factors	Stock and vehicle usage, artificial drainage input

Table 2 Factors influencing bank erosion **(**Knighton 1998)

flood event, other types of bank retreat, notably mechanical failures under gravity, are more closely related to pre-storm soil conditions produced by antecedent rainfall. Smaller floods attacking thoroughly wetted bank material during the winter months can produce more extensive and severe erosion than large summer storms that occur when bank material is hard and dry and not easily eroded. Multi-peaked flows, which are more characteristic of winter months, may be more effective than single flows of comparable or greater magnitude because of increased incidence of bank wetting. The degree of preparation of the bank material can give a seasonal effect to the erosion process (Knighton 1998).

3.2 Flow properties

Erosion of stream banks and bed occurs when the shear stress exerted by the water on the channel perimeter exceeds the strength of the material. The removal of bank material by hydraulic action is closely related to near-bank stream velocity conditions and in particular to the velocity gradient close to the bank, which determines the magnitude of hydraulic shear. High flows not only remove material directly from the bank but also scour the base, leading to bank over steepening and gravitational failures. High shear stress within flood-generated eddies can scour both bank and bed, enlarging existing embayments and increasing the amplitude of bank projections which are likely to become more susceptible to hydraulic erosional processes (Knighton 1998).

3.3 Bank material composition

Alluvial bank material can be broadly classified as non-cohesive, cohesive and stratified. **Non-cohesive bank materials** are relatively coarse grained and are usually well drained. As a result pore water pressure is seldom a significant problem (Thorne and Tovey 1981). Erosion tends to occur grain-by-grain. The rate of particle removal is affected by such factors as seepage, piping, and the magnitude, direction and fluctuation of the stream velocity adjacent to the bank (i.e. variations in shear stress). Often these factors will act concurrently.

Cohesive bank materials are less susceptible to erosion grain-by-grain, but can be eroded rapidly by mass movement. Failures result from the down slope gravitational component of the weight of bank material plus any positive pore water pressures. Since cohesive materials are more likely to be poorly drained, positive pore water pressure can develop particularly during rapid drawdown in the channel (Thorne and Tovey 1981).

The stability of cohesive banks is also affected by the presence of tension cracks. These are near-vertical cracks which develop from the ground surface downwards at some distance back from the bank. They result from the tensile stress exerted on the upper part of the bank close to a steep slope. Tension cracks adjacent to river banks can extend to a considerable portion of bank height, thereby weakening the overall stability of the slope. Weakening is further enhanced because cracks form pathways for water to move downward from the surface to lubricate a potential slide plane (Environment Agency 1999).

Stratified banks are generally the product of the history of local sediment deposition by the river and consist of layers of materials of differing size, permeability and cohesion resulting in a mixture of cohesive and non-cohesive materials (Simons and Li 1982; Federal Interagency Stream Restoration Working Group 2001). The non-cohesive layers are eroded more quickly, producing a stepped bank with benches formed in the more resistant material. In general, the combination and type of erosion features will more or less be dependant upon the sequence, or order, of layering within the exposed bank, and the properties of the individual layers and how these respond to changing hydraulic forces. Piping is also common in stratified alluvial banks.

3.4 Bank Geometry

Bank height and slope are critical factors when assessing stream bank erosion potential, particularly when dealing with cohesive bank material (Rosgen 1996, Dapporto *et al*. 2003). Failures occur when the erosion of the bank and the channel bed adjacent to the bank, have increased the bank’s height and steepness to a point where it reaches a condition of limiting stability. The mechanics of failure are then dependant on the properties of the bank material and the geometry of the bank at the point of collapse.

3.5 Channel geometry

Channel geometry affects the hydraulic forces causing bank erosion and is important when considering the distribution of bank erosion along a channel reach. For example, the high rates of erosion commonly associated with stream curvature results from the higher velocity gradients and hence higher shear stresses against the outer banks of channel bends. Different channel geomorphic units (e.g., pools, riffles, runs) are associated with different flow velocity and stream gradient, and hence shear stress on the bed and banks. The geometry of the stream cross-section is a good indicator of the potential for stream bank instability.

3.6 Bank soil-moisture conditions

The process of weakening and weathering related to soil moisture conditions reduces the strength of intact bank material and decreases stability. The freeze-thaw cycle associated with frost action can play a preparatory role in bank weakening by widening pre-existing cracks and loosening surface material to leave the bank more susceptible to future erosion.

Hard dry banks are very resistant to erosion, while cycles of wetting and drying can cause swelling and shrinkage of the soil leading to the growth of fissures and tension cracks which encourage failure. Seepage forces can reduce the cohesion of bank material by removing clay particles, and may promote the development of soil pipes in the lower bank (Knighton 1998).

Cohesive stream bank material is normally in a condition of partial saturation, and consequently subject to negative pore water pressures (suctions) that produce an increase in apparent strength of the bank material. Negative pore water pressures in stream banks can fluctuate frequently due to rainfall, variation in river flow and evapotranspiration of the vegetation on the bank. During rainfall and rising stages, changes in bank storage cause an increase in water content and in pore water pressure due to the rising water table. During major events the bank material can become fully saturated, so that the apparent cohesion reduces and positive pore water pressure occurs. Under these conditions stability can still be maintained due to the confining pressure of the water in the stream on the bank face. However, bank failures are likely to occur particularly during rapid drawdown, when the bank material is still at or near saturation, and as the confining pressure of the water approaches zero (Casagli *et al.* 1999; Simon and Collison 2001).

Piping is common in alluvial banks. In stratified banks with lenses of sand and coarser material sandwiched between layers of finer cohesive material, flow is induced in the more permeable layers by changes in river stage (Simons and Li 1982). If the flow through the permeable lenses is capable of dislodging and transporting particles, the material is slowly removed. This can lead to undermining of portions of the cohesive upper bank leading to gravitation-induced block failures.

3.7 Vegetation

Vegetation provides a protective cover which helps to absorb the forces exerted by flowing water. It also influences the mechanical strength of bank material, as roots increase the shear strength of the soil (Watson and Marden 2004). Plant evapotranspiration can contribute to better drained and drier bank conditions.

The height of the stream bank in relation to rooting depth can be critical. With low banks roots are likely to cross any potential slide plane and provide reinforcement. If bank height is greater than the rooting depth, any potential slide plane is likely to pass below the rooted layer and undercutting of the lower unrooted layer may promote cantilever type failures (Environment Agency 1999). Trees and shrubs leaning over the water may lead to failure of steep banks if they fall and dislodge soil as they uproot.

3.8 Man-induced factors

High levels of trampling by stock and vehicle usage may damage vegetation on the bank, and compact the soil surface. Compaction can lead to reduced infiltration, followed by erosion of the bank surface by overland flow, rilling and/or gullying. Vehicle and animal stream-access tracks can create breaks or gaps in otherwise continuous stream bank systems and thereby create points of weakness in their structure.

4 Stream Bank Erosion Measurement and Assessment Techniques

A wide range of techniques can be used to characterise bank erosion. Some are best suited to high precision, short time-scale estimates while others are better suited to low precision, long time-scale estimates. Lawler (1993) provides a comprehensive review of measurement techniques and groups them into suitability at short-, intermediate- and long-time scales (Fig. 10). Techniques for long time-scales (>10s of years) include sedimentological and botanical evidence, and historic sources (maps and photos). Techniques for shorter time-scales (<10 years) include topographic survey (planimetric or cross section), photogrammetry, and erosion pins (metal or electronic). In this report measurement techniques are arranged approximately in order of their suitability for increasingly short time-scales, although this depends on the rate of erosion (i.e. techniques mostly suitable for longer time-scales may be suitable at shorter time-scales where erosion rates are high). Some of the techniques suited to long time-scales only provide semi-quantitative measurements of rates of bank erosion.

Probably the most comprehensive results come from using a range of techniques to assess and measure bank erosion. Green *et al.* (1999) integrated interdecadal aerial photography, interseasonal measurement of bank erosion processes, continuous monitoring of turbidity, and event sampling of suspended sediment to assess the significance of bank erosion in the Namoi River, New South Wales. Bull (1997) used a combination of manual and automated erosion pins, and continuous measurement of turbidity. In addition the type of bank erosion processes occurring will determine which techniques are suitable (Table 3). For example, slump or earthflow processes will require different techniques to hydraulic or slab failures.

Bank erosion assessment provides an alternative to detailed measurements, which can only be carried out in a small number of places. It can be used to select representative measurement sites, provide a basis for extrapolation of site-specific measurements, provide a rapid overview of bank erosion problems, and is more commonly used to guide mitigation measures than quantitative measurements (Thorne 1998, Environment Agency 1999, Federal Interagency Stream Restoration Working Group 2001). It provides a rapid field survey of key attributes relevant to bank erosion and gives an overview of the extent of bank erosion.

Mechanism	**Suitable measurement techniques**
Shallow slides	Topographic surveying, bank profiler
Rotational slip	Topographic surveying, bank profiler
Slab failure	Topographic surveying, bank profiler
Cantilever failure	Topographic surveying, bank profiler
Wet earth flow	Topographic surveying, bank profiler
Popout failure	Topographic surveying, erosion pins and frame, bank profiler
Dry granular flow	Topographic surveying, erosion pins, and frame, bank profiler
Piping failure	Topographic surveying, erosion pins, and frame, bank profiler
Bank undercutting	Topographic surveying, erosion pins, and frame, bank profiler
Bed degradation	Topographic surveying, erosion pins and frame
Basal cleanout	Topographic surveying, erosion pins, bank profiler
Precise measurement of planform change	Repeat aerial or ground-based photography with photogrammetry, topographic surveying
General change in planform	Stratigraphic evidence, historical sources (maps, surveyors notes, aerial photographs, newspaper articles)

Table 3 Techniques for measuring different types of bank erosion and channel change

4.1 Bank erosion measurement

4.1.1 Stratigraphic evidence

Alluvial histories and chronologies can be determined from the study of sedimentology and the distribution of preserved alluvial deposits (Starkel and Thornes 1981, Lawler 1993). This allows reconstruction of a history of river activity based on variation in the type of deposits, their spatial distribution, and age. Age can be determined by a range of techniques including numerical (radiocarbon, luminescence, and radionuclide dating) and botanical dating. Typically this is used for reconstructing histories over long time periods (>50 years). It helps to define the history of floodplain development, major channel pattern changes and is useful for determining the impact of major flood events and major land use change, such as catchment-wide deforestation.

Limitations of this technique include: incomplete preservation of deposits, complex spatial and temporal variation, poor exposure of deposits, and the resolution of dating techniques. Nevertheless it can often provide a valuable long-term perspective on channel and floodplain history.

4.1.2 Historical sources

Serial historical sources (such as maps, surveyors notes, aerial photographs, newspaper articles), can be used to detect large-scale channel change (Lawler 1993). It involves plotting stream courses from different sources on to a common base and calculating rates of channel migration. For aerial photos this involves manual plotting (usually using a Zoom Transfer Scope) from uncorrected photos, as opposed to the precise measurement from orthorectified photos described in section 4.1.3. The spatial and temporal resolution depends on the scale of the source documents, and the magnitude of change, but typically they are useful for large channel changes (10s to 100s of metres) over longer time periods (>10 years). In New Zealand map sources are available from the mid to late 1800s and there are usually 5-10 map sources available spanning the interval since then (see Fig. 10 for an example using historic and modern map sources for the Motueka River).

Limitations include generally coarse spatial and temporal resolution of these types of sources, and the difficulty of accurately locating common control points on all sources. Like stratigraphic sources they can provide a valuable long-term perspective on channel history.

4.1.3 Repeat photography and remote sensing

Aerial photographs and other remotely sensed images can be valuable for assessing channel change, and usually contain more detail than maps at the same scale (Lawler 1993, Gilvear *et al.* 1999). They can be used to provide information on channel change at a range of accuracies, depending on the resolution of the photography. Simple air photo interpretation can provide a rapid assessment of recent large scale channel change, and used to identify sites for detailed quantitative measurement. Higher levels of accuracy may be obtained using a Zoom Transfer Scope to transfer channel margins on uncorrected air photos to a rectified base map. Photogrammetric plotting machines and precise ground control can be used to precisely correct air photos for radial distortion, camera tilt and topographic elevation. The latter technique has often been used to define planimetric change (distance or area measures); however it can also be used to obtain volumetric information through the use of digital elevation models (Barker *et al.* 1997, Collins and Moon 1979).

Both vertical and oblique photography have been used to measure bank erosion. Calculating detailed planimetric and volumetric change is time consuming and has usually been applied to relatively small reaches of river (individual bank erosion sites or 10s-100s of metres), over short periods of time (a few years). However, the advent of more readily available high resolution digital orthophotography is increasing the opportunity to use this technique and allows rapid measurements to be made over tens of kilometres of river (Elliott and Jacobson 2004) – see Fig. 11 for an example

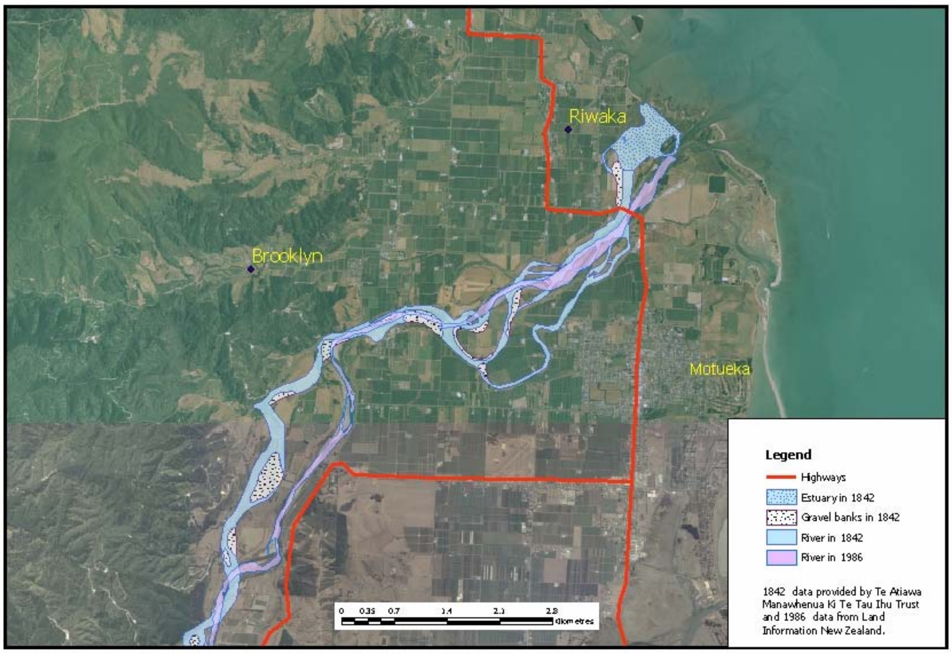


Fig. 10 Planform changes, lower Motueka River between 1842 and 1996 based on map sources (Basher 2003).

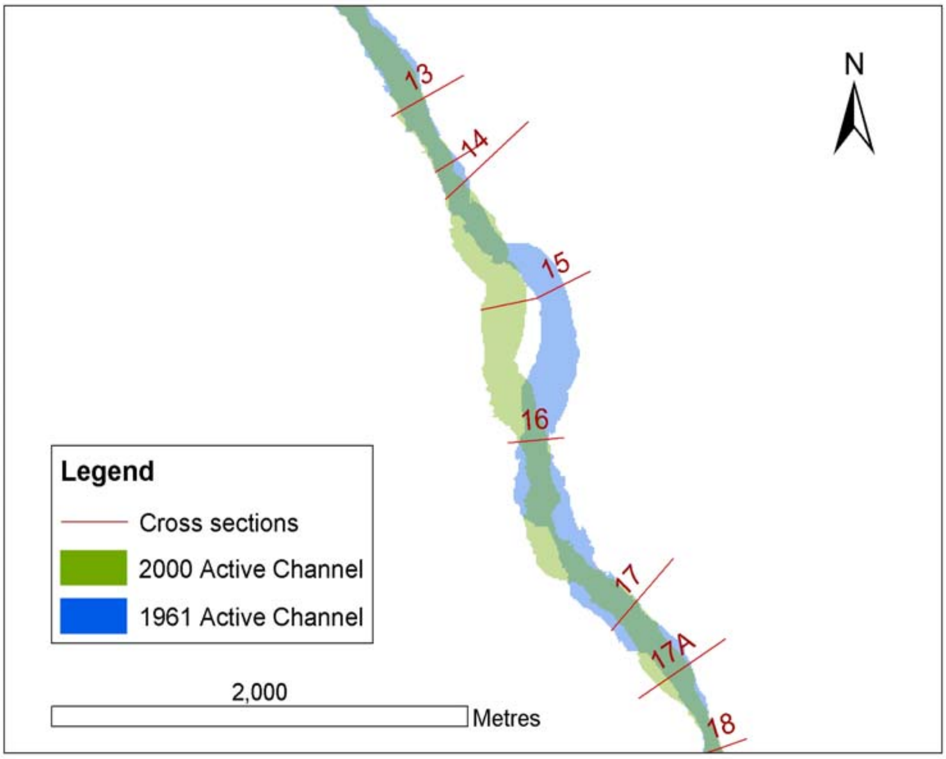


Fig. 11 Digitised planform of part of the Upper Motueka in 1961 and 2000 derived from digital orthophotographs (Ball 2004).

using this type of imagery from the Motueka River. Recently airborne laser scanners have been used to obtain detailed topographic data and measure bank erosion over tens of kilometres of river (Thoma et al. 2001).

Remote sensing techniques have the advantage that they do not involve contact with the stream bank, and can provide data over long periods of time with the use of historic imagery. Precision depends on the scale of the imagery, and the frequency at which images are available to define a time series of changes to stream banks. Analysis of aerial photographs taken over long time periods requires the location of common control points, which can be difficult.

4.1.4 Topographic surveying

This technique includes both repeat profiling along cross-sections and planimetric survey of channel form.

Planimetric surveys are particularly labour intensive and are often only applied in limited areas over short periods of time, although the use of survey-quality GPS is making this approach more feasible over larger areas. Cross-section surveys are limited in their spatial coverage, but have been carried out over long periods of time in New Zealand (e.g., Griffiths 1979, Sriboonlue and Basher 2003). Planimetric surveys are more difficult to apply where the bank morphology is complex and the bank and channel margins are difficult to define.

The repeatable cross-section profiling technique requires the establishment of a series of permanently marked cross-sections through a selected channel reach. By levelling the profile at various intervals, a record of recession of the stream bank can be established. From this data, eroded volumes and rates of erosion can be obtained. Just as importantly, changes in other parts of the reach can be noted, such as accumulation of point bars, and bedform development. The cross-section should be at right angles to the channel. To ensure exact reproducibility of measurement, the ends need to be permanently located and set back approximately one channel width from the bank top to allow for future stream migration. The end points should, in turn, be located with reference to two permanent control points. The profiling can be done in a number of ways. A common one-operator method involves a fixed horizontal datum across the stream, such as a taut tape or survey staff from which vertical measurements can be taken (Lawler 1993). This method is only appropriate for relatively small streams. For larger channels, levelling, stadia or an EDM (Electronic Distance Measuring) survey may be used. The set-up position of the instrument should also be relocatable (i.e. permanently marked and surveyed into the network as this will help relocate any lost survey end points. Surveying texts detail the appropriate procedures and checks to be made to ensure high quality, repeatable data is obtained (Bannister and Raymond 1977, Pugh 1975). This technique provides highly precise measurements at specific locations. However, it relies on these locations providing an adequate representation of overall channel and bank changes and results can be difficult to extrapolate.

Planimetric surveys of river channel and bank form can provide a means of defining changes in the 3 dimensional configuration of the channel and bank (Lawler 1993). However, usually only the location of the top of the channel bank is defined, less detail is generally obtained for individual locations (particularly if bank morphology is complex) and the precision of measurement of change is generally less than for cross section profiling.

4.1.5 Erosion pins

Erosion pins are probably the most popular technique for measuring stream bank erosion, and have been used in a wide range of geomorphologic contexts and fluvial environments (Lawler 1993). A small-diameter (6 mm or less) length of metal rod is inserted into the bank material so that only a small known portion remains visible. As bank erosion proceeds, more of the rod is exposed. Measurements from the end of the pin to the bank are made at predetermined time intervals, or after high flow events, to detect bank material removal (Thorne 1981). Techniques and guidelines for installation, reading and data interpretation are given in Lawler (1993) and Thorne (1981).

The method is suitable for a wide range of fluvial environments and is sensitive to small amounts of bank retreat (i.e. mm scale). No special equipment is required and a network of pins can be established, maintained and read quickly and easily by a single operator.

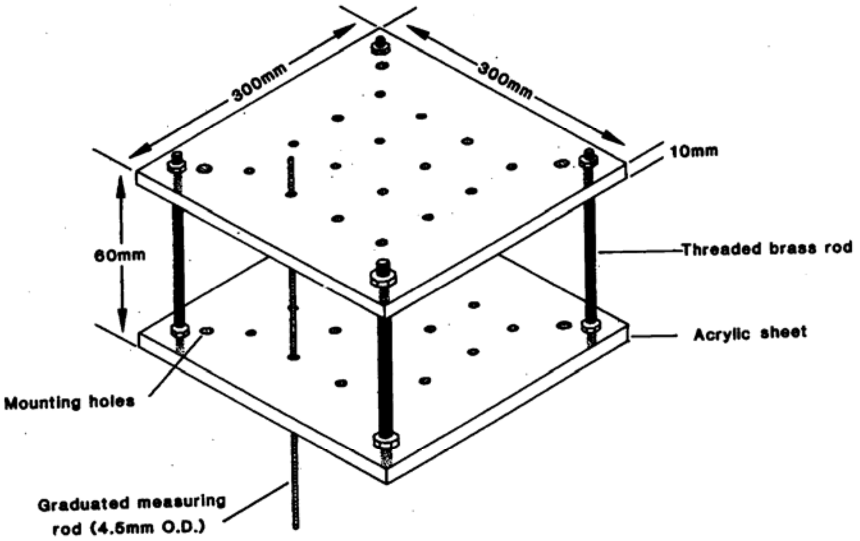
The limitations of erosion pins include:

- spatial sampling difficulties: a high degree of systematic (downstream and vertical) and random spatial variability can be expected making it difficult to derive volumetric estimates of change;
- interpretation of readings: problems can arise where bank movement occurs from swelling or contraction due to temperature and soil moisture fluctuations;
- movement and/or loss of pins;
- effect of pins on bank condition: loosening or loss of bank material can occur when pins are established, measured, or reset;
- complete loss of pins: erosion or burial of pins can occur, particularly where mass movement processes dominate;
- erosion pins are invasive, and tend to be less suited to coarse materials.

4.1.6 Erosion Frame

This is a lightweight aluminium or perspex frame built in a lattice configuration (Fig. 12) that Lawler (1993) suggests might be an alternative to erosion pins. When in operation the frame sits on 4 metal rods that are located permanently on site. Each supporting rod can be equipped with a welded stop to assist with frame relocation. Measurements are taken down to the soil face with a graduated dipstick through a number of holes drilled in the frame (Lawler 1993).

The frame is portable and can be operated by a single user. The method is sensitive to small amounts of bank retreat (i.e. mm scale) and does away with the problems of movement and/or pin loss often associated with erosion pins. The erosion frame also eliminates the effect of erosion pins on bank condition, as the measurement are not made in the zone of possible disturbance created by the supporting rods, but a short distance away.



'Acrylic-sandwich' erosion frame for soil or bank erosion studies

Fig. 12 Erosion frame (Lawler 1993)

4.1.7 Relocatable bank profiler

This is a micro-topographic slope-profiler and is based on the principle of a vertical datum, from which horizontal measurements to the riverbank can be periodically retaken (Fig. 13). Its use is described in Lawler (1993) and Hudson (1982). To ensure that measurements are made in the same site the device can be inserted into relocatable receiving sockets established a short distance from the top of the bank (Lawler 1993).

This method has several advantages:

- the device is portable,
- sites can be established, maintained and read quickly and easily by a single operator,
- no special equipment is required for installation,
- measurements are sensitive to small amounts of bank retreat (mm scale), and can be more repeatable than from conventional survey techniques,
- it is also suitable for rapidly measuring complex bank morphology, such as overhangs.

However it is affected by the same spatial sampling difficulties as many other techniques, with a high degree of longitudinal spatial variability making it difficult to derive volumetric estimates of change. It would be difficult to use where rates of bank retreat were rapid.

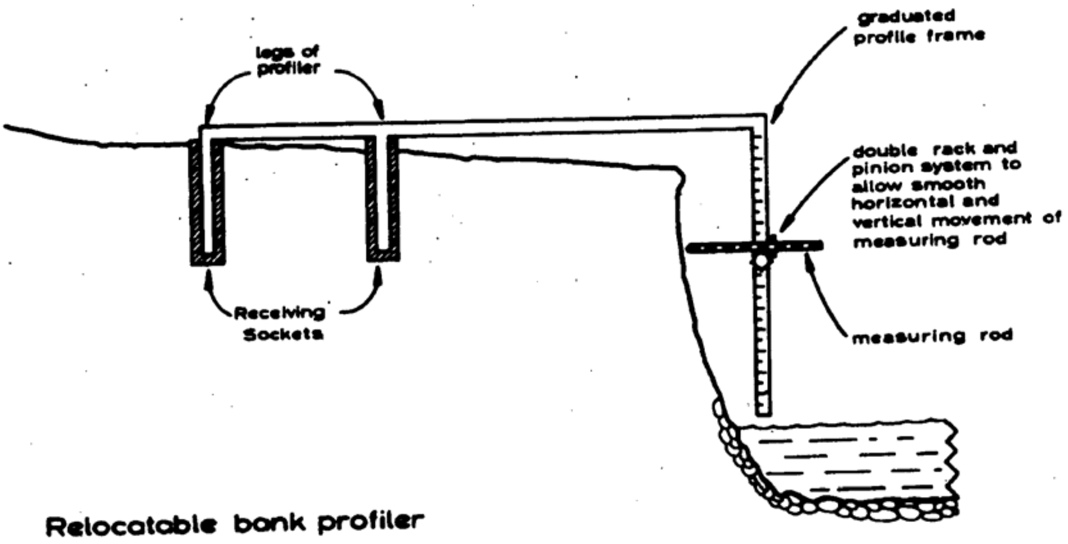


Fig. 13 Relocatable bank profiler (Lawler 1993)

4.1.8 Photo-electric erosion pins (PEEP)

Manual erosion pin monitoring techniques give an appreciation of the net changes in bank position since the previous measurement. The PEEP system can be used to supply information on the temporal distribution of erosional and depositional activity of the stream bank (Lawler 1992, 1993, 2005). Consequently bank erosion process studies, and model development and testing can be based on time series data for specific erosion and deposition events, which in turn can be related to time series data on rainfall, stream flow, sediment discharge, etc. PEEP can also be used to derive minimum threshold events (based on rainfall or stream flow) at which erosion and/or deposition may start to occur.

A PEEP sensor is a simple optoelectronic device containing a row of overlapping photovoltaic cells enclosed within a waterproof transparent tube. The sensor generates a voltage proportional to the total length of the tube exposed to light and this is recorded by a datalogger. Small networks of sensors are inserted into pre-augured holes in the bank face, and connected to a data logger programmed to receive data at a preset time-frequency. As retreat of a stream bank exposes more cells there is an increase in logger-detectable voltage output. Deposition reduces voltage output (Lawler 1993, 2003).

PEEP sensors have recently been modified to detect nocturnal events through the use of Thermal Consonance Timing, and to be used over a wider range of erosion rates (Lawler 2005). PEEP data can occasionally be degraded in low-light conditions such as that encountered in highly turbid water. Like erosion pins, PEEP tubes are invasive, and tend to be less suited to gravel materials and for large mass movement failure types.

4.1.9 Turbidity sensors

Turbidity sensors measure suspended solids in water, typically by measuring the amount of light transmitted through the water. When calibrated they provide a means of continuously monitoring suspended sediment concentration which, when combined with discharge measurement, can be used to derive the flux of suspended sediment. The difference in flux between two sites in a river, in the absence of any hillslope contribution, provides an estimate of the contribution of bank erosion to suspended sediment load. Bull (1997) used turbidity sensors at four sites on the River Severn, in combination with direct measurement of bank erosion, to assess the contribution of bank erosion to suspended load and to estimate the amount of material derived from bank erosion that went into temporary storage.

This technique provides detailed time series data on bank erosion, and when used in combination with direct measurement, can provide valuable data on the differences between supply and transport of sediment. Turbidity sensors require accurate calibration and maintenance to ensure consistent data collection, and manual sampling of suspended sediment is needed to ensure the measurements made at a point near the bank by the turbidity probe adequately represent the cross-section averaged sediment concentration. In addition discharge measurements are required, but if the turbidity probes are placed in reachs where there are no significant inflows of water then only a single discharge measurement site is needed.

4.2 Bank erosion assessment

Most bank erosion assessment procedures are aimed at appraising bank erosion problems and determining restoration options, rather than determining the contribution of bank erosion to sediment budgets. However, similar procedures are also appropriate for assessing the contribution of bank erosion to sediment budgets.

The Federal Interagency Stream Restoration Working Group (2001) developed procedures for geomorphic analysis of stream corridors which includes the qualitative and quantitative assessment of bank stability. The qualitative assessment was based on the geometry of the bank profile (steepness, profile shape and complexity), physical properties of the bank materials (bank sediment texture and layering), and dominant failure mechanisms. Quantitative assessment relied on a factor of safety analysis. The procedure also includes consideration of stream type and channel evolution models to predict likely stream changes following disturbance.

Thorne (1998), building on the earlier work of Thorne et al. (1996), details a field technique for stream description to provide a geomorphic basis for interpreting river channel form and stability, including bank erosion. It is intended to provide an organised and coherent technique to make available geomorphic data that can be applied to stream classification, engineering-geomorphic analysis of streams, identification of instability, channel design, and assessment and control of bank erosion. The elements of this procedure are a channel map, bank survey (including a map and bank profiles), analysis of the toe-sediment balance, and identification of the bank erosion problem and solution. Thorne (1998) provides field sheets divided into four sections to provide information on:

1) Scope and purpose of survey.
2) Region and valley description – regional geomorphic and human setting, including terrain, drainage pattern, geology, land use, vegetation, and channel planform (Fig. 14) and instability.
3) Channel description – deals with channel dimensions, flow type, natural or artificial controls on vertical and lateral activity, bed sediment, and channel geomorphic units.
4) Left and right bank surveys – a detailed description of the morphology of the left and right banks. Erosion data includes location and extent of erosion, rate of retreat or advance (where known), an interpretation of bank stability (Fig. 15) and severity of erosion (not defined), failure type and contributing processes, and toe sediment balance. In addition data is recorded on the nature of bank materials, geometry of the bank, evidence of cracking, vegetation, and protection status.

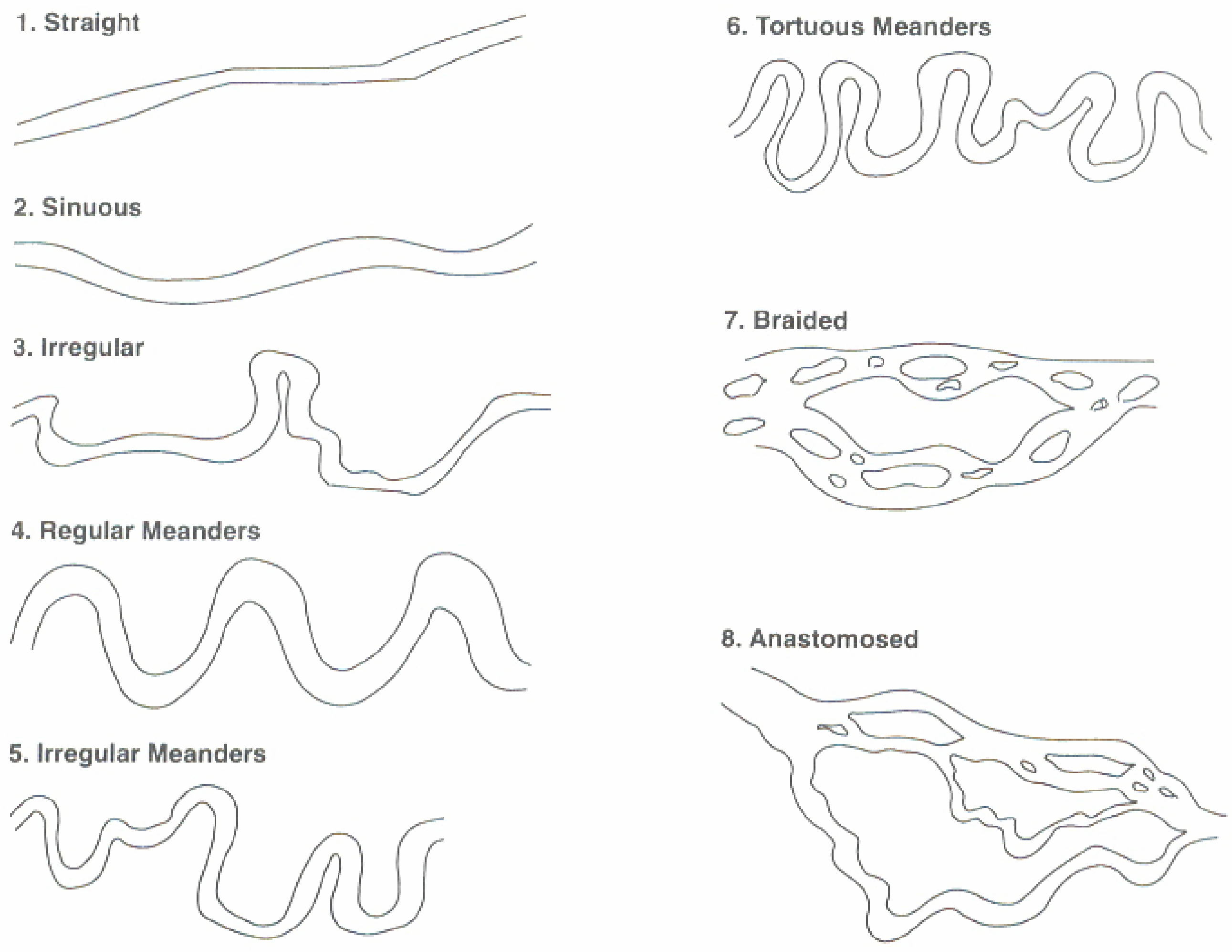


Fig. 14 Channel planform

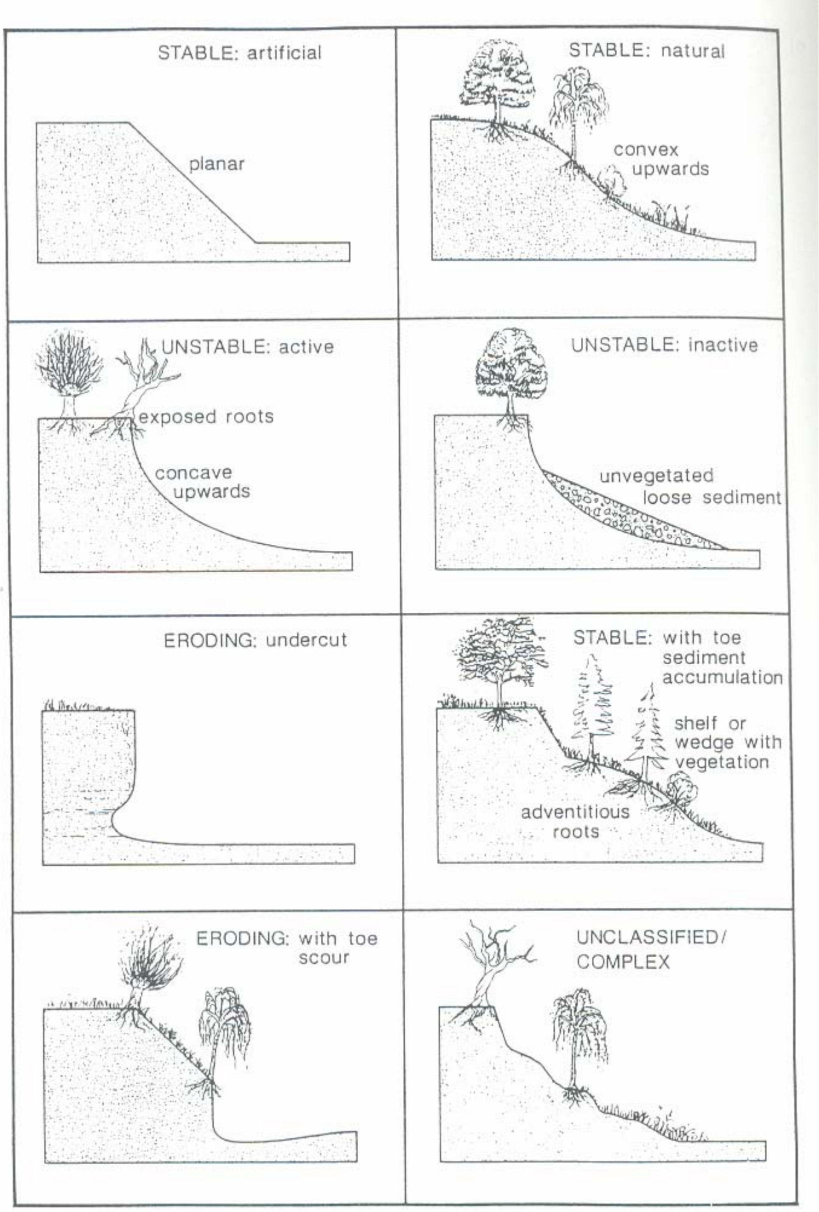


Fig. 15 Stability interpretation of typical bank profiles (from Thorne 1998)

The UK Environment Agency (1999) developed a procedure to match erosion problems with an appropriate control strategy. It is made in four stages: assessment of channel status, assessment of the consequences of bank erosion, assessment of the causes of bank erosion, summary of bank properties that influence mitigation measures. These provides a framework to identify and evaluate strategies for erosion control. Assessment of bank erosion problems is based on field survey using a bank survey record sheet that records the following information:

- site sketch map and cross sections,
- channel characteristics (channel type, planform, bed material, channel geomorphic unit or flow type, flow velocity at bankfull),
- information on erosion including location (i.e. toe, slope or bank top, left or right bank), severity, extent, mode of failure, contributing processes, age of scars and disturbed blocks, condition of the base of bank and material at base of bank, type and age of vegetation at base of bank, general evidence (such as exposed roots and undercut banks), evolutionary stage of the bank),

- evidence of water level drawdown,
- bank characteristics (materials, geometry, vegetation),
- existing remedial measures and bank modifications,
- bank condition (stable, eroding, accumulating, undercutting)

The main criteria for erosion severity (based on the earlier work of Hey *et al*., 1991) include: bank loading, bank height, bankfull velocity, and bank slope. A decision support system is then used to guide the user through a sequence of decision trees to arrive at a judgment on the severity and consequences of bank erosion.

Rosgen (1996) outlines a procedure for assessment of stream condition aimed at assessing how disturbed the stream is. This procedure sets the assessment in the context of a stream classification system that details the different morphology expected for different stream types, and evolutionary stages of channel development within different stream types. It includes consideration of width:depth ratio and channel/bank stability (following Pfankuch 1975), and a numerical assessment of streambank erosion potential, which is outlined in more detail in section 5 (bank erosion modelling).

The Australian River Assessment System (AUSRIVAS) is a standardised approach to biological assessment of stream health that includes a physical assessment component (Parsons *et al.* 2002). It includes a bank stability rank score (1-10) based on Pfankuch (1975).

A New Zealand-based procedure for characterising river channels is outlined by Mosley (1982). This was aimed at describing the appearance and character of rivers in New Zealand, but includes no description of bank stability other than general properties such as riparian vegetation, cross section shape, and amount of overhanging bank.

Each of these techniques has a number of common elements that could be used within a semi-quantitative technique to compare and rank (high, medium, low) stream bank erosion features along a stream profile. Important components to record include:

- bank material composition: type (non-cohesive, cohesive, stratified, rock), texture (gravel, sand, silt, clay, other), permeability, gradation;
- bank geometry: height, slope, profile shape (concave, straight, convex, complex);
- bank moisture conditions: wet, damp, dry;
- bank failure
    - location (toe, slope or bank top, left or right bank, GPS) and extent of erosion,
    - bank failure type
        - gravitational: wedge, popout, piping, cantilever (shear, tensile, beam), rotational, shallow slide, dry granular flow, wet earth flow, soil fall
        - hydraulic: undercutting, bed degradation, basal cleanout
        - contributing processes: freeze-thaw, rilling, gullying, stock damage, evidence of water level drawdown
    - bank toe sediment accumulation
        - absent,
        - present: type of material (gravel, sand, silt, clay), vegetation cover (percentage, type, age)
    - bank stability: exposed soil (percentage stable vegetation, percentage bare ground, percentage slumped sod), general evidence of stability (such as exposed roots, undercut banks, tension cracks)
    - activity rating (high, medium, low);
- stream bank vegetation: type (trees, shrubs, grass), percentage cover, age, rooting depth, exposed roots, stability);
- local channel geometry: width, depth, channel geomorphic unit(s) and stream gradient [steep (waterfalls, stepped pools), medium (riffles, pools), low (straight

runs, meander)], stream curvature (concave, convex, straight);

- riparian buffer characteristics: dominant vegetation (trees, shrubs, herbaceous plants, grass), location of vegetation (top, bank, toe), wetlands in buffer zone (yes, no);
- man-induced factors: stock use, vehicle use, artificial drainage, road runoff, logging;
- protection status: unprotected, existing remedial measures (rock work, groynes, trees), bank modifications (e.g., channel straightening, bank grading).

A minimum data set for determining the contribution of bank erosion to sediment budgets, identifying representative sites for detailed measurement and determining controls on bank erosion would include: location (GPS position, toe, slope or bank top, left or right bank), extent (length of feature, height of bank), type of sediment (cohesive or non-cohesive, particle size, stratification), type of failure and contributing processes (e.g., freeze/thaw, water drawdown), toe sediment accumulation, general evidence (e.g., exposed roots, undercut banks), severity of erosion/bank stability, geometry of the bank (height, slope, profile shape), evidence of cracking, vegetation, channel geomorphic unit, protection status.

5 Bank erosion modelling

Bank erosion modeling approaches range from empirical to process-based. Many catchment erosion models (e.g., SHESED, WEPP, CREAMS, Mike-11) have sophisticated routines for predicting in-stream sediment transport, sediment routing and bed erosion, but often neglect the contribution of bank erosion to sediment load (Merritt *et al.*, 2003). Most models with some process basis appear to deal only with some forms of gravitational failure (using factor of safety analysis to predict bank erosion) or hydraulic erosion (calculating sediment transport capacity from hydraulic shear stress/bank material strength analysis). Given the complexity of processes that can contribute to bank erosion (section 2) a comprehensive process-based model of bank erosion would be difficult to implement. Figure 16 illustrates some of the range of bank erosion processes observed in the Motueka and Raglan catchments.

Rosgen (1996, 2001) describes a method to predict bank erosion rates from two types of river systems in the United States. A bank erosion hazard index (BEHI), velocity gradient and near-bank stress are used to predict bank erosion rate. BEHI is rated from field measurements of:

- the ratio of streambank height to bankfull stage height,
- bank angle (the slope of the streambank),
- the ratio of root depth to bank height,
- root density,
- the amount of bank surface protection given by roots and other woody debris,
- soil stratification (bank material stratigraphy and presence of soil lenses), and
- particle size (the composition of streambank materials).

Each of these factors is assigned a rating based on criteria and diagrams published in Rosgen (1996, 2001) and is used to derive BEHI (Table 4). Published data on velocity profiles in streams is used to obtain velocity isolevels and gradients (Rosgen 1996), and the stream width is divided into thirds to apportion the near-bank shear stress. The velocity gradient and near bank shear stress are then converted into ratings (Table 5). BEHI and near bank stress are integrated in graphical form to predict bank erosion rate (Fig. 17).

In SEDNET (Sediment River Network model developed for Australia; Prosser *et al.* 2001) the rate of bank retreat (BE, m/yr) along any river segment is calculated as a function of bankfull discharge ($Q_{1.58}$)

$$BE = 0.008Q_{1.58}^{\;0.60}$$

This function was derived from an analysis of global river bank migration data. The flux of

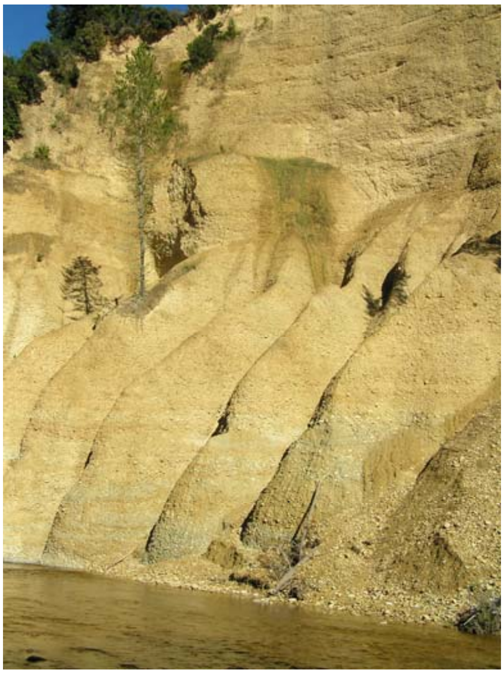
Slab failures, Raglan

Slab and soil fall failures, Raglan

Slump failures, Raglan

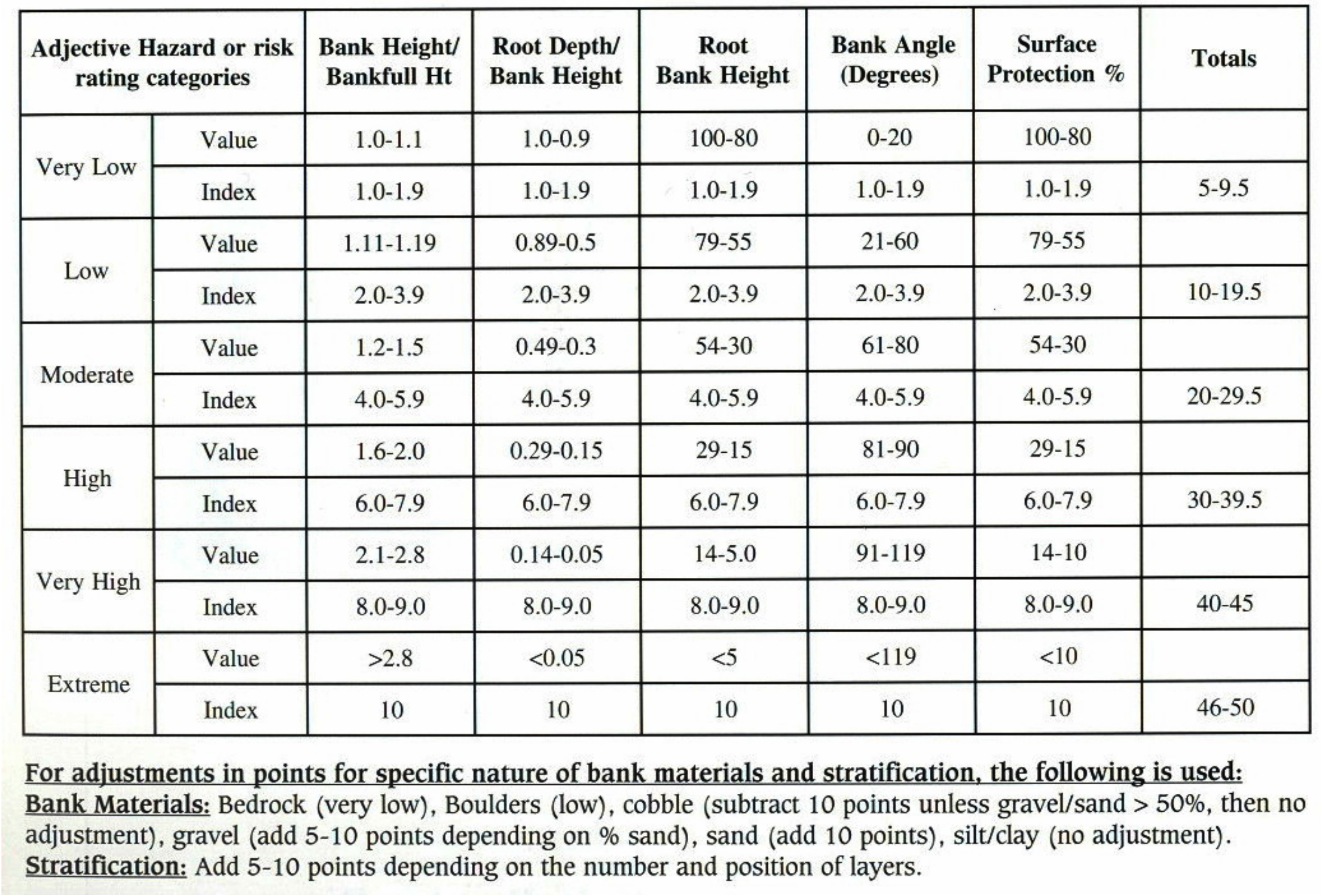
Slab failures and bank undercutting, Motueka River

Slab failures, Motueka River



Dry granular flow and gullying, Motueka River

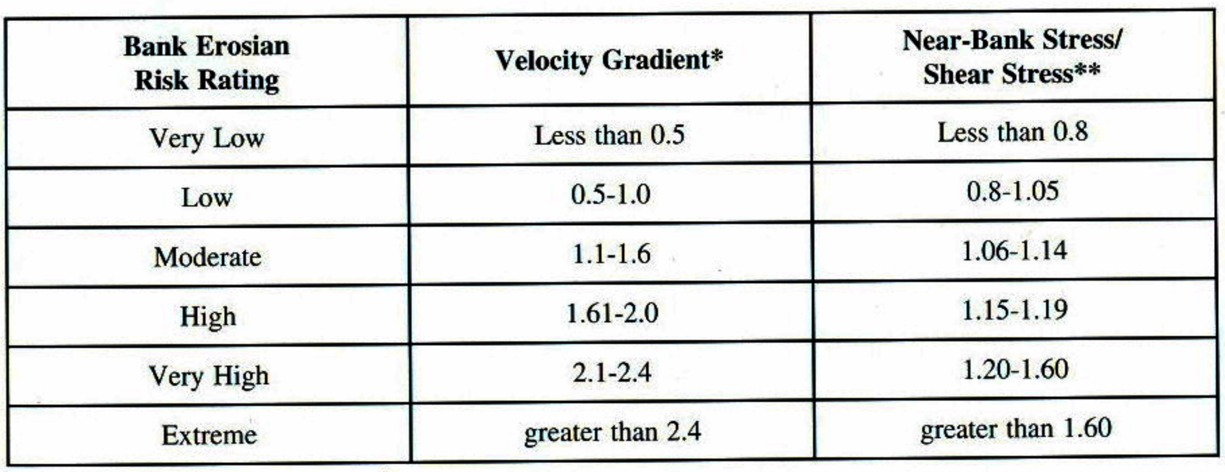
Fig. 16 Types of bank erosion in the Motueka and raglan catchments



Adjective Hazard or risk rating categories		Bank Height/ Bankfull Ht	Root Depth/ Bank Height	Root Bank Height	Bank Angle (Degrees)	Surface Protection %	Totals
Very Low	Value	1.0-1.1	1.0-0.9	100-80	0-20	100-80	
	Index	1.0-1.9	1.0-1.9	1.0-1.9	1.0-1.9	1.0-1.9	5-9.5
Low	Value	1.11-1.19	0.89-0.5	79-55	21-60	79-55	
	Index	2.0-3.9	2.0-3.9	2.0-3.9	2.0-3.9	2.0-3.9	10-19.5
Moderate	Value	1.2-1.5	0.49-0.3	54-30	61-80	54-30	
	Index	4.0-5.9	4.0-5.9	4.0-5.9	4.0-5.9	4.0-5.9	20-29.5
High	Value	1.6-2.0	0.29-0.15	29-15	81-90	29-15	
	Index	6.0-7.9	6.0-7.9	6.0-7.9	6.0-7.9	6.0-7.9	30-39.5
Very High	Value	2.1-2.8	0.14-0.05	14-5.0	91-119	14-10	
	Index	8.0-9.0	8.0-9.0	8.0-9.0	8.0-9.0	8.0-9.0	40-45
Extreme	Value	>2.8	<0.05	<5	<119	<10	
	Index	10	10	10	10	10	46-50

For adjustments in points for specific nature of bank materials and stratification, the following is used:
Bank Materials: Bedrock (very low), Boulders (low), cobble (subtract 10 points unless gravel/sand > 50%, then no adjustment), gravel (add 5-10 points depending on % sand), sand (add 10 points), silt/clay (no adjustment).
Stratification: Add 5-10 points depending on the number and position of layers.

Table 4 Streambank characteristics used to rate Bank Erosion Hazard Index (Rosgen 1996).



Bank Erosian Risk Rating	Velocity Gradient*	Near-Bank Stress/ Shear Stress**
Very Low	Less than 0.5	Less than 0.8
Low	0.5-1.0	0.8-1.05
Moderate	1.1-1.6	1.06-1.14
High	1.61-2.0	1.15-1.19
Very High	2.1-2.4	1.20-1.60
Extreme	greater than 2.4	greater than 1.60

Table 5 Velocity gradient and near-bank stress indices (Rosgen 1996).

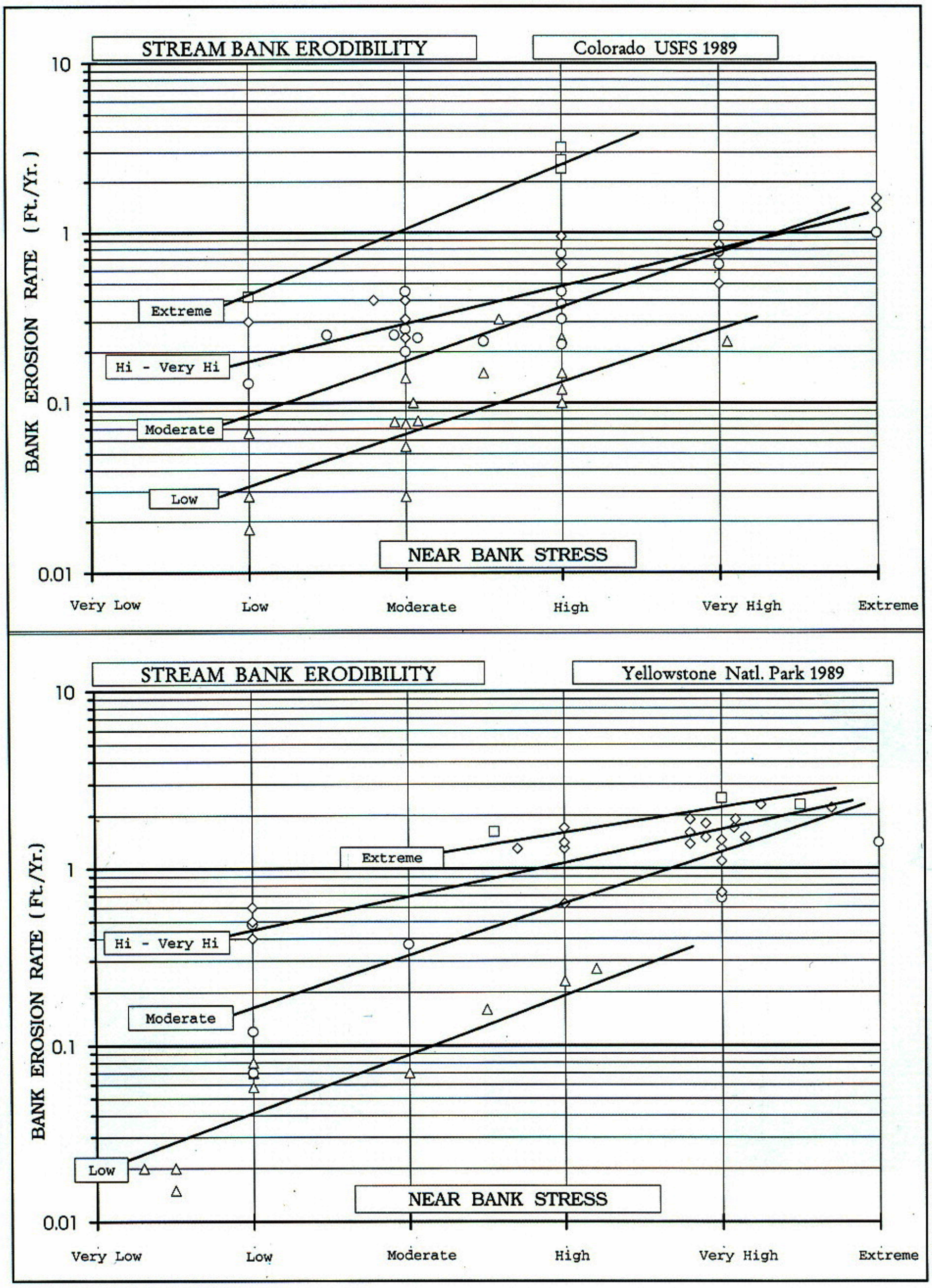


Fig. 17 Nomograms for predicting bank erosion rate from BEHI and near bank stress in two regions of the USA (Rosgen 1996).

sediment is calculated from the length of each segment, bank height, and sediment bulk density, and applied to the proportion of the river bank not protected by riparian vegetation.

Dickinson *et al.* (1989) used a similar empirical approach to predict bank erosion rates in Ontario, Canada:

$$Y_b = 2*10^{-10}\left(K^{2.5}A_{gf}^{7.2}\right)+1.75^{(0.5/H_s)}$$

Where Y_b is bank erosion rate (cm/yr), K is the USLE soil erodibility factor, A_{gf} is a numerical index of agricultural intensity, and H_s is the ratio between the critical flow depth for initiation of bed material transport and the bank-full flow depth.

Graf (1984) uses information on historical channel changes and floods to develop a function which describes the probability that a defined area of land will erode. The probability of bank erosion for any period of time is directly proportional to the sizes of annual floods during the time period and inversely proportional to the distance upstream and distance laterally from a channel. This approach was refined by Winterbottom and Gilvear (2000) by using GIS to map river channel planform change and incorporate geomorphic variables (bank morphology, sediment type, floodplain vegetation) into bank erosion probability prediction. Winterbottom and Gilvear (2000) found that removing upstream distance from the probability function greatly improved its performance in their study area.

Thorne and Abt (1993), based on the earlier work of Osman and Thorne (1988), developed a spreadsheet-based model for predicting bank instability caused by toe scour and lateral erosion. The model requires data on total and eroding bank height, slope angle, soil density, friction angle, cohesion and includes a tension crack index. These factors are used to

- find the initial factor of safety of the bank with respect to slab failure,
- test the sensitivity of bank stability to changes in the engineering properties of the bank material,
- analyse the response of bank stability to toe scour and/or lateral erosion and find the critical condition,
- find the geometry of the failure surface and failure block,
- analyse the response of bank stability to further toe scour and/or lateral erosion,
- find the geometry of the failure surface and failure block in subsequent failures.

This type of approach has been further developed by Simon et al. (1991, 1999) and Rinaldi and Casagli (1999) taking into account pore water pressures in the bank and confining hydrostatic pressure. Similarly, Pollen and Simon (2005) combine a model of root reinforcement from riparian vegetation with a bank stability (factor of safety) model to predict the effect of different tree species on bank stability.

Limitations of the factor of safety analysis led Darby and Thorne (1996) to develop an improved stability analysis of steep, cohesive stream banks. The limitations identified were use of simple, idealised bank geometry rather then real bank profiles, inadequate representation of tension cracks, constraints on location of the failure plane (at the toe of the bank only), inadequate treatment of soil pore water pressures and hydrostatic confining pressure from water in the channel, and inability to simulate failure over a wide range of bank slope. The improved approach can be used to predict bank erosion rates and sediment yield associated with bank erosion by planar failures and has been incorporated into a computer program by Darby *et al.* (2000). It predicts planar failures taking into account the characteristics of the bank material, the shape of the bank profile, and the relative elevations of the groundwater and surface water. It can predict the probability of failure or determine the amount of bed degradation and bank-toe erosion required to destabilise a stable bank.

Dapporto *et al.* (2003) investigated the role of river stage and pore water pressure in triggering slab and cantilever failures using two types of stability analysis:

- the limit equilibrium method was used to predict the effect of pore water pressure on bank stability;
- a seepage analysis based on hydrographs of different return periods was used to assess the effect of river stage and pore water pressure on bank stability

Darby *et al.* (2002) developed a numerical model of river morphology for meander bends with erodible cohesive banks. The model couples a two-dimensional depth-averaged model of flow and bed topography with a mechanistic model of bank erosion, and simulates the deposition of failed bank material debris at the toe of a bank and its subsequent removal. The governing conservation equations are implemented in a moving-boundary fitted coordinate system that can be both curvilinear and non-orthogonal to simplify grid generation in curved channels that experience bank deformation, to allow complex planform shapes associated with irregular natural channels to be simulated.

Darby *et al.* (2004) describe attempts to use a Computational Fluid Dynamics approach to model the shear stress on a river bank causing bank erosion in meandering rivers. Field based data sets (topographic, hydraulic, bank erodibility and retreat) from two rivers in Italy and UK were used to parameterise and verify the model.

6 Conclusions

Bank erosion is not a single process. It encompasses a wide variety of hydraulic and gravitational mass failure processes. The two process groups are often linked with hydraulic processes causing gravitational failures. Identification of bank erosion processes is important for determining suitable measurement techniques and for choosing appropriate remedial options.

A wide range of techniques can be used to measure bank erosion, with some suited to high precision, short time-scale estimates while others are more suited to low precision, long time-scale estimates. The main techniques that have been used to measure bank erosion are: erosion pins (metal or electronic), bank profilers, photogrammetry, topographic survey (planimetric or cross section), historic sources (maps and photographs), sedimentological and botanical evidence. Suitability also depends on the dominant type of bank erosion process with some suited to small scale failures (erosion pins, bank profilers) and others more suited to larger scale change (photogrammetry, topographic survey). Broad scale channel change can be derived from maps, photographs, sedimentological and botanical evidence.

Bank erosion assessment provides an alternative to detailed measurement, which in practice can only be carried out in a few selected locations. A minimum bank assessment data set for determining the contribution of bank erosion to an overall sediment budget, identifying representative sites for detailed measurement and determining controls on bank erosion would include: location (GPS, toe, slope or bank top, left or right bank), extent (length of feature, height of bank), type of sediment (cohesive or non-cohesive, particle size, stratification), type of failure and contributing processes (e.g., freeze/thaw, water drawdown), toe sediment accumulation, general evidence (e.g., exposed roots, undercut banks), severity of erosion/bank stability, geometry of the bank (height, slope, profile shape), evidence of cracking, vegetation, channel geomorphic unit, protection status.

Bank erosion modeling approaches range from empirical to process-based. Many catchment erosion models have sophisticated routines for predicting in-stream sediment transport, sediment routing and bed degradation, but often neglect the contribution of bank erosion to sediment load. Most models with some process basis deal only with some forms of gravitational failure (using some form of factor of safety analysis to predict bank failure) or hydraulic erosion (calculating sediment transport capacity from hydraulic shear stress/bank material strength analysis). With the complexity of processes that can contribute to bank erosion a comprehensive process-based model of bank erosion would be difficult to implement.

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