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# Review of good practice in managing riverbank instability and erosion



## WWF-Malaysia Project Report



July 2018

# **Review of good practice in managing riverbank erosion and instability**

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Report Produced Under Project SW010603-831-CORP SCP-CIMB

Long Semadoh Riverbank Erosion Project

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## Foreword and acknowledgements

This review of good practice was written for WWF Malaysia as part of the River Trusan project (Project code SW010603-831-CORP SCP-CIMB). The purpose of the review is not to provide technical or engineering details of specific erosion control techniques, but to summarise what academics, researchers and practitioners agree as being the best approaches to identifying and implementing appropriate measures for dealing with problems of erosion. Thus, rather being a user manual to help with the installation of particular erosion control structures, it aims to set out the things that river managers need to consider in order to identify and properly implement appropriate strategies.

The report is based on the philosophy that good practice involves understanding and dealing with the cause(s) of the problem, rather than with the piecemeal treatment of its symptoms. It begins by providing an overview of some of the major causes and types of riverbank erosion. This is followed by a review of a framework for dealing with erosion issues; the framework is set by the four-dimensional nature of river systems and the scale at which different measures are applied. It then provides details of specific measures, including case studies to show where they have been implemented successfully.

The report draws heavily on the knowledge from expert scientists and practitioners who work on river management around the world. It would not have been possible to prepare this review without their work, so we gratefully acknowledge all the authors cited in the reference list. We have also benefitted greatly from collaborations with academics and both government and non-government agency staff over a number of years, all related in one way or another to sustainable river management; in this regard we particularly thank colleagues from the Environment Agency in the UK.

All photographs are by the authors, unless stated otherwise.



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## Executive summary

1. Rivers are dynamic elements of the landscape that, almost by definition, erode. They exist in a state that is often termed a 'dynamic equilibrium'; i.e. they are not stable, but range within certain bounds. These natural bounds form the starting point for recognising when erosion is excessive and, consequently, when intervention may be needed. Intervention can be at the catchment, corridor or river reach scale.
2. Before specific measures are implemented, it is important to understand the causes of any unexpected erosion. This understanding should be developed as part of a formalised project management framework that starts with the definition of project objectives, followed by agreement on how project success is defined. Appropriate interventions can then be identified based on monitoring and diagnosis that is focussed on identifying the causes of the erosion. The framework also provides the mechanism for post-project appraisal and adaptive management, whereby new objectives can be defined and, if necessary, new or modified interventions developed.
3. Very often the problems of localised erosion can be attributed to activities upstream or within the catchment; often they are a response to cumulative activities of changes. Consequently, interventions that can be considered as being sustainable frequently involve better catchment management, especially related to land use activities and associated runoff. The need to allow rivers to erode within their natural bounds is recognised in corridor-scale approaches to management, exemplified by the 'freedom space' concept of Piégay *et al.* (1997). This involves, for example, better spatial zonation of floodplain activities, retaining some areas for agriculture or development but 'giving other areas back to the river'. Even when localised intervention is deemed necessary, the long-term success of such measures will be facilitated by complementary actions at the catchment and/or corridor scales.
4. Historically, localised interventions have involved 'hard engineering'. These are expensive, unsightly and frequently only partially successful. Badly conceived engineering may simply displace the problem (e.g. cause erosion downstream) or even exacerbate it. As a result, the last 2 decades have seen the emergence of so-called 'soft' or 'bio-engineering' approaches. These involve the use of a variety of plant materials, inserted or planted in ways that add cohesive strength to the banks and help dissipate the river's energy.
5. Bio-engineering approaches that have been shown to be successful include the use of live fences, live palisades and root wads. All of these involve large woody species. Work in the tropics, including research in Malaysia, has provided lists of recommended native tree and shrubs species to use for these structures. In addition, the grass Vetiver (*Chrysopogon zizanioides* L.) has been used widely in tropical regions to control erosion on steep slopes, both along roads and rivers.

6. Key to the success of bio-engineering approaches is ensuring that plants have time to establish and set down roots. This may involve constructing barriers to protect them from flow forces during the interim phase. Once established, these plants contribute to riparian biodiversity and can play important functional roles within this ecotone.

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## 1 Introduction



*River Trusan, Sarawak, Malaysia, February 2018.*

Erosion is a natural phenomenon in most rivers (Charlton, 2008) and part of the healthy functioning of fluvial systems (Florsheim *et al.*, 2008). Rivers adjust to maintain a dynamic equilibrium, and respond to external pressures (natural or anthropogenic) by modifying their dimensions, profiles and patterns (Petts and Gurnell, 2005; Gendaszek *et al.*, 2012). Rivers that show some equilibrium between erosion and deposition – to a level that depends on local characteristics – are usually described as ‘dynamically stable’ (Charlton, 2008). Human activities such as gravel mining, the construction of dams, channel engineering, deforestation and land use change are examples of external pressures that alter the dynamics and morphology of river channels - they result in instability (Kondolf, 1997). Human activities can have greater and longer-lasting impacts on rivers than natural phenomenon such as floods, droughts and landslides. A useful way to conceptualise human impacts on rivers is to recognise that if one or more external pressure changes, the river is no longer in equilibrium; it will respond by altering fluvial processes, and these in turn will alter its character.

The human occupation of river corridors renders any changes to river dynamics potentially problematic. Riverbank erosion is often perceived as a “natural disaster” (e.g. Das *et al.*, 2014) or “natural hazard” (Piégay *et al.*, 2005) that can not only cause displacement of populations but have major socio-economic and geopolitical consequences (Dragičević *et al.*, 2013; Das *et al.*, 2014). The negative impacts of bank erosion include the loss of land and associated resources, along with damage to property and infrastructure (Piégay *et al.*, 1997). In such cases, mitigating the effects of bank erosion is necessary.



Management of water and sediment at the catchment scale is imperative because of the connectivity between river channels and their hinterland. Much evidence exists that catchment-scale changes in land use, and particularly deforestation, strongly influence the hydrology and sediment dynamics of rivers (Bonan *et al.*, 2004; Coe *et al.*, 2011). Conversely, afforestation plays a role in controlling runoff and may also reduce sediment delivery to rivers (Buendía *et al.*, 2016). Growing scientific evidence of the importance of viewing catchments as whole systems has led to a major paradigm shift in hydrology over the last 20 years. This shift has coincided with a rapid evolution of tools and techniques that allow us to observe and quantify processes at such large spatial and temporal scales (e.g. remote sensing, computer modelling). Thus, we now have concepts and tools to approach sustainable river management at the most appropriate scales.

Catchment-scale modelling can provide valuable information on the risks associated with land use and land cover changes (e.g. Bussi *et al.*, 2014; Buendía *et al.*, 2016). New tools are also being developed to model bank erosion processes at the spatial (i.e. catchment) and temporal (i.e. event) scales that allow better catchment management (e.g. D-SetNet, Wilkinson *et al.*, 2014; SHETRAN, Janes *et al.*, 2018). Although this large-scale approach is crucial to ensure that the integrity of rivers is preserved, it can be difficult to convey to local communities whose interest (and understanding) tends to be at the very local scale – at the scale of eroding sections of riverbank.

Growing emphasis is given to a more inclusive, ecosystem-centred approach to river management (Brierley and Fryirs, 2005; Biron *et al.*, 2014), drawing from observations that traditional approaches may not be ecologically, socially or economically sustainable (Piégay *et al.*, 2005; Kondolf, 2011). Classic hard engineering ‘solutions’ are increasingly questioned due the frequent maintenance required (Kline and Cahoon, 2010) and the detrimental effects these can have on both river channel and floodplain habitat, as well as the connectivity between these two (Kondolf, 2011). As some form of intervention is needed when bank erosion threatens human populations, infrastructure or livelihoods (Kondolf, 2011), a broad “river-based” approach that combines geomorphological and engineering insights is most likely to be successful (Brierley and Fryirs, 2005).

Several closely related concepts have emerged to help with the development of this river-based approach – the ‘Room for the river’ (Baptist *et al.*, 2004), ‘Erodible Corridor Concept’ (ECC, Piégay *et al.*, 2005), ‘Fluvial territory’ (Ollero, 2010), ‘River corridor’ (Kline and Cahoon, 2010), and “Freedom space” (Biron *et al.*, 2014) concepts. The underlying principles of these are similar; they consist of defining a corridor in the alluvial plain, within which decision-makers and landowners agree to keep free of erosion-control structures. Their purpose is to create a balance between the environmental benefits of allowing rivers to migrate freely and the socio-economic benefits of protecting properties and infrastructures outside of the corridor (Piégay *et al.*, 2005). They represent an alternative solution to traditional river bank protection schemes at the scale of functional units (i.e. river corridors), while also integrating space for flooding (e.g. Biron *et al.*, 2014). The concepts can be difficult to implement when the whole of the floodplain valley is occupied, particularly when floodplain resources are the only way for local populations to maintain their livelihoods. In such cases, they may have to be

implemented alongside site-specific actions that recognise local needs; these actions may involve a certain degree of engineering. Thus, strategies for dealing with riverbank erosion often require adoption of a number complementary approaches.

Asia is the continent most affected by disaster-induced population displacement (IDMC, 2017), and river-related events are commonplace. For instance, about 2 million people were displaced by floods in the Yangtze River in 2016. Malaysia is subject to large floods every year, particularly during the Northeast Monsoon Season, with several casualties and thousands of people affected annually (Zafirah *et al.*, 2017). Such disasters are likely to increase in the future as a result of climate change (Arnell and Gosling, 2013), forcing local communities and decision makers to seek solutions to river erosion problems.

It is important to generate knowledge about individual systems before implementing action plans, in order to identify the most appropriate interventions and to understand the associated risks. Implementing an “objective-based” management strategy requires stakeholders and managers to define clear objectives (e.g. Dufour and Piégay, 2009). These objectives will vary depending on the context and priorities. Some may focus on societal needs (e.g. flood defence, clean water, recreation, landscape) while others may focus on natural processes or on the protection of biodiversity and/or particular species (Wohl *et al.*, 2005; Newson and Large, 2006; Gilvear *et al.*, 2012). In reality, management strategies have to balance both societal and environmental objectives while recognising that favouring one will be at the cost of compromising the other. The process of identifying priorities means that stakeholders have to define exactly where the cursor should be placed between nature and society. As well as outlining some of the specific measures that can be used to help resolve erosion issues, this report describes how they can and should be integrated within a wider framework that forces decision makers to think carefully about their decisions.

## 2 Key terms and concepts



*River Trusan, Sarawak, Malaysia, February 2018*

### 2.1 Definitions

As this report reviews good practice for dealing with issues of riverbank erosion and instability, it is important to start by defining what these and other important terms mean. Good practice also requires understanding some of the links between rivers and their catchments. This section provides definitions of some key terms and gives a conceptual overview of river-catchment links.

#### Good practice

“Good practice” is defined by the Food and Agriculture Organisation (FAO) as a practice that *“is not only good, but a practice that has been proven to work well and produce good results”* (FAO, 2014). Within the context of the conservation and restoration of freshwater habitats, the Scottish Environment Protection Agency (SEPA) refers to good practice as *“the course of action that serves a demonstrated need, while minimising ecological harm, at a cost that is not disproportionately high”* (SEPA, 2008). Several criteria can help define whether a practice is a good practice (FAO, 2014), including:

- Effectiveness and success (i.e. it is the most effective way to achieve a specific objective)
- Environmental, economic and social sustainability (i.e. it meets current needs without compromising the ability to address future needs)
- Technical feasibility (i.e. it responds to local constraints, and is easy to learn and/or implement)

- Inherent participation (i.e. it allows development a joint sense of ownership of decisions and actions amongst the community)
- Replicability and adaptability (i.e. it is adaptable to similar objectives in varying situations).

In short, a “good practice” is one that has been tested and validated as being successful and which deserves to be shared with the wider community so that a greater number of people can adopt it.

### Riverbank

Florsheim *et al.* (2008) provide a *geomorphic* definition of the ‘riverbank’ as the landform distinguished by the topographic gradient of the riverbed, along the lateral land-water margin, up to the highest stage of flow or the topographic edge where water begins to spread laterally over the floodplain. Riverbanks are often characterised by bare sediment, live vegetation, or snags (Charlton, 2008). Riverbanks are usually tightly linked to the wider riparian zone.

### Bank erosion and instability

Bank erosion refers to the collapse, failure or direct removal of material from the riverbank landform. Bank instability refers to the propensity of riverbanks to be eroded. Bank (in)stability depends on sediment characteristics (e.g. cohesiveness, porosity), vegetation and disturbances (e.g. cattle trampling). Further description of these processes and their implications are given in Section 3.

### Management

The term ‘management’ refers to any activity at any scale or level, from management *per se* (i.e. at the catchment-scale), to river corridor scale interventions and to every localised, site-specific interventions. Engineering interventions may be either traditional (hard) ones (sometimes called ‘grey’ engineering) or so-called ‘nature-based’ alternatives. Nature-based interventions typically involve the use of wood or plants and so are sometimes referred to as ‘bio-engineering’ techniques (Donat, 1995) or sometimes ‘soft-engineering’ (SEPA, 2002). All of these are detailed further in subsequent sections.

Approaches to dealing with riverbank erosion have a tradition of being site-specific and based on hard-engineering. However, the factors responsible for erosion in a particular location frequently operate at a different (larger) scale (e.g. related to land use and land cover changes in the catchment), and sometimes problems may actually stem from ill-placed or wrongly-designed engineering interventions.

Riverbank stabilisation techniques are regularly described in textbooks and manuals as ‘river restoration’ or ‘river rehabilitation’ (e.g. Rutherford *et al.*, 2000; Polster, 2008). Although they might be used as part of river rehabilitation schemes, river stabilisation should not be labelled as restoration (Gillilan *et al.*, 2005) but simply as what it is; i.e. as riverbank stabilisation (e.g. Polster, 2003). Nevertheless, parallels can be found with restoration or rehabilitation projects because of the decision-making frameworks within which actions should be designed and implemented. This framework is presented in Section 5.

## 2.2 Links between rivers and their catchments

Water and sediments are continuously transferred from upstream to downstream areas, from erosional to depositional zones and through reaches where transportation is the main process (Schumm, 1977). Although in perennial river systems water is transferred continuously, this is not the case for sediment – its movement is dictated by the frequency at which entrainment thresholds are exceeded. Transfers of water and sediment mean that rivers are inextricably linked to their catchment areas. Understanding these links helps us to understand river dynamics, and in turn to appreciate how dealing with erosion problems very often involves looking not at the river channel but its entire catchment. The inability to appreciate this link may lead to the failure, or only partial success, of riverbank management actions.

Over the last decade or so, the term ‘connectivity’ has come into common usage within hydrology to help conceptualise these links; it is particularly useful to help represent channel responses to water inputs and the wider set of connections between river channel sediment loads and water chemistry, and the processes occurring out in the catchment. Recent reviews of connectivity are given by Bracken *et al.* (2015) and (Wohl, 2017). Ward and Stanford (1989) provide a four-dimensional conceptual model that helps represent connectivity; this model is represented diagrammatically in Figure 1.

Hydrological connectivity can be defined as the water-mediated transport (flux) of matter, energy and organisms within or between elements of the hydrologic cycle. Upstream to downstream interactions constitute the longitudinal dimension (Figure 1). The lateral dimension includes interactions between the channel, and riparian and floodplain systems. Significant interactions also occur vertically, between the channel and subsurface zones – the hyporheic zone and contiguous groundwater. The fourth dimension, time, provides the temporal scale – it helps express the timescale(s) over which interactions occurring in the first three dimensions take place. Rivers develop geomorphic characters in response to dynamic patterns and processes occurring across these four dimensions.

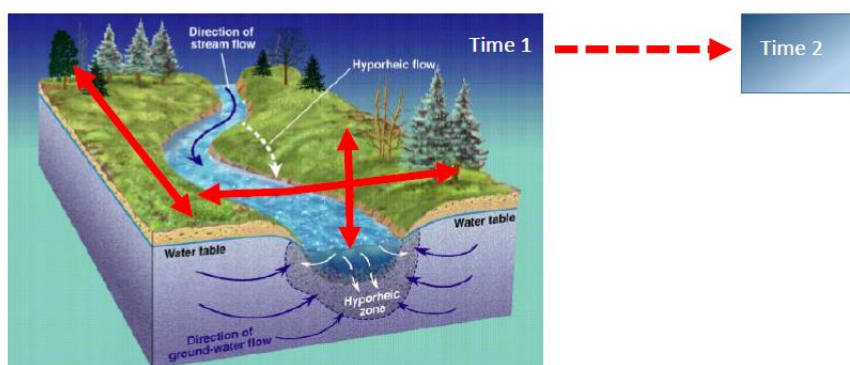


Figure 1. The four dimensions of river systems (red arrows), as defined by Ward and Stanford (1989). The three main dimensions are longitudinal, lateral and vertical. The fourth dimension is time, and represents how processes or characteristics observed at one point in time are at least partly a function of those at a previous point in time. Note that the three main dimensions are bi-directional.

The spatial structure and temporal dynamics of the pathways of connectivity are usually driven by climatic factors, but are mediated by catchment characteristics, including landscape properties such as cover, roughness and slope. This is relevant for river management, and especially for how erosion problems should be dealt with. For example, the nature of precipitation (its timing, intensity and duration) influences how channel flow responds to the input of water, in terms of runoff rates and the speed and magnitude of changes in channel discharge. In turn, these things influence the stream's energy budget (stream power and related hydraulic conditions) and consequently the possibility of channel erosion. Thus, erosion can be triggered by events or changes far away from the channel. Also, relevant for sustainable catchment management is the connectivity between catchment sediment courses and the channel network. Specifically, the spatial distribution of hillslopes where erosion occurs influences how tightly coupled the river channel and catchment sediment sources are, and this coupling determines how rapidly channel sediment dynamics respond to rainfall and erosion out in the catchment. Changes in the availability of sediment (an increase or decrease in coupling, or an increase or decrease in load) or to the river's capacity to convey sediment reaching the channel (via a change in runoff) can lead to disequilibrium.

Much research effort in hydrology has been directed at understanding the complex spatial structure (e.g. Tetzlaff *et al.*, 2007) and threshold-like dynamics (e.g. Tromp-Van Meerveld and McDonnell, 2006; Malcolm *et al.*, 2008) of the connections between hillslopes and channel networks. For the moment these connections are best understood at the scale of relatively small experimental hillslopes and small catchments; connectivity at the larger (catchment) scales where many ecological processes are evident (and where management decisions are often needed) are not well understood (Soulsby *et al.*, 2016). In general, our current knowledge of how connectivity maintains the physical and ecological integrity of 'natural' river systems is limited by: (1) the inherent complexity of water movement within and between the atmosphere and surface–subsurface systems, and (2) the extent and magnitude of human alterations, which often occur before we understand how hydrologic connectivity affects natural landscape scale ecological patterns and processes.

Headwater streams compose over two-thirds of the total stream length in a typical catchment and directly connect the upland landscape to the rest of the stream system. Altering headwater streams by channelization, diversion through pipes or landcover change is especially damaging as it modifies the production of sediment and runoff, as well as the connectivity between uplands and downstream river segments. Some of these effects are immediate and localised and, therefore, rather obvious. Less obvious are alterations in hydrologic connectivity that exhibit a time lag and which can manifest themselves at geographic locations far from the source of disturbance. These issues need to be borne in mind when trying to understand the cause(s) of erosion and planning remedial action.



## 3 Processes of bank erosion



*River Trusan, Sarawak, Malaysia, February 2018*

### 3.1 Context

Bank erosion is a significant environmental issue (Florsheim *et al.*, 2008). In most rivers, bank erosion is a natural process (Charlton, 2008) and one that is integral to the functioning of the river, including its ecosystem (Florsheim *et al.*, 2008). Fundamentally, the erosion, transport and deposition of sediment is a response to the need for rivers to dissipate energy (Schumm, 1977). Sediment eroded in one location is deposited further downstream in areas of lower energy (e.g. inside of bends, on the floodplain, in pools). When channel deposits are re-worked, former deposits are able to re-enter the system and re-integrate within the sediment cycle (Charlton, 2008). As part of this, the erosion and collapse of banks fulfils several ecological purposes, such as the renewal of habitats (riparian and instream, local and further downstream; Florsheim *et al.*, 2008), and evidence suggests that bank erosion is a necessary ecological process in rivers (Piégay *et al.*, 1997, 2005). It can represent a considerable source of sediment in some rivers (Trimble, 1997), used by fish for spawning, and so is not always deleterious (Florsheim *et al.*, 2008).

According to Charlton (2008), bank erosion is not a process in itself but is brought about by a number of processes. These can be classified in three groups:

- (1) *Pre-weakening processes* (e.g. cycles of wetting and drying) that 'prepare' the bank for erosion.
- (2) *Fluvial processes* where particles are removed by direct entrainment.
- (3) *Processes of mass failure*, involving the collapse, slumping or sliding of bank material.

As bank material is detached, it usually accumulates at the base of the bank until it is broken down or transported downstream (Charlton, 2008). The rate of bank erosion is partly controlled by the rate of

removal of this accumulated material, which acts as a protection from further erosion (Thorne, 1982). Bank erosion is therefore accelerated when material at the foot of the slope is quickly conveyed downstream, but is also controlled by the type of erosion that is occurring.

### 3.2 Types of bank erosion

Erreur ! Source du renvoi introuvable. summarises the main types of bank erosion and their general characteristics. These types are usually defined by the composition of material involved. Sands and coarser material are usually detached grain by grain, while more cohesive sediments may resist thanks to inter-particle friction and will detach as aggregates (Charlton, 2008).

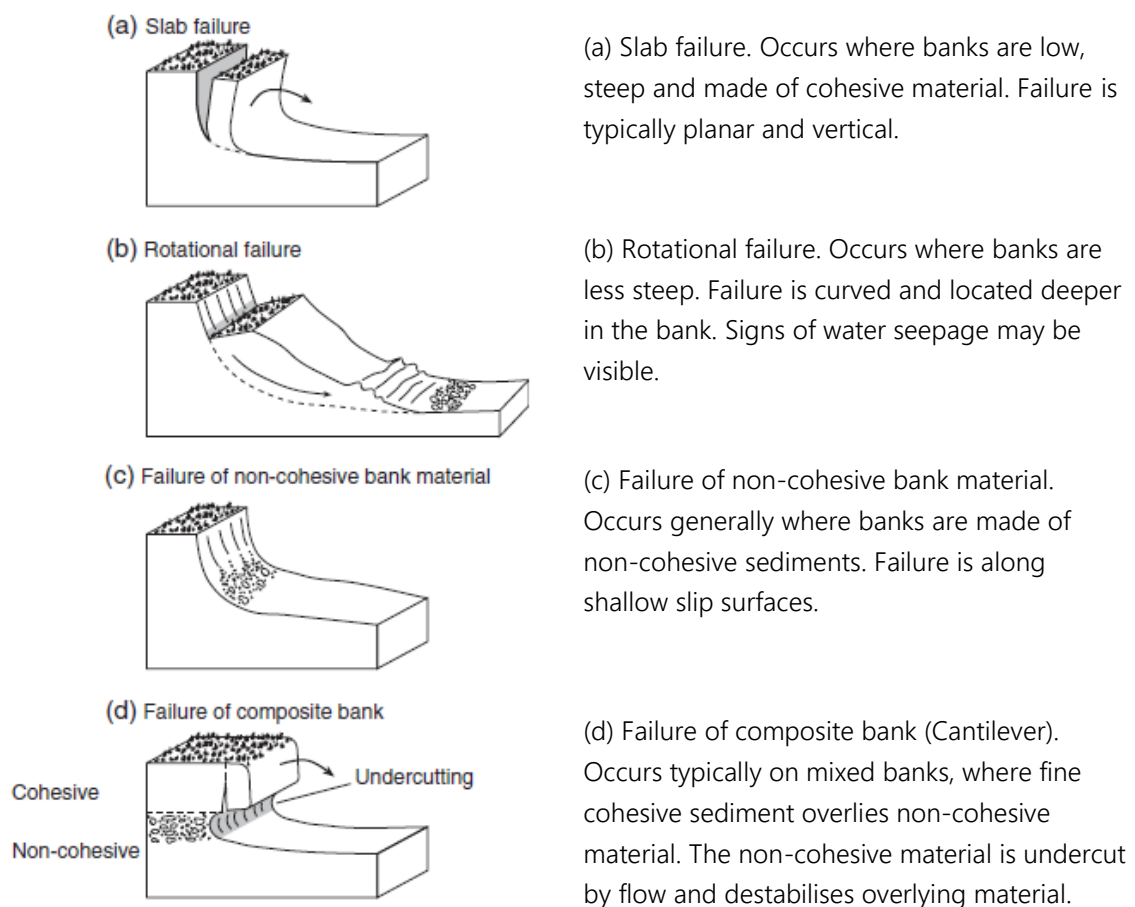


Figure 2. Main types of bank erosion (Adapted from Charlton, 2008).

### 3.3 Factors controlling bank resistance to erosion

Several factors influence the propensity of riverbanks to resist erosion, and some of these are important considerations when implementing engineering solutions. Important bank properties include material weight and texture, shear and tensile strength, groundwater level, permeability, stratigraphy, geometry and vegetation (see Abernethy and Rutherford, 1998). Bio-engineering techniques have limited impact on the weight, texture, stratigraphy and geometry of riverbanks, but

instead reduce erosion by altering bank strength, permeability and vegetation. Altering the weight, texture, stratigraphy and geometry of riverbanks are the focus of hard engineering solutions, which frequently involve the use of concrete or boulders to improve bank stability (Polster, 2003).

The presence of riparian vegetation promotes bank stability (Bartley *et al.*, 2008). For instance, Beeson and Doyle (1996) found that bends with no riparian vegetation were 30 times more likely to undergo major bank erosion than vegetated ones. Bank erodibility, and hence for example the rate of meander migration, is higher in river reaches surrounded by agricultural land than in those flanked by riparian forest (Micheli *et al.*, 2004). The density and type of vegetation cover as well as its root characteristics and density can influence bank erosion (Abernethy and Rutherford, 1998). As a result, land-use changes that remove riparian vegetation have significant influence on riverbanks (Allan and Castillo, 2007).

The moisture content of riverbanks is also an important factor, especially for cohesive sediment whose strength varies with the degree of saturation (Hooke, 1979). Matric suction forces hold water within the sediment pores. These forces increase when the soil dries out but decrease when water levels increase rapidly or the banks become saturated (Charlton, 2008). Thus, actions taken to improve water infiltration and reduce pore water content can help strengthen banks and improve their resistance to erosion.

## 4 Approaches and methods to address bank erosion problems



*River Trusan, Sarawak, Malaysia, March 2018*

### 4.1 Key aspects of good practice

First and foremost, appropriate management of river-related issues (whether it is bank erosion, flooding, fine sediment deposition, lack of habitat, etc.) should primarily focus on diagnosing and tackling the *causes*, and not simply treating the *symptoms*. History provides ample evidence that, for example, attempting to resolve flooding problems by building higher and longer levees will likely only displace the problem further downstream. Similarly, re-enforcing banks over a section of river will prevent bank erosion locally, but likely increase erosion up- and/or downstream from this section. Efforts to treat the causes of bank erosion (e.g. deforestation, bank disturbance by human activities, misuse of the river) are more likely to be effective and sustainable for riparian communities. As such, even if local actions need to be implemented in response to a critical situation, it is important for this decision to be made (i) with full recognition that it is not dealing with the cause, (ii) while also considering implications elsewhere, and (iii) in concert with the community.

Remediation solutions to bank erosion can be classified into three main categories (Erreur ! Source du renvoi introuvable.):

- Management strategies, usually implemented at a larger (i.e. catchment or sub-catchment) scale aimed at tackling the causes of erosion. Typically, they focus on addressing issues related to land cover, land management or water management.
- Corridor scale strategies which allow practitioners to identify areas of higher and lower priority. They may focus on places of high value while allowing the river to behave more naturally elsewhere.

- Engineering solutions, designed to control erosion locally (i.e. channel scale), but whose implementation needs to be thought and planned within the broader river corridor context.

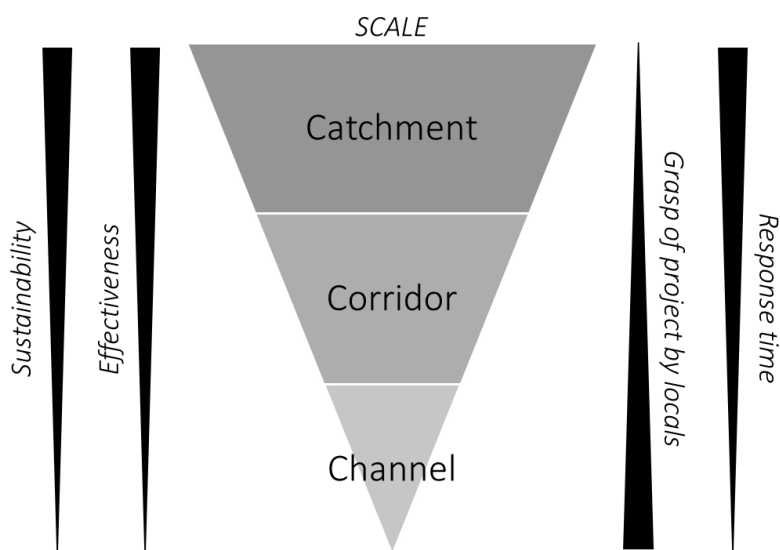


Figure 3. Conceptual representation of the different scales of actions and their related characteristics.

The remaining parts of Section 4 summarise key aspects and review current thinking about each of these categories. Section 5 stresses the need for monitoring and assessment, with Section 6 then providing some case study examples to help illustrate reasons for success and failure of actions.

## 4.2 Things to consider before implementing remediation

Valuable knowledge can be gained from previous experience, both from technical (i.e. which technique did or did not work, and why) and geomorphological (i.e. how does the system behave in response to interventions; Alexander and Allan, 2007). The clear definition of project objectives is an important starting point (Bradshaw, 1996; England *et al.*, 2008); defining these objectives can be guided by previous experience. In the absence of clearly stated objectives, stakeholders, local communities and all parties involved in the project are left at risk of being unable to determine the success (or failure) of the project, leaving individuals to assess the success (or failure) based on their own personal views and expectations which may differ from those of others. This can lead to misunderstanding, confusion and potential conflicts between stakeholders.

These objectives, along with the decision for intervention, should be based on a careful diagnosis of the river system (Hilderbrand *et al.*, 2005). The failure of many rehabilitation projects has been attributed to poor appraisal of broader scale interactions and processes (Roni *et al.*, 2008). As such, both pre- and post-action evaluations are important (Bernhardt and Palmer, 2011; Pander and Geist, 2013) across a range of scales. The diagnosis of river conditions is most suitable when done as 'dynamic' (as opposed to 'static') (Rutherford *et al.*, 2000). For example, bank erosion should not only be assessed on the basis of how bare the banks look, but efforts should be made to describe changes



in conditions over time or by using hydrodynamic models to study erosion patterns in a dynamic way (e.g. simulating effects of different stressors).

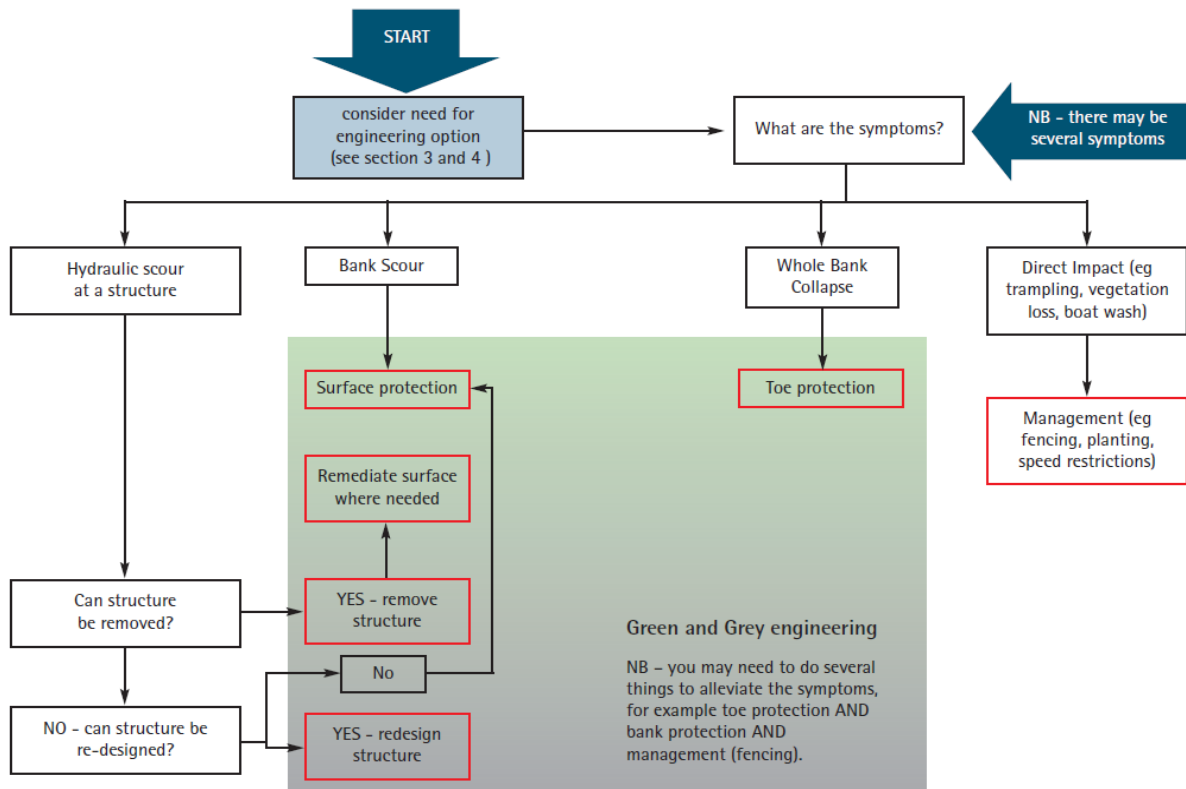


Figure 4. Solution selection tree for best practice in riverbank stabilisation (Source: SEPA, 2008).

One of the basic principles of good practice is to consider all alternatives options (SEPA, 2008). The best practical environmental option can only be determined if all alternatives are considered beforehand, and the possibility of using a combination of measures (perhaps at different scales; Figure 3). To help with decision making, SEPA (2008) has created a decision tree to guide the choice of remediation solutions (Figure 4). Following the philosophy of good practice, the underlying concept of this decision-tree is to avoid engineering solutions wherever possible. Similarly, so-called 'green' engineering (i.e. nature-based techniques) should be favoured over 'grey' (i.e. hard) engineering.

### 4.3 Catchment-scale management strategies

#### 4.3.1 Forest protection

The destruction of primary forest ecosystems creates substantial damage to biodiversity (Berry *et al.*, 2010; Edwards *et al.*, 2011), produces important carbon emissions (Bryan *et al.*, 2010; Martin *et al.*, 2015) and has significant consequences for soils and waterways (Douglas *et al.*, 1992; Douglas, 1999; Girmay *et al.*, 2009; Coe *et al.*, 2011). Among all the ecosystem services provided by forests, they perform two key roles in relation to catchment functioning: the regulation of floods and soil erosion (Zafirah *et al.*, 2017). Examples can be found in the literature where catastrophic floods and deterioration of river conditions can be related directly to large scale logging (Bruijnzeel, 2004).



Malaysia is a known hotspot of tropical deforestation (Hansen *et al.*, 2013), particularly for industrial logging (Bryan *et al.*, 2013). Despite efforts to reform the logging industry, with the intention of preventing undesirable environmental and social effects while maintaining wood production (e.g. Reduced-impact logging, Blaser *et al.*, 2011), history has shown that these have been inefficient, at least in western Malaysia (Bryan *et al.*, 2013). Comparisons of forest cover in Malaysian Borneo and Brunei, where logging policies are radically different (i.e. forest protection in Brunei, selective logging in Malaysia) have revealed that preventing the logging of natural forests altogether remains the only viable approach to protect primary ecosystems (Bryan *et al.*, 2013). These authors have shown that protection schemes in regions where logging is authorised are not enough to limit forest destruction. It is worth stressing that most reduced-impact logging strategies are implemented with the goal of limiting impact on the forest while sustaining income for the logging industry; strategies rarely address the need to protect streams and rivers (Putz *et al.*, 2008).

Limiting (and ideally forbidding) the destruction of primary forests, or indeed other the degradation or loss of other natural landcover types, is an absolutely critical part of successful catchment-scale management of river health – it is a preventative measure, without which management is left only with the possibility of addressing the symptoms.

#### 4.3.2 Soil and water conservation practices in an era of climate change

The consequences of global warming differ around the world and several models exist to predict likely effects in different ecoregions (e.g. Hussain *et al.*, 2017). As for Malaysia, and South-East Asia in general, all predictions agree on an increase in mean annual precipitation and increased frequency and magnitude of extreme events (Amin *et al.*, 2016; Hussain *et al.*, 2017). An increase in rainfall, particularly in the form of intense events, will likely exacerbate soil and channel erosion, especially in vulnerable areas. Thus, good land management practice becomes even more imperative in an era of climate change.

The World Organisation for Conservation Approaches and Technologies (WOCAT) aims to develop efforts to prevent and reduce land degradation through the implementation of effective Sustainable Land Management (WOCAT, 2008). They recommend a variety of measures for land and water conservation, which they separate into categories of structural, agronomic and managerial.

(i) Structural measures are local actions that can be implemented to control surface runoff and fine sediment delivery to streams and rivers. These include the construction of retention systems such as furrows, terraces, ponds, bunds, hedge barriers and grass strips (WOCAT, 2008). However, their efficiency can be limited in time (i.e. rapid fill of retention systems) and space (i.e. little impact at catchment outlet) (Dagneu *et al.*, 2015). Additionally, badly designed soil and water retention structures may exacerbate global erosion (e.g. Ethiopian highlands, Mitiku *et al.*, 2006). Thus, local structures should be implemented as part of a strategic management plan, targeting (when possible) both agronomic and other usages of the land (Mitiku *et al.*, 2006; Dagneu *et al.*, 2015).

A key structural measure is floodplain retention. Over the last two decades this has become a key part of catchment- and corridor-scale approaches to managing flood risk and associated river erosion in many parts of the world. Major reviews of the benefits of and approaches to designing floodplain retention now exist, including estimates of capital costs of the associated engineering works (European Commission, 2006). Many detailed case studies exist for managers to learn from (see for example <http://nwrn.eu/list-of-all-case-studies> and <http://nwrn.eu/guide/files/assets/basic-html/index.html#1>). In general floodplain retention is only appropriate for larger catchments (a minimum of 10-100 km<sup>2</sup>) and where channel and floodplain gradients are within certain bounds (Habersack *et al.*, 2015), but where it can be used multiple benefits will accrue (European Commission, 2006).

(ii). The agronomic measures identified by WOCAT (2008) are practical actions that can be implemented to limit land degradation through changes in crop management. The main reasons for soil degradation in relation to agriculture are:

- Over-exploitation of vegetation for domestic use, or as a result of overgrazing;
- Erosion of soils by surface run-off during rainfall events;
- Soil compaction by cattle or heavy machinery;
- Soil crusting by raindrop splashing;
- Reduction of buffering capacity of wetlands because of drainage.

Other types of degradation can also be linked to poor crop management (e.g. pollution or loss of fertility), although these are not directly causing changes in the hydro-sedimentary dynamics of catchments so are not considered further here. The majority of factors listed above increase surface run-off (water is conveyed quickly to the stream network) but also increase the volumes of fine sediment delivered to river channels. Practices to improve crop management (Mitiku *et al.*, 2006; WOCAT, 2008) include:

- Preventing the drainage of wetlands;
- Maintaining a constant vegetation cover (even between crops) or use mulching techniques to protect soils;
- Developing rotational sequences of different crops (i.e. inter-cropping, sequential cropping, relay-cropping);
- Favouring zero or minimum tillage techniques or, when necessary, favour ploughing in contour/parallel to the slope;
- Improving timing and frequency/intensity of activities;
- Favouring compost and green manure to chemical fertilisers;
- Limiting cattle and machinery access to water-logged soils;
- Reducing the degree of mechanisation when possible.

(iii) Sustainable land management practices are best combined with other good practices, such as agronomic measures (WOCAT, 2008). For instance, maintaining grass strips along ditches and streams

helps slow surface run-off and reduce fine sediment delivery to the river network (Douglas *et al.*, 1992; Mitiku *et al.*, 2006). Similarly, tree hedges allow for a better retention and infiltration of surface water.

According to Wilcove *et al.* (Wilcove *et al.*, 2013), the profitability of logging and oil palm agro-industry makes protection of unlogged forests very expensive. Selective logging leaves a long legacy of disturbance (Luke *et al.*, 2017) that may be reactivated by rare large storms at any time; thus the time-scale of impact and recovery is much longer than usually anticipated (Douglas *et al.*, 1999). According to some authors, efforts to make oil palm plantations greener have so far yielded no significant benefits in terms of biodiversity conservation (Berry *et al.*, 2010; Wilcove *et al.*, 2013) and have only limited effects on river systems (Gibson *et al.*, 2011). Consequently, active protection of forests, such as the development of National Parks and other land protection schemes, are the most efficient way of maintaining river integrity and biodiversity (Edwards *et al.*, 2011; Gibson *et al.*, 2011).

The large extent and importance of rice paddies in Asia has ensured that they have been the focus of considerable interest. Much work has been done to understand and assess their social, cultural and economic importance, and increasing numbers of studies are being undertaken to assess their environmental effects. Most paddies have been in place for centuries and have profoundly shaped alluvial floodplains. Unlike many other forms of agriculture, paddies need to be flooded for part of the year, and usually during the wet season when rivers are likely to flood. Hence, they can help with flood retention and attenuation (Taniyama, 2002; Chen *et al.*, 2014). Active research on rice cultivation exists (e.g. International Rice Research Institute, <http://irri.org/>) and knowledge of how to improve production (e.g. <http://www.knowledgebank.irri.org/>), optimise fertilisation and limit impacts on biodiversity is being shared (e.g. ILEIA, 2013), although these resources include no recommendations in relation effects on rivers *per se*. While the precise hydrological effects of rice crops depend on the nature of the paddies (whether terraced paddies on hillslopes or those on floodplain areas) and local management (e.g. height of the water retention bunds surrounding individual fields), enough is known in general to argue that their influence on flood-related erosion is generally of less concern than other human activities on the floodplain.

## 4.4 Sustainable management at the river corridor scale

### 4.4.1 Freedom space

This approach is based on the philosophy that a healthy river can “heal itself” (Kondolf, 2011), and so places emphasis on respecting the physical and ecological processes occurring in rivers (Biron *et al.*, 2014). Where human infrastructures are threatened by flooding or severe erosion, hard engineering approaches remain a necessity (Kondolf, 2011). However, there are examples where channel stabilisation through engineering practices have actually exacerbated bank instability and worsened the problem (Brierley and Fryirs, 2005). Several authors have thus worked on defining alternative solutions by applying hydrogeomorphic processes and concepts (i.e. concepts that describe and

apply to river biophysical dynamics and their intimate relation with catchment water, sediments and energy budgets).

Application of hydrogeomorphology concepts involves combining Geographical Information System (GIS) or Remote Sensing analysis (e.g. aerial photographs and Digital Elevation Models) with field observations (Biron *et al.*, 2014). GIS data allow for the determination of key river attributes, such as bankfull discharge and floodplain width, along with understanding of the temporal evolution of the main channel (Biron *et al.*, 2014) and modelling of channel erosion sensitivity (Piégay *et al.*, 2005). Combining data in this way helps ensure connectivity across the four river dimensions (Section 2.2) is addressed.

Field assessment provides records of features of interest, such as stabilisation structures, zones of active bank erosion, qualitative grain size distribution, etc. Zones of past erosion (i.e. extent of past meandering patterns) and zones of future potential erosion can be modelled from field data and combined to define the 'erodible' or 'fluvial' corridor boundary (Figure 5 and Figure 6). The purpose of this approach is to define areas where more 'freedom space' can be allowed for the river to meander and dissipate its energy, and areas where bank protection is necessary due to the presence of settlements, agriculture or infrastructure. This 'give-and-take' approach is based on the principle that a trade-off is required to balance the need for the stabilisation of sections of the fluvial corridor by leaving zones of expansion. This type of river corridor scale planning has been applied successfully to many areas, including ones with different types of valley geometry and different levels of human activity (e.g. Piégay *et al.*, 1997, 2005; Larsen *et al.*, 2007; Biron *et al.*, 2014). The underlying principles are very simple, but their application to help develop management solutions requires high quality data (ideally long term) and analyses.



Figure 5. Schematic of the erodible river corridor concept. Left: illustration of historical changes in meanders, along with the boundaries of the erodible corridor. Right: illustrative example of assessment of the erosion hazard and risk within this erodible corridor (Source Piégay *et al.* 2005)

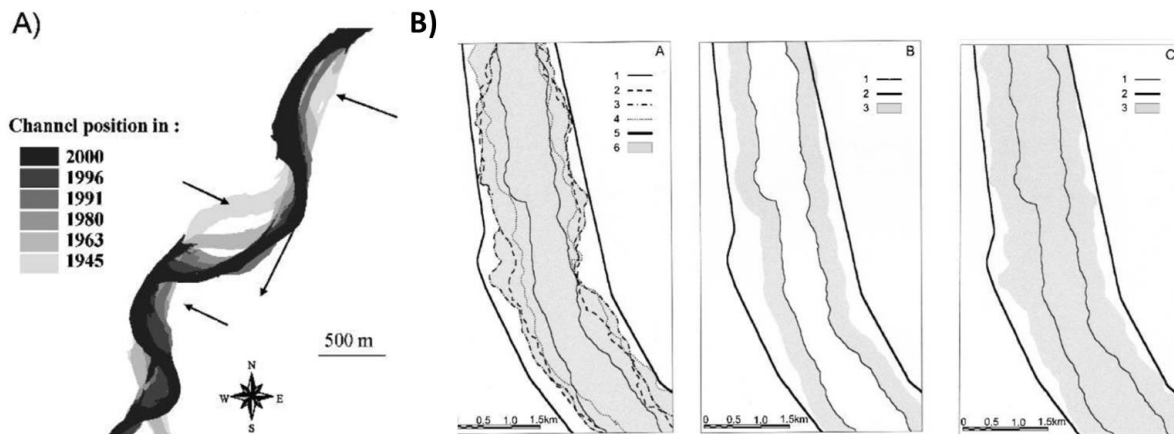


Figure 6. Information provided from aerial photographic analyses and modelling for two rivers: (A) schematic map showing six successive channel positions within a reach of Ain River, France, between 1945 and 2000, and (B) Definition of the erodible corridor along the Tagliamento River (Italy) through a geomorphological historical analysis. (B<sub>A</sub>) Identification of the corridor of channel shifting during the last 200 years: 1, active braided channel in 2001; 2, active braided channel in 1954; 3, active braided channel in 1891; 4, active braided channel in 1805; 5, levee; 6, corridor of channel shifting during the last 200 years. (B<sub>B</sub>) Possible erosion zones in the next 50 years: 1, active braided channel in 2001; 2, levee; 3, possible zones of erosion in the next 50 years. (B<sub>C</sub>) Erodible corridor: 1, active braided channel in 2001; 2, levee; 3, erodible corridor. The erodible corridor results from overlaying the corridor of historical channel shifting (B<sub>A</sub>) with the possible zones of erosion in the future (B<sub>B</sub>). (Source: adapted from Piégay et al., 2005).

#### 4.4.2 The riparian zone

More than any other area, retaining natural riparian cover is critical – poor or good management here can have disproportionately negative or positive impacts, respectively, on hydrogeomorphic processes. Allan (2004) highlights that riparian clearing also has a considerable influence on other processes occurring in rivers and streams. For example, canopy opening reduces shading, causing increases in stream temperatures and light penetration (Hannah et al. 2008; Malcolm et al. 2004). High temperature may be unsuitable for sensitive fish species. Increased temperature and light also favour vegetation growth and can result in algal bloom or the obstruction of rivers by macrophytes. Riparian vegetation also represents a key supplier of food for in-stream biota across the entire food-web, from dissolved and particulate organic matter to terrestrial invertebrates. It is also an important habitat for many terrestrial animals (beetles, amphibians, birds, etc). Alterations to these sources of nutrients and habitat may alter the entire trophic structure of rivers corridors. Restoring wooded vegetation along degraded river banks can contribute to restoring these processes as well as offering a natural protection against erosion. These benefits should not simply be considered as incidental ‘side effects’ of retaining riparian trees; instead what should be stressed when planning management is the absence of such benefits when traditional engineering solutions are used.

## 4.5 Remediation actions at the channel scale

### 4.5.1 Non-engineering solutions

Bank erosion can be generated or aggravated by factors which do not necessarily require engineering solutions, such as cattle trampling, recreation activities, vehicle access or burrowing by animals (SEPA, 2008). In such cases, erosion can be prevented simply by managing the problematic activities or controlling access to the river. Fencing cattle out of the river channel will prevent trampling of the banks and improve conditions for the establishment of riparian vegetation. Building bridges (particularly suspension bridges) can reduce the damage caused by vehicles crossing the river channel. Controlling the proliferation of burrowing animals will reduce their impact on bank erosion.

### 4.5.2 Nature-based engineering solutions

Traditional engineering methods designed to control riverbank erosion usually involve rip-rap, boulders or concrete elements. However, alternative solutions exist that rely on the use of vegetation (particularly wood). Examples of stabilising the banks of canals using willows can be found in the Middle Ages in France and the Netherlands (Donat, 1995), but this approach was later replaced by “hard” engineering with the development of civil engineering as a discipline and increasing urbanisation. Only in the mid 1950’s were plant-based techniques revisited and improved (Donat, 1995). A wide range of these bio-engineering techniques now exists, with different applications depending on local characteristics (local vegetation, degree of erosion, type of soil, slope, etc.) and hydraulic constraints. The general objective, however, remains similar; use the retention power of vegetation and its root system to control erosion.

Bio-engineering techniques have both technical and non-technical advantages compared to hard-engineering ones (Donat, 1995):

- Technical advantages: protection against both bank and surface erosion, increase of slope stability by root reinforcement, increase of water infiltration via the root system;
- Ecological advantages: improvement of soil water regime via interception, evapotranspiration and storage of water, regulation of stream water temperature, provision of habitat for riverine species;
- Economic advantages: lower construction and maintenance costs;
- Aesthetic advantages: better fit into the landscape.

An additional advantage, which can be of significance in remote areas where access is difficult, is that most bio-engineering techniques do not require heavy machinery (which can damage sites).

Bio-engineering techniques should be based on locally-sourced vegetation species. This increases the chances of success (e.g. Petrone and Preti, 2010). They are particularly recommended when (1) hard-engineering techniques are evidently inappropriate, or (2) where, due to administrative, legal or financial constraints, larger scale management strategies are unable to address the root cause of the problem (SEPA, 2002). Additionally, bio-engineering can be used as part of a suite of measures



applied at different scales. Nevertheless, it is important to recognise that two main geomorphic issues can arise from all types of bank stabilisation measures (Florsheim *et al.*, 2008): (1) they alter fundamental geomorphic processes, and (2) they may be ineffective over the long term, depending on their design capacity relative to flood recurrence intervals.

The section below summarises some of the most common bio-engineering techniques that can be applied to tackle bank erosion. The decision of which to use should be made via careful diagnostics of the problem and an understanding of the river system where they are to be implemented. The techniques summarised below have proven successful and all are potentially useful within Malaysia; others exist in the literature, but were not considered relevant to the tropical systems that are the focus of this review.

### Brush mattress

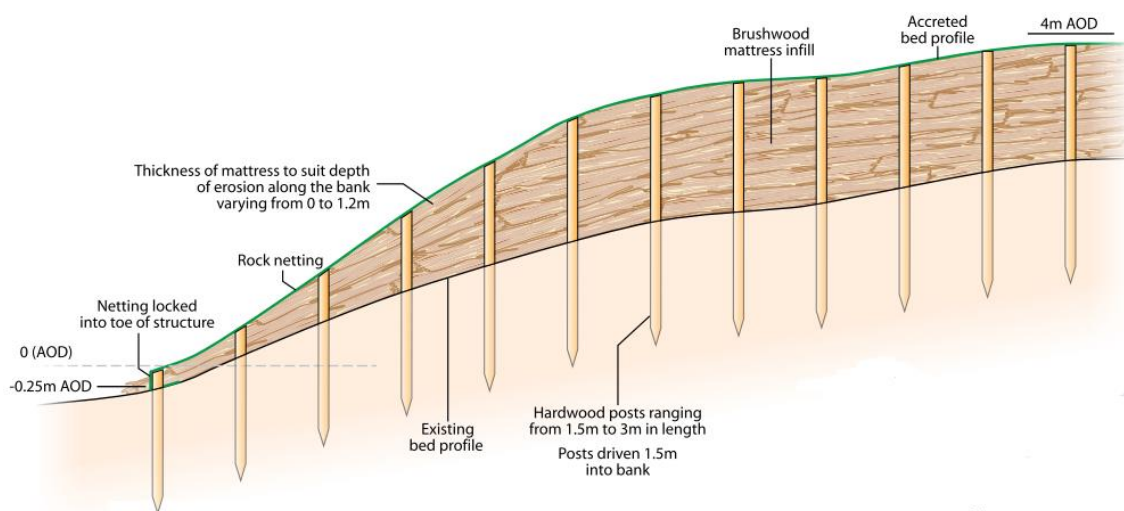


Figure 7. Example of brush mattress (Source: RRC, 2013).

This technique aims at the direct protection of eroding banks by covering them with live cuttings (Figure 7). These are placed perpendicular to the stream, with the butt ends buried in a small trench at the toe of the slope. Twine or wire is then used to tighten the cuttings to the streambank. Alternatively, the butt ends can be arranged to face upstream, and the branches overlapping like shingles; this directionality is justified as limiting the risks of woody debris destroying the mattress. Brush is held in place by posts.

### Live fencing or fascines

Live fences are protection built at water level in order to prevent the direct scouring of riverbanks (Polster, 2003). They consist of living cuttings laid perpendicular to the river, attached to wooden (possibly living) stakes and secured with wire or twines. The butt ends of the fascines/fences are inserted in the riverbanks. These structures are placed in the eroding bends and are typically arranged so that the upstream ends are located at the tangent point between opposing curves (Figure 25Figure 8). The structures are then filled with local material.

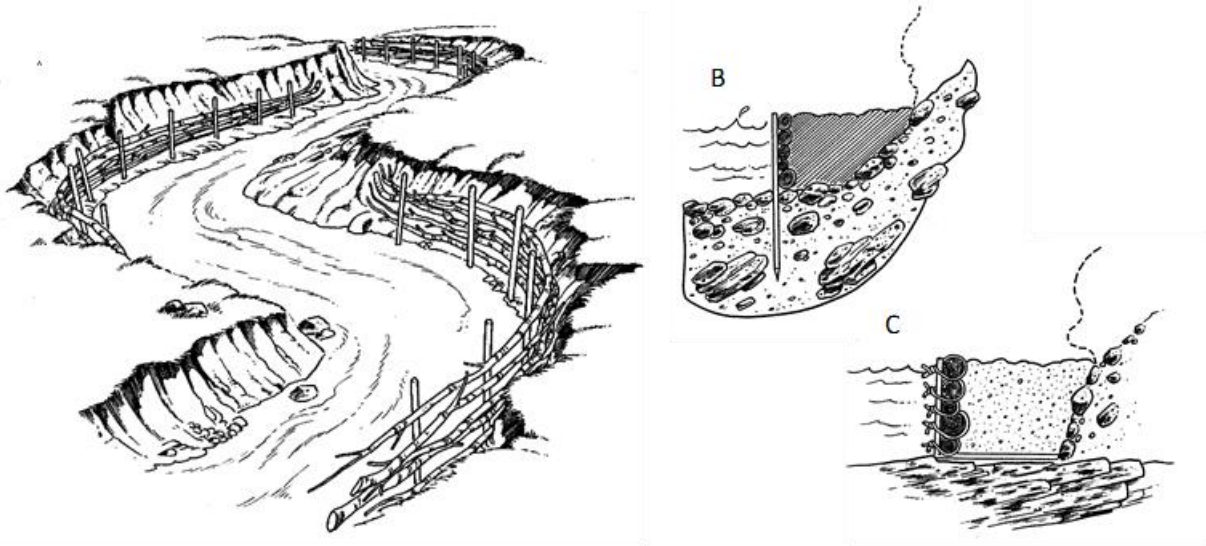


Figure 8. A- Live bank protection, used to control erosion of outside curves (backfill removed from drawing for clarity). B- Illustration of live fencing over unconsolidated bed material, and C- over a bedrock controlled channel (Source: Polster, 2008).

This technique can be improved by planting the backfills with cuttings of local tree species. The fences will protect the banks while the cuttings will develop roots and leaves, providing longer-term bank stabilisation solutions and all the additional benefits related to riparian vegetation.

#### Brush layers

Brush layers are horizontal rows of cuttings, buried either in a cut slope (Figure 9A) or a fill (Figure 9B) (Polster, 2003). This technique is particularly useful where eroded banks need to be rebuilt (e.g. Erreur ! Source du renvoi introuvable.B), and in areas where local slope is great. Long cuttings are inserted into the material fills as they are constructed; they act to directly increase shear resistance and thus reduce the risks of bank failure, but also improve bank stability by developing roots within the fills (Polster, 2008).

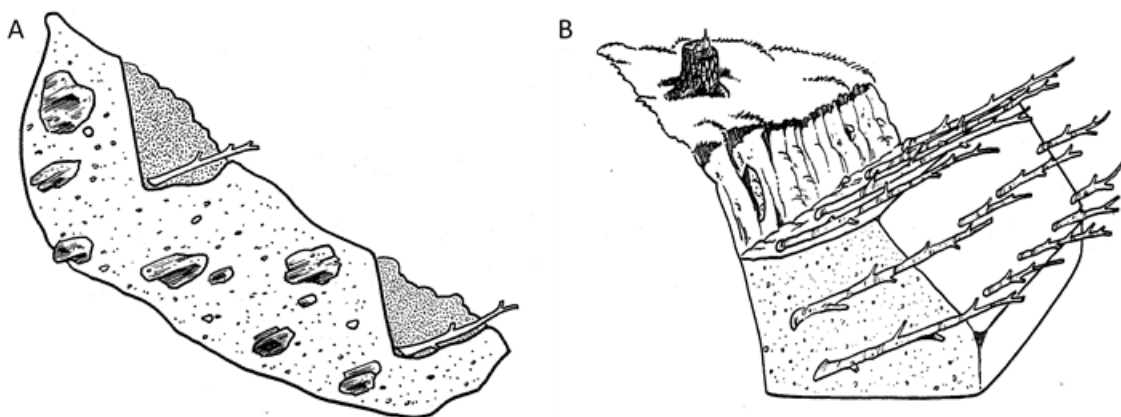


Figure 9. Brush layers are used on a cut slope (A) or to treat a slump (B). Source: Polster (2008).

### Live palisade

The objective of live palisades is to create a wall of trees along the riverbanks that are eroding or at risk of erosion (Figure 10) (Polster, 2003). Their purpose is to develop a dense root network that prevents major erosion. They are planted as a row two to three meters from the wetted edge. Long cuttings are used for live palisades, and are inserted down to the water level. They may consist of a variety of tree species, with additional cuttings inserted inside the trench to improve local diversity.

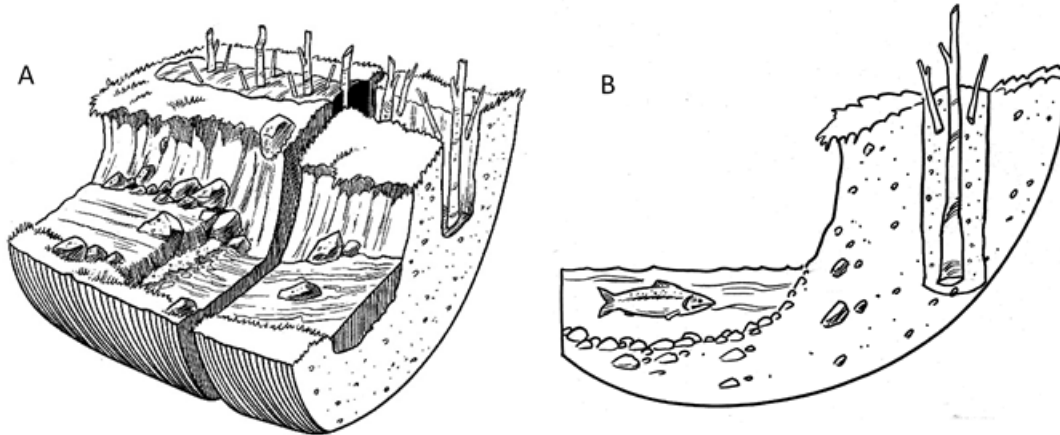


Figure 10. Illustration of live palisades, used to provide a row of dense root systems. A- Bank view and B- cross-section view of palisades (Source: Polster, 2008).

## Root wads

Root wads are made from large branches or felled trees (Erreur ! Source du renvoi introuvable.) and are used to deflect erosive flows and promote sediment deposition at the base of the banks. They are usually placed on the outer bend of eroding sections (RRC, 2013). Trunks are forced into the banks with the roots/branches exposed; these increase roughness and help dissipate energy. However, care should be taken as to where wads are placed due to the increased risk of scour at very high flows (SEPA, 2008).

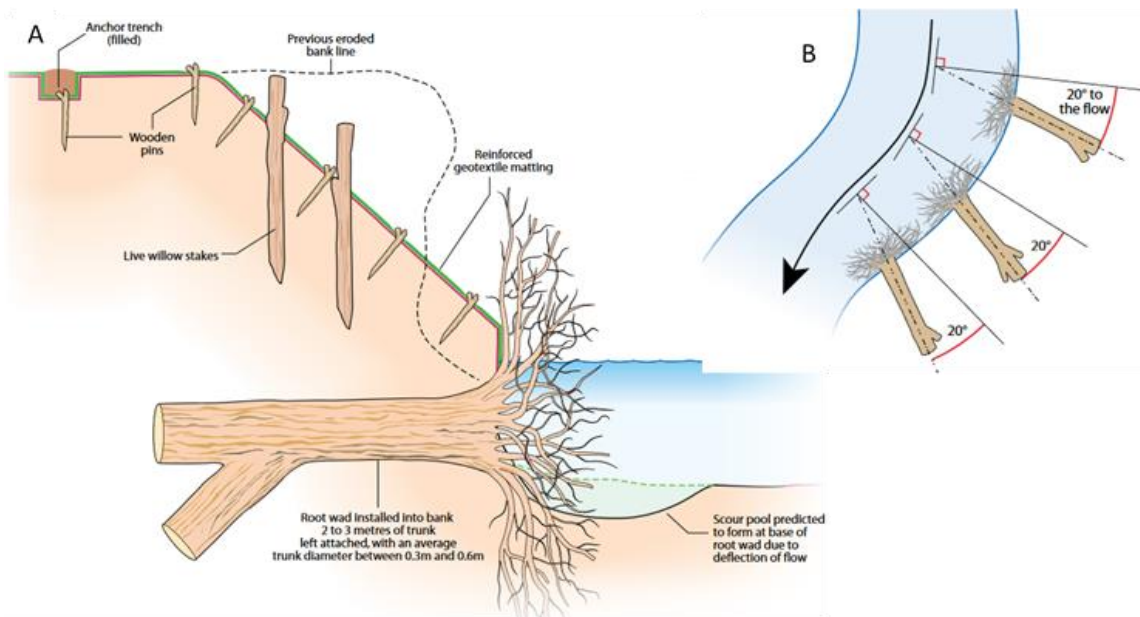


Figure 11. Illustration of root wads, using large woody debris (Source: RRC, 2013).

## Other techniques

Several techniques are found in the literature and can be used to tackle more specific issues, e.g. to control the erosion of high steep slopes, increase the stability of bars, enhance siltation and sediment deposition inside bends or prevent surface erosion (e.g. cordons, branch packing, live stacking, live siltation). For further details, the reader is referred to Polster (2003), Polster (2008), RRC (2013) or Baird *et al.* (2015).

### 4.5.3 Choosing the right species

The choice of species to use for bank and slope stabilisation is crucial, as not all species will be efficient and those with features of interest may be optimum when used under certain conditions (e.g. Saifuddin and Normaniza, 2016). Key physical parameters that define plant suitability for bank stabilisation include root system density, tensile strength, pull-out capacity and root morphology (Ali, 2010; Saifuddin and Normaniza, 2016). Their ecological properties are also important, as plants need to survive within the environment where they are placed. For instance, some may resist long dry period or permanent high soil moisture, while others may not. Norris *et al.* (2008) argue that plants used for such techniques should primarily meet the following criteria:

- Be pioneer plants that grow rapidly under given conditions (i.e. degraded land, steep slope, etc.)
- Have dense and deep rooting systems
- Have rapid rooting ability and extensive coverage
- Have fast and simple propagation, such as cuttings







Other practical requirements need to be considered, most notably the economic cost to the local population of the measures, the availability of suitable species (e.g. in local nurseries), the size of plants when mature, and their form, spacings, etc. (Norris *et al.*, 2008). The primary focus should be on the use of local plant species (Saifuddin and Normaniza, 2016) which can (and should) be chosen in concert with local communities and/or experts (e.g. Petrone and Preti, 2010). Choosing local native species will increase success of the planting and reduce long-term maintenance requirements (Norris *et al.*, 2008).

Some authors have tested plant species that are found in Malaysia for their root mechanical properties and their potential use for bank and slope stabilisation (e.g. Ali, 2010; Saifuddin and Normaniza, 2016). Those that were listed as suitable for bank and soil protection include:

- Black wattle (*Acacia mangium*)
- River tamarind (*Leucaena leucocephala*)
- Copperpod (*Peltophorum plterocarpum*)
- Malay padauk (*Pterocarpus indicus*)
- Sympoh ayer (*Dillenia suffruticosa*)
- Singapore rhododendron (*Melastoma malabathricum*)

Beyond the physical resistance properties of the roots themselves, Saifuddin and Normaniza (2016) argued that the architecture of the root systems defines conditions under which a given plant should be used (e.g. slope steepness, soil properties, position on the slope) (Table 1). Plants with shallow but dense and wide root system are better placed on top or toe of banks, while deep-type root systems should be placed in the middle of the slope (Figure 12).

Table 1. Root characteristics of main Malaysian plants tested in the literature. Sources: Saifuddin and Normaniza (2016), Hengchaovanich (1999), Ali (2010).

Species	Root characteristics				Remarks	
	System type	Tensile strength	Root diameter	Depth of 80% of root biomass (cm)		
<i>Acacia mangium</i>	H-type		+	++	60	Large roots but system not so dense, medium depth
<i>Peltophorum pterocarpum</i>	R-type		++	+++	-	Small roots but dense system, medium depth
<i>Leucaena leucocephala</i>	VH-type		+++	+	80	Very deep anchorage of main pivotal root
<i>Pterocarpus indicus</i>	VH-type		++	+++	60	Deep anchorage of rather dense system
<i>Dillenia suffruticosa</i>	M-type		+	+++	30	Shallow soil Dense system of small roots Top and toe of banks/slopes
<i>Melastoma malabathricum</i>	M-type		+	++	30	

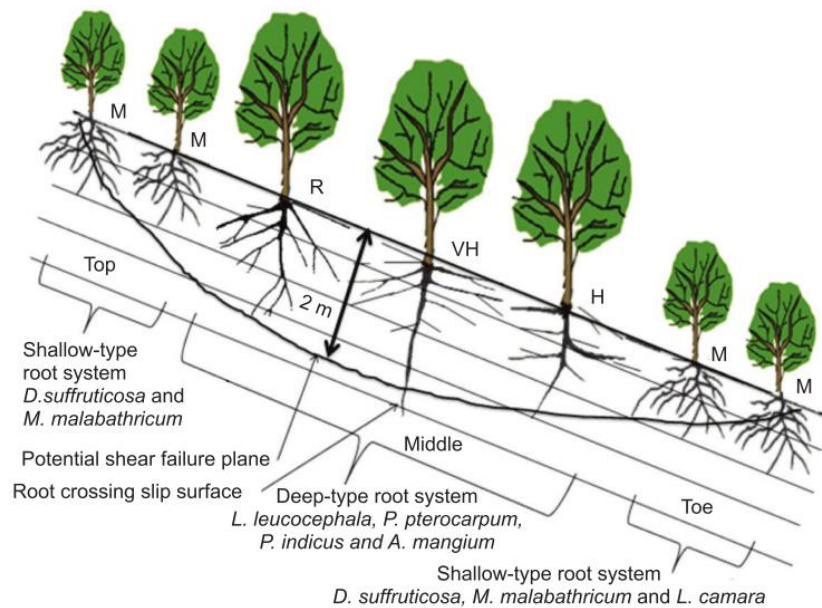


Figure 12. Suggested position of plants along a slope profile based on their rooting architecture and characteristics. Source: Saifuddin and Normaniza (2016).

### Grass species

Because the purpose of bank and slope stabilisation techniques is to prevent further erosion and/or degradation, it is important that the actions taken are effective rapidly. One of the issues of using nature-based solutions is the need for plants to grow and develop before being able to stabilise the riverbank. As reported by Norris *et al.* (2008), it is particularly important during this “interim” phase of tree growth to use pioneer and fast-growing plants whose root system will develop quickly. In order to fulfil these needs, the use of grasses has expanded recently, and particularly in Asia (Truong *et al.*, 2008). Of particular interest is the use of Vetiver (*Chrysopogon zizanioides* L.), a plant classified as a grass but whose characteristics resemble those of trees (Hengchaovanich, 1999). Originally from India,



evidence of the usage of Vetiver in Malaysia exists since the early 1900s, for the purpose of stabilising steep banks (Grimshaw and Helfer, 1995). It has been used widely across Asia as permanent hedges and for soil conservation by sugar cane farmers for decades, particularly in arable fields with steep slopes (Grimshaw and Helfer, 1995). It is successful for soil retention and steep slope stabilisation (Truong *et al.*, 2008), though has also been used for waste-water treatment and phyto-remediation of contaminated land and water. It is recommended by technicians, academics, planners and government officials in many tropical countries (e.g. Figure 13).

Vetiver has unique morphological and physiological characteristics that have made its use commonplace (Hengchaovanich, 1999; Truong *et al.*, 2008). It can grow very fast and quickly develop large, deep and thick root systems (to 4 m deep). It is rather tolerant to drought periods and offers some resistance to flowing water because of the absence of ligneous stems. Once planted, the formation of underground shoots allows the plant to resist fire, frost and heavy grazing pressure. It has been used successfully for bank stabilisation in medium high acidity, alkalinity, salinity and sodicity

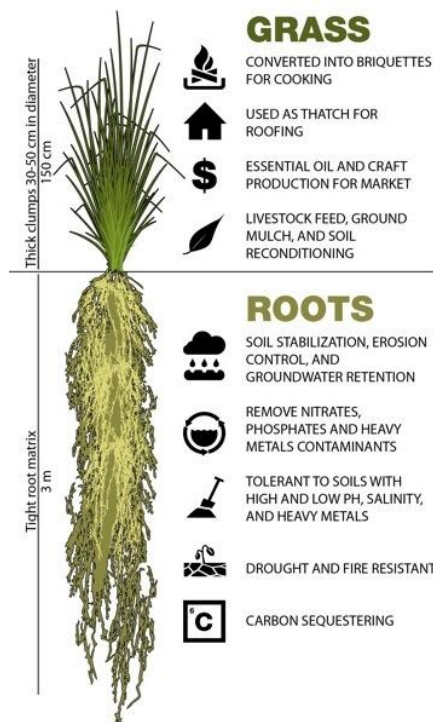


Figure 13. Vetiver and its main uses  
(Credit: Dr. Chandra Shekhar Gupta,  
[www.fragrantica.com](http://www.fragrantica.com).)

conditions. However, like many tropical grasses, it is intolerant to shading. Finally, Vetiver presents limited risks of invasiveness; it produces neither stolons nor rhizomes and mostly spreads via root subdivision. It has been used for decades in some tropical countries (e.g. Fiji, India) with no signs of invasiveness (see Grimshaw and Helfer, 1995; Truong *et al.*, 2008 for more details).

### Woody species

As detailed above, local woody plants can be used for bank stabilisation; they can be dead or recently cut, used as stakes or woven together to form a fence (e.g. live fencing or fascines). Some authors argue that bamboo represents an interesting alternative in South-East Asia (e.g. Hengchaovanich, 1999). Bamboo grows naturally, rather fast and in large densities in Malaysia and possesses a high

strength-to-weight ratio. Examples of its use in the protection of expressway embankments in Malaysia are reported by Hengchaovanich (1999). It can be used for live fencing, brush or palisade.

#### 4.5.4 Summary of local measures

Figure 14 integrates information provided above to illustrate the effectiveness of different plant groups over time.

- Bamboo can be used to construct a physical barrier and provide immediate protection for heavily eroded banks. Some bamboo trees may generate roots and take part in further enhancing bank protection, although most elements will slowly decay and disappear over time;
- The void between the newly constructed fences and the top of the bank needs to be filled with locally-sourced soil;
- This soil should be covered with Vetiver plants, which will quickly provide improved strength (typically about 1 year). Vetiver will play a crucial role in bridging the gap between the need for immediate physical protection and the development of trees and shrubs which requires more time;
- Other local species should be planted among the Vetiver, with the objective of providing longer-term protection. These will need more time to grow and develop, with their root systems expanding further and more deeply. As the trees and shrubs develop, they will increase shading locally and start controlling naturally the expansion of Vetiver. All planted species will eventually form part of the riparian plant community, which brings additional ecological benefits to the river.

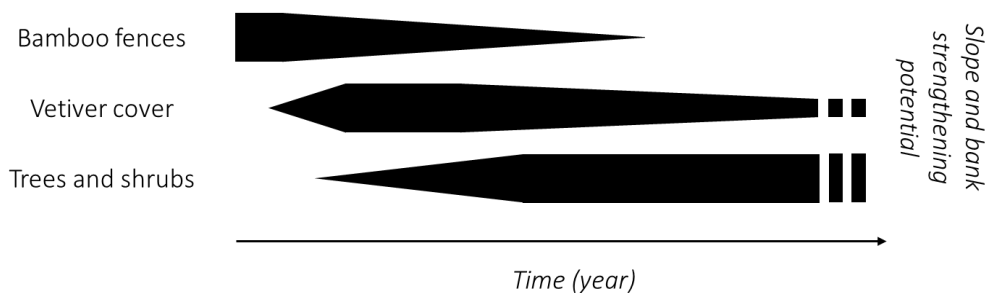


Figure 14. Successive evolution of the strengthening potential of the different components proposed for sustainable nature-based bank stabilisation.

## 5 The need for pre- and post-project monitoring and appraisal



*River Trusan, Sarawak, Malaysia, March 2018*

As with any river restoration or management action, it is vitally important that the effects of any work are assessed; this involves both pre- and post-project monitoring. Such assessment is key to determining whether project objectives have been achieved, and therefore whether the project can be considered by all stakeholders as being successful. This part of the process links back to the need to set out clear project objectives that are agreed upon by all; if the project has been conceived and designed properly, what constitutes 'success' for each objective will have been explicitly discussed and agreed upon at the outset. The objectives may fulfil different needs for different stakeholders, be ranked in order of importance or priority, and may have explicit timescales (i.e. they may represent, for instance, short and medium-term goals).

Assessing whether objectives have been achieved requires some sort of post-project monitoring and appraisal. Appraisal should focus on each of the objectives and, where these have explicit timescales, be undertaken over an appropriate timeline. The monitoring and appraisal needs to be done in such a way that it can address the following:

1. Whether objectives have been achieved.
2. If they have not been achieved, the appraisal or data collected through the monitoring need to be able to identify why not.
3. It needs to provide information that help redesign actions if previous ones have not been successful; i.e. it needs to provide the basis for adaptive management.

Ensuring these can be addressed needs careful thought, and so post-project monitoring needs to be planned just as rigorously as the management actions themselves (e.g. Jungwirth *et al.*, 2002; Palmer *et al.*, 2005; Friberg *et al.*, 2011; Pander and Geist, 2013).

The results of remediation work represent valuable sources of knowledge to the scientific community as well as to practitioners, land managers and local experts. Unfortunately the opportunity to learn from projects has all too frequently been lost because of the complete lack of or limited post-project monitoring (Wohl, 2005). Often this lost opportunity results from limited or poorly balanced project budgets. Sometimes the need for monitoring has been neglected altogether, while sometimes its importance has not been appreciated and so too small a proportion of project budget has been set aside for monitoring and appraisal; the result is that data collected post-project are inadequate to either properly assess success or underpin adaptive management.

Project objectives need to build on an accurate understanding of the river system and its processes. Poor appraisal of broader scale interactions (connectivity across the 4 dimensions) is the reason for the failure of many river management projects (Roni *et al.*, 2008). This was referred to as 'The myth of the cookbook' by Hilderbrand *et al.* (2005) – this represents the idea that a successful project cannot necessarily be applied elsewhere as similar-looking systems may exhibit considerable differences in variables that regulate processes. Misguided or overambitious objectives can be prevented by making the best use of local community knowledge. In addition, although they may be non-specialists, staff from local government or non-government agencies develop considerable knowledge of their systems, and this is highly valuable in the decision-making process (Kelly, 2014).

It may be the case that objectives cannot be set immediately – general goals may be discussed and agreed upon at the beginning of a project, but some initial monitoring or assessment may be required in order to set goals which are 'SMART' (Figure 15). In other words, a key part of the initial stage of any project is to undertake whatever work is necessary to help define SMART project objectives. Figure 16 shows a model structure and information flow for river management projects, including those focused on bank remediation.



Figure 15. The definition of 'SMART' goals and objectives (Source: <https://career.uconn.edu/blog/2016/10/20/developing-long-term-career-goals/>).

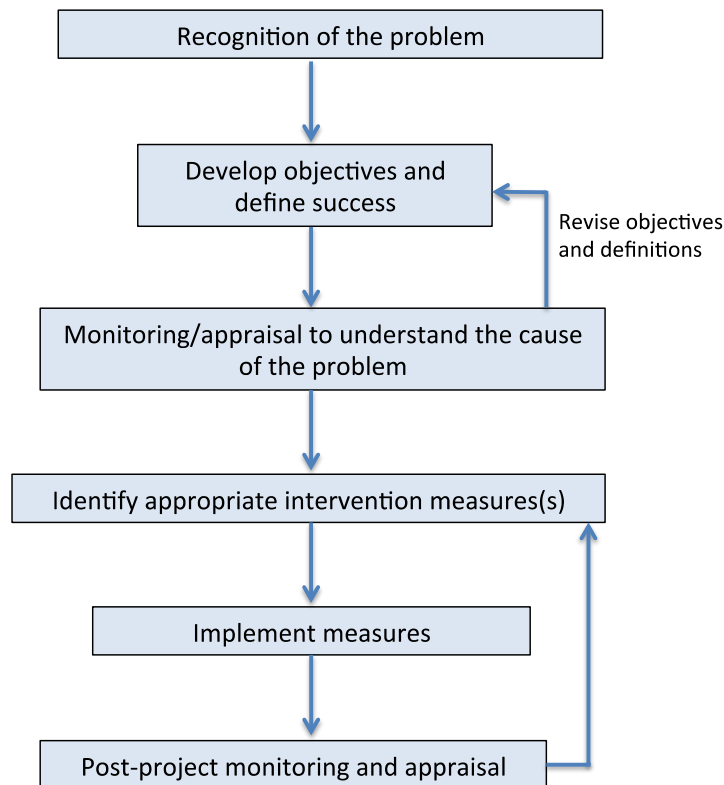


Figure 16. Optimum structure and information flow within river management projects. Feedback occurs at two key points. The first is after monitoring or appraisal has been undertaken to understand the problem. This understanding may require project objectives to be revised and new definitions of project success to be articulated. The second follows the post-project appraisal. Insights provided by this may cause some new measures to be identified, to help deal with any unanticipated consequences of the initial measures.



## 6 Case studies of bank erosion management



*Ben Gill, a tributary of the River Ehen, Cumbria, UK, May 2018.*

This section provides examples of successes and failures in the management of bank erosion. Where possible, examples are drawn from South-east Asia or other Tropical regions, though as catchment and corridor-scale initiatives are rare here, some case studies are drawn from Europe. Although specific aspects of the solutions presented in other countries may differ from what is possible in Malaysia, the philosophies and principles underpinning projects, as well as certain physical aspects, remain transferable.

### 6.1 Catchment-scale management: The River Tarland Initiative

The River Tarland is a 70 km<sup>2</sup> catchment located in North-east Scotland. Impetus for the project came more than 20 years ago and was initially focussed on tackling flooding issues experienced in the village of Tarland. In recognition of the need to tackle problems at cause and in an integrated way, the 'Tarland Catchment Initiative' was set up. The project is managed by the James Hutton Institute (JHI), a partly-government-funded research centre which aims to provide policy advice to help develop sustainable natural research management strategies. Information on what JHI thoughtfully termed 'Your Tarland Catchment' and the work undertaken in the last two decades can be found on the project website: <http://yourcatchment.hutton.ac.uk/2012/04/24/30> (see Figure 17).

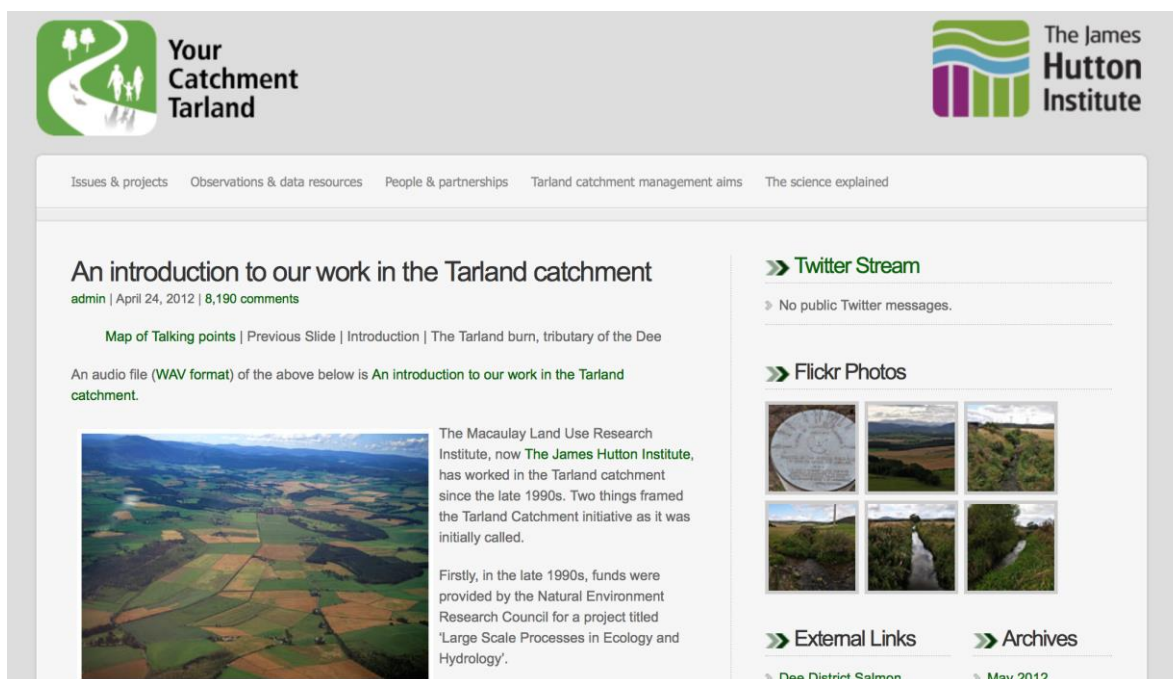


Figure 17. Screenshot of the web site of the Tarland catchment project (site accessed May 2018) (Source: <http://yourcatchment.hutton.ac.uk/2012/04/24/30>)

The Tarland Initiative is a partnership between researchers, land managers, regulators, and the local community. The overall goal is to promote better catchment-scale management, to help manage flood risk, to improve water quality and promote biodiversity within the catchment, as well as to increase awareness of catchment management more generally. The Tarland Burn is a tributary of the River Dee, a large river that is of historic, cultural and economic importance. The main stem River Dee and its tributaries are designated a Special Area of Conservation under the provisions of the European Habitats Directive. The Tarland is the most upstream tributary of the Dee that is dominated by intensive land use; 25% of the Tarland catchment area is under arable farming, while plantation forestry covers 19%, improved and unimproved grassland 36 and 10%, respectively, heather moorland 8%, and mixed broadleaved woodland 2%. The only settlement is the village of Tarland which has around 650 inhabitants.

The Tarland forms part of the wider UK River Restoration network; it both draws on best practice from other areas and is itself an exemplar catchment within the network. Stakeholders have been involved in the establishment and prioritisation of a range of actions. In the very first phase of the project, farmers and practitioners were informed via formal and informal meetings about catchment management, environmental issues facing the catchment, and the need for intervention. To get the messages across and to learn from the experience of land managers and farmers, a number of meetings have taken place – often based around visual graphical display of information that is readily understood and discussed with non-specialists (see [www.macaulay.ac.uk/tarland/](http://www.macaulay.ac.uk/tarland/)). A steering group was set up following the initial meetings, formed by the principal land managers (the MacRobert Trust) together with Agency and research staff (Scottish Environmental Protection Agency, Scottish Natural Heritage, JHI, and Aberdeenshire Council). This group has taken the available information and



views expressed by the stakeholders, together with their individual expertise, and through consensus agreed on the priority, scale, and type of interventions that have been needed.

For all the individuals and organisations involved, there has been a need to improve the level of understanding of how a catchment operates and to highlight some of the pressures and constraints. This understanding has been developed by scientists based at JHI who, along with collaborators at universities and government agencies, have set up several long-term monitoring projects within the catchment. General awareness of particular issues in the catchment, along with this scientific understanding, led to development of management goals and objectives. The steering group had to modify the scope of the interventions to try to ensure they met with other requirements. For example, some planned buffer strips were widened to incorporate a community footpath network, which in turn provided increased awareness of the role and importance of buffers. Discussions have resulted in a greater willingness to undertake intervention.

Most relevant to this review are aspects of the project that deal with flooding and related degradation of the river environment. The project managers have been careful to take a catchment approach, facilitated by good relations with farmers and local communities. Work has been undertaken to disseminate information on good land management, both to limit flooding and its impact and to help prevent soil loss from the valuable agricultural land. This has involved providing advice on harvesting practices (timing, more sustainable approaches) but in particular better management of riparian areas. Many tributaries within the Tarland have been planted with riparian buffers strips (Figure 18-20) to help with flood attenuation, and to limit runoff of fine sediment and excessive nutrients from fertilizers. Better livestock management (e.g. drinking areas) helps limit impacts of cattle on the river channel.

Actions in the Tarland extend across the three scales outlined in earlier sections of this report – catchment management (e.g. floodplain retention land husbandry) involving all landowners and land managers, corridor scale actions including planting of riparian buffers etc, and local scale actions related to riverbank management to minimise flooding in the main settlement of Tarland. In themselves, the specific actions undertaken are not novel or innovative, so the key lessons that can be learnt from the project relate to the generic reasons why it has been successful. These can be summarised as:

- The size of the catchment means that it is amenable to management; specifically, it is small enough that 'catchment management' truly involves the whole catchment
- It has clear project goals, jointly developed by all stakeholders
- It has involved a range of interventions implemented at all three scales
- The different interventions are planned in a spatially integrated way
- It benefits from longer term commitment by JHI, enabling monitoring of actions and their effects



Figure 18. Screenshot of information on the Tarland project web site, illustrating some issues and management being implemented in riparian areas. Upper photos show a section of stream before and just after the creating of a riparian buffer zone. The lower plates show a section of stream before and after a fence was moved further away from the stream channel with the goal of minimising trampling by cattle; the fence was set back around 5 metres (set as a multiple of the channel to keep cattle away from the riparian area, which was planted with samplings (Source: <http://yourcatchment.hutton.ac.uk/2012/04/24/30>).

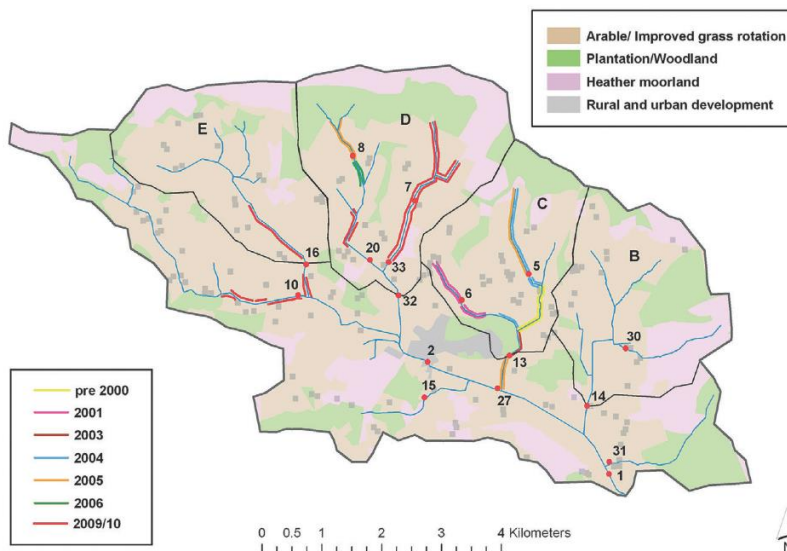


Figure 19. Tributaries of the Tarland where riparian buffers have been created (coloured lines) and monitoring stations (numbered points) where a range of water quality, physical habitat and ecological data are collected (Source: <http://yourcatchment.hutton.ac.uk/2012/04/24/30>).

## Stream-bank Buffer Strips Provide Multiple Benefits

Marc Stutter | May 18, 2012 | 3,244 comments

### What are buffer strips and how can they help?



Catchment riparian areas are considered key zones in which to target mitigation measures aiming at interrupting the movement of pollutants from agricultural land to surface waters. Hence, unfertilised buffer strips have become a widely studied and implemented 'edge of field' mitigation measure assumed to provide an effective physical barrier against nitrogen, phosphorus and sediment transfer across them.

The James Hutton Institute has led an initiative to look at wider aspects of managing buffers to achieve a number of multiple diffuse pollution mitigation, stream and riparian habitat and social functions. A workshop was held in 2010 in Ballater, UK to highlight research on riparian buffer strips brought together under the EU COST Action 869 knowledge exchange programme.

Figure 20. Screenshot of the on page from the Tarland Initiative web site promoting actions related to buffer strips (Source: <http://yourcatchment.hutton.ac.uk/2012/04/24/30>).

## 6.2 Corridor-scale management initiatives: an example from France (Piégay *et al.*, 1997)

This study reports on one of the first attempts to apply a process-based approach to river management at the corridor scale in France. It was designed with the philosophy that *"respecting fluvial geomorphological processes and satisfying riverside landowners are considered to be of equal importance"*. It was brought forward by local organisations who recognised that not all unstable banks can be protected, because of costs and the short-term effects of traditional engineering solutions (30% of previous bank stabilisation projects had been damaged within a few years). On the other hand, there was an increasing demand from local landowners for the protection of their land from erosion.

The comprehensive approach set out by Piégay *et al.* (1997) was based on 3 elements: (i) a study of channel mobility and behaviour, in order to evaluate natural hazards and erosion potential; (ii) a study of risks, undertaken by comparing maps of erosion with maps of land use and economical value; and (iii) an opinion poll, to integrate landowners' desires and vision of the river. From these different elements, a sustainable management plan was proposed and tested with riverside dwellers.

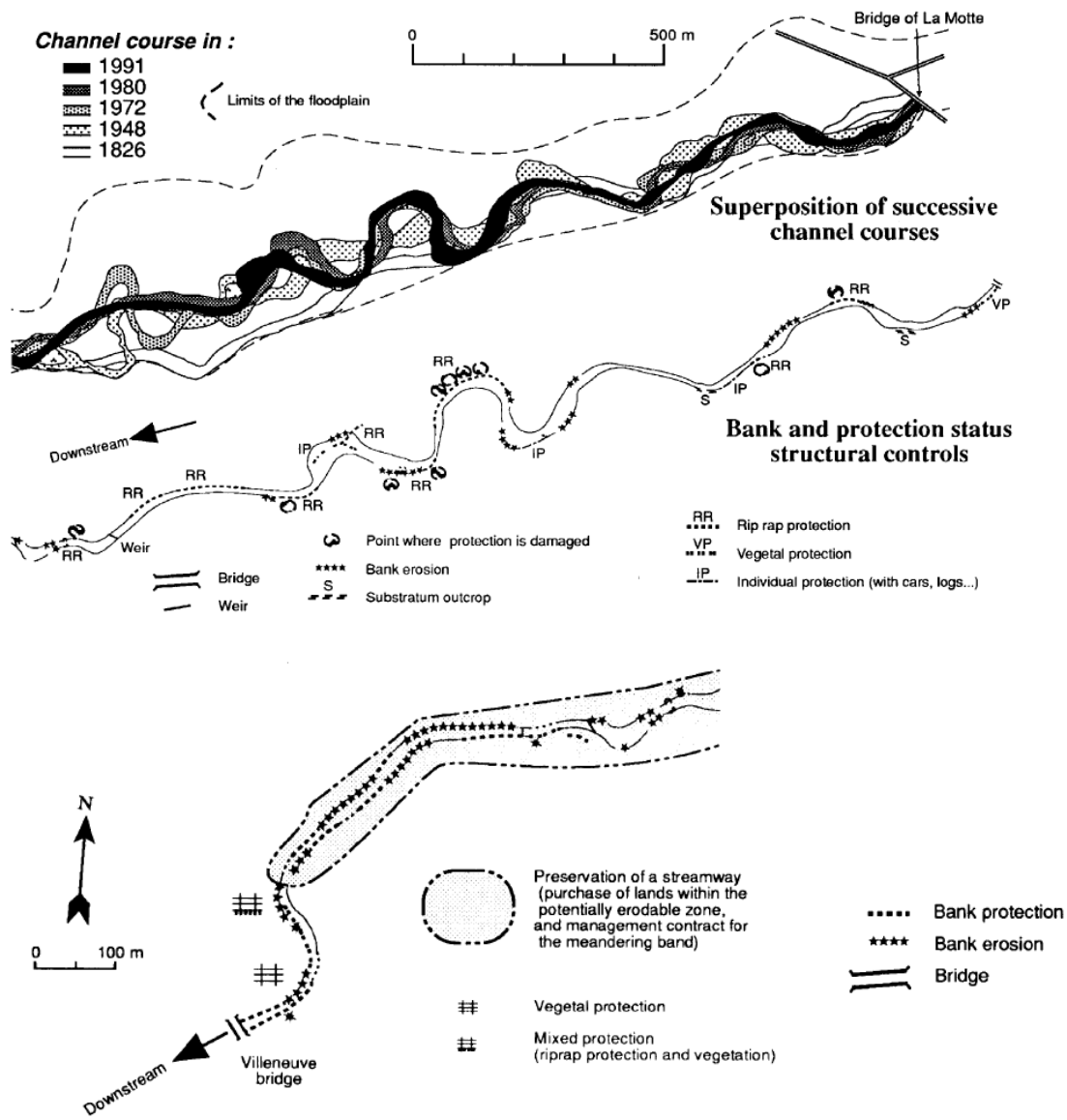


Figure 21. Some key outputs from the work of Piégay et al. (1997) on the Galaure River, France. Upper: Long term changes in meander patterns. Centre: Schematic of existing bank protection measures along the same section. C: example of proposals for bank protection in a sub-section of the river.

This approach was successful in identifying river areas with different degrees of stability. Having access to aerial images from back in the 1850s, they were capable of retracing the historical evolution of their 45-km study reach and were able to infer how much urban settlements had impacted the river’s room for mobility, and how this was now translated into so-called “bank instability” issues. The authors also identified that 67% of landowners believed bank protection should be applied along the entire corridor, although most of the population considered that local governments should be paying for it.

The mapping of bank erosion and land use/value allowed the definition of a strategic plan for a sustainable management of riverbank erosion along the entire corridor. This plan included only limited active bank protection along urbanised sections, on the basis that room should be given for the river to meander in areas of lower economic but higher ecological value (i.e. wetlands, open fields,

etc.); this plan was presented and explained to riverbank landowners and dwellers. After a detailed description of the plan and an explanation of the rationale of the project were presented, 73% of the locals saw it as an alternative to complete traditional engineering intervention, but that it needed to be accompanied with some compensatory measures scheme. The authors advocate that, although it is not always possible, State purchase of land is a viable solution, particularly on the long-run. Other compensatory measures can be offered in exchange for the creation of buffer zones along the river where no action is taken to protect the banks.

The main limitation to application of this type of scheme to other areas relates to the fact that it was proposed by a local State organisation with significant financial capacity; this capacity allowed involvement of academic experts and river management professionals to provide guidance, as well as the costs of the works themselves. This is difficult to apply in places where local landowners are left to work independently or with only limited support, and where plans are sketched by villagers. Nevertheless, the hydro-geomorphological approach used by the authors and the scale at which it was applied remain valuable and applicable everywhere around the globe; what is needed is the resource to support it and framework that allows for the project structure presented in Erreur ! Source du renvoi introuvable. to be implemented.

## 6.3 Channel-scale bank stabilisation initiatives: examples from all parts of the world

### 6.3.1 Root wads, USA

This technique is advocated where root wads are locally available and access to the banks is relatively easy. In the example shown in Figure 23, a combination of root wads, log deflectors and live stakes (on slopes) were used with success in a fast-flowing bend in a stream in the USA. Vegetation quickly expanded in the area and (from Figure 23C) flows seem to be deflected further instream, decreasing the risks of erosion at the foot of the bank.

Although no data exist about its efficiency, Figure 22 illustrates the installation of root wads in the same stream. Provided that the trunks are well embedded in the bank, they provide strong resistance to the flow, and the roots decrease velocity at the foot of the bank and increase sedimentation locally. Vegetation can quickly expand and cover the exposed root wads.





Figure 23. Photos of a fast-flowing river bend where a combination of root wads, log deflectors and live stakes were used for bank stabilisation: (A) before work, (B) just after the end of stabilisation work, and (C) 2 years after the work. (Source: Rob Cronauer, Westmoreland Conservation District, 2016).



Figure 22. Photos of a river bend where root wads were installed to prevent further erosion: (A) before work, (B) just after the end of stabilisation work, and (C) 2 years after work. (Source: Rob Cronauer, Westmoreland Conservation District, 2016).



### 6.3.2 An example of plant selection for bank stabilisation in a humid tropical area (Nicaragua, Petrone and Preti, 2010)

A village in central Nicaragua was subject to soil erosion and slope instability (including riverbanks) because of deforestation and poor land management. Since discussion with the powerful landowners was difficult, and remediation solutions not possible at the catchment scale, the local community voiced the need to find a low-cost and 'easy to use' solution to prevent slope erosion. The requirement was to trial and then more widely implement slope protection and bank stabilisation techniques using local vegetation, and with minimum costs. To do so, the authors of this study selected a few native plant species, which can be found in large quantities, and decided to experiment with two bio-engineering techniques (live palisade and live crib wall). The plants used were also chosen based on their tolerance to differing soil conditions, their shoot propagation properties, and their size at adulthood. As shown in Figure 24, the techniques were successful in protection slopes (A and B) and banks (C and D) from erosion. In addition, their tests revealed that some species were better suited for riverbank protection (i.e. closer proximity to water table) but failed to survive on dryer soils, and vice-versa.



Figure 24. Photographs of the live palisade (A) just after construction and (B) 18 months after construction; and photographs of the crib wall (C) just after and (D) 1 year after construction. (Source: Petrone & Preti, 2010).

The authors also reported additional, more general, conclusions about their bioengineering experience. First, they found that bioengineering techniques are far cheaper to put in place in so-called developing countries than in Europe, and are financially sustainable for local communities as they require very little equipment. Second, they concluded that the involvement of local landholders

was important in the success of the project. The knowledge gained from this experience, both technically and ecologically (i.e. selecting the right plants for the right type of work) is highly valuable for future projects and easily transferable to other communities.

### 6.3.3 Bank protection using Vetiver: a common practice in south-east Asia

Numerous examples can be found of the use of Vetiver for slope stabilisation in tropical countries (e.g. Hengchaovanich, 1999; Truong *et al.*, 2008; Ghosh and Bhattacharya, 2018). Given the initial success of this technique for stabilising slopes along highways, it has subsequently been used widely for riverbank stabilisation (e.g. Jaspers-Focks and Algera, 2006; Man *et al.*, 2011). Different tests have proven that Vetiver can efficiently prevent erosion from rapid draw downs (Jaspers-Focks and Algera, 2006), it can resist high velocities and steep slopes (Ghosh and Bhattacharya, 2018), and it is also resistant to flash-floods (Man *et al.*, 2011).

Man *et al.* (2011) relate examples of the use of Vetiver from Vietnam (see Figure 25). Following disastrous events in 1999, when a typhoon crossed the central coast of Vietnam and caused severe damage due to high waves and floods, the government of Vietnam (with the aid of the international donor community) gathered efforts to launch a Natural Disaster Mitigation Partnership. The main purpose of this partnership was to develop appropriate and effective management and infrastructure



Figure 25. Photographs of riverbank stabilisation using Vetiver in an estuary (A, before & B, after work) and along a large river (C, during & D, after work) (Source: Man *et al.*, 2011).



solutions for the mitigation of natural disasters, but also to strengthen community-based management of these disasters.

Summarising experiences from different countries, Ghosh and Bhattacharya (2018) describe how Vetiver requires 2 to 3 months for initial establishment, during which the plants need to be protected from grazing and high flow velocities. Newly planted Vetiver requires careful periodic inspections until it is fully established. It then becomes self-repairing and requires little maintenance. Nonetheless, although Vetiver can resist some degree of drought and salinity, it still requires enough nutrients to thrive and can be sensitive to shading. In addition, there are ways for local communities to gain economically from Vetiver - some examples exist of the exploitation of Vetiver for oil extraction (for medicinal use) and basketry (Ghosh and Bhattacharya, 2018). Care needs to be taken to plant the species in appropriate locations (Figure 26), as it does not always establish successfully.



Figure 26. Examples of limited success, caused by (A) shading and (B) poor soil fertility. (Source: Man et al. (2011)).

#### 6.3.4. The importance of gaining local support: example from Australia (Rutherford et al., 2000)

In their Rehabilitation manual, Rutherford et al. (2000) relate a story illustrating the importance of appropriate public communication:

*“A catchment authority employed consultants to assess the condition of streams in a large catchment, and to develop priorities for managing them. Part of the task was to map and categorise the condition of all frontages on large streams. The consultants walked the length of the larger streams, categorising the frontages, and eventually produced a GIS map of priority and problem areas. The plan was technically sound and may even have worked except... The GIS map was presented at a public meeting. Some influential farmers discovered, to their surprise, that the river frontage to their properties was coloured red and labelled ‘very poor condition’. The farmers, predictably, were offended by this, and the river managers lost support for their plan even before it was fully presented. The issue here is not whether the assessment of frontage condition was correct (it probably was), but of how this ‘fact’ was managed. It will take a lot of work to get the affronted farmers back on side, let alone involved in the stream rehabilitation procedure. Without their support, the ambitious plans will not be achieved.”*

## 7 Key points

1. Rivers are dynamic systems that, even in the absence of human pressure, erode their banks. In their natural state, they exist in what is referred to as a 'dynamic equilibrium' – that is, they are not stable, but alter their course and characteristics within certain bounds. It is important to recognise that the processes of erosion, transport and deposition of sediment occurring within these bounds are critical for helping to maintain the physical and biological integrity of the river system. Thus, the goal of river management should not be to prevent erosion *per se*.
2. Decisions about the need for intervention in cases of perceived erosion should start by recognising when human pressures have caused a river to shift beyond its normal bounds. These pressures may be local to the point where erosion is occurring, they may be upstream or they may be out in the wider catchment. Very often, there are multiple pressures, and they may interact in complex ways.
3. Interventions should be conceived and implemented as part of a strategic plan that recognises (i) the spatial relationships between cause and effect, and (ii) that badly conceived interventions in one location may exacerbate the problem in that location or simply transfer the problem to somewhere else.
4. The goal of intervention should always be to tackle the cause(s) of the problem rather than treating local symptoms. Very often this involves working upstream from the erosion or out in the catchment; and it may mean dealing with a very localised problem at larger scales (the corridor or catchment scale). Successful intervention may require difficult decisions – for instance, 'giving back' land to the river.
5. Many bio-engineering approaches to combatting local erosion exist, using a variety of woody and non-woody plants. Enough evidence has now been amassed to show that when planned and implemented carefully, these can be successful. This often requires a suite of long and short term, local and larger scale measures to be implemented in parallel – e.g. using short term protection to allow plants roots to develop on the eroding slope, while at the same time dealing with the root causes upstream.
6. Dealing with soil moisture is also an important consideration when planning interventions, as saturated areas are more prone to erosion.
7. Local community involvement in decisions is key, and further 'buy-in' can be facilitated by involving them in the remediation works.
8. All interventions should start with clear objectives and agreement on how project success is defined. Pre-project diagnosis and post-project monitoring are needed to define objectives and design measures, and to assess success and, where necessary, adapt future management.

## 8 References

- Abernethy B, Rutherford ID. 1998. Where along a river's length will vegetation most effectively stabilise stream banks? *Geomorphology* **23**(1): 55–75. DOI: 10.1016/S0169-555X(97)00089-5.
- Alexander GG, Allan JD. 2007. Ecological success in stream restoration: Case studies from the midwestern United States. *Environmental Management* **40**(2): 245–255. DOI: 10.1007/s00267-006-0064-6.
- Ali F. 2010. Use of vegetation for slope protection: Root mechanical properties of some tropical plants. *International Journal of Physical Sciences* **5**(5): 496–506.
- Allan JD. 2004. Influence of land use and landscape setting on the ecological status of rivers. *Limnetica* **23**(3–4): 187–198. DOI: 10.1146/annurev.ecolsys.35.120202.110122.
- Allan JD, Castillo MM. 2007. *Stream Ecology: Structure and Function of Running Waters*. 2nd Ed. Springer: Dordrecht, The Netherlands
- Amin MZM, Shaaban AJ, Ohara N, Kavvas ML, Chen ZQ, Kure S, Jang S. 2016. Climate Change Assessment of Water Resources in Sabah and Sarawak, Malaysia, Based on Dynamically Downscaled GCM Projections Using a Regional Hydroclimate Model. *Journal of Hydraulic Engineering* **21**(1): 1–9. DOI: 10.1061/(ASCE)HE.1943-5584.0001242.
- Arnell NW, Gosling SN. 2013. The impacts of climate change on river flow regimes at the global scale. *Journal of Hydrology* **486**: 351–364. DOI: 10.1016/j.jhydrol.2013.02.010.
- Baird DC, Fotherby L, Klumpp CC, Sculock SM. 2015. *Reclamation Managing Water in the West: Bank Stabilization Design Guidelines*. Report No. SRH-2015-25. Denver, Colorado
- Baptist MJ, Penning WE, Duel H, Smits AJM, Geerling GW, van der Lee GEM, van Alphen JSL. 2004. Assessment of the effects of cyclic floodplain rejuvenation on flood levels and biodiversity along the Rhine river. *River Research and Applications* **20**(3): 285–297. DOI: 10.1002/rra.778.
- Bartley R, Keen RJ, Hawdon AA, Hairsine PB, Disher MG, Kinsey-Henderson AE. 2008. Bank erosion and channel width change in a tropical catchment. *Earth Surface Processes and Landforms* **33**: 2174–2200. DOI: 10.1002/esp.
- Beeson CE, Doyle PF. 1996. Comparison of bank erosion at vegetated and non-vegetated channel bends. *Journal of the American Water Resources Association* **31**(6): 983–990.
- Bernhardt ES, Palmer MA. 2011. River restoration : the fuzzy logic of repairing reaches to reverse catchment scale degradation. *Ecological Applications* **21**(6): 1926–1931. DOI: 10.2307/41416628.
- Berry NJ, Phillips OL, Lewis SL, Hill JK, Edwards DP, Tawatao NB, Ahmad N, Magintan D, Khen C V., Maryati M, Ong RC, Hamer KC. 2010. The high value of logged tropical forests: Lessons from northern Borneo. *Biodiversity and Conservation* **19**(4): 985–997. DOI: 10.1007/s10531-010-9779-z.
- Biron PM, Buffin-Bélanger T, Larocque M, Choné G, Cloutier CA, Ouellet MA, Demers S, Olsen T, Desjarlais C, Eyquem J. 2014. Freedom Space for Rivers: A Sustainable Management Approach to Enhance River Resilience. *Environmental Management* **54**(5): 1056–1073. DOI: 10.1007/s00267-014-0366-z.
- Blaser J, Sarre A, Poore D, Johnson S. 2011. *Status of Tropical Forest Management 2011*. International Tropical Timber Organization: Yokohama, Japan
- Bonan GB, Defries RS, Coe MT, Ojima DS. 2004. Land use and climate. In *Land change science*, Gutman G (ed). Kluwer Academic Publishers: Amsterdam; 301–314.
- Bracken LJ, Turnbull L, Wainwright J, Bogaart P. 2015. Sediment connectivity: A framework for understanding sediment transfer at multiple scales. *Earth Surface Processes and Landforms* **40**(2): 177–188. DOI: 10.1002/esp.3635.
- Bradshaw AD. 1996. Underlying principles of restoration. *Canadian Journal of Fisheries and Aquatic Sciences* **53**(S1): 3–9. DOI: 10.1139/f95-265.
- Brierley GJ, Fryirs KA. 2005. *Geomorphology and River Management: Applications of the River Styles Framework*. Blackwell Publishing Ltd.
- Bruijnzeel LA. 2004. Hydrological functions of tropical forests : not seeing the soil for the trees ? *Agriculture, Ecosystems and Environment* **104**: 185–228. DOI: 10.1016/j.agee.2004.01.015.
- Bryan J, Shearman P, Ash J, Kirkpatrick JB. 2010. Impact of logging on aboveground biomass stocks in lowland rain C ommunications C ommunications. *Ecological Applications* **20**(8): 2096–2103. DOI: 10.1890/09-1818.1.

- Bryan JE, Shearman PL, Asner GP, Knapp DE, Aoro G, Lokes B. 2013. Extreme Differences in Forest Degradation in Borneo: Comparing Practices in Sarawak, Sabah, and Brunei. *PLoS ONE* **8**(7) DOI: 10.1371/journal.pone.0069679.
- Buendía C, Bussi G, Tuset J, Vericat D, Sabater S, Palau A, Batalla RJ. 2016. Effects of afforestation on runoff and sediment load in an upland Mediterranean catchment. *Science of the Total Environment* **540**: 144–157. DOI: 10.1016/j.scitotenv.2015.07.005.
- Bussi G, Francés F, Horel E, López-Tarazón JA, Batalla RJ. 2014. Modelling the impact of climate change on sediment yield in a highly erodible Mediterranean catchment. *Journal of Soils and Sediments* **14**(12): 1921–1937. DOI: 10.1007/s11368-014-0956-7.
- Charlton R. 2008. Fundamentals of fluvial geomorphology. Routledge: London
- Chen S-K, Chen R-S, Yang T-Y. 2014. Application of a tank model to assess the flood-control function of a terraced paddy field. *Hydrological Sciences Journal* **59**(5): 1020–1031. DOI: 10.1080/02626667.2013.822642.
- Coe MT, Latrubesse EM, Ferreira ME, Amsler ML. 2011. The effects of deforestation and climate variability on the streamflow of the Araguaia River, Brazil. *Biogeochemistry* **105**(1): 119–131. DOI: 10.1007/s10533-011-9582-2.
- Dagnew DC, Guzman CD, Zegeye AD, Tibebu TY, Getaneh M, Abate S, Zemale FA, Ayana EK, Tilahun SA, Steenhuis TS. 2015. Impact of conservation practices on runoff and soil loss in the sub-humid Ethiopian Highlands: The Debre Mawi watershed. *Journal of Hydrology and Hydromechanics* **63**(3): 210–219. DOI: 10.1515/johh-2015-0021.
- Das TK, Haldar SK, Gupta I Das, Sen S. 2014. River bank erosion induced human displacement and its consequences. *Living Reviews in Landscape Research* **8**(1): 1–35. DOI: 10.12942/lrlr-2014-3.
- Donat M. 1995. Bioengineering Techniques for Streambank Restoration A Review of Central European Practices by Bioengineering Techniques for Streambank Restoration A Review of Central European Practices
- Douglas I. 1999. Hydrological investigations of forest disturbance and land cover impacts in South-East Asia : a review
- Douglas I, Bidin K, Balamurugan G, Chappell NA, Walsh RPD, Greer T, Sinun W. 1999. The role of extreme events in the impacts of selective tropical forestry on erosion during harvesting and recovery phases at Danum Valley , Sabah. *Philosophical transactions of the Royal Society of London Biological sciences* **354**: 1749–1761.
- Douglas I, Spencer T, Greer T, Bidin K, Sinun W, Meng WW. 1992. The impact of selective commercial logging on stream hydrology, chemistry and sediment loads in the Ulu Segama rain forest, Sabah, Malaysia. *Philosophical transactions of the Royal Society of London Biological sciences* **335**(397–406)
- Dragičević S, Tošić R, Stepić M, Živković N, Novković I. 2013. Consequences of the River Bank Erosion in the Southern Part of the Pannonian Basin : Case Study – Serbia and the Republic of Srpska. *Forum Geographic* **XII**(1): 5–15. DOI: 10.5775/fg.2067-4635.2013.008.i.
- Dufour S, Piégay H. 2009. From the myth of a lost paradise to targeted river restoration: forget natural references and focus on human benefits. *River Research and Applications* **25**: 568–591. DOI: 10.1002/rra.
- Edwards DP, Larsen TH, Docherty TDS, Ansell FA, Hsu WW, Derhe MA, Hamer KC, Wilcove DS. 2011. Degraded lands worth protecting: the biological importance of Southeast Asia’s repeatedly logged forests. *Proceedings of the Royal Society B: Biological Sciences* **278**(1702): 82–90. DOI: 10.1098/rspb.2010.1062.
- England J, Skinner KS, Carter MG. 2008. Monitoring, river restoration and the Water Framework Directive. *Water and Environment Journal* **22**(4): 227–234. DOI: 10.1111/j.1747-6593.2007.00090.x.
- European Commission. 2006. Ecoflood guidelines: How to use floodplains for flood risk reduction. Blackwell MSA and Maltby E (eds). European Communities
- FAO. 2014. Good practices template [online] Available from: [www.fao.org/fileadmin/user\\_upload/goodpractices/docs/GoodPractices\\_Template-EN-March2014.docx](http://www.fao.org/fileadmin/user_upload/goodpractices/docs/GoodPractices_Template-EN-March2014.docx). (Accessed 20 January 2018).
- Florsheim JL, Mount JF, Chin A. 2008. Bank Erosion as a Desirable Attribute of Rivers. *BioScience* **58**(6): 519. DOI: 10.1641/B580608.
- Friberg N, Bonada N, Bradley DC, Dunbar MJ, Edwards FK, Grey J, Hayes RB, Hildrew AG, Lamouroux N, Trimmer M, Woodward G. 2011. Biomonitoring of Human Impacts in Freshwater Ecosystems: The Good, the Bad and the Ugly. *Advances in Ecological Research* **44**: 1–68. DOI: 10.1016/B978-0-12-374794-5.00001-8.
- Gendaszek AS, Magirl CS, Czuba CR. 2012. Geomorphic response to flow regulation and channel and floodplain alteration in the gravel-bedded Cedar River, Washington, USA. *Geomorphology* **179**: 258–268. DOI: 10.1016/j.geomorph.2012.08.017.
- Ghosh C, Bhattacharya S. 2018. Landslides and Erosion Control Measures by Vetiver System. In *Disaster Risk*



- Governance in India and Cross Cutting Issues*, Pal I and Shaw R (eds). Springer Nature: Singapore; 387–413.
- Gibson L, Lee TM, Koh LP, Brook BW, Gardner TA, Barlow J, Peres CA, Bradshaw CJA, Laurance WF, Lovejoy TE, Sodhi NS. 2011. Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature* **478**(7369): 378–381. DOI: 10.1038/nature10425.
- Gillilan S, Boyd K, Hoitsma T, Kauffman M. 2005. Challenges in developing and implementing ecological standards for geomorphic river restoration projects: A practitioner’s response to Palmer et al. (2005). *Journal of Applied Ecology* **42**(2): 223–227. DOI: 10.1111/j.1365-2664.2005.01021.x.
- Gilvear DJ, Casas-Mulet R, Spray CJ. 2012. Trends and issues in delivery of integrated catchment scale river restoration: lessons learned from a national river restoration survey within Scotland. *River Research and Applications* **28**: 234–246.
- Girmay G, Singh BR, Nyssen J, Borrosen T. 2009. Runoff and sediment-associated nutrient losses under different land uses in Tigray, Northern Ethiopia. *Journal of Hydrology* **376**(1–2): 70–80. DOI: 10.1016/j.jhydrol.2009.07.066.
- Grimshaw RG, Helfer L. 1995. Vetiver grass for soil and water conservation, land rehabilitation, and embankment stabilization: a collection of papers and newsletters compiled by the Vetiver network
- Habersack H, Schober B, Hauer C. 2015. Floodplain evaluation matrix (FEM): An interdisciplinary method for evaluating river floodplains in the context of integrated flood risk management. *Natural Hazards* **75**(1): 5–32. DOI: 10.1007/s11069-013-0842-4.
- Hansen MC, Potapov P V., Moore R, Hancher M, Turubanova SA, Tyukavina A, Thau D, Stehman SV, Goetz SJJ, Loveland TR, Kommareddy A, Egorov A, Chini L, Justice CO, Townshend JRG, Patapov PV, Moore R, Hancher M, Turubanova SA, Tyukavina A, Thau D, Stehman SV, Goetz SJJ, Loveland TR, Kommareddy A, Egorov A, Chini L, Justice CO, Townshend JRG. 2013. High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science* **342**(November): 850–854. DOI: 10.1126/science.1244693.
- Hengchaovanich D. 1999. 15 years of bio-engineering in the wet tropics
- Hilderbrand RH, Watts AC, Randle AM. 2005. The myths of restoration ecology. *Ecology and Society* **10**(1): 1–19.
- Hooke JM. 1979. An analysis of the processes of river bank erosion. *Journal of Hydrology* **42**(1–2): 39–62. DOI: 10.1016/0022-1694(79)90005-2.
- Hussain M, Yusof KW, Mustafa MRU, Mahmood R, Jia S. 2017. Evaluation of CMIP5 models for projection of future precipitation change in Bornean tropical rainforests. *Theoretical and Applied Climatology* : 1–18. DOI: 10.1007/s00704-017-2284-5.
- IDMC. 2017. Global Report on Internal Displacement
- ILEIA. 2013. SRI - much more than more rice. ILEIA: Wageningen, The Netherlands
- Janes V, Holman I, Birkinshaw S, O’Donnell G, Kilsby C. 2018. Improving bank erosion modelling at catchment scale by incorporating temporal and spatial variability. *Earth Surface Processes and Landforms* **133**(April 2017): 124–133. DOI: 10.1002/esp.4149.
- Jaspers-Focks DJ, Algera A. 2006. Vetiver grass for river bank protection. 1–14 pp.
- Jungwirth M, Muhar S, Schmutz S. 2002. Re-establishing and assessing ecological integrity in riverine landscapes. *Freshwater Biology* **47**(4): 867–887. DOI: 10.1046/j.1365-2427.2002.00914.x.
- Kelly M. 2014. Simplicity is the ultimate sophistication: Building capacity to meet the challenges of the Water Framework Directive. *Ecological Indicators* **36**: 519–523. DOI: 10.1016/j.ecolind.2013.09.005.
- Kline M, Cahoon B. 2010. Protecting river corridors in Vermont. *Journal of the American Water Resources Association* **46**(2): 227–236. DOI: 10.1111/j.1752-1688.2010.00417.x.
- Kondolf GM. 1997. Hungry Water: Effects of Dams and Gravel Mining on River Channels. *Environmental Management* **21**(4): 533–551. DOI: 10.1007/s002679900048.
- Kondolf GM. 2011. Setting Goals in River Restoration: When and Where Can the River “Heal Itself”? In *Stream restoration in dynamic fluvial systems: scientific approaches, analyses, and tools. Geophysical Monograph Series, vol. 194*, Simon A, Bennett SJ, and Castro JM (eds). American Geophysical Union: Washington, DC; 29–43.
- Larsen EW, Girvetz EH, Fremier AK. 2007. Landscape level planning in alluvial riparian floodplain ecosystems: Using geomorphic modeling to avoid conflicts between human infrastructure and habitat conservation. *Landscape and Urban Planning* **79**(3–4): 338–346. DOI: 10.1016/j.landurbplan.2006.04.003.
- Luke SH, Barclay H, Bidin K, Chey VK, Ewers RM, Foster WA, Nainar A, Pfeifer M, Reynolds G, Turner EC, Walsh RPD, Aldridge DC. 2017. The effects of catchment and riparian forest quality on stream environmental conditions across a tropical rainforest and oil palm landscape in Malaysian Borneo. *Ecohydrology* **10**(4): 1–14.

DOI: 10.1002/eco.1827.

- Malcolm IA, Soulsby C, Youngson AF, Tetzlaff D. 2008. Fine scale variability of hyporheic hydrochemistry in salmon spawning gravels with contrasting groundwater-surface water interactions. *Hydrogeology Journal* **17**(1): 161–174. DOI: 10.1007/s10040-008-0339-5.
- Man T Van, Thang H Van, Truong P. 2011. VST in river and canal bank stabilisation in central Vietnam: success and failures ten years later. 1–15 pp.
- Martin PA, Newton AC, Pfeifer M, Khoo MS, Bullock JM. 2015. Impacts of tropical selective logging on carbon storage and tree species richness: A meta-analysis. *Forest Ecology and Management* **356**: 224–233. DOI: 10.1016/j.foreco.2015.07.010.
- Micheli ER, Kirchner JW, Larsen EW. 2004. Quantifying the effect of riparian forest versus agricultural vegetation on river meander migration rates, central Sacramento River, California, USA. *River Research and Applications* **20**(5): 537–548. DOI: 10.1002/rra.756.
- Mitiku H, Herweg K, Stillhardt B. 2006. Sustainable Land Management - A New Approach to Soil and Water Conservation in Ethiopia. Mekelle, Ethiopia: Land Resources Management and Environmental Protection Department, Mekelle University; Bern, Switzerland: Centre for Development and Environment (CDE), University of Bern, and Swiss National Centre of Competence in Research (NCCR) North
- Newson MD, Large ARG. 2006. “Natural” rivers, “hydromorphological quality” and river restoration: a challenging new agenda for applied fluvial geomorphology. *Earth Surface Processes and Landforms* **31**: 1606–1624.
- Norris JE, Di Iorio A, Stokes A, Nicoll BC, Achim A. 2008. Species selection for soil reinforcement and protection. In *Slope stability and erosion control: Ecotechnological solutions*, Norris JE, Stokes A, Mickovski SB, Cammeraat E, van Beek R, Nicoll BC, and Achim A (eds). Springer: Dordrecht, The Netherlands; 167–210.
- Ollero A. 2010. Channel changes and floodplain management in the meandering middle Ebro River, Spain. *Geomorphology* **117**(3–4): 247–260. DOI: 10.1016/j.geomorph.2009.01.015.
- Palmer MA, Bernhardt ES, Allan JD, Lake PS, Alexander G, Brooks S, Carr J, Clayton S, Dahm CN, Follstad Shah J, Galat DL, Loss SG, Goodwin P, Hart DD, Hassett B, Jenkinson R, Kondolf GM, Lave R, Meyer JL, O’Donnell TK, Pagano L, Sudduth E. 2005. Standards for ecologically successful river restoration. *Journal of Applied Ecology* **42**(2): 208–217. DOI: 10.1111/j.1365-2664.2005.01004.x.
- Pander J, Geist J. 2013. Ecological indicators for stream restoration success. *Ecological Indicators* **30**: 106–118. DOI: 10.1016/j.ecolind.2013.01.039.
- Petrone A, Preti F. 2010. Soil bioengineering for risk mitigation and environmental restoration in a humid tropical area. *Hydrology and Earth System Sciences* **14**(2): 239–250. DOI: 10.5194/hess-14-239-2010.
- Petts GE, Gurnell AM. 2005. Dams and geomorphology: Research progress and future directions. *Geomorphology* **71**(1–2): 27–47. DOI: 10.1016/j.geomorph.2004.02.015.
- Piégay H, Cuaz M, Javelle E, Mandier P. 1997. Bank erosion management based on geomorphological, ecological and economic criteria on the Galaure River, France. *Regulated Rivers: Research & Management* **13**(5): 433–448. DOI: doi: 10.1002/(SICI)1099-1646(199709/10)13:5%3C433::AID-RRR467%3E3.0.CO;2-L.
- Piégay H, Darby SE, Mosselman E, Surian N. 2005. A review of techniques available for delimiting the erodible river corridor: A sustainable approach to managing bank erosion. *River Research and Applications* **21**(7): 773–789. DOI: 10.1002/rra.881.
- Polster DF. 2003. Alternatives for bank Stabilization- Literature review. Lethbridge, Alberta
- Polster DF. 2008. Soil Bioengineering for Land Restoration and Slope Stabilization. Course materials for training professional and technical staff. Duncan, BC
- Putz FE, Sist P, Fredericksen T, Dykstra D. 2008. Reduced-impact logging: Challenges and opportunities. *Forest Ecology and Management* **256**(7): 1427–1433. DOI: 10.1016/j.foreco.2008.03.036.
- Roni P, Hanson K, Beechie T. 2008. Global Review of the Physical and Biological Effectiveness of Stream Habitat Rehabilitation Techniques. *North American Journal of Fisheries Management* **28**(3): 856–890. DOI: 10.1577/M06-169.1.
- RRC. 2013. Manual of River Restoration Techniques
- Rutherford ID, Jerie K, Marsh N. 2000. A Rehabilitation Manual for Australian Streams. Volume 1. LWRRDC and CRCCH: Canberra
- Saifuddin M, Normaniza O. 2016. Rooting Characteristics of Some Tropical Plants for Slope Protection. *Journal of Tropical Forest Science* **28**(4): 469–478.
- Schumm SA. 1977. The Fluvial System. John Wiley & Sons, Inc.: New York
- SEPA. 2002. Managing River Habitat for Fisheries: a guide to best practice. : 32.

- SEPA. 2008. Engineering in the Water Environment Good Practice Guide. Bank Protection: Rivers and Lochs
- Soulsby C, Birkel C, Tetzlaff D. 2016. Modelling storage-driven connectivity between landscapes and riverscapes: towards a simple framework for long-term ecohydrological assessment. *Hydrological Processes* **30**(14): 2482–2497. DOI: 10.1002/hyp.10862.
- Taniyama S. 2002. Water Resources and Rice Paddy Cultivation in the Asian Monsoon Region By : *International Water Conference*
- Tetzlaff D, Soulsby C, Bacon PJ, Youngson AF, Gibbins C, Malcolm IA. 2007. Connectivity between landscapes and riverscapes - a unifying theme in integrating hydrology and ecology in catchment scienc? *Hydrological Processes* **21**: 1385–1389.
- Thorne CR. 1982. Processes and mechanisms of river bank erosion. In *Gravel-bed Rivers: Fluvial Processes, Engineering and Management*, Hey RD, Bathurst JC, and Thorne CR (eds). John Wiley & Sons, Ltd.: Chichester, UK; 227–272.
- Trimble SW. 1997. Contribution of stream channel erosion to sediment yield from an urbanizing watershed. *Science* **278**: 1442–1444.
- Tromp-Van Meerveld HJ, McDonnell JJ. 2006. Threshold relations in subsurface stormflow: 1. A 147-storm analysis of the Panola hillslope. *Water Resources Research* **42**(2): 1–11. DOI: 10.1029/2004WR003778.
- Truong P, Tan Van T, Pinners E. 2008. Vetiver system applications - Technical reference manual. 2nd Editio. Truong P, Tan Van T, and Pinners E (eds). The Vetiver Network International
- Ward JV, Stanford JA. 1989. Riverine ecosystems: the influence of man on catchment dynamics and fish ecology. *Canadian Journal of Fisheries and Aquatic Sciences* **106**: 56–64.
- Wilcove DS, Giam X, Edwards DP, Fisher B, Koh LP. 2013. Navjot’s nightmare revisited: logging, agriculture, and biodiversity in Southeast Asia. *Trends in Ecology & Evolution* : 1–10. DOI: 10.1016/j.tree.2013.04.005.
- Wilkinson SN, Dougall C, Kinsey-Henderson AE, Searle RD, Ellis RJ, Bartley R. 2014. Development of a time-stepping sediment budget model for assessing land use impacts in large river basins. *Science of the Total Environment* **468–469**: 1210–1224. DOI: 10.1016/j.scitotenv.2013.07.049.
- WOCAT. 2008. A Framework for Documentation and Evaluation of Sustainable Land Management - Technologies. Centre for Development and Environment (CDE), Bern, Switzerland; Food and Agriculture Organization of the United Nations (FAO), Rome, Italy; International Soil Reference and Information Centre (ISRIC), Wageningen, Netherlands
- Wohl E. 2005. Compromised rivers: Understanding historical human impacts on rivers in the context of restoration. *Ecology and Society* **10**(2): 1–16. DOI: 10.1111/j.1749-8198.2007.00049.x.
- Wohl E. 2017. Connectivity in rivers. *Progress in Physical Geography* **41**(3): 345–362. DOI: 10.1177/0309133317714972.
- Wohl E, Angermeier PL, Bledsoe B, Kondolf GM, MacDonnell L, Merritt DM, Palmer MA, Poff NL, Tarboton D. 2005. River restoration. *Water Resources Research* **41**(10): 1–12. DOI: 10.1029/2005WR003985.
- Zafirah N, Nurin NA, Samsurijan MS, Zuknik MH, Rafatullah M, Syakir MI. 2017. Sustainable ecosystem services framework for tropical catchment management: A review. *Sustainability* **9**(4): 1–25. DOI: 10.3390/su9040546.

### **About WWF-Malaysia**

WWF-Malaysia (World Wide Fund for Nature-Malaysia) was established in Malaysia in 1972. It currently runs more than 90 projects, covering a diverse range of environmental conservation and protection work, from saving endangered species such as tigers and turtles, to protecting our highland forests, rivers and seas. The national conservation organisation also undertakes environmental education and advocacy work to achieve its conservation goals. Its mission is to stop the degradation of the earth's natural environment and to build a future in which humans live in harmony with nature, by conserving the nation's biological diversity, ensuring that the use of renewable natural resources is sustainable, and promoting the reduction of pollution and wasteful consumption.

### **WWF-Malaysia**

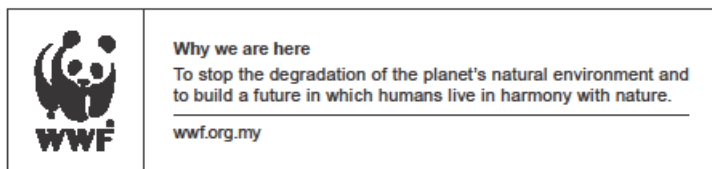
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