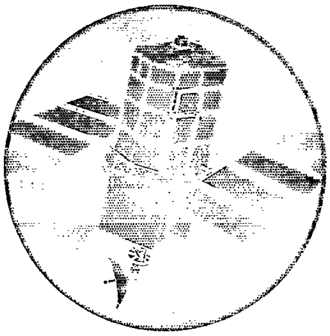
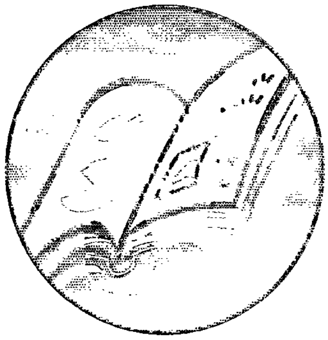
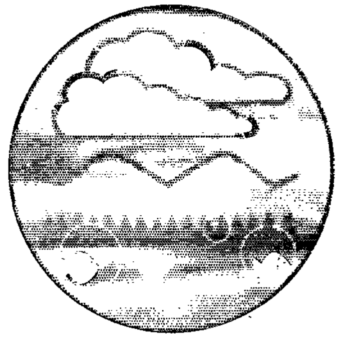
Riverbank Protection Using Willows
Scoping Study

Research and Development

Technical Report

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ENVIRONMENT AGENCY

Riverbank Protection Using Willows

Scoping Study

Technical Report W154

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This report is intended for use by research scientists and engineering in bringing forward proposals for theoretical and experimental studies of key areas and topics related to the use of willows in riverbank protection.

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EXECUTIVE SUMMARY

Under the Water Resources Act 1991, the National Rivers Authority had a duty to promote the conservation and enhancement of the natural beauty and amenity of inland and coastal waters, and the conservation of flora and fauna dependent on the aquatic environment. This requirement was carried forward to the Environment Agency (Agency) under the Environment Act, 1995.

A key area in which this duty can be performed relates to bankside vegetation, yet there can be potential conflicts between this conservation duty and the powers of the Agency in respect of flood defence. There is already a move towards using natural materials for bank protection wherever possible, rather than artificial materials such as steel piling or concrete revetment, but more information is needed on the suitability of such options, and the risks entailed in their use. The role of all vegetation in the river environment is complex, but the role of trees such as willows is especially so. Willows are all the more important because of their abundance in UK river corridors. The interactions between vegetation, water and soil processes are not well understood by the practitioner, and there appears to be little scientific basis for the way in which vegetation is used, or discounted, for river management projects.

In 1996 the Engineering and Physical Sciences Research Council (EPSRC) approved funding for a scoping study on River Bank Stabilisation with Special Reference to Willows, to which the Agency contributed additional funding.

This scoping study examined the existing information and data that had been gathered, on a world-wide basis, on the potential for and limitations of using vegetation for bank stabilisation, concentrating on the use of willows. The study was not intended to carry out any original research work, but to draw together existing knowledge from other researchers and practitioners in the UK and abroad, and in particular identify clearly and concisely areas where further research work should be concentrated.

The study covered three main topics:

- **Flow Erosivity** covered the effect of bankside vegetation on retarding velocities of main channel flow adjacent to a river bank, and its consequent effect on channel capacity. Floodplain conveyance was also covered in this topic;

- **Bank Erodibility and Stability** examined the potential for soils to erode, and how vegetation could affect this potential. This covered the effects of soil properties, plant health and bank hydrology on vulnerability of soil to erosion. On a slightly larger scale, this topic also addressed the positive effects of buttressing, and the negative effects of surcharge and wind loading on bank stability when the bank is considered as an entity; and,

- **Bank Accretion** addressed the problem of bankside vegetation encouraging siltation, which leads gradually to reduced channel conveyance. In addition large vegetation can create a source of large woody debris in a channel, again with the potential to reduce capacity, especially at existing bottlenecks.

The study included a comprehensive literature review, and the text contains many cross-references to other work. In addition a bibliography is provided for further information on matters not specifically referred to in the report text (Appendix C).

Data and information were gathered from a number of structured interviews and site visits, both in the United Kingdom and overseas. The interviewees and their responses are presented in tabular form in the report (Appendix A).

A number of site visits were also included in the study, and these were recorded on site assessment sheets, an example copy of which are also included in this report (Appendix B).

During the study sources of willow materials within the UK were identified, and these sources are listed in Appendix D.

The report summarises the currently available information on vegetation, and particularly on willows, and identifies, under the three topics listed above (but covering eleven separate sub-topics), a total of 35 separate areas which are recommended for future research.

Keywords

Willows, riverbank protection, scoping study, erosion, stability, accretion, flow conveyance, research topics

1 INTRODUCTION

1.1 Background to the scoping study

This scoping study was carried out to establish the scientific basis for the multi-disciplinary studies necessary to investigate the potential and limitations for bank protection and stabilization schemes with special reference to the use of willows (*Salix* spp.). A sound understanding of the effects of vegetation on bank processes is an essential prerequisite for widening the use of vegetation in bank protection. Previous studies funded by the National Rivers Authority (NRA) and, subsequently, the Environment Agency, have identified broad areas where a lack of understanding of interactions between vegetation, water and soil processes inhibits the wider use of vegetation in stream bank stabilization projects. However, these studies have not identified the specific topics requiring research at the level of detail required to support the writing of successful research proposals.

There are serious gaps between the type of fundamental research being conducted on vegetation-soil-water interactions and the needs of practitioners working in river management agencies and consultancy companies. Specifically, many design engineers and river managers find that fundamental research does not currently address key problems or produce results that can be applied in practice.

In light of these issues and concerns, an eight-month scoping study was jointly funded by the Engineering and Physical Sciences Research Council (EPSRC) and the Environment Agency (Agency) with reference to willow, which is the genus most widely used in vegetative bank protection works. The results of the scoping study are reported here, with the aim of enabling research scientists and engineers to bring forward proposals for theoretical and experimental studies of key areas and topics, in consultation with practitioners.

The role of willows as they affect stream banks is complex. In presenting the findings and recommendations of the scoping study it is convenient to divide this broad and multi-disciplinary subject into a number of self-contained topics. However, when considering the results of the scoping study it is important to remember that in reality the effects of willows on bank erosion, stability, morphology and environment operate interactively to produce a complex and changing inter-relationship between the plants and the bank. Depending on the nature of that inter-relationship, the net impact on bankline stability may be positive or negative. In essence, there are no simple relationships between willows and bank stability. However, while every situation is, in detail, unique the results of this scoping study identify more general, causal relationships that point the way towards the theoretical, laboratory and field-based research necessary to unravel the complexities of fundamental relationships between willows, water and soil.

1.2 Practical relevance and technological context

In the 1980s and 1990s the disadvantages of approaches using artificial materials in rigid structures have been recognized and there has been a resurgence in the use of innovative engineering approaches which employ flexible structures and natural materials. While the adverse environmental and aesthetic impacts of hard engineering have received most publicity, experience has also shown that in many applications hard structures are also ineffective in solving erosion problems, are uneconomic and introduce secondary problems of instability at adjacent, unprotected sites. However, there are situations where a hard structure is appropriate and a soft solution based on vegetation is not viable and there have been spectacular failures of some soft schemes. It can be concluded that current bast practice with regard to the use of vegetation in bank protection schemes suffers from a lack of geomorphological and engineering-design guidance.

If engineering technologies using natural materials are to be safely and successfully applied, more rigorous analysis and design methods must be developed. The development of these design methods is the task of river and waterway management agencies such as the Environment Agency and British Waterways. Both agencies are currently developing new design guidance aimed at promoting the use of innovative engineering and the results of this scoping study are timely in that they can feed existing knowledge into the design manuals while also bringing to the attention of designers the current gaps in knowledge that might be addressed through trial schemes and post-project monitoring/appraisal of bank protection works using vegetation.

The technology for using vegetation in bank protection schemes is not new. Willow has been used in the form of fascine mattresses and spiling fences since the 16th Century. However, during the 1960s and 1970s its use declined as the popularity of artificial materials with known engineering properties, such as concrete, plastic, and steel, in hard structures increased. There is an increasing realisation that the use of natural materials produced from renewable resources has environmental and economic advantages and may assist in the promotion of sustainable river management.

In this regard, the technological relevance of using willow for bank protection may be illustrated with reference to a document produced under the Government's Technology Foresight Programme titled, "Progress Through Partnership: Key Points for Agriculture, Natural Resources and Environment" (Office of Science and Technology, 1995). The wider use of willow would be consistent with several of the priorities identified in that document including:

- **sustainable resourcing** of construction materials and other natural resources. Wood is regarded as a novel construction material, which is a biodegradable, renewable, energy efficient and environmentally cost-effective and its use in sustainable systems is emphasized;

- **technologies** for soil remediation; and,

- improved technology for utilising **forest products**. (Especially materials produced by coppicing which are currently regarded as waste products but become by-products when used for vegetative bank protection).

Widespread use of willows would seek to achieve these goals within the broader context of multi-functional river and riparian corridor management. This places the use of willows within key areas recommended for extra investment:

- **Integrated ecosystem management** for terrestrial, aquatic, coastal and oceanic systems;

- improved understanding of **soil structure** and **soil-microbe-flora-fauna interactions**, and their role in agriculture and natural habitats;

- Development of technologies for the **remediation** of urban and rural habitats; and,

- Taking steps to begin implementation of **integrated management of inland river catchments.**

The use of vegetation for bank protection is consistent with the concept of partnership with the catchment community and it encourages their participation in sustainable management of rivers and water courses. This is the case because many of the simpler, low-technology vegetative techniques are amenable to the involvement of community groups including voluntary organizations, wildlife and nature conservation groups and students. Involvement of the catchment community in this way is entirely consistent with modern approaches to integrated basin management.

2 FLOW EROSIVITY

2.1 Retardance of near-bank velocities

2.1.1 Introduction

Knowledge of the hydraulic effects of woody riparian vegetation falls within three categories; theoretical derivation, flume studies and field experience. No large, quantitative data sets exist from which to derive prediction capability, especially capability that can be applied under the conditions encountered along natural streams and rivers.

Contemporary workers in theoretical hydraulics of flow through channels with bank vegetation include: Marcelo Garcia at the University of Illinois, Champaign-Urbana USA; Craig Fischenich, US Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS, USA; Tetsuro Tsujimoto, University of Kanazawa Hydraulics Laboratory, Japan; Dan Naot, Center for Technology Education, Holon, Israel; and Stephen Darby, USDA Agricultural Research Service, National Sedimentation Laboratory, Oxford, MS, USA.

2.1.2 Damping turbulence

An important effect of bank woody vegetation on the near bank flow field is to affect turbulence. It is now recognized that bank material detachment and entrainment usually occur during turbulent sweeps, when velocities and stresses may, for short durations, attain values triple the time-averaged mean (Jackson, 1976; Leeder, 1983). Vegetation, especially if erect but flexible, may damp local turbulence and so reduce the magnitude of instantaneous velocity and shear stress peaks. Large stands of vegetation may also act to suppress meso- and macro-scale eddies, which will further reduce the erosive attack of the flow on the bank. While grasses and other herbaceous plants are effective in protecting the soil surface at low velocities, their impact decreases as velocity increases, and may be eliminated once the plants are flattened by fluid drag forces. Stiff woody stems continue to retard flow up to very high velocities, but may generate serious local scour through convective acceleration of flow around their trunks and through eddy-shedding. The effects of spacing and structure of plants are crucial and this is discussed further below.

Flexible woody stems at or near the near-water margin offer much greater bank protection than herbaceous bank colonisers, especially when the above ground and below ground impacts are considered together. In this regard, the density of vegetation and its relative continuity from water margin to top of bank are also likely to be important. European research indicates much more potential for structural uses of woody vegetation than is employed for bank protection at present (Schiechtl, 1980).

2.1.3 Retardance of near-bank velocities

A great deal of sound theoretical and empirical work on vegetation and flow resistance has been undertaken by Nicholas Kouwen at the University of Waterloo, Canada (for example see Kouwen, 1970; Kouwen and Unny, 1973; Kouwen and Li, 1979; Kouwen, Li and Simons, 1980). This work has sought to show that the extremely complicated nature of flow over a vegetated surface precludes a complete mathematical description based on the physics of flow. Much of the complication arises because of the tendency of natural vegetation to bend when subjected to a streamwise drag force. The amount of bending depends on the flexural stiffness of the stem and the magnitude of the fluid drag. But drag depends on the flow velocity, which in turn depends to some extent on degree of bending. The velocity distribution remains approximately logarithmic throughout, the major effect of bending being to move the virtual origin of the distribution (the height above the bed at which the velocity goes to zero) progressively nearer the boundary as bending increases.

Using these facts, it has been possible to develop a model which is process-based and incorporates the basic flow and boundary parameters, and which, on this basis, is an improvement over purely empirical methods (Kouwen, 1987). Kouwen's model is the basis for a procedure to calculate the effective roughness height and velocity distribution for vegetated channels used by the US Department of Agriculture (1980). The models input parameters are: vegetation height; vegetation stiffness (a function of type, height and health of plant (US Department of Agriculture, 1954)) and channel geometry and slope. This approach could form the basis for development of a physically-based method to calculate and predict the response of near-bank velocity distributions to the presence of a particular type of bank vegetation.

Prior to the 1970s, most studies relating flow and vegetation focused on grasses, and deformation of turbulence under uniform flow with submerged vegetation. Li and Shen (1973) published an analysis of vegetation flow resistance using stiff, non-submerged cylinders. The analysis was intended for comparison of the relative effects on sediment yield of various combinations of spatial patterns for tall vegetation.

Theoretical calculation of the drag coefficient was based on the average flow velocity, the cylinder diameter and cylinder Reynolds number. Calculation of the wake width and decay length was given for a single cylinder, then multiple cylinders to compute the velocity distribution in the wake. Practical tests were made of the drag balance for a single cylinder and for multiple cylinders in parallel, staggered and random patterns, (perpendicular to flow). The tests involved measuring average velocity and then computing the mean drag coefficient.

Results from Li and Shen (1973) showed that for parallel patterns, mean drag coefficients increased with increasing spacing between cylinders. However, drag decreased with increasing spacing for staggered patterns. The staggered pattern with moderate distances between rows of vegetation gave the highest rates of sediment retention. The average boundary shear stress was not sensitive to variation in discharge or sediment size, but was sensitive to slope and vegetation diameter variation. In the 1990s, this work has been extended by Tsujimoto and Kitamura (1992) and by Naot et al (1996), by modelling the components of turbulent flow structure in greater detail, and by using model channels which allow for both channel and floodplain, and the interaction of these flows with simulated vegetation.

Petryk and Bosmajian, (1975) developed a model to segregate vegetation roughness from bed roughness, assuming uniform or gradually varied flow and non-submerged, non-bending vegetation. A drag coefficient was developed for various vegetation densities, based on the area of the stems presented to flow (vegetation density), hydraulic radius and Manning n value for bottom roughness without vegetation.

They found that vegetation density decreases with increasing flow depth, and that for the n value to remain constant, vegetation density must decrease with increasing depth of flow. According to their findings, the stem density of large diameter trees on a floodplain remains relatively constant with flow depth, while n value increases with depth. n values as high as 0.4 have been reported for heavily-vegetated floodplains. One of the potential applications of this work is an evaluation of n values as a function of flow depth. The value of this work may be enhanced once it can be related to contemporary work on drag coefficients.

2.1.4 Boundary layer effects

Bank vegetation increases the effective roughness height of the boundary, increasing flow resistance and displacing the zero plane of velocity upwards, away from the bank. This has the effect of reducing the forces of drag and lift (and their surrogate, boundary shear stress) acting on the bank surface. As the boundary shear stress is proportional to the square of near-bank velocity, a reduction in this velocity produces a much greater reduction in the forces responsible for erosion. Quantification of this effect is especially difficult in the field.

Much of the contemporary work in woody vegetation effects on flow now seems to be moving away from reach-scale studies using Mannings "n" and Darcy-Weisbach friction factor values to represent gross flow resistance, and toward characterization of the effective roughness height and form drag effects exerted by stems on near boundary turbulent flow structures. While this new approach, based on boundary layer theory, is perhaps still in its early stages, it may have profound significance for river engineering where incorporation of bankside vegetation is emphasized. For example, detailed studies employing numerical modelling of velocity profiles, drag forces and turbulence are being conducted both in Illinois and Japan. The results can be used to investigate the effects of bank vegetation on near-bank sediment entrainment, transport and deposition as well as flow structures and flow resistance .

2.1.5 Channel flow regime

Spacing of trees or shrubs along the channel is important. Single trees or small groups of trees are impediments to the flow that generate large-scale turbulence and severe bank attack in their wakes. Hence, trees or groups of trees which are widely spaced along the bankline act as isolated hardpoints and are vulnerable to being outflanked by the flow. For trees to be effective in reducing flow attack on the bank they must be spaced sufficiently closely that the wake zone for one tree extends to the next tree downstream, preventing re-attachment of the flow boundary to the bank in-between. In this regard, the hydraulic effects of trees may continue even after the death of the plant. An isolated, downed tree may generate local scour and, unless removed, can become a locus of serious channel instability. But a dense accumulation of downed timber on a bank can be quite effective in protecting the bank from flow scour, if it forms a natural crib wall structure.

The scale of fluvial processes and vegetation effects must be considered in river management. For example, fallen trees on a small river can divert the flow and may generate significant scour of the bed and opposite bank, effects obviously negligible in large rivers. As stream order increases in the downstream direction, floodplain vegetation effects on overbank flow become less significant on stage or discharge, but may still play an important role in local shear stress reduction and bank protection.

The additional flow resistance associated with a stand of vegetation on the banks of a river is seen as a disbenefit by many river engineers. This view is based on the assumption that by increasing roughness, bank vegetation significantly reduces channel capacity, thereby promoting flooding. On these grounds, bank vegetation is often removed in a clearing and snagging operation, the stated aim of which is to increase the channels conveyance, despite the fact that standing vegetation will trap floating woody debris and prevent it from accumulating at more vulnerable constrictions such as bridge piers.

In fact, in most natural channels at high in-bank flows, the contribution of bank roughness to total channel resistance is small. This is the case because resistance in channels of high width-to-depth ratio flow (w/d > 20) depends mostly on bed roughness and channel shape, not bank roughness. For such channels, any increase in conveyance achieved through clearing bank vegetation is likely to be lost when channel instability triggered by the reduction in bank erosion resistance leads to a sequence of morphological adjustments that involve: widening, siltation and aggradation of the bed by bank erosion-derived sediments, an increase in the width-to-depth ratio, and a reduction in both the area and hydraulic efficiency of the channel cross-section. Frequent desilting or capital dredging will then be required to restore and maintain channel depth and conveyance to pre-bank clearance levels.

2.1.6 Plant form and the maintenance regime

The type and frequency of maintenance as well as vegetation density affects the form of riparian plants and, hence, their impacts on near bank flow distributions. Creeping willows will tend to remain multi-stemmed and flexible, as will shrub-types if coppiced at periodically. While tree willows tend to mature to taller and more rigid forms, they can also be maintained in a flexible, multi-stem condition but may require more frequent husbandry (K. Stott, pers. comm. 1996).

2.1.7 Future research

Fundamental research is underway on the effects of riparian vegetation on near-bank velocity distributions, turbulent structures and flow fields. This research must continue, through application of boundary layer principles and the theory of burst and sweep to develop process-based equations capable of predicting the effective roughness height of either flexible or stiff vegetation. Field and laboratory studies are required to calibrate and validate the theoretical relationships identified from boundary layer theory and turbulence modelling.

Applied research linking maintenance regimes to vegetation response and plant form is needed to establish the medium to long-term hydraulic effects of different maintenance regimes and to underpin the development of optimum maintenance regimes that produce the desired level of flow resistance for the minimum expenditure of time and money.

2.2 Stem characteristics

2.2.1 Introduction

Botanical and horticultural perspectives

From a botanical perspective, *Salix* species in Britain and the temperate northern hemisphere are a robust group which hybridize easily, and many introductions have been made. The phenomenal capability of *Salix* species to propagate is the basis for the popularity of the genus for bank protection. While it is unclear whether native species perform better or worse than exotic species in terms of bank protection, ecologists have legitimate concerns about the introduction of non-native species. For example, the Forest Authority Dendrologist at Westinburt Arboretum , J. E. White has suggested there is concern for the integrity of native species because of these introductions, and river restoration efforts could take the precautionary measure of identifying native species and employing them in river bank protection activities (White, 1994).

From a horticultural perspective, willows as a pioneer group of species are remarkably resilient to pests and diseases, especially when grown under natural conditions. Problems with diseases such as yellow fungus, Chrysomelid beetle, and numerous chewing and sucking insects, have been noted in willow biomass production, where large monocultures of a single clone are grown in high densities (Parfitt and Greaves, 1996). Monocultures are less desirable in sustainable agricultural systems, and diverse plant groupings increase diversity in insect and fungal populations, which tend to prey on each other to the benefit of the plants. This approach suggests that a diversity of both plant species and plant genera is advisable when developing vegetative strategies for river bank protection.

Hydraulic perspective

From a hydraulic perspective, vegetation parameters include form, (single rigid trunk, multiple woody stems, semi-woody or herbaceous clump and vine), stem brittleness, plant spacing, stem density, foliage density and seasonality, and their change over time. There are significant differences in form and stem brittleness among *Salix* species, as shown in the Table 2.1 below, reproduced by courtesy of Dr. George Argus, noted salicologist from Canada (species shown are mainly those native to Britain, although not all British or European willow species have been evaluated).

Branch brittleness is determined by flexing the base of the stem by pressing it toward the main axis. If no branches break off at the base the plant is scored as flexible. If all branches break the plant is scored as highly brittle. If many but not all break the plant is scored as somewhat brittle. Only in *Salix floridana* are the branches brittle when flexed anywhere along their length, not just at the base.

Environmental perspective

From an environmental perspective, woody plants on the bank margins not only reduce overbank flow velocities, enhance sedimentation and increase the physical stability of the bank zone, but also influence the growth of other vegetation. Streams with moderate to dense forest cover on their banks benefit from being more shaded, as are channel margins, because of reduced in-channel aquatic plant growth, which can otherwise decrease channel capacity for in-bank flows. Higher in-channel velocities indicate greater sediment transport capacity, with potential adverse consequences for the micro-habitat of aquatic organisms. Consequently, streamside shade has more profound environmental effects on lower order streams than on higher order ones.

2.2.2 Plant growth and form by species

Early seral (successional) stages of stream bank and floodplain plant communities are characterized by their dynamic response to flooding and high levels of post-flood disturbance.

Moist alluvial or clay soils support germination of annual grasses and forbs, which respond quickly to available light, moisture and nutrients. Wind and water-dispersed *Salix* seeds also germinate quickly, and are dependent on continued contact with surface moisture or groundwater (Krasny et al, 1988).

Seedlings on point bars and other mobile features are easily scoured, but may survive under altered disturbance regimes such as flows with dam impoundments, or prolonged unseasonably dry conditions. This factor is of importance in relying on natural recolonization of restored rivers, whose flood capacity may be sensitive to such in-channel growth, and for which planting trees on the bank top may imply a significant maintenance commitment. While willow stems can grow more than 1 metre in a single season, they can also display more average tree or shrub growth rates, or grow very slowly. This depends on the species and the growth environment.

Table 2.1 Stem flexibility characteristics and ratings for some British willows
(after Dr. George Argus; Salicologist, Canadian Natural History Museum)

Branch brittleness rating system: 1 = flexible at base; 2 = somewhat brittle at base; 3 = highly brittle at base; 4 = brittle throughout

Species	Flexibility rating	Nativity
Salix alba L.	1. flexible at base 2. somewhat brittle at base	UK
Salix amygdaloides Andersson	1. flexible at base 2. somewhat brittle at base	USA
Salix babylonica L.	3. highly brittle at base	China
Salix caprea L.	1. flexible at base	UK/ EUR
Salix atrocinerea L.	1. flexible at base	UK/ EUR
Salix cinerea L.	1. flexible at base	UK/ EUR
Salix cordata Michx.	1. flexible at base	UK
Salix elaeagnos Scop.	unknown	UK
Salix eriocephala Michx.	1. flexible at base	UK/ EUR
Salix exigua-s.s. Nutt.	1. flexible at base	USA
Salix interior	1. flexible at base	USA
Salix fragilis L.	3. highly brittle at base	UK/ EUR
Salix herbacea L.	1. flexible at base	UK
Salix nigra Marshall	3. highly brittle at base	USA
Salix pentandra L.	1. flexible at base	UK/ EUR
Salix purpurea L.	1. flexible at base 2. somewhat brittle at base	UK/ EUR
Salix reticulata s.l. L.	1. flexible at base	UK
Salix X rubens Schrank	3. highly brittle at base	Hybrid of UK & EUR
Salix sitchensis Sanson ex	1. flexible at base	origin
Bong.	3. highly brittle at base	West Coast Canada, USA to
Salix viminalis L.	1. flexible at base	Mexico
		UK/ EUR

Tree willow species in the subgenus *Salix* such as *S. alba, S. alba caerulea; S. fragilis, S. pentandra* have rather high nutrient requirements for carbon (as organic matter, such as that from decomposition of deposited woody debris), as well as nitrogen and phosphorus (Newsholme, 1992), as they have evolved in fertile valley soils. Equally as important is the requirement for light and when shaded willows will decline in vigour. This pioneer feature of the riparian genera *Salix*, as well as *Populus*, can be used in a maintenance regime where early stabilization of alluvial soils by willows can be followed through plant succession by longer-lived genera such as Ash (*Fraxinus*), Oak, (*Quercus*), Poplar (*Populus*), Maple (*Acer*), etc. (Malanson, 1993).

Left unmanaged, tree willows will tend to develop one or a few stems over time, and can attain heights of 20 m or more. Tree willows respond well to pruning, coppicing or pollarding in a multi-year maintenance regime. This is the case because they are a disturbance-dependent genus, adapted over millions of years to the various parameters of their native flooding regime, including damage by high shear stresses and wind-loading.

Shrub (to small tree) willow species in the subgenus *Vetrix* include *S. caprea, S. cinerea, S. purpurea*, and *S. viminalis* (Meikle, 1986). The osier willows *S. purpurea, triandra*, and *viminalis* are the common basket willows, with fast-growing stems of great flexibility (Parfitt and Greaves, 1996). The sallows *S. aurita, caprea* and *cinerea* are also shrub willows, adapted to poorer soils such as marshes, compacted and infertile soils. The sallows have great potential for use in reclaiming polluted and disturbed moist soils (Newsholme, 1992).

Dwarf and creeping willows in the sub-genus *Chamaetia* originate in landscapes of maximum exposure, such as montane and Arctic streams, and include such species as *S. lanata, S. myrsinites*, and *S. repens* (Meikle, 1986). They have lower nutrient requirements than the larger lowland shrub and tree willows. These species are generally adapted to conditions of poorer soils, and tolerate colder climates. Owing to the low growth form, they require less pruning to maintain growth and vigour, and grow more slowly. These dwarf and creeping willows are better suited for ornamental uses in lowland Britain than for bank protection uses, but should be considered where conditions require their hardiness.

The old English saying, "growth follows the knife" illustrates the fact that willows grow best when older wood is removed periodically. For this reason, the successful use of willows for bank protection requires some kind of regular maintenance, both for removing excess stem growth to improve light conditions, and to allow some regular infusions of the macro-nutrients either by periodic flooding or fertilization. However, cutting stimulates new growth, so the method of pruning has dramatic effects on the subsequent growth form. The judicious removal of stems can create either a dense bush, an open habit or a single tree, for the same species (RSPB et al, 1994). This flexibility should be regarded as of great value for enabling adaptive management of the riverine marginal habitat (Parfitt and Greaves, 1996).

2.2.3 Traditional uses of willows for bank protection

Traditional maintenance in the UK and Europe regimes often employ spiling, where live branches are woven horizontally along a line of live vertical stakes (RSPB et al, 1994): fascine bundles, also called willow wattles, are long willow, chestnut or hazel stems bound into long rolls of any length, placed usually on the contour, used effectively for slope stabilization and bank drainage, although this is considered to be a technique for upland erosion control (Gray and Leiser, 1983; Schiechtel and Stern, 1996). Willows have also been used extensively in lowland settings because of their ability to provide erosion protection in poor, fenland soils. Cuttings are made and used in the dormant period, usually November-March.

Coppicing and pollarding methods historically used on riverside trees are described in the New Rivers and Wildlife Handbook (RSPB et al, 1994). Thinning of lower branches on single-stem trees improves both flood conveyance and wildlife utility, while encouraging the development of under-storey plant communities. A diversity of under-storey shrubs, grasses and herbs improves habitat values for vegetated banks, and may improve other buffer zone functions such as sediment retention and pollutant attenuation (Schultz et al, 1994). Other traditional uses developed in Europe, such as those described by Scheichtl, 1980, are structural in nature, and are well suited for slope and bank protection needs in the UK, especially on alluvial and high gradient streams.

Curiously, descriptions of riparian vegetation in the New Rivers and Wildlife Handbook (RSPB et al, 1994) seem to assume that much of the natural riparian vegetation of England is predominantly grasses and swards of grasses and herbs. Yet numerous authors have documented that historic riparian and floodplain plant communities of the mid-temperate latitudes were extensive forests prior to 1700 (Petts, 1990.) How reasonable is it to assume that contemporary vegetation conditions reflect local geomorphological and hydrological conditions, given the past and present effects of agri-industry? Or to use for river rehabilitation only locally native material in patterns which were found in living memory? As the work of Edgar Milne-Redhead on the status of the English Black Poplar (*Populus nigra ssp. betulifolia*) illustrates, native trees of formerly wide distribution can be nearly lost to common landscapes (Mabey, 1996). The breadth and diversity of English riparian landscapes may well benefit from greater use of the diversity of willows and other riparian tree and shrub or scrub genera.

Those using willow for bank work tend to use only what is locally available, whether or not the plants are native. In highly modified urban and rural landscapes, appropriate species may no longer be locally available. Examples of inappropriate use of non-native plants include the introduction *of Salix* species into Australia and New Zealand, where they have become serious pest weeds (B. Abernathy, Monash Univ., pers. comm., 1996.) Many willows now local in Britain are hybrid introductions, and some care is needed to encourage those native plants which are most likely to have positive ecological benefits to wildlife (White, 1994).

The use of hybrids outside their native area may result in poor performance, as in the use of northern American hybrids in the American South, where they grow poorly despite the best horticultural efforts (J. Snider, US Department of Agriculture, Natural Resources Conservation Service, pers. comm., 1996). However, less vigorously rooting species with otherwise valuable bank protection properties may be neglected if workers choose only those species with high survival rates.

If greater maintenance required, the economic case for the use of willows for bank protection must be established. Economic analyses should account for other traditional uses of these remarkably useful plants such as fuel wood, fibre for construction materials and paper, fodder for livestock and the potential for increased use of the landscape by wildlife including, for example, otters. Well-managed stream banks featuring willows may not, in fact, require more maintenance in the long-term compared with conventional revetments, when multiple functions including dredging of excessive sediment deposits and repair and replacement costs for hard protection are included in the economic analysis.

2.2.4 Maintenance regimes and overbank flow behaviour

Plant maintenance history is reflected in the growth form. Recently coppiced stems are very flexible, but they become more rigid, single-stemmed and, in some species brittle (for example, *S. fragilis*), with age. Other species, such as *S. viminalis*, retain stem flexibility to a great age and tend to retain the multiple trunk form (Newsholme, 1992). Cutting bank vegetation to remove dead wood and encourage growth may reduce competition from other trees which do not tolerate cutting as well as willows. The selected maintenance strategy can also be used to influence plant succession, depending on the landscape and habitat goals and other constraints. During the early establishment stages of bank revegetation, extra maintenance is advisable to ensure that plant requirements are satisfied (Gray and Leiser, 1983).

During overbank flow, the stems of woody species (in contrast to grasses and herbaceous plants) continue to retard the flow up to very high velocities, bending but resisting being flattened. Vertical redistribution of momentum transferred from the fluid to the stems increases the height of the boundary layer, reducing local shear stresses at the ground surface. Wake length is important because an isolated wake effect may generate serious bank scour through the local acceleration of flow around a tree trunk (Li and Shen, 1973). Hence, the height, density and spacing of plants are important factors when designing and maintaining vegetative bank protection. Plant ecology, geomorphology, hydrology and hydraulics must be integrated to estimate adequately the design flood stage and the expected wake lengths for the range of design floods the channel and floodplain are expected to convey. The maintenance regime must then work within the boundaries set by these performance requirements.

2.2.5 Future research

Following the lead given by Dr. Argus in Canada, more research is needed to identify the stem flexibility qualities of species of the genus *Salix* so that their response to fluid drag forces can be better characterized.

Basic research is needed to identify, or re-discover what probably was known historically, concerning the stem characteristics of each *Salix* species, their responses to fluvial shearing and wind-loading.

Applied research should seek to establish impacts on stem characteristics and morphological responses of various *Salix* species to different maintenance regimes.

Applied research is also required to develop improved cost-benefit analyses capable of accounting for all the benefits and disbenefits of using willows in bank protection schemes. Particular emphasis must be placed on including environmental benefits and on properly evaluating the comparative long-term maintenance costs of vegetative versus hard engineering for bank protection.

2.3 Channel capacity and floodplain conveyance

2.3.1 Introduction

Several types of model have been used to investigate the effects of vegetation on flow, both in the UK and abroad. While computational methods have progressed rapidly in recent years, few of the developed to date models have drawn on sufficiently extensive field work to verify whether they accurately simulate reality. Further field work therefore is needed both to verify modelling, and to guide further modelling to address practical needs in terms of the many issues involved. The advances in hydraulics research will thus be brought closer to the needs of the river manager to address the complex challenges in river maintenance.

2.3.2 Models of vegetation influence on flow dynamics

Over the last 25 years, the use of models has progressed scientific understanding of vegetation influences on channel processes. Hydraulic models have quantified plant form-drag, based on assumptions concerning plant resistance to flow (Lopez and Garcia, 1996) and bed roughness (Masterman and Thorne, 1994). Numerical models have begun to quantify plant deformation by flowing water (Tsujimoto et al., 1996; Naot et al., 1996). Reach-scale models have identified methods for quantifying effects of vegetation on flood stage (Darby and Thorne, 1996, Fukuoka and Fujita, 1993). Some empirical models used to predict effects of bank vegetation on stage-discharge curves for two-stage channels are based on the work of Wark et al, 1994 (Darby and Thorne, 1996).

Physical models using vegetation have concentrated on grass-lined channels (Ree and Palmer, 1949; Kouwen, 1970, Kouwen and Li, 1979), and tests have been made on prototype reinforced and unreinforced grass channels and spillways (Hewlett et al, 1987, Temple et al, 1987). Dowels have been used to represent mature, single stemmed trees (Li and Shen 1973, Lopez and Garcia, 1996). Physical modelling of flexible woody stems, particularly in clusters, is needed to develop hydraulic parameters to predict the effects of early seral (ecological development stage) or coppiced woody vegetation on flows and sediment transport during overbank events. Parameters that have tentatively been identified so far include: widths of vegetative (or buffer) zones, spacing between plant clumps or groups, and density of flexible stems within plant clumps or groups . These parameters have measurable impacts on patterns of sediment deposition for the range of overbank flow stages which it is possible to envisage on the basis of a typical flood hydrograph.

Scope exists to improve understanding of vegetation maintenance on channel capacity (Darby and Thorne, 1996). Research should be guided by the needs of practitioners in flood defence, ecology, geomorphology, landscape, etc., designing river restoration, wildlife enhancements in flood defence schemes, and maintenance programmes. It should also include changes in vegetation form and structure over time, to guide riparian investment planning (e.g. for wildlife habitat, energy coppicing, pollution reduction or other buffer zone applications). Understanding the influences of woody vegetation on channel morphology, sediment transport and plant community structure will allow more appropriately targeted maintenance expenditure, a topical issue in England and Wales. Also, since trees and bushes are still widely regarded as undesirable, for example by many of the farmers in Denmark's river restoration programme, changing misconceptions over time will require reliable and irrefutable data. Equally, the sizing of major elements in flood defence schemes which incorporate habitat enhancement using vegetated banks requires a sound understanding of the affects of riparian vegetation on flood conveyance.

2.3.3 Vegetation in hydraulic models

Based on flood hydraulics experiments in the UK (at HR Wallingford), in Germany and elsewhere, we are beginning to understand the nature of flow structure during overbank conditions. Channel-floodplain interactions are complex, dependent on stage, local long profile and lateral slope conditions, channel topography and bed and planform roughness (Pasche and Rouve, 1985). The influence of various types of vegetation on local and reach roughness conditions are not well understood. Most hydraulic modelling on the effects of bank vegetation do not discriminate between the substantial hydraulic differences among herbaceous plants such as grasses, reeds and sedges, the flexible but resistant stems of young willow shoots and the rigid stems of single or multiple trunks of mature trees. Extensive work has been conducted on grass-lined channels (Ree and Palmer, 1949; Kouwen 1970, Kouwen and Li, 1980), and artificial short flexible vegetation at different densities (Pepper, 1971, Shen, 1972).

Numerical simulations indicate that effects of bank vegetation decline rapidly as width- depth ratio increases (Masterman and Thorne, 1994). A useful bibliography on the hydraulic resistance of vegetated watercourses, primarily for in-channel vegetation, is included here for a cross-disciplinary compendium (Dawson and Charlton, 1988).

2.3.4 Vegetation in physical models

Spacing between plants and width of vegetative zones across the floodplain are important parameters in physical modelling, to quantify the effects of woody vegetation on overbank flow structure and sediment deposition patterns (Davis et al, 1995). Recent research suggests that the width of the vegetative buffer has strong influence on both geomorphic and ecological conditions (Ledwith, 1996.)

The use of flexible and stiff vegetation for bank protection could be modelled using the Flood Channel Facility at HR Wallingford, based on the type of meandering channel/floodplain interaction studies conducted under Series B and C (Wark et al, 1994). Where flood flows in meandering rivers are affected by roughness due to vegetation on point bars, the effects on flood stage, overbank flow structure and sediment transport of shrub and tree vegetation on the bar surface should be investigated. This work is relevant as these areas may be proposed for revegetation as part of environmental rehabilitation or river restoration. Based on flow structures observed in FCF Series A and B programmes, further experiments are needed to model tall, rigid trees above the upper bank on outside bends (RHJ Sellin, pers. comm. 1996), where threshold values may be identified for changes in the contributions of trees and roots to bank stability with changing flood stage (for example, conditions under which trees contribute to stability, and when conditions change to become destabilising).

Experiments using the FCF at HR Wallingford could develop better materials to simulate flexible woody vegetation from both live and dried natural materials such as coconut husk fibre. Flume experiments using simulated vegetation should examine changes in overbank flow structure owing to vegetation placement on the river planform, and plant grouping density and width effects on sedimentation. Although not within the Series C scope, studies are needed to address the effects of changing stage on roughness and flexible vegetation behaviour, simulating flood flow behaviour. Physical modelling could also provide useful links in demonstrating the effects of maintenance on channel response.

2.3.5 Vegetation studies in field experiments

Field experiments in the physical consequences of riparian forest relating hydraulic and physical model findings to actual river conditions form two of the most promising areas for future research. While ecological concerns for wildlife habitat in riparian areas is increasing public and scientific demand for streamside trees (for example, see Malanson, 1993), past approaches to flood defence and hydraulic analysis have prevented widespread planting of trees or shrubs along river channels.

Research is needed to support field studies using geomorphic survey methods to document vegetation configuration parameters, and to monitor the effects of vegetation on channel capacity, sedimentation patterns and geomorphic responses to vegetation growth, such as change in sediment transport and deposition regimes. The growing interest in soil bioengineering methods should provide ample opportunities to measure these parameters from an engineering perspective. Monitoring of natural floodplain forest, such as that on the River Spey, should also be included in such a research programme, to verify the revegetation models which bioengineering schemes are intended to emulate or enhance and provide base data on the potential for increased exploitation of riparian forest products for energy generation, charcoal and other economic activities.

In river restoration, apart from specific bank stabilization to protect land from erosion, among many workers the current trend is toward natural recolonization (Brookes et al, 1996). This trend should be monitored to determine the fate of naturally recruited vegetation and the effect this approach may have on channel capacity, bank stability and other criteria. There are concerns that natural recruitment may not achieve the desired ecological/ geomorphological results on river reaches where adjacent land uses place constraints on channel evolution.

For example, after a reach has been mechanically re-meandered, summer dry conditions may typically limit survival of woody plant seedlings on upper banks. Willow seedlings in particular will survive near the summer low water margin, and typically produce a thicket of bushy stems in 2-3 years, yielding high roughness values in the part of the channel which is expected to pass flood flows. This strategy is unlikely to produce overhanging shade from upper bank trees, and dense stems in the inner channel may induce sufficient sediment deposition to alter channel morphology. This result may well constrict channel capacity, and allow undue criticism of the working with nature philosophy by those concerned by the present uncertainty in such designs.

Prediction of the evolution of riparian vegetation communities and associated changes in bank roughness and channel conveyance, together with the development of optimum maintenance strategies for juvenile, developing and mature riparian communities should be addressed through long-term field monitoring at trial sites coupled with physical and mathematical modelling. The River Restoration Project sites might provide ideal field monitoring sites.

2.3.6 Vegetation and channel maintenance operations

The additional flow resistance associated with a dense stand of vegetation on the banks of a river is seen as a disbenefit by many river engineers (Masterman and Thorne, 1994). This view is based on the assumption that by increasing roughness, bank vegetation significantly reduces channel capacity, thereby promoting flooding. On these grounds, bank vegetation is often removed in a clearing and snagging operation, the stated aim of which is to increase the channels conveyance.

As noted in Section 1.1.5, theory indicates that in most natural channels at high in-bank flows, the contribution of bank roughness to total channel resistance is small. In light of this, clearing and snagging operations to clear bank vegetation for flood conveyance purposes may not be justified and, in any case, field methods in plant cutting, flaying, etc. have much scope for modification. For example, flaying spread cutting widely and, especially in the case of willows, these cuttings are likely to root and propagate, leading to new willow growth. It is this type of inappropriate maintenance that promotes the myth that willows spread uncontrollably, rather than any intrinsic property of the species.

Appropriate maintenance operations should also be fully integrated into a long-term management strategy which balances the requirement for maintenance of channel capacity for flood conveyance, bank erosion protection, water quality, fish and wildlife habitat functions and scenic amenity. Selective and judicious removal of woody plant stems and mowing operations may be important elements in achieving multi-functional objectives, and such an integrated approach is likely to be more cost effective as well. Riparian trees and shrubs are important components of the river landscape and ecosystem and allowance must be made for them in the maintenance and management regimes. This makes it essential to provide managers and maintenance engineers with guidance on how to estimate the effects on flood stage, sedimentation, channel stability, water quality, in-stream and riparian habitats, and visual amenity value of existing and proposed riparian plant communities.

The current practice of removing downed trees along rivers should be reconsidered. Downed trees provide valuable habitats (especially refugia), supply food and act as significant sources of carbon to the fluvial system. It is not always the case that downed trees promote local bank erosion or present a hazard to navigation and, in any case, most erosion/navigation problems may be solved by re-positioning the downed tree, rather than removing it entirely. In England and Wales, dealing with downed trees is actually the riparian landowners responsibility; provided there is no risk to flood defence or navigation. However, management agencies should take the initiative in raising the awareness of landowners to the disadvantages of removing downed trees.

There is still significant concern that river maintenance in England and Wales is not carried out on the basis of any sophisticated computation or modelling of channel capacity as it is affected by vegetation roughness. Optimising the frequency of maintenance and, hence, value for money of this expensive activity, would be greatly enhanced by the application of reliable models to simulate the effects of vegetation on channel capacity. The current Section 30/92 surveys provide an ideal opportunity to apply river modelling to assist decision-making over maintenance schedules (Environment Act, 1995). Multiple design criteria, such as those which have been applied for capital works, are likely to be more effective in achieving flood defence channels which meet these additional environmental benefits (Gardiner, 1991), but there is currently considerable uncertainty associated with such decision-making (Brookes and Shields, 1996).

To provide simple guidance applicable in the field, an approach based on the presumption of allowing natural processes, rather than trying to find reasons for removing trees, would prove helpful. Currently there are too many parameters involved in channel maintenance to expect staff to carry out maintenance decisions on site without further guidance.

2.3.7 Future research

Physical model research programmes need to be developed to investigate the effects of rigid and flexible vegetation on channel and floodplain conveyance. Experiments should be designed more closely simulate the flexural properties of natural plant stems. They should also employ different patterns of planting and widths of riparian corridor, for the ranges of channel/floodplain depths, widths and velocities experienced in real rivers.

As vegetation is known to affect sediment transport and patterns of sedimentation, additional physical model experiments should be performed to investigate the longer-term effects on channel and floodplain conveyance associated with morphological adjustments induced by vegetation.
Field monitoring and post-project appraisal of bank protection and river restoration schemes which involve planting bank vegetation are essential to compare actual performance against design specification and build up a body of reliable evidence on vegetation effects on flood defence and land drainage.

New an innovative techniques are required to facilitate rapid measurement and evaluation of vegetation for studies of the type envisaged in above. Applications of ground-based, stereo, digital photography to survey vegetation stands and GIS to store and analyse spatial data on patterns of vegetation and sedimentation should be developed.

3 BANK ERODIBILITY AND STABILITY

3.1 Soil Erodibility

3.1.1 Introduction

The role of soil in the willow habitat is an aspect of riparian ecology and river bank stability that has not yet been addressed in depth. The paucity of bibliographic references combined with the concerns on the subject within the practitioner community highlights the need to study willow-soil relationships. Site assessments with varying photographic evidence of the presence or absence of under-storey vegetation, compounded with conditions of stability or instability under riparian willows highlight the necessity to address the roles of soil structure/type in the willow habitat and vice versa. Most willows generate substantial leaf litter, even in poor soils. Leaf litter may trend to inhibit the development of an herbaceous under-storey, but provides cover against raindrop erosion. The effects of weathering, possible splash erosion from direct precipitation at the edge of the under-storey and rain drops penetrating through the foliage, as well as stem flow down the tree trunk during heavy rainfall may have a cumulative erosional effect on the bank soil.

Compared to an unvegetated or fallow state, slopes covered by a good stand of close-growing vegetation experience an increase in erosion resistance of between one and two orders of magnitude (Carson and Kirkby, 1972; Kirkby and Morgan, 1980). Vegetation not only protects the soil surface directly, but the roots and rhizomes of plants bind the soil and introduce extra cohesion over and above any intrinsic cohesion that the bank material may have. The presence of vegetation does not render a bank immune from flow erosion, but the critical condition for erosion of a vegetated bank is the threshold of failure of the plant stems by snapping, stem scour, or uprooting rather than that for detachment and entrainment of the bank material itself. Vegetation failure is usually associated with much higher levels of flow intensity than soil erosion *per se*.

3.1.2 Soil properties

The main properties affected by the presence of growing willows on a bank are soil bulk density, soil shear strength and soil moisture content. Little is known about variations in these physical properties as a result of the growth of willows within and above the soil. The effects on root growth and pattern (collectively known as root architecture) of riparian trees of factors such as soil porosity, grain size distribution, stratigraphy and variations in both moisture levels and drainage conditions are poorly understood.

Soil bulk density

In a geomorphological context soil bulk density plays a key role in soil stability as well as soil erodibility. Higher bulk density is correlated with decreased stability of the bank. The effects of plant debris accumulation and the implications of loss of soil stability is discussed by Ohu et al. (1976).

When woody vegetation grows on and shades the bank, there develops a process of accumulation of plant debris and detritus on and within the bank soil. Accumulation of leaf litter on the soil surface is a result of leaf fall. Accumulation of plant detritus within the soil matrix is due to earthworm or other burrowing animal activity.

Soil shear strength

Relationships between soil shear strength and root development are well documented. Although the influence of tree roots on the increase of shear strength has been subjected to much survey and experimentation (Gray, 1978; Gray and Leiser, 1983; Waldron, 1977; Waldron and Dakkessian, 1982) no work has so far been evident on the shear strength variations of soils under willows. Those interviewed in the UK expressed opinions that roots of any vegetation (irrespective of the type of willows, i.e. tree, shrub or herb) will increase the stability of the soil because all plant root systems hold the bank soil together.

This commonly held view contradicts some of the site observations. For example, there was evidence of erosion around the base of willow trees, while accretion was clearly evident behind willow spilings and coppiced Osier willows (*S. viminalis*) at other sites. While there was a belief that uprooting of willow trees from the upper slopes of the banks may be due to soil instability below the root ball, there was evidence of uprooting within the root-soil matrix (while large lateral or tap roots were attached to the lower strata of the bank) or, in some instances, disorientation (vertical to a lateral) of the stem and foliage of tree willows.

Soil moisture content

The significance of moisture content of the soil as relevant to soil stability/erodibility is well documented. Amarasinghe (1992) measured the variation of percentage moisture content of the bank top soil (to 15cm depth) and identified the lower bank as inherently much higher (70 - 100%) while the upper banks (above 1 meter from the toe-line) as low as 15% in moisture content. An inverse correlation between moisture content and bank shear strength was identified for a non-stratified river bank with an ambient channel flow height of 1 to 1.5m depth. Hooke (1977) identified increased bank instability and bank erosion following saturation of bank soil by channel inundation. In terms of modelling bank stability, the crucial factors of pore water pressure distribution in riparian bank and hill slope stability under vegetated conditions have been identified in the models developed by Osman and Thorne (1988), Darby and Thorne (1996) and Collison and Anderson (1996).

3.1.3 Rooting patterns

At the Salecitum Arboretum in Brno, Czechoslovakia, nearly 350 species of *Salix* from around the world were grown. In research using this collection, Chmelar (1974) identified two basic types of rooting patterns in *Salix* species. The diffuse type form adventitious root initials along the entire length of a branch, and these initials can be stimulated to generate root cells by exposure to high moisture conditions. Basal type rooting was observed on some species where root initials are generated only on the circumference of the lower cutting surface. Diffuse-rooting species are the most common, and included the better-rooting species. Modern workers in Switzerland interviewed for this study told us that round-leaved willows do not root well, but this hypothetical correlation between round leaves and basal-type rooting pattern is untested. Chmelar did not publish a list of diffuse rooting species. There is concern over the horticultural bias of cultivating only willows that root or grow well, as this functional criterion may bias results against species that have other important ecological or geomorphological values.

In terms of this scoping study, a majority among those interviewed were of the opinion that willows as a genus were associated with considerable uptake of water from the main channel (they drink water through their roots was a commonly expressed view). Some interviewees elaborated on the reddish/purple fibrous root matting invasive into the channel waters from the base of tree species such as *S. alba*; functions solely for the purpose of imbibing water from the channel. Functions of these root structures have not been identified from a plant anatomical point of view.

3.1.4 Under-storey vegetation

Field observations

The role of under-storey vegetation in willow dominated habitats has not hitherto been addressed in relation to bank stability within the disciplines of geomorphology, ecology or plant biology. In the riparian corridor, site assessments indicate that within certain reaches, willow trees such as *S. alba* may or may not have any understorey vegetation. For example, within a three kilometre distance of the River Ouzel in Buckinghamshire, there was one site with mature trees of this species established more than 30 years ago, where there was considerable and uniform growth of herbaceous species such as Nettle (*Urtica dioica*), while the site further down river with a similar stand of willows was devoid of any under-storey vegetation. The willows on the former site were densely grown along one side of the bend apex, while the other site had willows along the mid-bank as well as the apex region. The latter site was directly adjacent and further along an actively eroding meander bend. The former was prior to a meander bend that had commenced active erosion in 1986 but was revetted with steel piling thereby arresting the migration of the meander.

Allelopathy in under-storey exclusion

Nichols-Orians et al. (1994) found a highly significant difference in production rates of phenolic glycosides between species of willows. They state that concentrations of salicortin and 2'-cinnamoyl salicortin varied extensively between clones and exhibited broad-sense heritability. If there is a significant correlation between the concentration and possible exudation (either by excretion from the foliage or from the decaying leaves on the ground) and the survival or establishment potential of under-storey vegetation, then, this feature of willows may exert strong controls on herbaceous plant community development. However, many genera of trees, both hardwood and coniferous have been observed in the field as saplings having germinated under dense willow cover.

3.1.5 Future research

Research is required to determine whether the planting of willows on and near banks leads to surface cracking due to loss of soil moisture within the bank or whether depletion of bank soil moisture leads to higher shear strength of the bank soil. It is unclear at present whether the net effect of willows is to increase or decrease soil erodibility under the conditions typically encountered in natural streams.

The significance of variations between the above-ground and below-ground plant physiology of various species of riparian willows in terms of reducing soil erodibility should be investigated. Research should seek to identify which species are potentially of most benefit to bank protection through reinforcing the soil and reducing bank moisture.

The specific function of dense mattress of fibrous roots dipping into the water edge below many willow stands should be investigated.

Research should investigate if the usefulness of willows in reducing soil erodibility is limited because the root density, and possibly the tensile strength of the root-soil matrix, is not uniform. The roots of individual plants tend to form strong "root balls", separated by weaker areas in between.

Research should address the demographic limitations on under-storey vegetation below willow canopies. Aspects such as allelopathy arising from exudates of the willow canopy or the roots, as well as the better known implications of shading under willows, must be addressed.

3.2 Plant health, succession and the bank environment

3.2.1 Introduction

Relevant disciplines for this objective include botany, horticulture, ecology, soil physics, hydrology and geomorphology. Studies in plant inundation tolerance have been carried out but few studies exist on the *Salicaceae*, or on species within *Salix* or *Populus*. Horticulturally, the *Saliceae* are relatively well documented for their responses to propagation treatments. The life cycle and expectancy of willows are not well understood and are especially complicated by the phenomenal ability of willows to re-sprout from severely damaged, coppiced or pollarded conditions. However, for bank protection purposes, potential life span of willows may not be as important as their capability for regeneration. Few studies exist of *in situ* root growth, metabolism and decay.

Design guidance in bank protection using willows has to be far-sighted to allow for natural process of plant growth, regeneration, ecological aspects of intra- and inter-specific competition and inundation tolerance.

3.2.2 Inundation tolerance

A discussion on protection of banks of an open channel with vegetation lining must encompass a multi-disciplinary overview on the ability of willows to tolerate periodic or long term inundation and submergence. The scoping study identified lack of professional knowledge among interviewees on inundation tolerance of willows.

Gill (1970) and Kozlowski (1984) identified responses to flood inundation for a number of floodplain genera, including *Salix* and *Populus*. Whitlow and Harris, (1979), identified specific plant anatomical and morphological responses to inundation stress, most commonly adaptive mechanisms for transferring oxygen to roots to counter anoxia and reduction in nutrient availability.

Many interviewees stated that willows are 'water loving trees'. However, Mike Greaves, the Head of the Centre for Aquatic Plant Management at Long Ashton Research Station states that it is a false belief. While willows in general may tolerate short periods of flooding, as confirmed in recent experiments at Long Ashton, this does not mean that *Salix* will favour permanently saturated conditions. In experiments conducted at Long Ashton, newly rooted cuttings grown in pots with saturated soil indicated root preference to follow the outer edge of the pot, likely following the oxygen gradient.

There is a rule of thumb that 40 days is the temporal limit of submergence tolerance by willow roots (Mike Greaves, pers. comm.), but more rigorous testing of species tolerances and natural habitat preferences will advance knowledge of management applications. Field experience from the River Waal in the Netherlands indicates that willow bank protection certainly fails when plants are inundated for more than 200 days per year (Splunder, pers. comm., 1996).

From theoretical and applied ecological perspectives, identification of the range of niches for willows is by no means complete. Hupp (1992) identified species preferences along a cross section of Passage Creek in northern Virginia, USA, and identified willows as associated with the channel shelf rather than the bank edge. This may augur well for the second stage of a two-stage channel if one wishes to promote willows as bank or riparian protectors.

3.2.3 *Salix* morphology: potential and actual uses

Within the diversity of tree and shrub willows, the most prevalent riparian types in the UK are *S. alba, S. caprea, S. cinerea, S. fragilis, S. viminalis, S. purpurea* and *S. triandra.* Of these, *S. viminalis* and its hybrids are the main willows used for the traditional bank protection technique of spiling. All interviewees were of the opinion that *S. viminalis* is a bushy willow. However it is evident that this misconception has arisen owing to the traditional technique of coppicing, compounded with its ability to generate large numbers of new shoots with dense foliage from the coppiced stock. In fact van Splunder et al. (1994) compared the growth rates of willow saplings of the above four species of willows noted that *S. viminalis* grows the tallest and is clearly a tree species if allowed to grow.

This caused concern among most interviewees (managerial, technical and conservation staff) on the long-term outcome of willow spiling as a mode of bank protection. Causes for their concern included the possibilities of wind-throw, excessive channel narrowing and formation of secondary currents increasing erosivity of the flow, as well as possible exclusion of fringe vegetation due to overhanging foliage.

3.2.4 Dead/live root turnover and seasonality

Root growth and decline has been dealt with by previous authors (Bohm, 1979), though not specifically to riparian willows. Knowledge on this aspect, of possible geomorphic significance in bank protection using vegetation, was non-existent within the professionals interviewed. Most were of the opinion that willow roots intrinsically had a high tolerance to water and hence would not die except during winter when all temperate plants were expected to have dead roots.

Brandon (1989) advocates pollarding to prevent root death from causing trees to topple over into the channel. If proven, the benefits of pollarding should be taken into account in the design of maintenance regimes for willows.

The proportion of dead roots may have significant impacts on the effectiveness of willows in producing increased cohesion in the bank soil matrix and thereby increasing erosion resistance. If most bank erosion occurs during winter, during the season of highest root mortality, then the effect of root reinforcement may be much less pronounced than would be indicated from the results of laboratory tests using healthy plants.

The tensile strength of roots plays a major role in enhancing the mechanical strength of the soil (Endo and Tsuruta, 1968; Gray, 1974; Wu et al. 1979; Waldron and Dakkessian, 1982). If willow roots lose their tensile strength due to death in winter or their inability to survive waterlogged and anoxic conditions, reduction in shear strength of the bank soil could result. This may, in turn, lead to bank instability.

3.2.5 Sediment trapping

Exposed willow roots may act as surface meshes to trap sediment and floating plant propagules and to act as nurseries for toe-invasive species which may be crucial to lower bank stabilization. Opinions among interviewees on the possibility of exposed willow roots acting as traps for sediment and floating plant propagules varied considerably. Two types of exposed roots were discussed: larger roots exposed within the channel due to uprooting of a tree; and, dense, fibrous root mats that were exposed by bank erosion. Clearly, the former result from either wind-throw or mass failure of the bank while the latter were mostly due to corrosion (surface erosion by in-channel fluid shear stress). Fibrous root mats offered a cushion effect and acted as a physical barrier between the fluvial forces and the bank surface in the erosion-vulnerable region near the bank toe.

Both types of exposed roots may have significant yet contrasting geomorphological significance. Many interviewees had neither expected nor observed accretion of sediment within the large exposed roots. However almost all suggested that root matting protruding from the basal region may act as a trap for sediment as well as floating plant propagules, though the retention period depended on the intensity of channel flow.

Evidence of either root system acting as a nursery for toe-invasive species was inconclusive both in interviews and site assessments. Some interviewees had observed the presence of herbaceous vegetation such as Nettle (*U. dioica*) and Willow herbs (*Epilobium spp.*), grasses and seedlings of many riparian species during summer, within the exposed larger willow roots at the bank-toe. There was evidence of this on some sites surveyed (e.g. on the River Ouzel). What is essential is to identify the role such roots play in the establishment of inundation tolerant species of a herbaceous nature. These may play a critical role in end point control of the bank in terms of bank corrosion as well as bank stability.

3.2.6 Succession

Conservation staff stress that it is nature that determines which species are present in the climax riparian community, irrespective of the planting of willows or other bank vegetation for bank protection. The issue of inevitability and desirability of the dynamic changes in plant communities within the riparian corridor due to secondary succession has been long recognized and this is reflected in the literature (Hefley, 1937; Hickin and Nanson, 1975; Nanson and Beach, 1977).

A multi-disciplinary approach to river corridor management is essential when using vegetation as a key component in a bank protection scheme. Hupp (1992) discusses a case study of Passage Creek basin in northern Virginia, USA. Hupp's appraisal of the distribution patterns of woody vegetation within clearly defined hydro-geomorphological zones (channel bed, channel bar, channel shelf, floodplain and terrace) illustrates the diversity of tree species that may be present in a river corridor and highlights the importance of selecting the species best suited to each fluvial landform when employing vegetation for channel stabilization.
The generalised cross-section along Passage Creek identifies herbaceous plants as associated with channel bars, shrubs on the channel shelf and tree species on the floodplain and terraces. These associations are consistent with what most British conservation and river engineer staff envisage as the ideal vegetation pattern for a low-maintenance channel with high stability. Reference to the position of *Salix* in the riparian cross-section stated that, "*Salix nigra*, typically a channel shelf species, occasionally grows on channel bars that are normally dominated by herbaceous aquatic plants". This indicates that the north american *Salix nigra* is identified as a suitable occupant of the dry shelf region, but that it also grows on the wetter bars. This finding is not directly to the UK, and it suggests that equivalent geomorphic-taxa associations should developed for British willows. Furthermore appraisals should address regional variations within British rivers and species.

The designers of bank protection schemes involving willows must be able to understand why a certain species of *Salix* is successful at one site and position in the cross-section, but not at another. They must also be able to gauge the likely long-term geomorphological, ecological and flood defence implications of placing willows at a particular location. This requires a multi-disciplinary analysis or river channel form, process and function coupled to a fulsome understanding of the morphology and successional characteristics of *Salix* dominated plant communities.

3.2.7 Future research

Recent investigations at Long Ashton on the physiological adaptive capabilities of different willows should be extended. Some of the possible implications have already been identified. For example, if compacted soil and clayey soil are deterrents to willow root colonization, then the suitability of willows to lowland England (Oxford Clay regions) may be questioned on possible geomorphological significance.

Willow rooting pattern and depth are subject to reach-specific hydrological complexities and research projects must be formulated to identify the critical limits of stability of a bank with willows growing under conditions representative of typical bank environments.

Two-stage channels are now regarded positively by most river engineers (D. van Beeston, pers. comm., 1996) and the effects of bank vegetation on them has been the subject of academic appraisal for almost a decade (Sellin and Giles, 1988). It is recommended that a project which addresses the optimal position (habitat) for willows on the banks should be initiated. The introduction of a species on the bank may not ensure its ultimate survival in that position. Implicit within this is the aspect of survival under varying levels and periods of submergence and the ecological concept of the realised niche.

Experiments should be conducted on the viability of using exposed willow root systems as nurseries for cultivation of semi-aquatic species that are tolerant to regular inundation and changeable fluvial erosive forces. This topic would form an excellent multi-disciplinary research project with interests in many fundamental concepts of fluvial geomorphology, ecology and plant physiology.

The implications of root death and turnover for bank protection using willows are extremely important and research is urgently required. Specific research topics to be addressed include work to:

- establish whether there is significant root death/turnover within willows during winter;
- to investigate if root death has any effect on the vulnerability to uprooting of willows under different levels of channel inundation. On the basis of the results, it should be possible to identify critical limits and predict tree instability;
- examine the effects of pollarding on dead/live root turnover in willows and use the results to design improved maintenance regimes to reduce the risk of tree toppling;
- identify the geotechnical effects of decreased cohesion arising from the death of willow roots due to seasonal effects or bank saturation;
- perform a scientific appraisal of live/dead root turnover on a species specific basis. This may enable the identification of certain willow taxa as superior for long-term bank protection due to superior root survival characteristics;
- define the ability of willows to tolerate heavy clay soils under stressful soil water conditions and so identify limits to the capability of willows to provide enhanced erosion resistance and bank stability; and,
- further research is needed to support the identification and introduction of 'appropriate vegetation' on protected river banks, taking account of the position of the vegetation in the channel cross-section and future succession of vegetation species within the riparian corridor, as well as the initial capability of the plants to protect the bank.

3.3 Bank hydrology

3.3.1 Introduction

Three types of influences are considered under which willows, bank tree and shrub vegetation might be expected to destabilise river banks; on certain types of bank materials, under certain climatic conditions and under certain hydrological conditions where shrubs and trees may adversely influence bank drainage. This objective seeks to identify those conditions under which bank vegetation could have destabilising influences.

Most studies divide the effects of bank vegetation into those which change bank hydrology and those which change the soil mechanical properties. The New Rivers and Wildlife Handbook illustrates some examples of the potential destabilising influence of willow trees on the river banks (RSPB et al, 1994).

3.3.2 Hydrological impacts

The main hydrological effects of willows are reduction of effective precipitation reaching the ground, increased infiltration capacity and soil permeability with a net reduction in moisture content, and the height of the water table (Greenway, 1987). Reducing effective precipitation, increasing infiltration capacity and increasing soil permeability are considered beneficial effects on bank hydrology.

Infiltration capacity at the surface of a vegetated soil is generally much higher than for the unvegetated state. Consequently, the volume of surface runoff for a given precipitation event is reduced, decreasing its effectiveness in generating surface erosion.

3.3.3 Hydrological effects on bank stability

With reference to bank stability, Thorne (1990) states that bank vegetation enhances stability through increased interception of precipitation, elevated evapotranspiration and enhanced drainage. Of these effects, the ability of willows and other riparian plants to imbibe soil water and transpire it to the atmosphere may be particularly effective since it reduces the moisture content of the bank soil between precipitation events and lowers the water table. In addition, suction pressures in the soil are enhanced, increasing the effective strength of the soil. The uptake of water by the roots also supports a higher capillary fringe, which acts as a pathway for the loss of water from the water table to the evaporating surfaces at the ground surface.

The effects of subsoil composition and structure on tree root growth are discussed by Collison and Anderson (1996). They noted that where soils and subsoils are thin, this enables the roots of trees to penetrate the entire profile. This is contrasted with locations where soils are much deeper, preventing the colonization of lower layers by roots and opening the possibility of slope failure surfaces developing within the soil below the rooting depth of the trees.

The inability to penetrate subsoil is offered as a possibility for a perched water table (enhanced by lack of matrix suction from the root system) which may further promote the development of a shear surface below the root zone, especially where a potential shear surface already exists due to bank composition.

3.3.4 Soil depths and rooting zones

Major areas of uncertainty exist concerning environmental controls on willow rooting patterns. In the interviews, comments were made of instances where the willow tree on the bank slope may slide en *masse* into the channel because of its formation of a root ball in the upper layers of the bank. Therefore, the possibility of what Collison and Anderson (1996) describe as development of a 'perched water table beneath the root zone' may pose a serious risk to bank instability.

The interviews produced no good information regarding the mechanisms of bank-water-vegetation interactions or how these interactions could be addressed through research projects. General comments on the suitability and unsuitability of particular willow species were mostly personal views rather than based on sound field observations or scientific understanding. Field visits and site assessments were based on visual assessment rather than the compilation of any quantitative data.

3.3.5 Future research

Research projects should address the potential for variability within willow cultivars and clones in developing rooting patterns that enhance transpiration (source to sink facilitation) and the ability of roots to increase suction pressures of the bank soil. The national collection of willows at Long Ashton would be an excellent source of live material for field and laboratory research.

Recent research has established that willows have fast growth rates during the first few years of establishment (van Splunder et al.,1994). This feature of a pioneer genus could yield researchers excellent opportunities to formulate short and medium term (3-10 year) studies to examine the intra-specific diversity of *Salix* species, and to examine the impacts of a cohort of willows of on stream bank and floodplain hydrology. For example, projects could determine whether riparian trees moderate or exacerbate diurnal and seasonal fluctuations in groundwater levels.

Willows may produce improved stability through their hydrological impacts on bulk unit weight and shear strength. Research should address the species-specific characteristics of willows in improving the stability of banks through their rooting patterns and allied physiological abilities that lead to better drainage. An advantage for such experimentation may be the considerable intra-specific diversity within the willow genus.

The implications of research on willow rooting patterns at the Long Ashton Research Station, in terms of the limitations of willow roots in growth into or in saturated soils, must be further explored. Little is known about rooting patterns in willow species in general, making this a primary subject for further study. Specifically, detailed work is required to determine which species, cultivars or clones can contribute to enhanced bank drainage and thereby to bank stability under specific soil and bank conditions.

Further work is needed to understand the physiological adaptive attributes within the *Salix* genus. If a particular willow species is limited in its inability to adapt to subsoil hydrological and associated anoxic conditions, then the surcharge weight of the tree compounds its inherent deficiencies in contributing to bank stability through low suction pressure and transpiration. Research projects should seek to identify such instances of bank instability arising from interactions between tree roots and perched water tables. A survey of field locations with the hydrological assessment of groundwater levels, together with the soil structure and composition of the banks may assist in clarifying these relationships.

3.4 Bank stability

3.4.1 Introduction

The structure of the root system reflects the genetic attributes of the species, the geotechnical properties imparted by the bank soil-root matrix, and the dynamic nature of the root-soil matrix when compared with the static nature of an artificial bank revetment and the soil. Any research projects of an experimental nature or aimed at development of models on the geotechnical effects of root reinforcement of banks by willows must account for the dynamic nature of the matrix irrespective of the in-channel fluvial regimes.

3.4.2 Influence of roots on soil strength

The description of soil strength stems from the Mohr-Coulomb analysis, expressed by

$$\tau = c + \sigma \tan \phi$$

where, τ = shear strength, c = cohesion, σ = normal stress and ϕ = angle of internal friction.

Although modern soil mechanics has amplified and added to this equation considerably, it remains the basis for the analysis and prediction of soil shear strength.

The Mohr-Coulomb analysis demonstrates that cohesion, angle of internal friction, and normal stress must be quantified in a given soil to characterize its shear strength. Therefore, the influence of willow roots on each of these parameters must be addressed in detail under conditions representative of riparian bank conditions. Also, limits and constraints on the effects of willow trees in affecting these parameters must be identified.

Experimental work

There is considerable criticism of standard soil mechanics analyses when applied to natural, unreformed soils. For example, Johnson et al. (1983) note that in actual practice a linear failure envelope may not adequately describe the actual shear behaviour of the soil. Kassif and Kopelovitz (1968) used a double shear apparatus to quantify the shear strength properties of root permeated soils. Unlike Kaul (1965), who used a matrix of millet roots grown in a growth chamber, Kassif and Kopelovitz used synthetic fibre made of 80% P.V.C and 20% di-octyl-pthalate. These were embedded vertically in two types of soil.

Furthermore, they fixed one set of fibres to a base while the other set was without 'fixity'. While the study was directed at an understanding of root permeated agricultural soils to a cutting tool, the effects of increase of shearing resistance by roots in soils was conclusively observed. As the authors themselves conclude, this type of simulation of roots by synthetic fibres 'suffers from limitations'. Kaul (1965) demonstrated a similar increase in shear strength with his millet roots grown under controlled laboratory conditions, but his results could not be compiled together due to the extreme variation in the homogeneity of the samples. These limitations not only illustrate the difficulty of compiling results from different experiments, but, given that they represent real variability in soil properties, they may also indicate the impossibility of generalising the results at all.

This brief review of experiments in root reinforcement indicates limitations to:

(i) the performance of existing models of soil behaviour;

(ii) artificial simulations; and,

(iii) natural plant materials (due to extreme variability between the properties of different samples).

A factor of significance from Kaul's study was that the friction angles of the soil samples with roots were larger than those of a similar soil without roots. This is ascribed to 'the action of rootlets making larger virtual particles out of smaller ones'. Even though there is no comment or criticism of this postulation in subsequent literature it is worthwhile discussing the possible implications of such a phenomenon in the context of existing theory and in light of the practical implications.

Kaul's suggestion that plant rootlets tend to make larger virtual particles out of smaller ones has to be considered in conjunction with the observations that:

- it is highly possible that rootlets actively contribute to increased cohesion of soil particles by root exudates (Reid and Goss, 1980, 1981) which have constituents such as muco-polysaccharides that have a highly adhesive nature;

- an increase in the angle of internal friction increases the critical levels of stability of the soil and hence this proposal contributes to the validity of using standard soil mechanics equations to represent the shear strength of the soil; and,

- it is uncertain as to what is meant by 'rootlets'. In plant biological terms these are physiologically highly active organs of the plant which may be minute in size (Bohm, 1979). If size is a criterion in recording the total effect of the rootlet in resisting shearing forces then the currently accurate instruments of 'direct shear' may not be suitable. This is because the rootlets are so minute that they may not offer the tensile resistance to planar shearing devices. Whether the rootlets are fixed to the plant or an artificial base the shearing device would have to be extremely precise in addition to being minute.

In addition, the rootlets are distributed in a network of ramified orientations (Bohm, 1979), Such diversity in orientation greatly reduces the applicability of the fundamental theoretical model (Waldron, 1977) on the effects of plant roots on shearing stress which is based on a vertically oriented root being subjected to horizontally applied direct shear. Waldron and Dakkessian (1982) observe that grassy species including *Phalaris tuberosa* produced a denser root mattress and higher shear strengths in a short period of growth when compared with pine saplings of similar age.

Waldron and Dakkessian (1982) proposed that the higher soil stability ascribed to tree species, as opposed to grasses, in the field situation is due to both the tensile properties of their roots and their ability to 'extract more water from a greater depth than does grassy vegetation, so that where trees are present, the onset of saturation requires more rainfall'. This is, however, a rather simplistic synopsis of the differences between trees and grasses. It ignores many other obvious and potentially significant contrasts between grasses and trees such as differences in canopy shading and interception, root architecture and life cycle.

The inclusion of the latter hypothesis compounds the complex nature of soil stability studies on a river bank slope with a mixed vegetation (leading to complexities in root tensile properties, root density at different depths etc.) and a moisture profile gradient up the bank which varies in keeping with both the flow levels and precipitation. If shear strength variations in a particular soil are to be studied accurately, such as the effects of varying normal stresses within a range of stress values, it is necessary to use more sophisticated shearing tests. Torsional shear devices may useful in that through their use soil cohesion and friction angle can be quantified *in situ*..

What is clear is that increases in tensile strength can be considerable. In studies of alluvial bank materials in Mississippi bluff-line streams, Thorne, Murphey and Little (1981) found the tensile strength of rooted samples to be on average ten times that of unrooted ones. Hence, vegetated banks are better able to resist the development of tension cracks due to desiccation and to tensile stresses behind steep banks that often trigger both slab-type and cantilever failure of unvegetated banks.

Synthesis of findings

Cohesion is a major factor that has been insufficiently assessed. Cohesion arises from within the soil matrix as well as due to the exudates from the roots and especially the rootlets (Reid and Goss; 1980,1981). This is insufficiently understood or addressed so far in terms of the contribution of roots to geotechnical strengthening of banks.

Normal stress in the soil and substrate varies with location within a stand of a mature trees, such as *S. alba*. This is due to the vertical stress (surcharge) being highest around the immediate surroundings of the tree trunk if the tree is isometric and vertical. Field evidence indicates that usually bank willows such as S. fragilis lean into the waterway, thereby complicating the factor of normal stress on the bank. The effects of leaning on the distribution of normal loading in the bank require closer scrutiny.

Soil type and bank stratigraphy may compound the problems of analysing the stability of banks with willows. Thorne (1978) discussed the implications of non-cohesive, cohesive and composite channel banks with reference to fluvial erosion. A stratified bank with a matrix incorporating a diverse range of root sizes of varying tensile strengths, varying cohesive contributions and normal pressures may limit the validity of a model that does not account for these site specific factors.

Moisture content of the bank is a critical factor in bank stability and erosion (Hooke 1977; Amarasinghe, 1992). Variation of geotechnical properties of a soil arise from the moisture status of different soils. Clay soils have higher cohesion values arising from van der Waals forces (electro-physical forces due to varying ionic status depending on the moisture and molecular structure in the clay).

3.4.3 Bank height and root architecture

Bank height

Root reinforcement of soil extends down only to the rooting depth of the vegetation. For grasses this is usually of the order of centimetres, for shrubs a few tens of centimeters and for trees is seldom more than a meter, although there are exceptions to these generalizations. Bank height is therefore an important factor in limiting the effectiveness of root reinforcement in stabilizing the bank. If the bank height is less than or equal to the rooting depth, then roots almost certainly cross the potential shear surface and reinforce it against failure. However, if the bank height significantly exceeds the rooting depth then slip surfaces for toe failures will pass beneath the zone of root reinforcement.

Riparian tree root architecture

Roots will continue to prevent shallow slips and still bind the failure block together during and after collapse-so that failed blocks are more likely to remain at the toe and protect the intact bank from further erosion, but the stabilizing effect of root reinforcement on deep-seated failures is lost (Gray and MacDonald, 1989). This phenomenon is clearly demonstrated on the banks of streams that are subject to severe degradation. Trees switch from holding the banks up to dragging them down in response to increasing bank heights and angles caused by basal lowering and toe erosion (Simon and Hupp, 1986; Harvey and Watson, 1986).

Generally, a species with a dense network of fibrous roots is of more benefit than one with a sparse network of woody roots. Woody roots may disturb the structure and any imbrication of the bank material, and weaken it through root wedging, though research by Gray (1978) suggests that this is at most a second-order effect.

To be effective, vegetation must extend down the bank at least to the average low water plane, otherwise the flow will undercut the root zone during significant flow events. In this respect, plants which are tolerant of inundation are more effective than terrestrial species. For overall bank protection, a mixture of riparian and terrestrial species would appear to provide the best bank protection.

3.4.4 Bank stability models

Bank stability modelling is increasing in popularity (Collison and Anderson, 1996; Darby and Thorne, 1995, 1996). In predicting bank instability, Darby and Thorne (1996) develop and test a bank stability analysis for steep, cohesive, non-layered river banks that fail along planar surfaces which may not necessarily pass through the toe of the bank. Their model does not, however, incorporate the effects of trees or shrubs on the bank. They emphasize the key roles played by confining pressure and pore water pressures at the moment of failure as they influence the failure plane angle. If willow trees are on the banks, they would have considerable effects on both these aspects, subject to the root characteristics of depth and density and tree physiological (mainly transpiration) state.

While limiting analysis of instability to cut slopes in non-riparian environments, Collison and Anderson discuss the effects of vegetation, including tree species, on slope hydrology/stability.

They identify that soil matrix permeability determines whether vegetation has a beneficial or detrimental effect on slope stability. Where the change in permeability due to vegetation is small compared with the matrix permeability, the impact of vegetation is observed to be beneficial. When the converse is the case, the impact is detrimental, implying that the permeability discontinuity at the base of the root zone causes increased pore water pressures to develop.

Their discussion on the identification of the optimal vegetation configuration for slope stabilization encompasses the diversity of plant morphology (for example, long grasses and trees), and they identify all key aspects of plant soil relationships (that is, the hydrological and mechanical effects) in developing predictive models based on the critical issue of the factor of safety with respect to mass failure. This is a significant development in the appraisal of slope stability on vegetated slopes. However, the realisation that the time taken to achieve stabilization using a vegetation cover (20 years) and the need for the root balls to coalesce poses limitations on the degree to which vegetation alone can ensure bank stability. Plant biologists are bound to question the expectation of root balls coalescing since there is competitive interaction between the root systems of plants. Realised niche spaces of plants in a habitat are not necessarily limited to above ground competition. Further, a span of 20 years is sufficiently long for secondary succession to have implications for renewed surface erosion (Wolman and Schick, 1967; Rickson, 1990) by precipitation on fallow soil with sparse vegetation.

3.4.5 Anecdotal evidence

Anecdotal evidence and preconceptions on the role of tree roots in bank stability were clearly evident in the interviews. All those interviewed expressed the opinion that roots of bank vegetation contributed to holding the banks together. On enquiry as to *how* roots specifically carried out this function, opinions varied. Some interviewees suggested that this was obvious and had given the question little thought. Others stated that when a plant is pulled out of the ground a clod of soil usually adhered to the roots. No scientific research was cited in the interviews with respect to the mechanics of willow roots (or in fact any other riparian vegetation) in reinforcing channel banks.
The role of tree roots in anchorage was offered usually as a secondary function of the root system. There were instances of criticism of the negative effects of tree roots in disrupting the integrity engineering structures and revetments on the banks of waterways lined with synthetic fibre, geotextile, gabions or concrete. For example, interviewees were concerned about evidence of:

- tree roots growing through the synthetic bank impermeable liners and thereby creating potential leakage paths and causing permanent damage to the banks; and,

- trees growing through gabions or concrete on banks leading to disruption of the structure and potential bank instability.

3.4.6 Future research

Fundamental research must directly investigate the mechanisms by which roots contribute to soil strength, especially through their impacts on cohesion and friction angle. Though Gray (1978) discusses the 'adhesive role of the root surface area' , there has been no thorough assessment of variations in cohesion due to presence of roots from different species and cultivars of willow. Further work is also needed to account for the effects of plant age and root size.

Studies are required to establish the chemical composition of root exudates and the role of mycorhized fungi in soil particle cohesion.

While the geotechnical engineers usually model soil-root systems on the basis of the physical aspects alone, agricultural researchers (for example, Reid and Goss, 1980; 1981) identify the live root exudate properties as the key factor in what they term as 'soil aggregate stability'. Two allied academic disciplines are currently addressing plant root-soil interaction in contrasting fashions. Multi-disciplinary research is required to consider both the physical and chemical impacts of roots on soil strength and stability.

Research is urgently required to establish how root distributions through the soil vary by species. Bounding studies should determine, under ideal conditions, how deep willow roots are likely to grow. The importance soil macropores to root oxygen gas exchange should be established and the information used to predict the soil limiting factors for *Salix* species. The response of root growth to extended durations of drought or flood should be examined.

There are serious limitations to further developing and validating bank stability models that incorporate the effects of vegetation due to lack of data on natural colonization (secondary succession) of banks over reasonable periods of time. A viable study approach might be through use of historical ground/aerial photographs to identify tree species succession over a period of time and couple this with identification of historical rates of bank retreat and field measurements of contemporary root-reinforced bank properties.

Some species of willows may in fact may accelerate erosion of the bank for their own benefit. Once the bank has collapsed the channel may be diverted away from the tree, leading to an enhanced habitat for that benefits the willow or its successors. Field monitoring surveys and experiments could be performed to investigate the role of willows in driving bank instability as part of their own survival and propagation strategy.

3.5 Buttressing and hardpoints

3.5.1 Introduction

Buttressing or lateral restraint against movement in shallow slopes is provided by firmly anchored, rigid tree trunks (Gray and Leiser, 1983). Arching in slopes occurs when soil attempts to move through and around a row of trees firmly anchored in an unyielding lower stratum of soil. Therefore, in gentle hill and bank slopes the trees may act as a cantilever piles, with soil arches formed upslope from them. Thorne (1990) proposes that buttressing and soil arching on a river bank should increase bank stability with respect to shallow and deep-seated slips, and soil creep. Wang and Yen (1974) and Ito and Matsui (1975) offer theories for describing lateral restraint by piles (applicable to trees) embedded in a slope.

Hardpoints are relatively short, erosion resistant reaches bank line which are invulnerable to destruction by direct attack. Deep embayments may develop around and between hardpoints due to local disruption of the flow field and continued fluvial erosion of the soil between the hardpoints. However, unless the flow is unable to erode behind the erosion resistant material it cannot flank the hardpoint. Under these circumstances, hardpoints may be able to prevent general retreat of the bankline.

When a closely spaced row of willows grows along a channel bank-toe, the trees may act as both buttresses and hardpoints in stabilizing the bankline, even though there may still be clear signs of erosion between the trees. The crucial elements are the rooting depth of the trees and their spacing along the channel.

3.5.2 Interview results

Interview results indicate that the majority did not understand buttressing or soil arching. The geomorphic significance of these two phenomena were therefore not identified by them. They were of the opinion that buttressing may have some significance on stable as well as potentially erodible bank slopes. There was a majority view that even if the trees grew at the bank toe with closely spaced linear formation, the long term effects on river bank slope stability may be much in contrast to a similar situation on dry land or roadside banks. The motive fluvial forces arising during storm flows as well as periods of long but high flows may lead to ultimate erosion of the banks behind the trees. There were suggestions that embayments between trees in such rows may act as localised whirlpools that may themselves be a danger to the long term stability of the bank. Apart from the addition of overburden of Large Woody Debris (LWD), to the channel, maintenance expenses may be high for the riparian owner as well as the Environment Agency in flood protection aspects.

It was suggested that soil arching may only be a temporary phenomenon due to regular inundation of the banks by storm flows which could wash away any accreted material above even a well-anchored tree. The action of trees as hard points along the bank-toe was confirmed by most professionals. There was concern about the risk of continued erosion behind the willow trees in the riparian corridor. Personal observations of most interviewees suggested a creation of a localised concave eroded bank area behind mature willow trees which had been established in the mid to lower region of river banks. All interviewees stated that soil arching would not merit research as a priority when compared with the creation of hard points.

3.5.3 Site investigations

Site investigations confirmed the opinion of engineering and conservation staff of the Environment Agency as to the rare evidence of buttressing effects of willows on the river banks. The roots exposed on the banks did not show any special morphological adaptive shapes and sizes that authors such as Turmanina (1965) and Vanicek (1973) ascribe to buttressing effects of trees and other vegetation. On the contrary, there was evidence that the roots may have been exposed due to erosion of the top soil of the banks. This was specially significant under willow trees devoid of any under-storey vegetation. Creation of hard points along river banks by individual trees or rows of willow tree species along the bank-toe is evident in some bottom land forest fluvial ecosystems.

3.5.4 Future research

Research is required to address:

- the frequency and conditions under which buttressing occurs due to the natural action of willows should be investigated;

- the potential for creation of hard points for bank protection using willows;

- the performance of artificially introduced willows over an extended period should be investigated. This is needed because, in the interviews and site visits, there were no examples of the effectiveness of tree willows over the longer time scales (>10 years), required for them to develop into buttresses or hardpoints; and,

- the establishment of under-storey vegetation at and between hard points as secondary bank toe-colonisers and protectors.

3.6 Surcharging and wind-loading

3.6.1 Introduction

Surcharging, in the context of bank protection studies, refers to the effects of the additional weight of vegetation or structures on the bank. Thorne (1990) addresses the possible effects of surcharging by vegetation on bank stability. The weight of trees growing on a steep bank add mostly to the downslope component of weight and, thereby, decrease stability. However, trees growing on a gently sloping bank add mostly to the slope-normal component of bank weight and act to increase stability. Wind-loading occurs due to forces aerodynamic drag exerted on trees by air movements. These forces may break the limbs or trunk of the tree, or may uproot it entirely - a process termed wind-throw. Drag forces are also transmitted into the bank via the roots and may decrease bank stability to trigger a mass failure.

3.6.2 Interview results

The term surcharging was generally understood by engineers, but was unfamiliar to most interviewees engaged in conservation and managerial positions. The significance of surcharging depends primarily on the position of the tree on the bank, with trees at the bank top being potentially most damaging to bank stability. However, a secondary effect may be introduced if the upper bank is grazed. As pointed out by interviewees, the trees may then be asymmetrical, leading to additional turning moments that cause trees to lean over and fall on to the river channel, dragging the bank down with them.

In the case of tree species of willow, wind-loading often causes branches or even the trunk to break, inputting large woody debris to the channel. Crack willows (*Salix fragilis*) are regarded as particularly vulnerable to this type of wind damage. In extreme cases, the entire tree may topple over, supplying debris and creating a mass failure of the bank around the root ball. Wind-loading, therefore, creates legitimate concerns for flood defence, navigation and river management staff.

Among all the interviewees, there was criticism of willows as a recommendable bank tree species, because of the perception that they generate significant problems through surcharging and wind-throw. However some conservation staff in the Environment Agency, expressed the view that the toppled tree root balls and scarps provided valuable habitats for animals and nesting sites kingfishers. Hence, to the conservationist toppling due to surcharging by tree weight or wind-loading was a positive benefit of having willows on the banks of a water course, while for the engineers it was a serious problem.

Surcharging and wind-throw are only issues for tree willows (alba species) and this favours the use of shrub willows for bank protection. However, not all river managers seem to be aware of the difference between shrub and tree willows. For example, some individuals were concerned that willows growing from the spilings used for bank protection in a number of recent schemes would, once established, grow to be large trees within a few years. This concern was voiced despite the fact that the individuals concerned had no idea whether spilings came from shrub or tree species.
In the case of tree species, limb loss, toppling and bank failures due to surcharging can in any case be avoided simply by coppicing or pollarding at the intervals prescribed for the species and setting by forest managers. Tree management using these measures also facilitates access to the channel for river maintenance using machinery. There are other environmentally-sound reasons for tree management, however, including the prolongation of tree life, improved under-storey growth and diversity due to increased light penetration and the supply of coppice products to the expanding market for these materials. A possible negative impact of coppicing and pollarding is reduced shading, which might adversely effect the fishery and allow stronger growth of aquatic plants.

It is clear from the interviews that while pollarding is a traditional technique endemic to southern England, its advantages are less appreciated and the procedure is less practised in the northern regions of the British Isles.

3.6.3 Future research

Further research should address the needs of river managers and engineers in developing best practice to avoid the undesirable effects of surcharging.

Specific topics to be addressed should include:

- the relationship between bank profile geometry, tree position, tree morphology and the destabilising impact of surcharging;

- the vulnerability of different species of willow to limb breakage, stem snapping or uprooting by surcharging and/or wind-loading;

- the development of optimum maintenance regimes to suppress surcharging and wind-loading problems on banks protected by willows;

- the impacts of grazing due to unrestricted stock access on the vulnerability of willows to surcharging and wind throw; and,

- the development of user-friendly procedures to support the selection of the best species, bank re-profiling strategy and maintenance regime to avoid surcharging and wind-loading problems in a bank protection scheme using willows.

The research necessary should employ field surveys to establish a catalogue of cases involving bank failure or management problems due to the effects of surcharging (windthrow and uprooting) along rivers and navigable waterways, together with theoretical studies and laboratory investigations to simulate the effects of surcharging and wind loading under conditions representing a diverse range of bank environments in computer models.

4 BANK ACCRETION

4.1 Channel narrowing

4.1.1 Introduction

Concerns exist over the use of vegetation for bank stability where the cross-sectional area of the channel may be decreased and conveyance be reduced due to the morphological effects of vegetation. A review of current literature on this topic suggest three mechanisms by which vegetation may reduce cross-sectional area through inducing the channel to narrow. These are:

- seedling establishment within the active channel owing to change in the hydrologic regime (such as a drought), which leads to sediment trapping and bank advance;

- changes in sediment transport regime leading to sedimentation within stands of maturing trees; and,

- reduction in channel capacity by branches and large woody or organic debris leading to a decrease in the magnitude of the channel-forming flow and associated reduction in channel size.

A small but growing body of literature reports studies of the link between riparian ecology and fluvial geomorphology in the USA, where it is demonstrated that streams in different climatic and physiographic settings display contrasting responses to changes in catchment hydrology, sediment yield and vegetation growth. Observations of channel narrowing due to vegetation impacts reported in some of this literature are included in this review, because the geomorphological and biological mechanisms identified in them may have relevance to British rivers.

4.1.2 Mechanisms of channel narrowing

Riparian vegetation is responsive to catchment hydrology, and under "natural" conditions, vegetation types and assemblages reflect the river regime, floodplain hydrology and channel forming discharge. Natural streams experience a wide range of flows, and the effective or dominant discharge together with the low flow regime are responsible for determining the hydraulic geometry and in-stream channel morphology. Rivers with sand and gravel-bed materials exhibit mobile-bed conditions under a wider range of channel-forming flows than clay-bed streams. Hence, seeds and propagules of riparian species typically experience greater extremes in stresses in sand and gravel-bed streams than under the more mesic and cohesive soil conditions of clay rivers. Few data exist on survival conditions of riparian tree species for silt-bed rivers.

4.1.3 Pioneer species and sedimentation

For germination, species of the pioneer genera *Salix* or *Populus* generally require open, full-sun conditions and a moist, porous substrate (Nishishin, 1958; Siegel and Broch, 1990). Freshly scoured banks and bars or new deposits of sediment near the channel are likely zones for willow seed beds. Seeds are light and may be carried by wind or high water to freshly deposited silt/ sand/ gravel bars (Newsholme, 1992). Recruitment typically is very high, and many germinated seeds are lost to the first flushing flows (Lautenschlager, 1984, Sacchi and Price, undated). Where seedlings become established, localised hydraulic roughness can induce distinct sediment deposition patterns downstream of seedlings and saplings. These exaggerated deposits raise the level of the bed, and may cause a reduction in channel area or capacity (Davis, et al. 1995).

The geomorphic change caused by flow variability is sequence-dependent. For example, one flood may remove all vegetation and fine sediment. If a second flood of similar magnitude occurs before vegetation and bank composition have recovered, the amount of channel change can be greater than usual for a flow of that magnitude (Schumm and Lichty, 1963, Burkham 1972, Osterkamp and Costa 1987).

4.1.4 Narrowing due to the establishment of trees

Seedling establishment of riparian tree species is limited by the availability of moist soils with suitable substrates and adequate drainage. Seeds of the *Salicaceous* trees, including *Salix* and *Populus*, are short-lived and must germinate within a few weeks of ripening. Typically, many seeds germinate on the moist soils of point and braid bars and along the margins of low flow channels. Seedlings are vulnerable to being swept away by the high flow events, demonstrating that temporal variation in discharge exerts a controlling influence on seedling survival. In the absence of high of flushing flows, seedling establishment can influence channel morphological evolution.

For example, in the Western United States, during periods of drought and along channel reaches below dams, seedlings are observed to become established at or near the low-flow channel margin (US Fish and Wildlife Service, 1995). Seedling establishment is strongly related to elevation relative to the low-water plane, as moisture gradients above groundwater level govern root access to moisture. While some seedling deaths at low bank elevations are caused by inundation stress during relatively steady low flows, seedlings at slightly higher bank elevations may survive droughts to become fully established (Brown, 1993).

After establishment (considered to occur two years after germination), rates of sapling survival may be high. If there is a period of a few years without a channel-forming flow, or under the reduced peak discharge regime found below dams, riparian saplings may develop to the point that they are able to survive formative discharges that drive morphological channel change through differential sedimentation and bar formation. In this case, saplings will accelerate local rates of siltation by reducing local sediment transport capacity through increased boundary roughness, damping turbulence and filtering suspended sediment. Sedimentation and bar formation generates increased bed, bar or bank elevation, reducing the frequency with which vegetation is attacked by the flow. Stabilization of bars and banks along the low-flow margins causes the river channel to narrow. Bank vegetation may be lost due to flow deflection by vegetated bars and scour below the root zone during high flows. Conversely, establishment of riparian vegetation on opposite sides of the river may significantly reduce the lateral mobility of the channel, decreasing its rate of migration and promoting channel degradation (Brown, 1993).

4.1.5 Narrowing associated with mature trees

Mature trees in valley bottom lands experience severe disturbance due to a range of fluvial processes, the most important of these being fluid drag and shear stress during flood flows, impacts from floating debris, ground level changes around the stem due to sediment erosion and deposition, anoxia during inundation and stress due to low moisture during periods of very low flow (Friedman, 1993.) Natural bottom land vegetation patterns are controlled by the affinity of species to particular fluvial environments and landforms, especially in relation to the depth to water table and the tolerance of the species to inundation. Bands of pioneer tree species, such as willows, of approximately the same age are observed to parallel to many streams (Friedman, 1993; Malanson, 1993). This pattern results from the influence of fluvial processes on establishment and maintenance of these species.

Pre-existing vegetation plays an important role in influencing changes in channel morphology that occur due to channel evolution or as a result of changes in extrinsic controls of hydraulic geometry such as climate (changes in catchment climate or rainfall/runoff relation) or hydrological regime (dams, abstraction, etc.) Sedell and Beschta (1991) demonstrated how resulting changes in plant communities can influence river morphology indirectly, producing channel changes that are addition to those driven directly by alteration of the fluvial regime. In inferring historical patterns of vegetation and channel processes, a plant ecological method known as 'successional analysis' is often applied. It must be borne in mind that this method assumes that environmental processes remain constant while plant species interact to establish mixed species and age classes. However, in practice changes in catchment hydrology and fluvial geomorphology can have direct and pronounced influences on vegetation composition (Friedman, 1993.)

4.1.6 Future research

In contrast to bank erosion, and stability analyses little emphasis has been placed on research concerned with channel narrowing due to bank accretion. It is, therefore, difficult to suggest specific research topics at the moment. There is, however, a need for fundamental research on bank accretion in general. Within this general field, a strong case can be made for projects focused particularly on the processes and mechanisms by which bank vegetation initiates, promotes and sustains bank accretion.

Practising engineers have voiced legitimate concerns about the effect of vegetative bank protection in driving morphological changes that narrow the channel. Most of their evidence is anecdotal, however, and field monitoring of sites with vegetative bank protection is required to confirm or refute the widely held belief that narrowing poses risks to channel stability, navigation or flood capacity. the establishment of monitoring sites and collection of base data would in due course lead to more focused research of specific issues.

4.2 Effects of large woody debris

4.2.1 Introduction

A mixture of woody species growing along river banks implies growth and maturing of that vegetation. In streams which are not heavily maintained, some trees and branches will fall into the stream channel. Large fallen trees or tree limbs constitute Large Woody Debris (LWD).

Numerous studies have established that LWD has multiple beneficial consequences for the fluvial geomorphic function of the stream (Keller and Talley 1979, Bilby and Likens, 1980; Wallerstein et al, 1997). However, conventional river management has typically sought to remove LWD, often because of maintaining a standard of service for land drainage, but sometimes because of a perceived need to tidy the landscape, even in rather remote areas.

4.2.2 Stable and unstable systems

The net effect of LWD is to introduce elements of stability into the fluvial system, by acting as bed level controls and slowing the rate of sediment transport through storage behind partial or stream-wide debris dams. LWD provides many positive contributions to ecological habitat structure and function, and fish populations are higher on streams with greater concentrations of wood in the channel (Bryant, 1981).

LWD contributes to channel stability by reducing local high water velocities in the ponded area or backwater. Large trees connected to the bank at one end and lodged in the stream bed at the other increase scour at the bed to form pools around the trunk and branches. Such pools provide storage for sediment and important habitats for many aquatic organisms. Pools behind LWD dams raise water levels during base flow and may reduce flood peaks by increasing in-channel storage. Thus, the presence of LWD (with vegetated banks and floodplains) along a river corridor can improve low flow conditions (Davis et al, 1995).

However, deflector-type jams can drive significant bank instability due to toe-scour in the pool at the end of the jam, leading to planform change and channel migration in otherwise stable systems.

Large floods typically destroy LWD jams, so that their impacts on flow levels and channel conveyance during significant events is relatively small. An important exception occurs at bridges and other in-stream hydraulic structures, where the accumulation of LWD can massively reduce conveyance, leading to flooding and, in extreme cases, failure of the structure. Experience in Europe and the USA indicates strongly that the cost-effective solution to dealing with LWD at hydraulic structures is to design them to pass debris rather than to attempt to prevent debris from arriving at the structure (Wallerstein and Thorne, 1996).

In unstable systems, recent research in the southeast United States has established that streams with substantial amounts of LWD tend to stabilise naturally more quickly than do streams lacking LWD. Also, streams with LWD possess more habitat diversity and trapping of sand behind LWD jams in incised stream reduces downstream impacts of instability due to the transmission of sediment (Wallerstein et al, 1997). In incised systems, loss of channel capacity is not usually an issue.

Where stream banks must be managed for navigation, LWD and overhanging branches pose hazards to boat passage. Development in the floodplain often restricts the allowable width of the design flood, which has reduced the area allowed for vegetated bank protection.

4.2.3 Future research

Fundamental research is required to clarify the role of LWD in the fluvial system under stable and unstable conditions. Specifically, work is needed to establish the roughness introduced to the fluvial system by debris jams and to characterize the way in which channel evolution is affected by the morphological effects of LWD.

Bank protection strategies which utilise trees, including willows, will require innovative approaches to the management of LWD generated by tree death, toppling or wind-throw. Maintenance strategies must acknowledge the potential benefits of LWD, through bed stabilization, sediment storage and provision of habitats and, on this basis, allow for some LWD in the channel while preventing problems associated with bank stability, navigation, flood defence and hydraulic structures.

Applied research should also be undertaken to develop improved management and maintenance strategies for LWD from riparian trees that recognise its complex roles in affecting channel stability, sediment dynamics, bank stability, hydraulic structures and aquatic habitats. Specific issues to be addressed centre on modelling and predicting morphological response to various maintenance strategies including: clearing and snagging to remove all woody vegetation on the banks; selective removal in key areas/reaches, active tree management to prevent toppling or failure; and, allowing LWD to remain in the channel.

5 RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 Flow erosivity

5.1.1 Retardance of near-bank velocities

- Fundamental research on the effects of riparian vegetation on near-bank velocity distributions, turbulent structures and flow patterns must continue. Field and laboratory studies are required to calibrate and validate theoretical relationships developed from boundary-layer theory and turbulence modelling; and,

- Applied research is needed to establish the medium to long-term hydraulic effects of different vegetation maintenance regimes and to support the development of regimes that produce the desired levels of bank protection and flow resistance for the minimum cost and environmental impact.

5.1.2 Stem characteristics

- Fundamental research is needed to identify the stem flexibility characteristics of various *Salix* species so that their response to water and wind drag forces can better be characterized; and,

- Applied research is required to develop enhanced cost-benefit analyses capable of accounting for the benefits and disbenefits of using willows in bank protection schemes. Particular emphasis must be placed on environmental benefits and on accurately evaluating the comparative long-term maintenance costs of vegetation and hard engineering in bank protection schemes.

5.1.3 Channel capacity and floodplain conveyance

- Fundamental research should continue to use physical modelling to investigate the effects of rigid and flexible vegetation on channel and floodplain conveyance. Experiments should better represent the flexural properties of natural plants and be designed to simulate the ranges of channel/floodplain depths, widths and velocities experienced in natural rivers;

- Physical model studies should also address the affect of riparian vegetation on sediment transport and on patterns of sedimentation, including the long-term effects on flood conveyance associated with any morphological adjustments that are induced by vegetation; and,

- Post-project monitoring and appraisal of bank protection schemes employing vegetation are essential to compare actual performance against design specification, identify limits to the effectiveness of such schemes and build up a body of reliable evidence on riparian vegetation effects on flood defence, navigation and land drainage functions.

5.2 Bank erodibility and stability

5.2.1 Soil erodibility

- Fundamental research is required to determine whether the presence of willows on banks actually leads to a net increase or decrease of the bank erodibility under the range of conditions typically encountered in natural streams;

- The significance of variations between the above-ground and below-ground plant physiology of various *Salix* species in terms of reducing soil erodibility should be investigated through empirical research;

- Field research should address the demographic limitations on under-storey riparian vegetation below willow canopies. Aspects such as allelopathy arising from willow canopy or root exudates, as well as the implications of shading, should be addressed;

- The specific function of dense mattress of fibrous roots dipping into the water edge below many willow stands should be investigated; and,

- Applied research should investigate whether the effectiveness of willows in reducing soil erodibility is limited because the roots of individual plants tend to form strong "root balls", separated by zones less reinforced soil.

5.2.2 Plant health, succession and the bank environment

- Fundamental research on the physiological adaptive capabilities of different willows should be extended to identify limits to the capability of specific species in stabilizing a bank under the stressful conditions typically encountered in river bank environments;

- Empirical research should be conducted on the viability of using exposed willow root systems as nurseries for cultivation of semi-aquatic species that are tolerant to regular inundation and changeable fluvial erosive forces;

- The implications of root death and seasonal turnover for bank protection using willows are extremely important and applied research is urgently required to shed light on this neglected topic; and,

- Applied research and field trials are needed to support the identification of 'appropriate vegetation assemblages' for bank protection, taking account of the position of the vegetation in the channel cross-section and secondary succession of vegetation species within the riparian corridor, as well as the initial capability of the plants to protect the bank.

5.2.3 Bank hydrology

- Fundamental research should investigate the species-specific capabilities of willows to increase bank stability through their rooting patterns and allied hydrological impacts that lead to enhanced transpiration, increase suction pressures or improved drainage;

- Applied research is required to establish the practical limits to the growth of willow roots into or through saturated or poorly-drained soils typical of stream bank environments; and,

- Empirical research is needed to clarify the physiological adaptive attributes of the *Salix* genus. Projects should seek to identify instances of bank instability arising from interactions between tree roots and perched water tables.

5.2.4 Bank stability

- Fundamental research must directly investigate the mechanisms by which roots contribute to bank stability. Follow-up work is also needed to account for the effects of plant age and root size;

- Empirical studies are required to establish the chemical composition of root exudates and the role of mycorhized fungi in affecting soil cohesion;

- Research is urgently required to establish how root distributions through the bank are affected by soil conditions and vary by willow species. The information used to predict the factors limiting root penetration for major *Salix* species; and,

- Field monitoring is required to address the current shortage of data on natural colonization (secondary succession) of banks that is hampering further development and validation of bank stability models that incorporate the effects of vegetation.

5.2.5 Buttressing and hardpoints

- Fundamental research is required to establish the conditions under which willows act as buttresses and hardpoints and the frequency with which these conditions actually occur in natural river banks;

- Applied research is required to develop design criteria and limitations for the use of willows as buttresses and hard points for bank protection; and,

- Field monitoring studies are needed to evaluate the performance of artificially-introduced willow trees at trial sites over the extended periods required for them to develop into buttresses or hardpoints.

5.2.6 Surcharging and wind-loading

- Fundamental research is required to delineate the relationship between bank geometry, tree position, tree morphology and the destabilising impact of surcharging;

- Fundamental research is required to establish the vulnerability of different species of willow to limb breakage, stem snapping or uprooting due to wind-loading;

- Applied research and field studies at trial sites are needed to support development of maintenance regimes that prevent surcharging and wind-loading problems on banks protected by willows; and,

- Applied research and field monitoring should be performed to facilitate the selection of the best plant species, bank re-profiling strategy and maintenance regime to avoid surcharging and wind-loading problems in bank protection schemes using willows.

5.3 Bank accretion

5.3.1 Channel narrowing

- Fundamental research is required on channel narrowing in general as this is an under-researched topic. Emphasis should be placed on projects designed to elucidate the processes and mechanisms by which bank vegetation initiates, promotes or sustains bank accretion; and,

- Applied research and field monitoring of sites with vegetative bank protection is required to confirm or refute the widely held belief that this type of bank protection poses risks to channel width stability, navigation and flood conveyance.

5.3.2 Effects of large woody debris (LWD)

- Fundamental research is required to develop analyses to quantify the roughness introduced to the fluvial system by LWD and debris jams;

- Further fundamental research should be performed to establish how trends, rates and outcomes of morphological channel evolution are affected by the hydraulic and sedimentary effects of LWD; and,

- Applied research is required to support the development of innovative approaches to channel maintenance that allow some LWD to remain in the fluvial system, while preventing LWD-related problems for bank stability, navigation, flood defence and hydraulic structures.

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APPENDIX A

COMPILATION OF INTERVIEWS

The Authors would like to thank Mike Greaves (IACR - Long Ashton) and Jonathan Newman (CAPM - Sonning) for their cooperation and contribution to this report, as well as all those involved in the interviews and discussions during the project.

Questions used in structured interviews (see **Summary Tables A1 and A2** for responses)

1. Background Information on Respondent (not included in summary tables A1 and A2) A= academic; C = consultant; E = engineer; G = government employee; P = practitioner; R = researcher.

2. Do you have direct experience in bank protection/use of willows?

3. Collaboration with organizations, professionals and consultants?

4. Do you make use of published design guidance for bank protection?

5. Have you used willows for (a) bank protection, (b) aesthetic value, (c) ecological value?

6. With what type(s) of stream environment(s) you have been involved?

7. Do you use the diversity of species and shape of willows to suit bank requirements?

8. What general comments can you make of the suitability of willows in bank protection?

9. Have you undertaken any field or laboratory investigations of the effects of willows in slowing near-bank velocities?

10. Are willows effective in protecting the bank from erosion?

11. Are laboratory experiments using artificial roughness needed to develop practical approaches to predicting near bank flow retardance?

12. Do you consider field work essential?

13. Have you any knowledge of research which considers the effects of both above- and below- ground influences of willows on bank stability?

14. Are the life stage or morphological features of willows or bank vegetation considered in planning a maintenance regime?

15. Do you know of any documentation of vegetation maintenance regimes for flood defence or other channel design criteria?

16. Do you know of research which addresses inter-species variations in the growth rates of willow stems?

17. Do you know of research which addresses inter-species variations for the growth rates of willow roots?

18. Do you know of studies on the effects of vegetation on flow, specifically: the influence on flow resistance/stage height of plants owing to their spacing?

19. Do you know of studies on the influence on flow resistance/stage height of plants owing to their stem density?

20. Do you know of studies on the influence on flow resistance/stage height of plants owing to their plant height/foliage density?

21. Do you know of studies on the relations between channel width and roughness coefficient (e.g. Manning's n) for various vegetation densities?

22. Do you believe that available information is too scientific for the practitioner to understand?

23. Do you believe that roots of willows will enhance bank soil stability?

24. Have you collated data on the type of erosion prevented by willow roots: surficial?

25. Have you collated data on the type of erosion prevented by willow roots: bank collapse?

26. Have you collated data on effects of the soil medium in which the willows are planted?

27. Have you any documentation on inundation tolerances?

28. Have you any documentation on rate of propagated growth?

29. In your opinion, can roots act as mesh traps for sediment or as nurseries for toe-invasive species which may aid in bank stability?

30. Do you know of research addressing influences of vegetation on bank hydrology?

31. Do you know of research addressing rainfall interception by leaves and infiltration increase or reduction due to plants?

32. Do you know of research addressing reduction of soil moisture due to transpiration?

33. Do you know of research addressing root influence on bank drainage due to changes in soil structure or hydraulic conductivity?

34. Have you conducted any experiments on the soil/root matrix and influences on bank stability such as changes in soil shear strength?

35. Have you documented differences in the soil moisture regime due to presence, absence or type of vegetation?

36. Have you any data on root effects on development of soil tension cracks?

37. Have you conducted any experiments on rooting depths of willows?

38. Have you any data on the relationship between root depth and bank height?

39. Have you any data on root depth, bank height and the potential slip surface?

40. Have you any data on research which addresses the role of stream bank trees for soil reinforcement by arching or buttressing?

41. Have you any data on research which addresses the role of stream bank trees for soil reinforcement by acting as hard points for maintaining the bankline?

42. Have you any data on role of willows or riparian trees in the change of bank surcharge stress?

43. Has work been done on the relations among bank geometry, channel maintenance history, access by livestock and surcharge rates?

44. Have you any data on the effects of riparian vegetation on sediment deposition or bank accretion?

45. Have you data on mechanisms of channel narrowing owing to riparian vegetation?

Best Management Practices

46. Has there been effort to quantify the channel/ bank/ floodplain features before the design process was completed?

47. Was catchment or channel hydrology included in the design process?

48. Were permanent survey benchmarks used in design and/or construction process?

49. Did the project have criteria or standards at the time of construction by which to measure success or failure of the project?

50. Was the project monitored quantitatively after construction?

51. Any documentation on costing of willow projects (capital and maintenance)?

52. Any documentation on failures of soft engineering schemes?

53. Have you knowledge of any schemes for post-project appraisal?

Table A1: United Kingdom Interview Summary

Interviewer: I. Amarasinghe

Organisations and Interviewees	Q2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
ENVIRONMENT AGENCY																				
BENNET Ray [Rivers Inspector (North West)]	Y	Y	Y	Y	Upl	N/A	G/B	N	N/A	N	Y	N	N	Y	N	N	N	N	N	Y
DALY Geraldine [Conservation Officer (Anglian)]	N	Y	N	Y	Nav/Low	Y	G	N	U	Y	Y	N	N	N	N	N	N	N	N	N
DRIVER Alastair [Regional Conservation Manager (Thames)]	Y	Y	Y	Y	Nav/Low	Y	G	N	Y	Y	Y	N/A	Y	Y	N/A	N/A	N/A	N/A	N/A	N/A
GOODWIN Tony [Catchment Engineer (Anglian)]	Y	Y	Y	Y	Nav/Low	N/A	N/A	N	N/A	Y	Y	N	N/A	Y	N/A	N/A	N	N	Y	Y
GREENE Richard [Assistant Conservation Officer (Thames)]	N	Y	Y	Y	Nav/Low	Y	G/B	N	U	Y	Y	N	N	N	N	N	N	N	N	N
HARPER Jonathan [Conservation Officer (South West)]	Y	Y	Y	Y	Nav	N	G	N	Y	N	Y	N	N	Y	N	N	N	N	N	N
HOLT Valerie [Conservation Officer (Midlands)]	Y	Y	Y	Y	Low	Y	U	N	Y	Y	Y	N	Y	Y	N	N	N	N	N	N
REED Susan [Environmental Assessment Officer (Thames)]	Y	Y	Y	Y	Nav/Low	N	G/B	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N
ROBINSON Eleanor [Conservation Officer (North East)]	Y	Y	Y	Y	Upl	Y	G/B	N	Y	U	Y	N	Y	Y	N	N	N	N	N	N
SANSOM Anne [Conservation Officer (North East)]	Y	Y	Y	Y	Upl	Y		N	Y	U	Y	N	Y	Y	N	N	N	N	N	N
SCHOLEY Graham [Conservation Officer (Thames)]	N	Y	Y	Y	Nav/Low	Y	G/B	N	U	Y	Y	N	N	N	N	N	N	N	N	N
SMITH Brian [Project Manager (Southern)]	Y	Y	Y	Y	Nav/Low	N	G/B	N	Y	U	Y	Y	Y	N	N	N	N	N	N	N
SPROAT Lesley [Conservation Officer (Thames)]	Y	Y	Y	Y	Nav/Low	Y	G/B	N	U	Y	Y	N	Y	Y	N	N	N	N	N	Y
STARLING Peter [Operations Engineer (Anglian)]	Y	Y	Y	N	Nav/Low	N/A	N/A	N	U	Y	Y	N	N/A	Y	N	N	N	N	N	N
WEBB David [Conservation Officer (Thames)]	Y	Y	Y	Y	Nav/Low	Y	G/B	N	Y	U	Y	Y	Y	Y	Y	N	N	N	N	Y
VAN BEESTON David [Operation Manager (Thames)]	Y	Y	Y	Y	Nav/Low	Y	G/B	N	N	N	U	N	Y	Y	Y	N	N	N	Y	Y
YATES Harry [Flood Defence Manager (North West)]	Y	Y	Y	Y	Upl	N/A	N/A	N	N/A	U	Y	N	N	Y	N	N	N	N	N	Y
BRITISH WATERWAYS																				
BRIGGS Jonathan [Conservation Ecologist]	Y	Y	Y	Y	BW	N	G/B	N	N	Y	Y	N	N	Y	N	N	Y	N	N	Y
INLAND DRAINAGE BOARDS																				
CAVES Geoff (Consultant Engineer, Middle Level Commisioners, IDB)	Y	Y	Y	N	D/C	N	U	N	U	Y	Y	N	N	Y	N	N	N	N	N	Y
ELSEY John	Y	Y	Y	Y	D/C	Y	U	Y	U	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
HONNOR John (South Holland & Deeping, IDB)	Y	Y	Y	Y	D/C	N	U	N	U	Y	Y	Y	Y	Y	N	N	N	N	N	Y
LOCAL AUTHORITY STAFF																				
ALDERMAN David [Arboricultural Officer, Bedfordshire CC]	Y	Y	Y	Y	Low	Y	G/B	N	Y	U	Y	N	N	Y	N	N	N	N	N	N
FOX Philip [Countryside Officer, Milton Keynes BC]	Y	Y	N	Y	Low	N	G	N	N	Y	Y	N	N	Y	N	N	N	N	N	N
RIVER RESTORATION PROJECTS																				
CARRE Joel [Project Officer, Ivel Valley Project]	Y	Y	Y	Y	Low	Y	G	N	Y	Y	Y	N	N	N	N	N/A	N/A	N/A	N/A	N/A
VIVASH Richard [General Manager, RRP]	Y	Y	Y	Y	All	Y	U	N/A	Y	Y	Y	N	Y	Y	N	N	N	Y	Y	Y
RSPB																				
BRADLEY Peter [Surlingham]	Y	Y	Y	Y	Nav	Y	G	N	Y	U	Y	N	Y	Y	N	N	N	N	N	N
BIO-ENGINEERING SALES STAFF																				
DONNER Martin [Ardon International Ltd]	Y	Y	Y	Y	All	Y	G/B	N	U	Y	Y	N	Y	Y	N	N	N	N	Y	Y
ELLIS Hugh [Maccaferry (UK) Ltd]	Y	Y	Y	Y	All	Y	G	N	Y	Y	Y	N	Y	Y	Y	N	N	N	N	Y
HECTOR Nigel [English Hurdle Co]	Y	Y	Y	Y	All	Y	G	N	Y	U	Y	N	Y	Y	N	N	N	N	N	N
CONSULTANTS																				
FISHER Karen [Scientist, HR Wallingford Ltd]	Y	Y	N	Y	All	N	G/B	N	U	Y	Y	N	N	Y	N	N	Y	Y	Y	Y
HOLMES Nigel [Alconbury Consultants]	Y	N	Y	Y	All	N	G/B	N	Y	N	Y	N	Y	N	N	N	N	N	N	N
NILES John	Y	Y	Y	Y	N/A	Y	G	N	Y	U	Y	N	N	N	N	N	N	N	N	N
NOBLE David [Association of Drainage Authorities]	Y	Y	Y	Y	All	N	G	N	U	Y	Y	N	N	Y	N	N	N	N	N	Y
WHITE John [Consultant Dendrologist]	Y	Y	Y	Y	N/A	Y	G	N	Y	U	Y	Y	Y	Y	Y	Y	N	N	N	N

B=bad
U= uncertain
allvl= alluvial
Nav= navigable
Low= Lowland
Upl= Upland
D/C= Drainage Channels
A= anecdotal
*=additional comments

Table A1 (cont/d...): United Kingdom Interview Summary
Interviewer: I. Amarasinghe

	Q#22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
BENNET	Y	Y	N	N	N	N	N	Y	N	N	N	N	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N	N	N	N	Y	Y	N	N	N	Y	Y	Y
DALY	Y	Y	N	U		N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	U	N	N	N	Y	N	N	N	Y		Y
DRIVER	Y/N	Y	N	Y		N	N	Y	Y	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N	N	N	N/A	N	N	Y	Y	Y/N	Y	Y	Y		Y
GOODWIN	Y	Y/N	Y/N	Y/N		Y	N	Y	N/A	N/A	N/A	N/A	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N	N	N	N	Y/N	N	Y	Y	Y	N	Y	Y
GREENE	N	Y	N	Y		N	N	N	N	N	N	N	N/A	N/A	N/A	N/A	N/A	N/A	N	U	Y	N	N	N	N	U	N	N	U	N		Y
HARPER	Y	Y	N	Y		N	N	Y	N	N	N	N	N	N/A	N/A	N/A	N/A	N/A	N	N	N	N	N	N	N	N	N	N	N	Y		Y
HOLT	Y/N	Y	N	N	N	N	Y	Y	Y	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	N	Y	N	N		Y
REED	Y	Y	Y	Y	N	N	N	Y	Y	Y	N	N	Y	N	N	N	N	N	N	N	N	Y	N	N	Y	Y	N	N	N	Y		Y
ROBINSON	Y	Y	Y	Y		N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N		N	N	Y	Y	N	N	N	N/A		Y
SANSOM	Y	Y	Y	Y		N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	U	Y	Y	Y	Y	N	N	N	N/A		Y
SCHOLEY	N	Y	N	Y		N	N	N	N	N	N	N	N/A	N/A	N/A	N/A	N/A	N/A	N	U	Y	N	N	N	N	U	N	N	U	N		Y
SMITH	Y	Y	Y	N		N	N	Y	N	N/A	N/A	N/A	N	N	N	N	N	N	N	N	N	U	N	N	N	N	N	N	Y	Y		Y
SPROAT	Y	N	N	U	N	N/A	N	N	N	N/A	N/A	N/A	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y		Y
STARLING	Y	U	U	Y		N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	Y	Y	Y	U		Y
WEBB	Y	N	N	N	N	N	N	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	N	Y	Y	N	Y	N	Y	Y	Y
VAN BEESTON	U	Y	N	N		N	N	Y	N/A	N/A	N/A	N/A	N	N	N	N/A	N/A	N/A	N/A	N	N	Y	Y	Y	N	Y	Y	Y	N	N		N
YATES	N	Y	N	N	N	N	N	Y	Y	Y	N	N	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N	N	N	N	Y	Y	N	N	N	Y	Y	N
BRIGGS	Y	U	N	N	N	Y	N	Y	Y	Y	Y	Y	N	N/A	N	N	N	N	N	N	N	N	N	N	N/A	N/A	N/A	Y	N	N	N	N
CAVES	Y	Y	N	N	N	N	N	U	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	N	Y	N	N	Y	Y
ELSEY	Y	Y	N	N	Y	N	Y	Y	Y	N	N	N	Y	N	N	Y	Y	N	N	N	N	Y	N	N	Y	Y	N	Y	Y	N	Y	Y
HONNOR	Y	Y	N	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	N	Y	N	N	Y	N
ALDERMAN	Y	Y	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	N	Y	N	N	Y	Y
FOX	Y	Y	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	Y	N		Y
CARRE	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Y	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N	N	Y	N	N	N	Y	N	Y	N	N	N	N
VIVASH	Y	U	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y
BRADLEY	Y	Y	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	Y	N	N	Y	N
DONNER	Y	N	N	N	N	N	N	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	N	Y	Y	Y	Y	N	N	Y	Y
ELLIS	N	Y	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	N	Y	Y	Y	Y	N	Y	Y	N
HECTOR	Y	N	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	Y	N	Y	Y	Y
FISHER	Y	Y	Y	N		N	N	Y/N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	U	Y	N		Y
HOLMES	Y/N	Y	U	Y		N	N	U/Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N/A	N	N	Y	Y	N	Y	Y	N		Y
NILES	Y	Y	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
NOBLE	Y	Y	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	NN	N	Y	Y	N	Y	N	N	N	N
WHITE	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	Y	N	N	N	N	N	Y	N	N	N	N	N	Y	N	N	N	N

Table A2: Overseas Interview Summary

Interviewers: C. Perala-Gardiner and J. L. P. Gardiner

Organisations and Interviewees	Q2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
UNITED STATES OF AMERICA																				
BESCHTA Bob [Hydrologist, Oregon State Univ. Dept. of Forestry, OR]	N	Y	N	N	hdwtrs	N	Y	B	Y	Y	Y	N	N	N	N	N	N	N	N	N
ENGBER Evan [Bioengineering Associates, Mendocino County, CA]	Y	Y	Y	a,c,b	mult	N	Y	N	Y*	NA	Y	Y	N	Y	N	N	Y	N	N	N
WILLIAMS Philip [Engineer, Philip Williams and Associates, CA]	N	Y	Y	a,c	mult	N	Y*	N	NA*	Y	Y	N	Y	Y	N	N	Y*	*	*	N
WATSON Chester [Engineering Research Center, Ft. Collins, CO]	Y	Y	Y	a	mult	Y	Y	N	Y	Y	Y	Y	N	Y	Y	N	N	N	Y	Y
WOHL Ellen [Geomorphologist, Colorado State Univ., CO]	N	Y	N	N	bdrx	N	NA	NA	NA	Y	Y	NA	NA	NA	NA	NA	NA	NA	NA	NA
JOLLEY Leonard [Rangeland Ecosystems, Colorado State Univ., CO]	Y	Y	Y	a,c	dsrt	N	NA	N	Y	NA	Y	NA	NA	NA	NA	NA	NA	NA	NA	N
ROSEBOOM, Don [Engineer, Illinois State Water Survey, IL]	Y	Y	Y	a,c	mult	N	Y	N	Y	Y	Y	N	N	N	N	Y	Y	Y	N	N
SOONG David [Director, Illinois State Water Survey, IL]	N	Y	Y	N	lrg	N	NA	N	Y	Y	Y	N	N	N	N	N	Y	N	N	N
NEVLING Lorin [Head of Dept., Illinois State Water Survey, IL]	N	Y	N	N	N	NA	NA	N	NA	NA	Y	N	N	N	Y	NA	NA	NA	NA	NA
GARCIA Marcello [Univ. Illinois, Dept Hydraulics, IL]	N	Y	N	N	N	N	N	Y	Y	Y	N	N	N	N	N	N	N	N	N	N
SOTIR Robbin [Robbin B, Sotir & Associates, Georgia]	Y	Y	Y	a,b,c	mult	N	hi	N	Y	Y	Y	N	some	Y	N	N	N	N	N	Y
NUNNALY Nelson [Geomorphologist, Robbin B, Sotir & Ass., Georgia]	Y	Y	Y	a,b,c	mult	N	hi	N	Y	Y	Y	N	some	Y	N	N	N	N	N	Y
FISCHENICH Craig [Engineer, Waterways Experiment Station, MS]	Y	Y	Y	a	mult	Y	Y	Y	Y	Y	Y	Y	N	Y/N	N	N	Y	Y	Y	NA
ALLEN Hollis [Ecologist, Waterways Experiment Station, MS]	Y	Y	Y	a,c	mult	Y	Y	Y	Y	Y	Y	NA	Y	Y	Y	Y	N	N	N	N
HALL Brad [Engineer, Waterways Experiment Station, MS]	N	Y	N	N	N	N	NA	N	NA	Y	Y	Y	NA	Y	N	N	Y	N	N	Y
FREEMAN Gary [Engineer, Waterways Experiment Station, MS]	N	Y	Y	N	NA	NA	NA	N	Y/N	Y	NA	N	N	N	N	N	Y	Y	Y	N
DERRICK Dave [Engineer, Waterways Experiment Station, MS]	Y	Y	Y	a,c	mult	N	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	N	N
SMITH Lawson [Geologist, Waterways Experiment Station, MS]	N	Y	Y	N	mult	N	NA	Y	Y	Y	Y	N	Y	N	N	N	N	N	N	NA
TAYLOR Buck [Engineer, Waterways Experiment Station, MS]	N	Y	Y	N	levee	NA	N	N	Y/N	NA	NA	Y	Y	N	N	N	NA	NA	NA	NA
SHIELDS F. Douglas [Engineer, USDA, Oxford, MS]	Y	Y	Y/N	a,c	ncsd	Y	Y	Y	Y	Y	Y	N	N							
SCHULTZ Richard [Forest Hydrology, Univ. Iowa, IO]	Y	Y	Y	a	mult	N	Y	Y	Y	NA	Y	N	N	N	N	N	NA	NA	NA	NA
EUROPE																				
BINDER Walter [Diplom. Eng. Bavaria Water Authority, Germany]	Y	Y	Y	a,b,c	allvl	N	Y/N	N	N	N	N	N	Y	Y	N	Y	N	N	N	N
FLORINETH Florin [Univ. Vienna, Inst, Austria]	Y	Y	Y	a,b,c	many	N	Y	Y	Y	Y	Y	N	Y	Y	N	Y	Y	N	N	Y
JAPAN																				
TSUJIMOTO Tetsuro [Univ. Kanzawa Hydraulics Lab, Japan]	N	Y	N	N	allvl	N	Y	Y	Y*	Y	Y	N	N	N	N	N	Y	Y	Y*	Y*

CRT=CRThorne DR = Don Roseboom *=additional comments A= anecdotal
N=no allvl= alluvial

Table A2 (cont/d...): Overseas Interview Summary

Interviewers: C. Perala-Gardiner and J. L. P. Gardiner

	Q22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
BESCHTA	N	Y	N	N	N	Y	Y	Y	Y	N	N	Y	Y	N	N	N	N	N	N	N	N	Y	Y	Y	NA	Y	NA	NA	NA	NA	NA	NA
ENGBER	N	Y	Y	Y	Y	Y	N	A	A	N	N	N	N	N	N	N	A	N	N	N	N	NA	Y	Y	Y	N	N	Y	N	Y	NA	NA
WILLIAMS	Y	Y	A	A	N	N	N	N	Y?	N	N	N	N	N	N	N	N	N	N	N	N	NA	Y	N	Y	Y	Y	Y*	N	N	N	N
WATSON	N	Y	Y	Y	Y	Y	N	N	N	N	N	N	Y	N	N	N	N	N	DG	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	DR	Y
WOHL	NA	Y	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
JOLLEY	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
ROSEBOOM	N	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	N	Y	Y	Y	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	Y
SOONG	N	Y	N	N	N	N	N	Y	N	N	N	N	N	N	N	Y	Y	N	N	N	Y	N	N	N	NA	NA	NA	NA	NA	Y	NA	NA
NEVLING	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
GARCIA	N	NA	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	NA	Y	N	N	N	N	N	N	N	N	N
SOTIR	N	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y	N	Y	N	Y	Y	Y	Y	N	Y	Y	Y	Y	Y
NUNNALY	N	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y	N	Y	N	Y	Y	Y	Y	N	Y	Y	Y	Y	Y
FISCHENICH	N	Y	N	Y	Y	Y	N	N	N	N	N	N	N	N	Y/N	N	N	N	Y	N	N	N	Y	Y	NA	NA	NA	NA	NA	NA	NA	NA
ALLEN	N	Y	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	N	Y	Y	N	Y	N
HALL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Y	NA	NA	NA	NA	NA	NA	NA	N	NA
FREEMAN	NA	Y/N	N	N	N	N	N	Y	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	Y	N	NA	NA	NA	NA	NA	NA	NA	NA
DERRICK	N	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	N	Y	N
SMITH	NA	Y	NA	NA	NA	NA	NA	NA	NA	NA	NA	Y	N	CRT	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Y	NA
TAYLOR	N	Y	Y	N	N	Y	Y	poss	N	N	N	Y	Y	N	N	N	N	N	N	Y	N	NA	NA	NA	NA	NA	NA	NA	NA	NA	Y	Y
SCHIELDS																																
SCHULTZ	NA	Y	N	N	Y	N	N	NA	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	Y	N	Y
BINDER	N	N	N	N	N	N	N	NA	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
FLORINETH	N	Y	N	N	N	N	Y	NA	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	Y	N	N	Y	Y	Y	Y	Y
TSUJIMOTO	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y*	Y	NA	NA	NA	NA	NA	NA	NA	NA

Summary of interviews outside the UK

Outside the German-speaking countries (where many of the techniques were developed), the generally accepted term for bank stabilization technology using live vegetation is Soil Bioengineering. The strongest overall impression gained from the interviews in both Europe and the USA was that of enthusiasm for the subject and a belief that this research is not only timely but also well worthwhile. The main reasons for this were often expressed, usually by engineers frustrated at a real or imagined inability to justify using vegetation for bank stabilization.

The current uncertainties surrounding the planning, design, maintenance, performance or overall costs of such work, means that little can be recommended to the client with complete confidence. This powerful message has important implications, since it is not only the science of the various applications but their economics, including ecological and social benefits and costs, which needs research.

Behind this dilemma there is a more fundamental issue, which is splitting the field into two distinct camps, and that is the vital distinction between process and product. The emergence of a strong and competitive product market, essentially based on geotextiles and eco-concrete, appears at first glance to provide the specifications for design. However, it has little to offer on how to assess whether the prime morphological influence is the catchment land use or the in-channel process; whether the river system is eroding or aggrading, or how to work subtly with natural forces to identify the least-cost option to provide the degree of stability appropriate to satisfy the local environmental and social (e.g. visual requirements, crime- suppression, access and child safety) criteria.

Soil bioengineering is therefore not an alternative solution to hard engineering, but a crucial component coming at the end of the overall process of catchment, stream system, reach and local assessment. Soil bioengineering is a powerful means to discover how to work with natural forces, adding the principles and practice to support the multi-functional, 4-dimensional approach to identify the best (i.e. long-term, least-cost and environmentally sensitive) solutions.

Another strong impression gained was that each practitioner had their own favourite ways of using vegetation in bank stabilization, and that few would be interested in using a multi-functional team to assess the problem and appropriate solutions, often limited by lack of financing across several disciplines or sectors. There appears to be little interest or support within their funding structure for taking a catchment (watershed in the USA) approach to establish the causes or even the areas of highest priority for treatment.

As independent researchers, it appeared to us that understanding the catchment processes and stream morphology are the first and necessary steps before looking at the reach dynamics and assessing the most appropriate treatment for each location. Only after a context study would a particular technique be chosen to provide that treatment. Each technique provides an unique solution to the engineering problem, but rarely an only solution and rarely a solution chosen to maximize particular engineering, ecological or social benefits. It became clear that a judicious mix of techniques would often provide a more satisfactory solution in this regard, but that significant effort will be needed to enable practitioners to become more widely aware of the various available techniques, their pros and cons, utility and methods of construction. This study is an opportunity to start this process, and a corresponding effort is needed to de-mystify catchment geomorphological assessment, in order to facilitate the process.

Among researchers, there was wide acceptance that the general topic is very complex and needs a coherent, networked approach to make substantial progress among the wide range of situations and possible options. Both practitioners and researchers agreed that there were many suitable applications for investigation, but that funding for the extended monitoring required was rarely forthcoming from clients, despite the fact that, with the current state-of-the-art, the enhanced, wider benefits and potentially lower cost of bioengineering are accompanied by a greater risk of performance failure, compared with more traditional engineering options. In the USA, the climate of litigation as retribution for design failure militates strongly against any desire to innovate; risk assessment would therefore seem an important factor in the acceptability of soil bioengineering on any scale.

Among practitioners, familiarity breeds a strong bias; what is known is usually what is chosen, whether or not the available technique is particularly appropriate for the given situation. Thus, the valuable spiling or wattle technique known for over 1000 years in the British Isles is effectively the only method extensively used in the UK. The South Tyrol, however, boasts 73 known techniques and in Austria, Germany and Switzerland over 50 methods have been described and are in current use. In English-speaking practice, folk wisdom predominates in construction application, and is often effective, without much numerical or quantitative analysis of stream channel conditions. However, we have seen several inappropriate uses of spiling in the UK, and without any cultural enthusiasm for post-project appraisal, it is difficult to see progress being made without more serious consideration of alternatives by the practitioner.

In the USA, there is a wide range of approaches to the issue of stream restoration. The public rangelands approach, exemplified in the policies of the USDA Bureau of Land Management, can be summarized as change to the land management, meaning (among other things) keeping cows away from riverbanks. This common sense philosophy, ripe for application world-wide, lies at one end of the spectrum, while at the other is the desire to apply treatments to the bank, especially in more urban areas. The former stance reflects the belief in nature's ability to heal herself, given adequate sediment supply, water and time. The latter is concerned to see as full a restoration as possible, as soon as possible. It is therefore largely in urban and constrained rivers where the engineering of vegetated stream banks and floodplains may make great contributions in the coming few decades. Bank re-vegetation must fit into the greater catchment and land use contexts to be sustainable, and yet should be more highly valued for its many benefits when considered against any apparent constraints due to land use.

With a multitude of consequences, channelization of rivers and constriction or severance of floodplains has had wide and negative impacts on our water environment. Without question, to regain environmental sustainability we must all give back to the River some portion of the floodplain land we have taken away, and encourage the return of native riparian vegetation to rebuild this essential habitat and recover its biodiversity. Perhaps impetus could be added to the strategy by adopting the combination of 'Leitbild' or vision, and 'Mehr Raum für die Natur' (more room for nature) which has led to increasing evidence of success in restoration of river corridors in Germany.

APPENDIX B

EXAMPLE SITE VISIT RECORD SHEETS AND PHOTOGRAPHIC PLATES

B1 Example Site Record contains observations and site notes

River Ouzel, Milton Keynes Valley Park

EPSRC - WILLOWS & BANK PROTECTION PROJECT
WILLOW SITE RECORD SHEET

Developed by Colin R. Thorne, University of Nottingham

SECTION 1 - BACKGROUND AND CONTEXT

Description of catchment, water course and problem:

CATCHMENT: flat land, presently parkland with foot paths and new bridges; this area has been affected by change of land use since 1970, from pasture and agricultural land to residential and industrial developments.
WATER COURSE: R. Ouzel flows from South to N.E. joining the R. Great Ouse at Newport Pagnell, around three kilometres down from the site; This reach of the river 'flow' is controlled telemetrically between two balancing lake systems (Caldecotte, upriver; Willen, down-river)
PROBLEM: Severe outer bank erosion at meander bend; mature willows on banks do not appear to prevent the process of erosion.

Brief Site History (including introduction date of willows etc.):-

This site has increased trampling pressure on the footpath adjacent to it due to the increase in population in surrounding areas, over the last two decades. There is bound to be changes in fluvial patterns since the introduction of the telemetric control infrastructure. The man-made lake systems (Caldecotte and Willen) with the artificial channelisation downstream has affected the flow regimes. Willows on the banks are all naturally established mature (over 25 years) trees; some have been regularly pollarded.

Logistics of Site Visit:-

RIVER NAME R. Ouzel LOCATION Ouzel Valley Park Milton Keynes DATE 23rd June 1996

PROJECT (as above) STUDY REACH From To

SHEET COMPLETED BY Ivan AMARASINGHE

RIVER STAGE Summer Ambience [c. 1.5m depth] TIME: START 12 40hrs. TIME: FINISH 1635hrs.

General Notes on Site Assessment Visit and Contact People/Organisations:-

Site visit recommended by Mike Street, Milton Keynes Parks Trust (Wildlife Officer)
Accompanied by Prof. John Gardiner and Ms. Christine Perala...

Bank Assessment Summary Sheet

Observed Condition of Bank including Existing Protection

1. no existing protection.
2. meander bend eroding rapidly
3. closer examination shows that the severity of bank erosion has been asserted by the presence of old/mature willow trees
4. peculiar process of corrasion behind and around willows; need further investigations (see: photos)
5. success of toe-~~erosion~~ regrowth vegetation establishment via roots acting as refuges for plant propagule establishment.

Processes, Extent, and Severity of Erosion Threat

1. Signs of extensive corrasion and possible mass failure;
2. Processes of (a) corrasion, (b) slumping ; N.B. no rotational slides.
3. Signs of severe frost heave during winter.

Significant Erosion Processes, Failure Mechanisms and Weakening Factors

see above 1, 2 and 3

Comments on Willows used for Bank Protection

Whether the willows have been naturally established or deliberately planted on the outer banks is uncertain as records do not go so far. As such this is a case of willows affecting bank protection rather than being "used".
While there is evidence of prevention of erosion of the bank due to the trees, the process of corrasion under the willow canopy appears to need further research.

Conclusions and Lessons Learned

1. the use of willows needs lessons from sites such as this where erosion occurs under and adjacent to mature willows, both pollarded as well as naturally grown.

PART 4: WILLOWS

Type of Willow
- Tree ✓
- Shrub
- Introductions
- Miniature
- Creeping

Maintenance
- None ✓
- Pollarding ✓
- Coppicing
- Other

Density + Spacing
- None
- Sparse/clumps ✓
- dense/clumps
- Sparce/continuous
- Dense/continuous

Location
- Whole bank
- Upper bank ✓
- Mid-bank
- Lower bank

Health
- Healthy ✓
- Fair
- Poor
- Dead

Height
- Short
- Medium ✓
- Tall ✓
- Height (m) 7-20m

Roots
- Normal ✓
- Exposed ✓
- Adventitious ✓

Diversity
- Mono-stand ✓
- Mixed stand
- Climax-vegetation

Age
- Imature
- Mature ✓
- Old ✓

Lateral Extent
- Wide belt
- Narrow belt ✓
- Single row

Taxa/spp. S. caprea, S. fragilis, S. viminalis

Orientation

Angle of leaning (°) vertical

Notes and Comments:-

See photographs

Willows vary from naturally grown, old trees of S. fragilis to newly planted clumps of saplings of S. viminalis.

Two old pollarded willows are present on outer bank.

PART 5: BANK GEOTECH FAILURES

Failure Location
- General ✓
- Outside Meander ✓
- Inside Meander
- Opposite a bar
- Behind a bar
- Opposite a structure
- Adjacent to structure
- Dstream of structure ✓
- Ustream of structure
- Other (write in)

Present Status
- Stable
- Unreliable
- Unstable:dormant
- Unstable:active ✓

Failure Scars+Blocks
- None
- Old
- Recent
- Fresh ✓
- Contemporary

Interpretative Observations

Instability:Severity
- *Insignificant*
- *Mild*
- *Significant*
- *Serious* ✓
- *Catastrophic*

Instability: Extent
- *None*
- *Local* ✓
- *General* ✓
- *Reach Scale*
- *System Wide*

Failure Mode
- *Soil/rock fall*
- *Shallow slide*
- *Rotational slip*
- *Slab-type block*
- *Cantilever failure*
- *Dry granular flow* ✓
- *Wet earth flow* ✓
- *Other (write in)*

Distribution of Each Mode on Bank

	Mode 1	*Mode 2*	*Mode 3*	*Mode 4*
Toe				
Lower bank	✓	✓		
Upper bank	✓	✓		
Whole bank				

Level of Confidence in answers (Circle one)

0 10 20 30 40 50 60 70 80 (90) 100 %

Notes and Comments on Bank Geotech Failures:-

See photographic evidence

SECTION 5 - BANK TOE CONDITION

PART 6: BANK TOE SEDIMENT ACCUMULATION

Stored Bank Debris
- None
- Individual grains
- Aggregates+crumbs ✓
- Root-bound clumps ✓
- Small soil blocks
- Medium soil blocks
- Large soil blocks
- Cobbles/boulders
- Boulders

Vegetation
- None/fallow
- Artificially cleared
- Grass and flora ✓
- Reeds and sedges ✓
- Shrubs ✓
- Saplings ✓
- Trees ✓

(only lower banks)

Age
- Immature ✓
- Mature ✓
- Old \
- Age in Years

Tree species (if known)

Health
- Healthy ✓
- Unhealthy ✓
- Dead

Roots
- Taproot ✓
- Fibrous ✓
- Rhizomes ✓
- **Exposed** ✓

Interpretative Observations

Toe Bank Profile
- *Planar*
- *Concave upward* ✓
- *Convex upward*

Debris Storage
- *No bank debris*
- *Little bank debris*
- *Some bank debris*
- *Lots of bank debris* ✓

Sediment Balance
- *Accumulating* ✓
- *Steady State*
- *Undercutting*
- *Unknown* ✓

Level of Confidence in answers (Circle one)

0 10 20 30 40 50 60 70 80 (90) 100 %

Notes and Comments:-

See photographs.

B2 Photographic Plates from Other Sites

River Waal, Lower Rhine, Netherlands

River Medway, Kent

River Yare, Norfolk

River Great Ouse, Brampton, Cambridgeshire

River Great Ouse, Milton Keynes

B3 Blank Record Sheets for copying

EPSRC - WILLOWS & BANK PROTECTION PROJECT

WILLOW SITE RECORD SHEET

Developed by Colin R. Thorne, University of Nottingham

SECTION 1 - BACKGROUND AND CONTEXT

Description of catchment and water course:-

Brief Description of Site and Bank Erosion Problem:-

Logistics of Site Visit:-

RIVER NAME LOCATION DATE

PROJECT STUDY REACH From To

SHEET COMPLETED BY

RIVER STAGE TIME: START TIME: FINISH

General Notes and Comments on Site Assessment Visit:-

SECTION 2 - REACH SCALE SKETCH MAP

Map Symbols

Study reach limits	Photo point	exposed island/bar	RHS veg types: tall herbs/grasses
Cross-section	Bank features	gravel deposit	scrub/bramble
North point	flow direction	sand deposit	Willow bank protection [WBP] piling
Estimate of distance	impinging flow		coppice
Scale	Cut bank	large woody debris [LWD]	pollard
			Willow species eg. S.viminalis=S.v

Representative Cross-section(s): Show locations on Sketch Map

A

B.

C.

D.

SECTION 3 - BANK SURVEY

PART 1: BANK CHARACTERISTICS

Type
Noncohesive ☐
Cohesive ☐
Composite ☐
Layered ☐
Even Layers ☐
Thick+thin layers ☐
Number of layers ___

Protection Status
Unprotected ☐
Hard protection ☐
Soft protection ☐
Mixed protection ☐

Bank Materials
Silt/clay ☐
Sand/silt/clay ☐
Sand/silt ☐
Sand ☐
Sand/gravel ☐
Gravel ☐
Gravel/cobbles ☐
Cobbles ☐
Cobbles/boulders ☐
Boulders/bedrock ☐

Layer Thickness
Material 1 (m) ___
Material 2 (m) ___
Material 3 (m) ___
Material 4 (m) ___

Ave. Bank Height
Average height (m) ___

Ave. Bank Slope
Average angle (o) ___

Bank Profile Shape
(see sketches in manual) ☐

Tension Cracks
None ☐
Occasional ☐
Frequent ☐

Crack Depth
Proportion of bank height ___

Distribution and Description of Bank Materials in Bank Profile

Material Type 1	**Material Type 2**	**Material Type 3**	**Material Type 4**
Toe ☐	Toe ☐	Toe ☐	Toe ☐
Mid-Bank ☐	Mid-Bank ☐	Mid-Bank ☐	Mid-Bank ☐
Upper Bank ☐	Upper Bank ☐	Upper Bank ☐	Upper Bank ☐
Whole Bank ☐	Whole Bank ☐	Whole Bank ☐	Whole Bank ☐
D50 (mm) ___	D50 (mm) ___	D50 (mm) ___	D50 (mm) ___
sorting coefficient ___	sorting coefficient ___	sorting coefficient ___	sorting coef. ___

Notes and Comments on Bank Characteristics:-

PART 2: BANK STRUCTURES

Structure Type
None ☐
Revetment ☐
Vertical wall ☐
Sloping wall ☐
Other (Specify) ☐

Materials
Rock ☐
Concrete ☐
Brick ☐
Timber ☐
Steel ☐
Other (Specify) ☐

Structure Data
Date Constructed ___
Length (m) ___
Height (m) ___
Side Slope (o) ___
Orientation ___

Structure Condition
Acceptable ☐
Marginal ☐
Unacceptable ☐

Problems Observed
None ☐
Flow Erosion of the structure ☐
Flow scour next to the structure ☐
Seepage failures in the structure ☐
Slumping of the structure ☐

Notes and Comments on Bank Structures:-

PART 3: BANK-FACE VEGETATION

Vegetation
None/fallow ☐
Artificially cleared ☐
Grass and flora ☐
Reeds and sedges ☐
Shrubs ☐
Saplings ☐
Trees ☐

Orientation
Angle of leaning (o) ___

Tree Types
None ☐
Deciduous ☐
Coniferous ☐
Mixed ☐

Tree species (if known)
___

Density + Spacing
None ☐
Sparse/clumps ☐
dense/clumps ☐
Sparce/continuous ☐
Dense/continuous ☐

Roots
Normal ☐
Exposed ☐
Adventitious ☐

Location
Whole bank ☐
Upper bank ☐
Mid-bank ☐
Lower bank ☐

Diversity
Mono-stand ☐
Mixed stand ☐
Climax-vegetation ☐

Health
Healthy ☐
Fair ☐
Poor ☐
Dead ☐

Age
Imature ☐
Mature ☐
Old ☐

Height
Short ☐
Medium ☐
Tall ☐
Height (m) ___

Lateral Extent
Wide belt ☐
Narrow belt ☐
Single row ☐

Notes and Comments:-

PART 4: WILLOWS

Type of Willow		Maintenance		Density + Spacing		Location		Health		Height	
Tree	☐	None	☐	None	☐	Whole bank	☐	Healthy	☐	Short	☐
Shrub	☐	Pollarding	☐	Sparse/clumps	☐	Upper bank	☐	Fair	☐	Medium	☐
Introductions	☐	Coppicing	☐	dense/clumps	☐	Mid-bank	☐	Poor	☐	Tall	☐
Miniature	☐	Other	☐	Sparce/continuous	☐	Lower bank	☐	Dead	☐	Height (m)	___
Creeping	☐			Dense/continuous	☐						
				Roots		**Diversity**		**Age**		**Lateral Extent**	
				Normal	☐	Mono-stand	☐	Imature	☐	Wide belt	☐
Taxa	______			Exposed	☐	Mixed stand	☐	Mature	☐	Narrow belt	☐
Orientation	______			Adventitious	☐	Climax-vegetation	☐	Old	☐	Single row	☐
gle of leaning (o)	______										

Notes and Comments:-

PART 5: BANK GEOTECH FAILURES *Interpretative Observations*

ailure Location		Present Status		*Instability:Severity*		*Failure Mode*		*Distribution of Each Mode on Bank*			
								Mode 1		***Mode 2***	
General	☐	Stable	☐	*Insignificant*	☐	*Soil/rock fall*	☐	*Toe*	☐	*Toe*	☐
Outside Meander	☐	Unreliable	☐	*Mild*	☐	*Shallow slide*	☐	*Lower bank*	☐	*Lower bank*	☐
Inside Meander	☐	Unstable:dormant	☐	*Significant*	☐	*Rotational slip*	☐	*Upper bank*	☐	*Upper bank*	☐
Opposite a bar	☐	Unstable:active	☐	*Serious*	☐	*Slab-type block*	☐	*Whole bank*	☐	*Whole bank*	☐
Behind a bar	☐			*Catastrophic*	☐	*Cantilever failure*	☐	***Mode 3***		***Mode 4***	
posite a structure	☐	**Failure Scars+Blocks**				*Dry granular flow*	☐	*Toe*	☐	*Toe*	☐
acent to structure	☐	None	☐	***Instability: Extent***		*Wet earth flow*	☐	*Lower bank*	☐	*Lower bank*	☐
ream of structure	☐	Old	☐	*None*	☐	*Other (write in)*	☐	*Upper bank*	☐	*Upper bank*	☐
ream of structure	☐	Recent	☐	*Local*	☐	______		*Whole bank*	☐	*Whole bank*	☐
Other (write in)	☐	Fresh	☐	*General*	☐						
______		Contemporary	☐	*Reach Scale*	☐						
				System Wide	☐						

Level of Confidence in answers (Circle one)
0 10 20 30 40 50 60 70 80 90 100 %

Notes and Comments on Bank Geotech Failures:-

SECTION 5 - BANK TOE CONDITION

PART 6: BANK TOE SEDIMENT ACCUMULATION *Interpretative Observations*

red Bank Debris		Vegetation		Age		Health		*Toe Bank Profile*		*ediment Balance*	
None	☐	None/fallow	☐	Immature	☐	Healthy	☐	*Planar*	☐	*Accumulating*	☐
Individual grains	☐	Artificially cleared	☐	Mature	☐	Unhealthy	☐	*Concave upward*	☐	*Steady State*	☐
gregates+crumbs	☐	Grass and flora	☐	Old	☐	Dead	☐	*Convex upward*	☐	*Undercutting*	☐
ot-bound clumps	☐	Reeds and sedges	☐	Age in Years	☐			*Present Debris Storage*		*Unknown*	☐
Small soil blocks	☐	Shrubs	☐			**Roots**		*No bank debris*	☐		
edium soil blocks	☐	Saplings	☐	**Tree species**		Taproot	☐	*Little bank debris*	☐		
Large soil blocks	☐	Trees	☐	(if known)		Fibrous	☐	*Some bank debris*	☐		
Cobbles/boulders	☐			______		Rhizomes	☐	*Lots of bank debris*	☐		
Boulders	☐			______		Exposed	☐				

Level of Confidence in answers (Circle one)
0 10 20 30 40 50 60 70 80 90 100 %

Notes and Comments:-

Site Sketch Map

Detailed, Local Scale Bankline Map and Profile Sketches

Map and Profile Symbols

Bank Top Edge

Failed debris

Engineered Structure

Bank Toe

Attached bar

Type of structure

Water's Edge

WE WE

Undercutting

Significant vegetation species

Vegetation(RHS landuse symbols)

Bankline Map

Broadleaf woodland BL
Coniferous plantation CP
Orchard OR
Moor/heath MH
Scrub SC
Tall Herbs (rank) TH
Rough Pasture RP
Improved Grassland IG
Tilled Land TL
Wetland WL
Suburban/urban SU

Typical Bank Profiles (Show Locations on Bankline Map)

a

b

c

d

Bank Assessment Summary Sheet

Observed Condition of Bank including Existing Protection

Processes, Extent, and Severity of Erosion Threat

Significant Erosion Processes, Failure Mechanisms and Weakening Factors

Comments on Willows used for Bank Protection

Conclusions and Lessons Learned

APPENDIX C

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APPENDIX D

SOURCES OF WILLOW MATERIALS IN THE UK

Sources of willow materials in the United Kingdom

National

National Willows Collection
IACR -Long Ashton Research Station
Long Ashton
Bristol BS18 9AF

http://www.res.bbcrs.ac.uk

Contact: Rod Parfitt - Curator tel: 01275 392181

Forestry Commission
Alice Holt Lodge,
Wrecclesham,
Farnham,
GU10 4LH

Contact: Alan Armstrong tel: 01420 22255
Gary Kerr - Hydrologist
Tom Nisbitt - Floodplain Research
Paul Tabbush - Forestry Authority

Wessex

Long Ashton Agroforestry Consultants
Alfoxton,
School Road
Wrington
Bristol BS18 7ND

Contact: Ken Stott

Roves Farm
Sevenhampton
Swindon
Wiltshire SN6 7QG

Contact: Rupert Burr tel: 01793 763939

Coppice Green Nurseries
Cleve
Bristol BS1 4PA

Contact: Edgar Watson

Chew Valley Trees
Winford Road
Chew Magna
Bristol BS 18 8QE

Contact: J Scarth tel: 01275 333752

Mount Pleasant Trees
Rockhampton
Berkeley
Gloucestershire GL13 9DU

Contact: P & G Locke tel: 01454 260348

Westinburt Arboretum
Tetbury
Gloucestershire GL8 8QS

Contact: The Chief Dendrologist tel: 01666 880220

John White
Consultant Dendrologist
11 Manor Close
Sherston
Malmsbury
Wiltshire SN16 0NS

Contact: John White tel: 01666 840790

West Country

Chris Coates
Mare Green Court
North Curry
Taunton
Somerset

Contact: Chris Coates

Nigel Hector
The Willows
Curload
Stoke St Gregory
Taunton TA3 6NA

Contact: Nigel Hector

Kingsfield Conservation Nursery
Broadenham Lane
Winshaw
Chard
TA20 4JF

Contact: M. White tel: 01460 30070

Burnoose & South Down Nurseries
Gwennap
Redruth
TR16 6BJ

Contact: C. H. Williams & D. Knuckey tel: 01209 861112

Natural Selection
1 Station Cottages
Hullavington
Chippenham
EX37 9PD

Contact: Martin Cragg-Barber tel: 01666 837369

Agroforestry Research Trust
46 Hunters Moon
Dartington
Totnes TQ9 6DW

Contact: Martin Crawford

Perrie Hale Forest Nursery
Northcote Hill
Honiton
EX14 8TH

Contact: N. C. Davey & J. F. Davey tel: 01404 43344

South

Rumsey Gardens
Drift Road
Clanfield
Waterlooville PO8 0PD

Contact: R. Giles tel: 01705 593367

Basket Makers Assn.
Pond Cottage
North Road
Chesham Bois
HP8 5NA

Contact: Ann Brooks

Midlands

Lionel Hill
Dunstall Court
Feckenham
Redditch B96 6QH

Contact: Lionel Hill

Hall Farm Nursery
Harpswell
Gainsborough
DN21 5UU

Contact: Pam Tatam & Mark Tatam tel: 01427 668412

Wales

Dingle Nurseries
Welshpool
Powys SY21 9JD

Contact: K. Hamer tel: 01938 555145

Y Fron
Llawr-y-Glyn
Caersws
Powys SY17 5RJ

Contact: Y Fron tel: 01686 430510

East Anglia

Ashmeades Farm
Kelvedon
Colchester CC5 9BT

Contact: Robert Goodwin

North

Ingerthorpe Hall Farm
Markington
Harrogate
HG3 3PD

Contact: Murray Carter

Weasdale Nurseries
Newbiggin-on-Lane
Kirkby Stephen
CA17 4LX

Contact: Andrew Forsyth tel: 01539 623246

Scotland

Ben Reid and Co.
Pinewood Park
Countesswells Rd
Aberdeen
AB9 2QL

Contact: John Fraser tel: 01224 318744

Plate 1: River Ouzel (Milton Keynes Valley Park) - erosion of banks behind the mature willows, *S. alba*

Plate 2: River Ouzel (Milton Keynes Valley Park) - corrosion (and not rotational slide) appears to be the process. Note the exposed lateral roots of the distant willow and the mature, rigid bifurcating roots of the nearside willow

Plate 3: River Ouzel (Milton Keynes Valley Park) - traditionally pollarded willow in the foreground with un-pollarded, yet mature, willows beyond. Note the extreme erosion before the pollarded willow, and under the un-pollarded willows. Note also the difference in herbaceous vegetation diversity between the willows

Plate 4: River Ouzel (Milton Keynes Valley Park) - note the mid- and upper-bank erosion

Plate 5: River Ouzel (Milton Keynes Valley Park) - well vegetated inner bank of meander band, unshaded by any trees

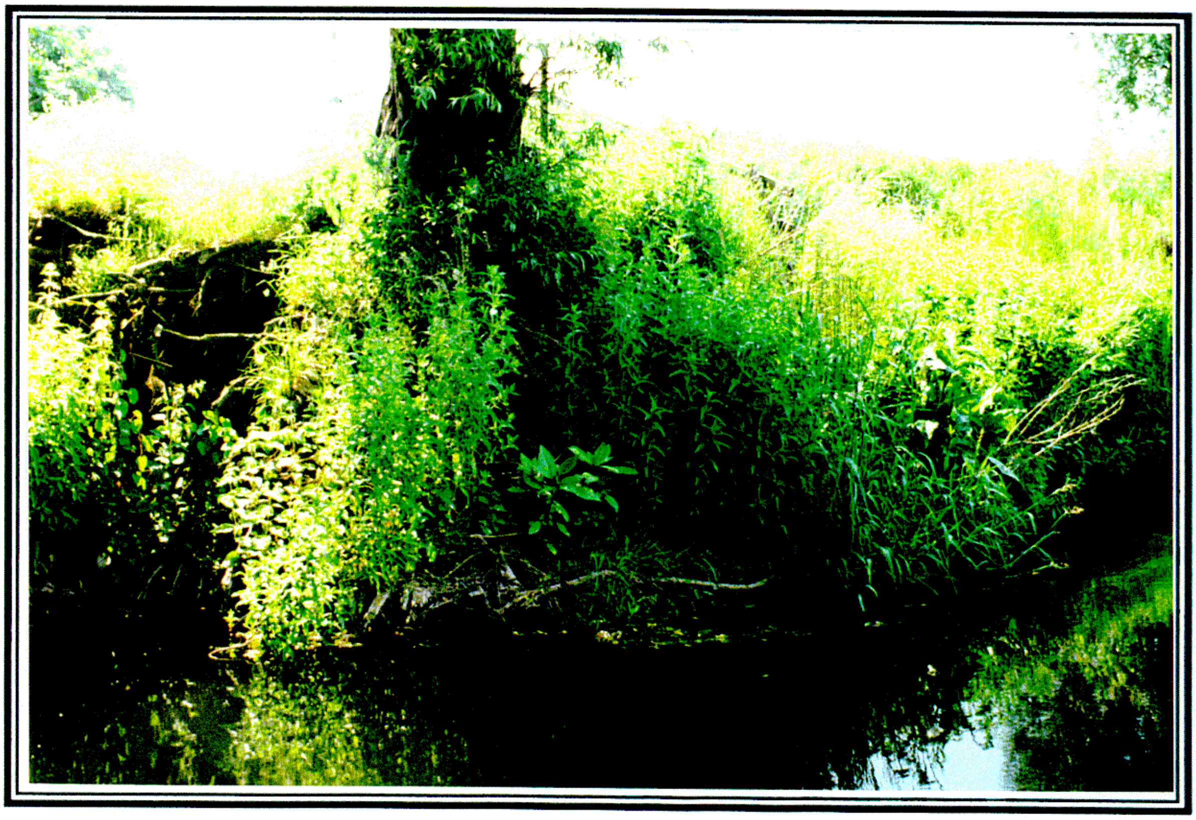

Plate 6: River Ouzel (Milton Keynes Valley Park) -note the exposed roots due to past erosion, and the diversity of herbaceous vegetation which has subsequently colonized the area of exposed roots

Plate 7:River Waal (Lower Rhine, Netherlands) - fallen willows at riverward edge of the stand. Willows to riverside have died due to inundation for 200+ days per year

Plate 8: River Waal (Lower Rhine, Netherlands) - willow stand showing accretion of sediments and lack of understorey

Plate 9: River Waal (Lower Rhine, Netherlands) - willow stand in eroding area at margin of protection plot

Plate 10: River Waal (Lower Rhine, Netherlands) - view south to main levee showing new construction and summer berm behind willow stand

Plate 11: River Waal (Lower Rhine, Netherlands) -view upsteam along bank to willow site in middle distance

Plate 12: River Waal (Lower Rhine, Netherlands) - view south from willow site to main levee across the washland (flooded in winter and dry in the summer)

Plate 13: River Waal (Lower Rhine, Netherlands) - volunteer willows on a rock groyne

Plate 14: River Medway (Oakweir, Kent) - willow spiling, within and at the outer edge of faggots, have grown. Note the bare toe region and the different densities of spiling foliage

Plate 15: River Medway (Banbridge, Kent) - note the well established willow bank protection

Plate 16: River Medway (Banbridge, Kent) - the willow spilings have grown, but note the excess horizontal growth of branches

Plate 17: River Medway (Banbridge, Kent) - overhanging spiling may inhibit the establishment of semi-emergent fringe vegetation but may protect against undercutting

Plate 18: River Yare (Norfolk) - footpaths along bank with young shoots of a previously coppiced willow

Plate 19: River Yare (Norfolk) - note the recent spiling with alder poles, willows and alder poles only

Plate 20: River Yare (Norfolk) - note the large willow leaning into the river, the attempts at wood piling and the large woody debris accumulated at the eroded bank

Plate 21: River Yare (Norfolk) - collection of woody debris in an erosion pocket between sections of heavily vegetated bank

Plate 22: River Great Ouse (Brampton, Cambridgeshire) -note the stability of the bank even though on the outer bend of meander reach. There are five species of willow, as well as other tree species

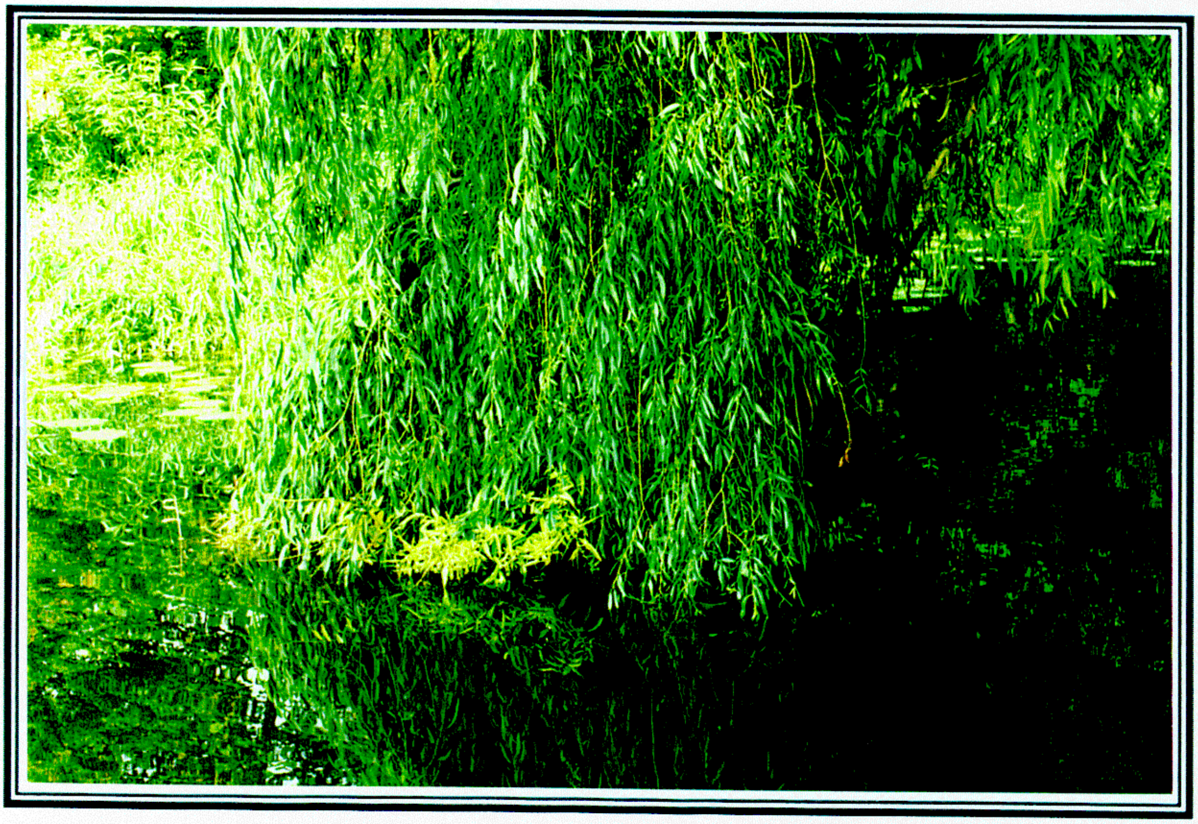

Plate 23: River Great Ouse (Brampton, Cambridgeshire) - close up of dense foliage impinging into a channel

Plate 24: River Great Ouse (Brampton, Cambridgeshire) - herbaceous vegetation on the banks dominated by nettles and sedges

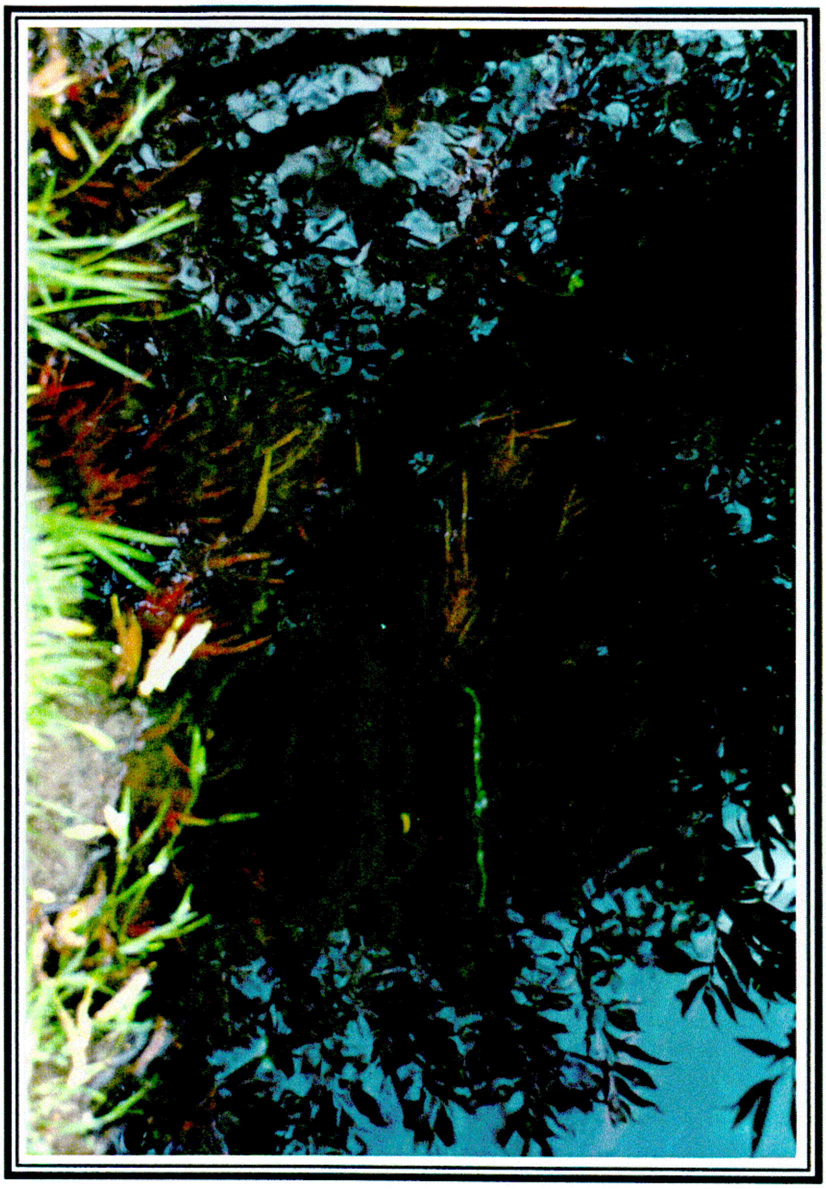

Plate 25: River Great Ouse (Brampton, Cambridgeshire) - note the dense, red-purple, fibrous root mattress "dipping-in" to the water from the base of fully grown willows, mainly *S. alba*

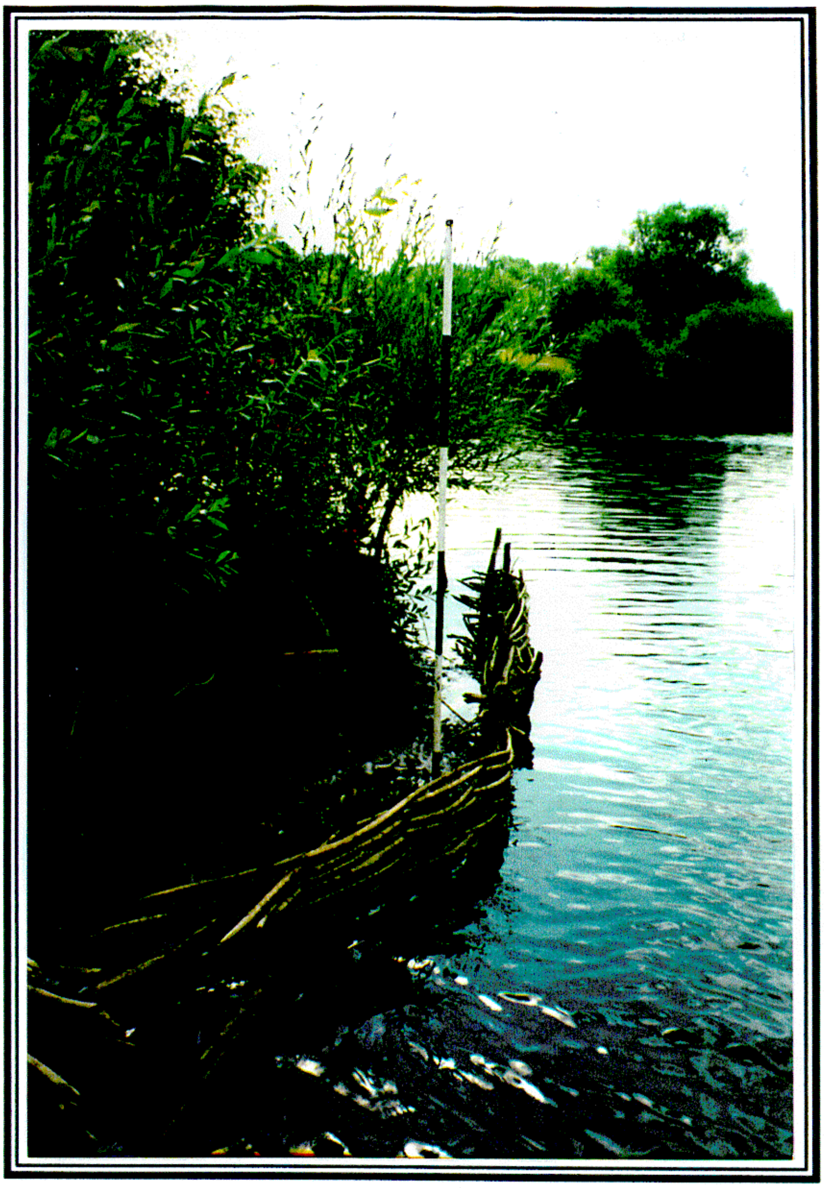

Plate 26: River Great Ouse (Milton Keynes) - a failed willow spiling

Plate 27: River Great Ouse (Milton Keynes) - note the willow poles have grown, but the spilings have not grown. The spilings act as a barrier to continued erosion

Plate 28: River Great Ouse (Milton Keynes) - willow poles and spilings have grown. Note the failed spilings in the foreground

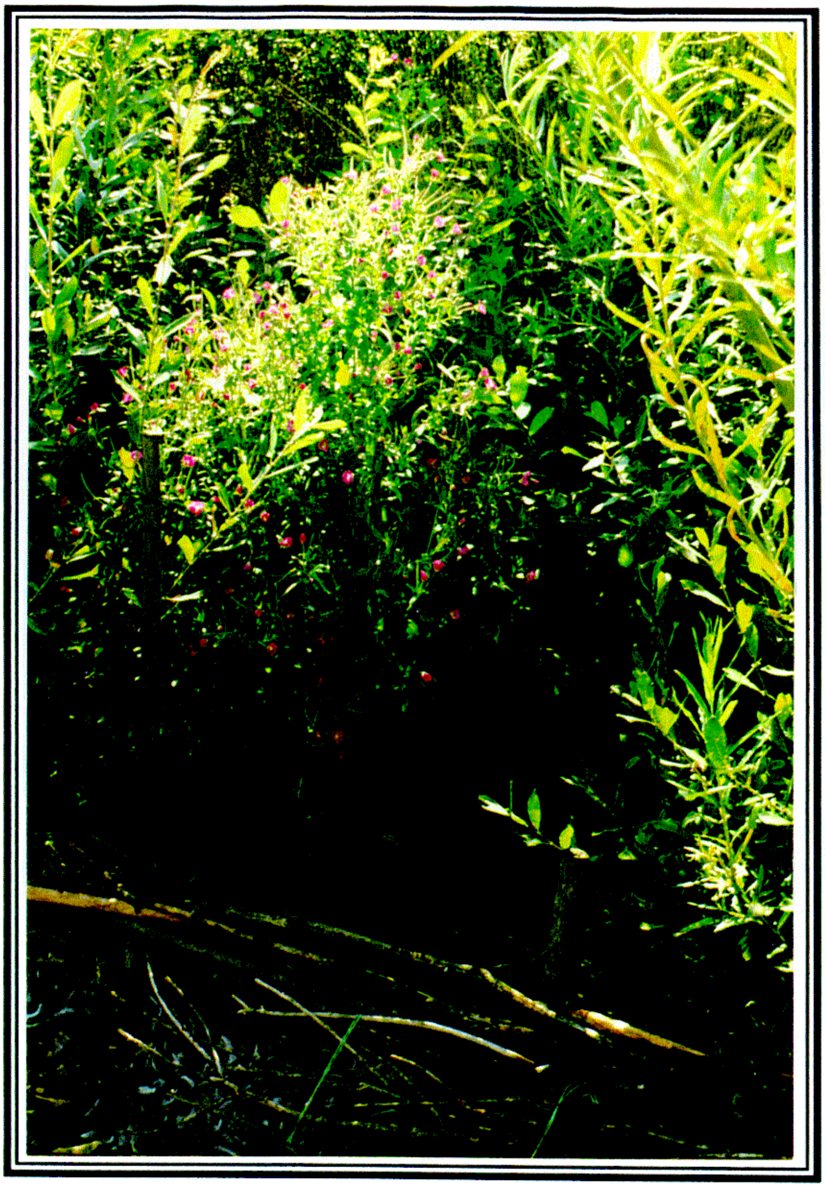

Plate 29: River Great Ouse (Milton Keynes) - note the failed spilings appear to form a physical barier to prevent erosion and promote enhanced growth of herbaceous vegetation

Plate 30: Crow Creek (Illinois, USA) - eroded cliff (glacial sand deposits) with stabilizing vegetation, planted using Roseboom's willow post method