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A geomorphic and hydraulic investigation in the context of floodplain revegetation; based on a soil bioengineering application on the Mattole River, Petrolia, California, USA.
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"A geomorphic and hydraulic investigation

in the context of floodplain revegetation;

based on a soil bioengineering application

on the Mattole River, Petrolia, California, USA"

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A thesis submitted to
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Abstract

As fluvial, riparian and floodplain ecosystem functions are recognised for their role supporting fisheries and ecological values, recovery of streamside vegetation is increasingly important in river 'restoration'. Fluvial geomorphology and hydraulic engineering do not yet account well for the role of vegetation in fluvial processes.

This research addresses the need for greater understanding of woody riparian vegetation influences on the hydraulics of overbank flow and floodplains sedimentation. Original hypotheses, research design, and data collection were generated by the student to address this gap in knowledge. A soil bioengineering design was constructed on the Mattole River, California, to revegetate the floodplain for better fish rearing habitat. Field data collection was carried out on this unregulated river for two flood events. The sediment samples resulting from a 1.25-year flow permitted the field testing of an hydraulic flume model of vegetation trapping efficiency. From velocity profiles measured during a 15-year storm event, the bed shear stress reduction caused by the vegetation was computed to be approximately 70-90%.

A survey conducted in the UK and internationally evaluated from literature, hydraulic researchers and practitioners of river revegetation, the extent of and gaps in knowledge with regard to river bank stabilisation using live vegetation. A flume flow visualisation study simulated the hydraulic behaviour observed on the Mattole floodplain, which enabled characterisation of flow behaviour through a porous filter medium. Results of this research indicate that flexible woody stems have a profound 'calming' effect on overbank flow. These effects are propagated in the downstream direction at least five and as much as ten times the width of the baffle, much further than previously indicated.

This research suggests that flexible vegetation is extremely effective in trapping fine (clay) sediments, contrary to general understanding and of importance for fish habitat. For hydraulic reasons, constructed zones of shrubs, such as the siltation baffle, could be spaced further apart than current design practise indicates.

Colin R. Thorne, for pioneering communications among fluvial geomorphologists and engineers with a style and grace that made such a bridge seem not only possible but logical, and for offering me the chance (while still in the USA) to work (in England) on the dream contract of the EPSRC 'Willows' project;

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To *my family*, who didn't see much of me for several years while I went out into the woods, and then migrated to England, and especially to my parents *Myra and Nestor Perala*, who fed me while I wrote the final drafts, and who always believed I could do anything I set my mind to, a most rare and valuable gift indeed.

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Chapter One: Introduction and Research Context

1.1.   Introduction – the context and need for recovery of vegetation on river banks and floodplains

For many centuries, but particularly in the last century, river engineering has sought to control river dimensions in response to societal demands. These demands are wide-ranging, for example to improve navigation, to generate hydropower, to reduce the land area occupied by the river, to "control" floods and distribute water throughout the human-dominated landscape (Petts, 1990). Such demands and nearly all other human activities along rivers have resulted in the reduction or loss of riparian plant communities, and in some places these ecosystems have been nearly or completely lost (Boon, 1992).

Riparian or streamside plant communities are essential components of landscape functions at many spatial and temporal scales. From catchment to reach scale, these plant communities moderate sediment transport processes, nutrient flows and sinks, surface and atmospheric hydrology, air currents and countless biological interactions with both land and water. From reach to site scale, plant communities stabilise river banks, and at even smaller scale they can determine the micro-ecosystem within the biota (Malanson, 1993).

Plant community structure and function varies at temporal scales as well. Vegetation mediates temperature at diurnal scales, which may influence measurements of water quality. Seasonal changes include deciduous leaf cover, affecting resistance to flow through plants from summer to winter (Armstrong, 1988). Over the scale of years, trees and shrubs mature, woody plants can invade grasslands, be set back by fire, and plant succession changes landscape processes (Botkin, 1990). Aquatic, riparian and floodplain plants both fix and contribute carbon (wood and leaves) to the stream ecosystem in many forms, providing the foundation of trophic webs from within the aquatic system (autochthonous food resources) and also from the riparian terrestrial areas (allochthonous resources) (Merritt & Cummins, 1984).

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Recovery of streamside vegetation is therefore becoming of increasing interest to river managers and communities throughout the world, for this wide variety of reasons. Trees, shrubs, grasses and grass-like plants are integral, essential components of the riverine ecosystem, but these plant communities have also proved extremely useful to human economy and have therefore been much exploited economically through the centuries. The loss of these plant communities has precipitated the decline of thousands of animal species dependent upon the riparian 'ecotone', the aquatic- terrestrial interface, for some or all of their life cycle (DeCamps *et al*, 1990). Today, many important game or 'keystone' animal species, especially fishes, as well as obscure but functionally integral species are in precipitous decline; many are threatened with extinction, and some riverine and riparian species have already become extinct (National Research Council, 1992). The continuing trend of riparian habitat loss may not be the only threat to these animal communities, but it is a vital aspect of their survival and until recently, a relatively neglected component in the modern river management paradigm.

Following pioneering work in Germany in the 1960s, interest in rehabilitation of riparian ecosystems has grown steadily in the Australia, New Zealand and the United States of America. Many more systematic management efforts are now being undertaken in these and other countries, such as Austria, Canada, Denmark, France, Hungary, Portugal, Spain and United Kingdom, to recover river morphology, ecosystems and lost plant communities along river margins. Germany, followed by the USA and Denmark, led the way in the 1970s and 80s in full rehabilitation of straightened and resectioned river channels (Brookes, 1988). The UK has more recently undertaken full rehabilitation works, after pioneering techniques since the 1970s (Purseglove, 1988), in the River Restoration Programme (Driver, 1997, Holmes & Nielsen, 1998).

Contemporary river management is founded largely on hydraulic engineering paradigms derived primarily from laboratory flume studies, which typically have modelled ideal flows in ideal channels, until recently without sediments (Newson, 1995). These models typically used the assumption of 'clear water flow', which means water flow without a sediment component. Such modelling has often grossly underestimated the effective roughness of the channel cross-section in debris-rich

flood flows (Williams, 1990). To date, relatively little hydraulic research has been conducted under natural stream conditions, especially for flood or overbank flows for obvious reasons of timing (i.e. being present during a flood event), access (i.e. having the right equipment to take measurements in flood flows) and personal safety. Some UK research was undertaken from gantries spanning small rivers, such as the work done on the R. Roding (Sellin & van Beeston, 1990).

In practice, trees are routinely removed from streambanks in the belief they "cause" flooding, based on the theory of the backwater effect (Chow, 1959). Trees on the banks of tightly-confined urban stream have attracted debris, sometimes causing enough blockage in a relatively small channel to retard the flow and send water over the bank top upstream (Gardiner, J., pers. comm., 1996) However, downed trees are significant elements of the stream ecosystem, (Harmon *et al*, 1986, Wallerstein, 1999) and should be incorporated into river management practise to the greatest extent possible.

Scale is important; the flow diversion and scour potential caused by downed trees or other blockages on small streams may have little or no effect on larger rivers (Thorne, 1990). In channels with a high width/depth ratio (w/d>30), resistance depends mostly on bed roughness and channel shape, and the contribution of the bank to overall roughness is small. For these channels, any increase in conveyance through vegetation clearance may be lost when bank erosion leads to increasing channel width (Thorne, 1990). A geomorphic approach to floodwater distribution, sediment transport and delivery suggests that a reach-scale strategy is needed to understand and manage flood and bedload dynamics (Kondolf & Larson, 1995).

Although there are now numerous workers in these fields, there are as yet insufficient hydraulic and fluvial geomorphic data available to predict the effects of streamside vegetation on the wide range of natural interactions among natural river channels, flowing water, and sediments. The lack of real-world data means that it is not yet possible to make hydraulic predictions of the consequences of revegetation of modern river banks and floodplains, although in-channel aquatic vegetation is relatively well defined hydraulically. Such predictive capability is greatly needed if initial efforts (which tend to be expensive) to recover riverine ecosystem functions

are to be successful. Demonstrated progress and increased factors of safety will be needed to maintain the political will for continued funding of these research efforts. Meanwhile, there is increasing demand for 'multi-objective' river management, sometimes prompted by legislation such as the UK's Wildlife & Countryside Act (1981) or the USA's Endangered Species Act (1974).

The knowledge gap between disciplines has been created partly by the reductionist scientific method, which has hitherto separated the study of physical and biological phenomena into unrelated disciplines for the valuable purposes of quantitative analysis. Where the physical sciences such as hydraulics and geomorphology intersect biological processes such as plant growth and plant community evolution, the many theoretical and data gaps have led to an incomplete understanding of natural processes. The practical aspects of how to 'work with nature' are becoming more than general guidelines (Federal Interagency Stream Restoration Working Group, 1998), based on relatively simple applications of fluvial geomorphology, but the heuristic approach of field experience lacks a solid base, as the few practitioners who earn their living revegetating streambanks and floodplains have little time to document their experience. The knowledge gap also exists partly because major funding agencies for science and engineering have found it difficult to support field studies which are aimed at relating practical aspects to theory. In the UK, this has historically meant that the research scope has fallen between the remits of the Engineering and Physical Sciences Research Council (EPSRC) and that of the National Environment Research Council (NERC).

Workers in both research and practice have stated to the author that adequate field data may never be available (see Thorne et al, 1998), for the reasons already stated, to formulate and test specific theories which include vegetation as well as hydraulics and geomorphology. For this reason, overbank flow behaviour has been simulated using physical models, although rarely with floodplain vegetation in the model. In the U.K., large-scale laboratory modelling work has been carried out at the flood channel facility (FCF) at Hydraulics Research (HR) Wallingford Ltd., in America at the Waterways Experiment Station of the Army Corps of Engineers, Vicksburg, Miss, and in Germany the German Association for Water Research and Construction (DVWK) have co-ordinated a research programme through the

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Technical Universities Aachen, Braunschweig, Darmstadt and Hanover. Other programmes exist in Japan, elsewhere in the USA and in Canada. Typical floodplain roughness elements have used wooden dowels for single trees (Garcia, 1996) or plastic filament filter mesh for general roughness (Kouwen & Li, 1980).

In the UK, beginning about 1987, the FCF has hosted a long-term, phased programme of increasingly complex modelling. Beginning with straight, clear-water, fixed-bed, compound channels (Ackers,1991), research progressed to model meandering, single-size sediment, and fixed-bed, two-stage channels (Wark *et al*, 1994), in an effort to reduce the 'noise' induced by the complex interactions in meandering, graded sediment, mobile bed, multi-stage channels. Those anxious to see results applicable in the field from such an apparently slow process of inquiry, have failed to understand the complex nature of the problem (Gardiner, J, pers. comm., 1997).

Comparison of FCF results with full-scale field experiments, such as those carried out recently at the University of Vienna, could be expected to inform the smaller-scale modelling, but the complexity of ecological, hydraulic and geomorphological factors remains a challenge to the acquisition of knowledge. Iteration between mathematical and physical models (from small to full-scale, and from laboratory to field) and communication of both qualitative and quantitative information between workers in these fields is vital to secure effective progress in knowledge that can be used to conserve and reclaim the rich heritage of our river corridors. Thus far, national and international research funding has been largely absent for multi-disciplinary research proposals, especially for the funding of either construction or monitoring of actual projects on the ground. In the Western USA and elsewhere, natural resources management agencies are now funding 'on-the-ground' projects, with little or no funding for assessment or monitoring.

The present research effort addresses this knowledge and data gap. In bridging across the disciplines of plant ecology, fluvial geomorphology and river hydraulics, this research is necessarily exploratory and more descriptive than quantitative in nature. The numerous disciplines needed effectively to address sustainable riparian and floodplain revegetation include botany, economics, engineering, fluvial

geomorphology, geography, geology, horticulture, hydrology, plant ecology, and sociology, (Kauffman *et al*, 1997) among others. Intersection of these disciplines requires specialist expertise in more than any one field. The task of communicating among the disciplines and with the public tends to stand 'outside' the scientific framework. However, there is evidence that the technical communication skills needed are being acknowledged by the scientific community and incorporated into a rigorous method of multi-disciplinary inquiry. The scientific community continues to debate whether understanding of natural systems is sufficient in itself, or whether scientific findings have real implications for the way society chooses to relate to natural systems (Michener & Haeuber, 1998). Communication among the scientific disciplines and with the lay public is key to the arduous process of taking effective action to prevent the loss of the ecosystems and the natural world on which human economy and well-being depends.

1.2   Relevant Findings of the EPSRC/EA Willows Project Report

Research undertaken in 1996-97 for the UK Engineering and Physical Sciences Research Council (EPSRC), directed by Prof. C.R. Thorne, partially funded the completion of this PhD thesis. The project examined the scope of knowledge regarding the use of woody vegetation for river bank stability. Following production of that report by the Environment Agency of England and Wales and the EPSRC (Thorne *et al*, 1998), a dissemination workshop was held 29 May 1998 at Middlesex University, Enfield, which brought together some 50 people from several disciplines in academic research and in practice (particularly in the Environment Agency), related to the theory and management of vegetation on river banks. The interactions among researchers and practitioners were widely regarded as a valuable exchange of views and information, and highlighted the need for further events of this kind.

In particular, wide agreement was reached that so much is lacking in the understanding of vegetation effects on rivers and bank stability, that fruitful exchange between research and practice could greatly benefit river management in the medium and long term.

Typically, vegetation in river processes and river engineering has been an interdisciplinary subject which has fallen into the purview of neither biological nor engineering research programmes. Many researchers have commented that funding for this type of research has fallen into a 'gap' between EPSRC, NERC and Biological and Botanical Sciences Research Council (BBSRC), none of whom in the past were able to sponsor research into vegetation in overbank hydraulics, vegetation influences on bank stability or engineering and geomorphic effects of Coarse or Large Woody Debris (C/ LWD), also called simply Large Wood. The Enfield meeting was held to take forward the project findings from the 'Willows' EPSRC/ Agency report, to aid in identifying the most urgent priorities among the thirty-five recommendations originally resulting from the scoping study.

From the original 35 recommendations for future research, the following ten recommendations relevant to the present research thesis were identified as top priorities for near-term funding in the UK.

Retardance of Near-Bank Velocities

1. *Vegetation effects on flow patterns.* 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.

2. *Maintenance and hydraulic regime.* 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.

Stem Characteristics

3. *Stem flexibility and drag.* 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 characterised.

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Channel Capacity and Floodplain Conveyance

5. *Flexible vegetation in physical modelling of 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.

6. *Vegetation effects on sediment transport and channel adjustments.* Physical model studies should also address the effects 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.

7. *Post Project Appraisal & monitoring of bank protection schemes.* Post-project monitoring and appraisal of projects employing vegetation are essential to compare actual performance against design specification, to 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.

Plant Community processes

16. *Vegetation assemblages, bank geomorphology and community succession.* 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.

21. *Role of mycorrhizal fungi and root soil cohesion.* Empirical studies are needed to establish the chemical composition of fungal root exudates and the role of mycorrhizal fungi in affecting soil cohesion, porosity and shear resistance.

Channel narrowing

31. *Woody vegetation & channel narrowing; processes & mechanisms.* 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.

32. *Vegetation, bank protection & channel width stability; risks to conveyance.* 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.

For ease of consideration, the overall recommendations were subdivided into four groupings; 1) Hydraulics of channels and floodplains; 2) Bank erosion; 3) Monitoring bank protection installed (including economic analysis); and 4) Natural systems/ processes. Only those which relate to the present thesis are given here.

Discussion of the EPSRC/EA Willows report and workshop findings

Convergence of views among the report findings, the workshop participants, and the assessors for this final exercise were not exact but there was wide agreement on some topics. First is that the use of vegetation on river banks and floodplains is a growing trend world-wide, and there is increasing demand in the UK that such approaches be brought into wider practice. Another topic of wide agreement is the need for multi-disciplinary research projects, and for multi-disciplinary teams in practice to advance care for the river environment. Related disciplines include engineering hydraulics, geomorphology, geotechnics, hydrology, and ecology/ conservation, landscape and land use planning, among others. Such 'best practice' needs to be promoted, and funding agencies need to be impressed with the fact that this apparently 'applied' area of science is actually where some research focus is needed.

Substantial technical obstacles do exist, but landowner/ public perceptions may be at least as limiting as the technical issues to changing river landscape management practices. Several workshop discussion groups identified the need to address landowner concerns and the education of public perceptions, issues which fall outside the remit of this thesis, but are nonetheless very important. Economics and sociology with respect to rivers and landscape processes are closely related research areas in need of funding, and undoubtedly the publicising of economically and socially-acceptable approaches applied on

demonstration sites throughout the country would prove most useful in gaining wider acceptance of the use of bankside and floodplain vegetation (Tunstall *et al*, 1998).

Water quality research in vegetative treatment of polluted waters (urban pollution, agro-chemicals and sediment) can make substantial contributions, potentially increasing the economic benefits of vegetative treatments of river banks, which were not included in the EPSRC/EA research remit.

In some cases, it is recognised that multiple-funding options may be needed to fill the research gap between the physical and social sciences, and to address the application of research findings. There is much potential for collaboration among academic institutions, practitioners such as the Environment Agency, private industry and landowners. There may be a need for creative financing of innovations in research and in practice.

The overall highest ranked recommendations from the report are:

1) Vegetation effects on flow patterns and

2) Maintenance and its effects on hydraulic regime.

Other high priority topics are:

- Dominant processes in bank erodibility;
- Vegetation as geomorphic hardpoints;
- Thresholds of failure for vegetative bank treatments;
- Identify properties of riparian plant species for bank/ floodplain revegetation;
- Vegetation effects on channel narrowing processes.

The report recommended that ecological research should be closely linked to engineering and geomorphological research in fluvial and floodplain processes. Also, water quality research topics should be related to the physical processes identified in the EPSRC/EA 'Willows' report. Further, related economic and sociological research is needed to advance the role and the application of vegetation along river corridors.

A model for integration of biotic and abiotic processes

A vision is needed which can illustrate the interactions among the physical processes in water and sediment transport influencing channel and floodplain morphology, and the biological factors which respond to and shape floodplain plant communities. The following diagram is offered as a starting point for such a unifying model.
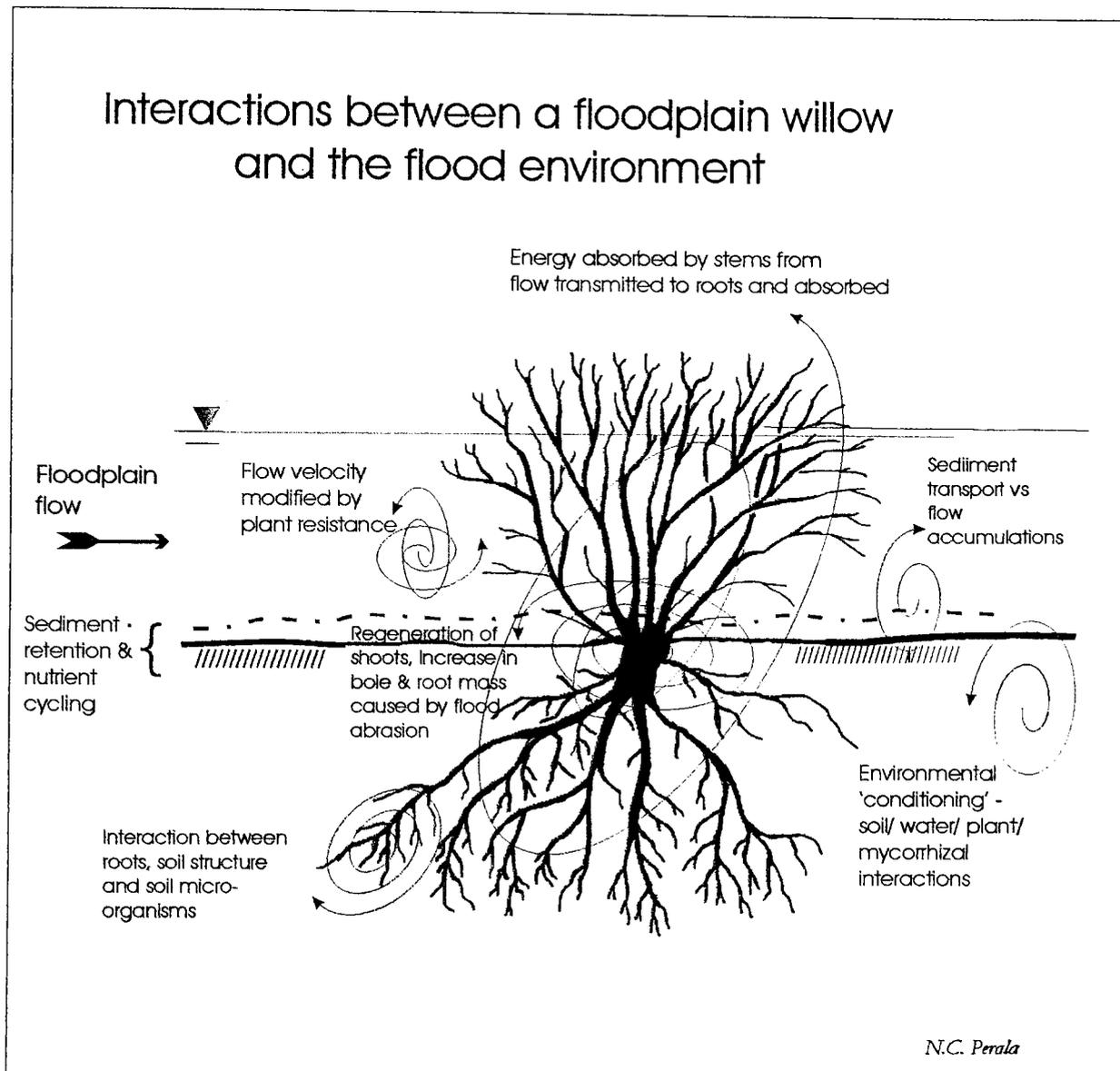
Figure 1.1. Integrated connections among hydraulic, geotechnical, geomorphic and ecological processes on river banks and floodplains during floods.

1.3   Assumptions used in this Thesis

The fundamental assumptions guiding this research programme from the outset may be expressed as follows:

The interactions among main channel morphology and its flow, overbank surfaces, overbank flows, sediments and riparian/ floodplain vegetation have substantial consequences for sediment transport, deposition, accretion, scour and bank erosion processes. Floodplain vegetation affects fluvial geomorphic processes in a variety of ways, but the geomorphic and hydraulic expressions of the physical processes of overbank flow account poorly for the effects of vegetation form and flexibility, and plant resistance both from above- and below-ground.

The effects of trees, shrubs, grasses and below-ground plant parts on bank and floodplain processes may be either stabilising and destabilising; they may either decrease or increase flood hazards for riparian landowners, depending on the type and condition of the vegetation, and the site and reach conditions. Many urban river reaches are so constrained by channelisation that adequate widths for rehabilitation must be regained before fluvial processes and the revegetation process can apply. In order for the benefits of riparian vegetation to be judged greater than any potential increased hazards which may be associated with their presence, the long, growing list of ecological benefits of woody riparian vegetation must be included in the economic calculations used in river management decision-making.

1.4   Thesis Hypotheses

This thesis seeks to address aspects of the highest ranked recommendations from the EPSRC/EA report. The fundamental hypotheses followed in the development of this thesis are as follows:

a. Flexible, emergent, woody vegetation interactions with overbank flows exert a non-logarithmic effect on the overbank velocity profile.

b. Flexible, emergent, woody stems in flood flows can be shown to have a profound effect on turbulence induction and sedimentation in the downstream direction.

c. Groups of willow stems will differentially filter sediments (contrasted with stony, non-vegetated geomorphic surfaces) from overbank flow in proportion to flow depth and duration.

1.5 Goals and Objectives

1.5.1 Goals

The overall goals of this thesis research programme are:

a. To review the major literature in fluvial geomorphology and river hydraulics on the subject of vegetative influences on overbank flow, floodplain sedimentation and channel morphology;

b. To measure the effects of revegetation on floodplain sediment deposition;

c. To test the assumption of the logarithmic velocity profile where flexible, emergent woody vegetation is present;

d. To relate field observation and data analysis with laboratory experimentation, to test current assumptions about the hydraulic effects of floodplain vegetation on overbank flow.

Despite these objectives being developed prior to the 1998 EPSRC/ EA "Willows" project, they coincide with the highest recommendations of the EPSRC/EA report, as areas identified with the greatest potential for progressing relevant knowledge and practice with regard to vegetation in hydraulics and sedimentation.

1.5.2 Field Objectives

Objective 1. Measure the extent and depth of fine sediment deposition for an overbank flood flow influenced by woody vegetation.

Objective 2. Assess the change in floodplain velocity profile owing to the presence of woody vegetation on the floodplain.

1.5.3 Flume Objectives

Objective 3. Simulate field conditions in a laboratory flume, holding the Froude number constant, to observe flow patterns in overbank flow influenced by a porous vegetative filter.

Objective 4. Develop qualitative observation of the effects of a vegetative filter on flow resistance and the backwater effect.

Objective 5. Vary the spacing between baffles to observe flow wake re-entrainment and the distance at which wake re-entrainment occurs

Objective 6. Vary the placement of the upstream-most baffle from perpendicular to parallel to flow, to observe whether a perpendicular angle or a 60° angle increases the volume of flow onto the floodplain.

1.6 Research methods

The thesis initially investigated a floodplain revegetation project (1993) on an unregulated stream in rural northern California. Starting with a focus on quantitative assessment of physical processes, the research was guided by the dramatic realities of fieldwork during flood events (1995), to examine the functions and processes of woody vegetation in floodplain flow and the resulting sediment deposition. The thesis is founded on an extensive literature research and analysis (1992-98), field investigation (1992-95) and a laboratory experiment of vegetation effects on overbank flow processes (1998). Two seasons of observation with two floods were used to gather data on sediment deposition, first by an annual flood, and second on observation of flows influenced by floodplain vegetation, which were measured on a floodplain during a 15-year storm event (1995). Subsequent to the field work, involvement in the EPSRC/ EA 'Willows' project (1996-97) scoped the gaps in knowledge with respect to woody vegetation influences on bank stability. This programme refined the present thesis research, broadened the literature review, and informed the need for flume work. Flume laboratory work was conducted (1998) to represent the flow conditions observed on the study site, to gain an understanding of the hydraulic effects of a porous vegetal filter on overbank flows in the downstream direction.

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The primary investigative methods used were fourfold:

    a. a review of the literature in plant ecology, fluvial geomorphology, fluvial hydraulics of overbank flow and vegetative influence on sediment deposition;

    b. field work undertaken to measure and make quantitative estimates of the sedimentation response around a known density of grouped willows at a given flow depth, and

    c. field work undertaken to compare overbank flows influenced by this flexible woody vegetation with comparable overbank flows over the same geomorphic surface without such vegetation influences.

    d. laboratory work undertaken to model in a flume (using clear-water conditions) the flows observed during a natural flood, to test additional hypotheses regarding the influence of flexible emergent woody vegetation structures on overbank flow structure.

From observing overbank flows in the field, a quantitative and intuitive grasp of the complex hydraulics involved then informed the laboratory exercise to recreate and reveal some of the basic processes involved, which could not be viewed in the field. An informed attempt is made to identify areas for further hydraulics research which are either not yet recognised or currently not considered as worthwhile research topics.

1.7   Structure of the Thesis and Signposts

The thesis is divided into eight chapters:

Chapter One provides the introduction, an overview to the structure of the thesis and the approach taken. A review of the research programme (which partially funded the thesis research) is presented, as this programme provided the author with a broad overview of the current research, the researchers and practitioners presently working in a range of related fields.

Chapter Two provides a literature review of relevant papers in fluvial geomorphology and floodplain ecology, to explore the state of our knowledge with regard to streambank and floodplain vegetation ecological and geomorphic functions, and to set the context for the desired future condition across a range of geomorphic conditions. Chapter Two reviews the work to date on vegetation interactions with fluvial geomorphic processes. Beginning with an introduction to riparian floodplains, their fluvial processes and ecology, the literature is examined with regard to the influences of floodplain vegetation on geomorphic processes during floodplain flow, bank erosion, effects of large wood on channel and floodplain morphology and fluvial processes, floodplain classification according to energy regime, anthropogenic influences on floodplain plant communities, and the role of 'buffer zones' or set-aside areas in riparian land management.

Chapter Three provides a literature review of relevant papers on vegetation in hydraulic engineering, some relevant work in geotechnical engineering as plant roots affect bank stability functions, and a review of some of the effects of the large woody debris generated by streamside forests. Chapter Three sets the context of the thesis within the discipline of engineering hydraulics.

Chapters One through Three taken together complete the framework of the research programme, and scopes the many disciplines required to investigate the complex phenomena in the field observed and measured in the case study and the laboratory experiment.

Chapter Four contains the background for the case study on the Mattole River, California. The physical setting of the field study is presented, the rationale for why this study was undertaken and the scientific framework is given in which the

revegetation work was conducted. The thesis objectives and hypotheses are detailed in the latter part of Chapter Four.

Chapter Five presents the Materials and Methods used in field data collection for the narrow category of grouped, flexible emergent vegetation effects on sedimentation, and these vegetation effects on flood hydraulics on a fluvially mobile, midchannel island. The hydraulic conditions measured in the field inform the flows set up in the laboratory flume to conduct a flow visualisation study of effects of simulated flexible vegetation on overbank flow. The theoretical framework is given linking the fieldwork with the need for and the relationship with the laboratory flume experiment.

Chapter Six presents the analysis of the field and laboratory data in three categories;

1. sedimentation response from an annual flood over the midchannel island, contrasting the vegetated area with bare surfaces;

2. velocity profiles taken during a 15-year flood upstream of and in among the vegetation structures, to segregate the bedform effects on roughness to the greatest extent possible; and

3. a qualitative analysis of a flow visualisation study, recreating in the laboratory flow conditions observed in the field to the extent possible.

Chapter Seven provides a discussion of the results of the field and laboratory work. The research findings are related to the EPSRC/EA Willows Report results and the literature presented in Chapters Two and Three. The goal of this section is to synthesise the fields of fluvial geomorphology, hydraulics and plant ecology with respect to the problem of overbank flow and sedimentation through streambank and floodplain vegetation, towards a hydraulically based 'riparian ecological horticulture'.

Chapter Eight provides the conclusions and recommendations for future research, by providing an informed consideration of the research needed further to improve practise in this field.

1.8 Sources of Data and Information

Primary field data on the Mattole River are supplemented by the field research undertaken by the Mattole Restoration Council (MRC) and its allied environmental groups, such as the Mattole Watershed Salmon Support Group (MRC, 1995). The set-up of the field experimental site would not have taken place without the essential contributions of the many people working to protect the native salmonids of the Mattole River catchment from extinction.

The literature review was progressed under a research programme funded by the UK Engineering and Physical Sciences Research Council, led by Prof. C. R. Thorne of Univ. Nottingham. The report for this programme titled, "River bank stabilisation using live vegetation, with special reference to willows", was published by the Environment Agency R&D Tech. Report W154 (Thorne *et al*, 1998).

The laboratory flow visualisation study was made possible courtesy of Dept. of Civil Engineering, Imperial College London. Use of this flume and valuable insights by staff into the flow processes involved extended the analytic value of the flow visualisation experiment. (Hardwick, pers. comm., 1998). It is true to say that this work provided the physical and mental 'bridge' between the field practice and the potential work to be done in the laboratory flume, and has opened the door to greater understanding of processes which cannot be readily seen in the field; the apparently chaotic, turbulent flows of a big flood through vegetation on a floodplain, especially in plan view.

1.9 A comment about the term "soil bioengineering"

The discipline of "soil bioengineering" ("Ingenieurbiologie" in German), was rediscovered in Austria earlier this century (Schiechtl, 1980), although its principles may be traced back to pre-Roman times in the reinforcement of trackways through British marshes with tree branches. Ancient Chinese engineers used large baskets of bamboo filled with rocks for river training (Farrelly, 1984).

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This use of living plant materials for structural engineering purposes bridges the 'traditional' hard engineering of the contemporary past with more flexible, ecological methods of the distant past and the near future, and points one way toward the practical work of assisting natural recovery of damaged plant communities and ecosystems.

The term 'soil bioengineering' distinguishes this effort from the practices of genetic manipulation of plants and animals, which also sometimes uses the term 'bioengineering'. The same distinction lies between the commonly-used alternative of "biotechnical" bank stabilisation and "biotechnical" engineering, meaning genetic engineering of DNA for such features as herbicide resistance.

Soil bioengineering techniques historically used large rock in engineered structures with live vegetation for erosion control measures. Use of large rock integrated with living plants continues to be integral to soil bioengineering and biotechnical engineering in modern river management practice.

Chapter 2: Riparian Vegetation in Fluvial Geomorphology and Floodplain Ecology, A Literature Review

2.1 Introduction to riparian floodplains, fluvial processes and ecology

Riparian landscapes are defined by Malanson (1993) as 'ecosystems adjacent to a river'. These features of river corridors are the subject of a rapidly increasing literature, because riparian elements of catchments mediate both physical and biological processes at many scales (Malanson, 1993). Historically, riparian vegetation has been removed from rivers world-wide by a variety of human activities such as settlement, grazing, agriculture, logging, mining, flood defence, and gravel extraction. The original distribution of riparian vegetation has been reduced in California by more than 90% over its historic distribution (Faber and Holland, 1988), and in the coterminous US by at least 56% (Swift, 1984), and is still declining (National Research Council, 1992).

The activities of flood defence operations affecting streamside vegetation include capital works such as dam and reservoir construction, weir construction, desilting and maintenance, river re-alignment, diversion, channel widening, straightening, dredging for navigation which strongly influences channel stability (Brookes, 1988), clearing and snagging, routine maintenance which often includes tree and brush removal (Royal Society for the Protection of Birds, 1995), spoil disposal and revetment or bank stabilisation (Holmes, 1994).

Various definitions of floodplain exist. It is defined by Leopold (1994) as "a (relatively) level area near a river channel, constructed by the river in the present climate and overflowed during moderate flow events." Geomorphic floodplains are functioning associations of landforms largely produced by alluvial deposition (Lewin, 1978). According to the US government, "floodplains are the relatively low and periodically inundated areas adjacent to rivers..., which lands combine with adjacent waters to form a complex, dynamic, physical and biological system that supports a multitude of water resources, living resources and societal resources – floodplains become part of the rivers (during floods)" (Interagency

Floodplain Management Review Committee, 1994). The commonly-used term, the "100-year floodplain" is that area of land which is inundated by the flood estimated to recur with a probability of 1% in any year, or statistically once in 100 years (Dunne & Leopold, 1978), assuming constant climatic conditions. Protection against the 1-in-100-year flood is the most common aim of flood defence capital works, and used standard for river engineering, and the 1-in-100-year floodplain is a common standard in land use planning (IFMRC, 1994).

Even compared with hydrology, interest in floodplain geomorphology is a relatively recent development, with numerous recent studies documenting landforms and processes at several scales (Lewin, 1978). Many floodplains experience regular inundation, and during overbank flow, accrete and store sediments at variable rates across the floodplain (Wolman & Leopold, 1957). Floodplains act as sinks for sediments and release materials when channels migrate laterally (Richards, 1982). Simm (1995) reviewed the literature in overbank floodplain sedimentation, and documented rates and patterns of overbank deposition for lowland floodplains. Two dominant processes drive floodplain deposition and evolution; the more frequent flood of low magnitude, often at imperceptible rates, and the less frequent flood of high magnitude. Substantial variability in deposition rates result from factors such as variation in suspended load and bedload transport, floodplain topographic variation and roughness elements such as vegetation (Simm, 1995). The subject of channel-forming flows or dominant discharge is a big topic, intensely debated among fluvial geomorphologists. Fewer studies have documented influences of vegetation on floodplain processes; this issue is discussed in section 2.4.

The generalized geomorphic features of the channel and floodplain are illustrated in Figure 2.1.

Geomorphic floodplain features, after Osterkamp & Hupp (1984)
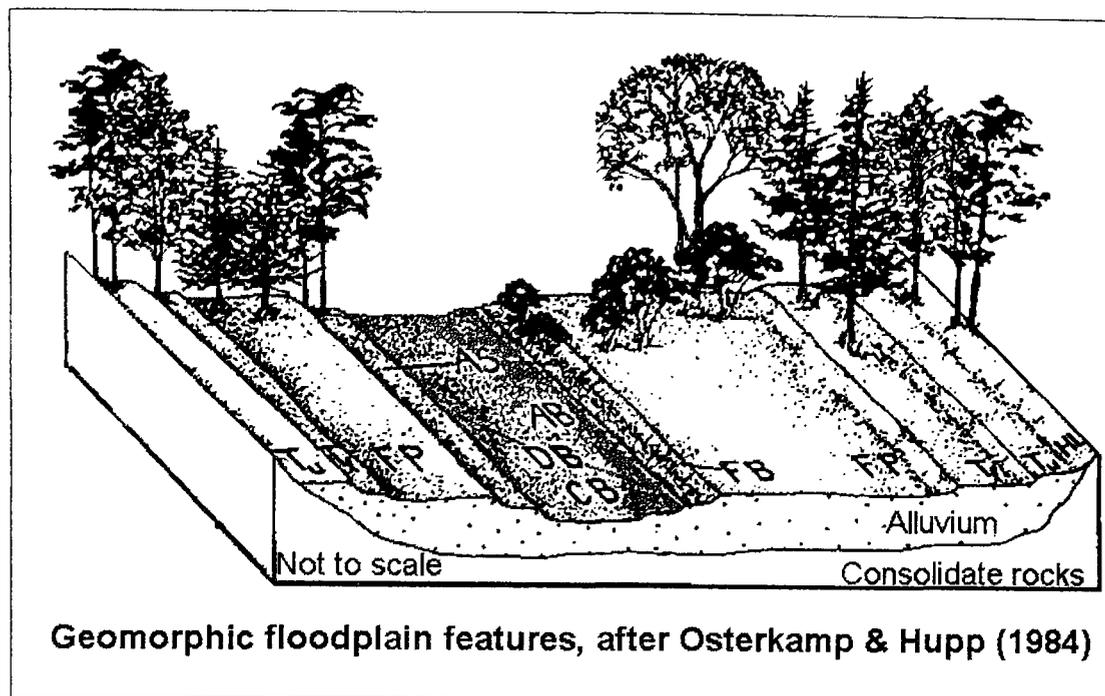
Figure 2.1. Definition image of floodplain geomorphic features, after Osterkamp & Hupp (1984). Terms are CB channel bottom, DB depositional bar, AB active bar, AS active channel shelf, FB fore bank, T terrace (upper and lower), FP floodplain, and HL hillslope.

The interest in floodplain geomorphology extends beyond sediment transport and deposition, however. Floodplain and riparian vegetation recovery is becoming more highly valued for its many geomorphic and ecological benefits, such as

- increased bank stability, when in equilibrium with the channel and reach geomorphic regime (FB/AS); (Thorne, 1990);

- increased bank and floodplain roughness which, in conjunction with increased floodplain retention, has the potential to reduce flood hazards in the downstream direction (FP); (Philip Williams & Associates, 1996);

- providing shade to the water course (FB/FP); (National Research Council, 1992),

- habitat cover for fish (AS/ FB/ FP); (Sedell & Beschta, 1991),

- migration corridors for birds, mammals, reptiles and amphibians (CB/ AB/ DB/ AS/ FB); (Harper & Ferguson, 1995)

- woody debris for channel and banks (CB/ DB/ AS/ FB/ FP); (Flosi & Reynolds, 1994),

- leaf litter and insects as food for macroinvertebrates and fish (CB/ DB/ AS/ FB/ FP/ TI)); (Merritt & Cummins, 1984), and

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- water quality improvements through pollutant uptake by plant roots and associated micro-organisms (FB/ FP/ Tl/ Tu); (Haycock *et al*, 1997).

Vegetated river corridors can also serve as important linking greenspaces for parks, recreational and amenity uses (Little, 1990). Vegetated riparian zones have been shown to improve water quality, as 'buffer zones' in agricultural watersheds take up nutrients such as nitrate from field runoff into the river (Peterjohn & Correll, 1984, Lowrance *et al*, 1984, Haycock *et al*, 1997). The controversy over guidelines on the width of the riparian buffer zone is reviewed later in this chapter.

Connected riparian corridors within the river catchment are important for:

- sediment deposition, storage and release (Richards, 1982)
- wildlife shelter and food sources (Mason, 1995; RSPB, 1994),
- wildlife migration routes (RSPB, 1994; Stanford & Ward, 1992),
- fish migration, habitat, spawning and rearing (Baltz & Moyle, 1984; Naiman 1992),
- habitat for mammals, reptiles and amphibians (Brode & Bury, 1984),
- habitat for birds (Anderson & Ohmart, 1984; Meents *et al*, 1984,) and
- shelter and food supply for insects or macroinvertebrates (Erman, 1984; Merritt & Cummins, 1994).

The vigour of the riparian plant community is interdependent with and linked to:

- the surface hydrological regime including volume of flow (Petts, 1990),
- flood history (Sigafoos, 1964),
- the range of variation of high- and low-flow discharges (Brookes, 1995, Petts, 1990),
- the sediment transport regime (Hey & Thorne, 1986) and
- the subsurface flow regime (Amoros *et al*, 1987, Kondolf, 1995).

2.2   Effects of floodplain vegetation on geomorphic processes during overbank flow

The effects of vegetation on floodplain hydrology and channel morphology remain poorly understood (Elmore & Beschta, 1988, Gurnell, 1996), although the importance of riparian zones for many geomorphic processes has been widely recognised (Hickin, 1984, Seddell & Froggatt, 1984, Petts, 1990, Thorne, 1990).

Hickin (1984) suggested that the science of fluvial geomorphology was flawed by shifting away from general, qualitative descriptions of river-related landforms towards quantitative analysis of fluvial processes, although such quantitative research has greatly progressed our understanding of river processes. Preceding 1984, the trend in geomorphic research was towards the exclusion from research topics, those processes which did not yield easily to statistical manipulation. The influences of vegetation on fluvial processes are non-linear, and are not easily quantified physically, yet there is growing agreement that floodplain vegetation has significant influence on bank morphology and floodplain fluvial processes (Petts, 1990).

Hickin (1984) suggests five mechanisms by which vegetation influences fluvial processes;

1. flow resistance, (which should include increased local turbulence)
2. bank strength,
3. nucleus for bar sedimentation,
4. formation and collapse of log-jams, and
5. concave- bank bench deposition.

This thesis will discuss all of these concepts except no. 5, concave-bank bench deposition. Topic no.4, formation of woody debris log jams, is an important factor in channel morphology, but is not part of the research focus of this thesis. Discussion of large wood is included because the generation of wood is a logical consequence of riparian revegetation, thus for reasons of sustainability the hydraulic consequences of large wood must be considered as part of the revegetation process.

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Many western American streams have experienced large-scale channel changes such as increase in width/depth ratio, due to historic catchment-scale impacts such as clear-cut logging, roading, agriculture and urbanisation in the recent 150 years (Wahrhaftig *et al*, 1968, Kondolf & Downs, 1996). Many formerly forested floodplains now exhibit persistently bare gravel bars which are resistant to natural plant recruitment, owing to the influx of high sediment loads and hydrologic regimes altered from their historic patterns, for example by groundwater abstraction and increased peak discharge from road runoff (Kondolf & Downs, 1996). Typical hydrological changes leading to the loss of native plant communities and altered topography include an decreased lag time to peak flows (Newson, 1992), which is illustrated in Figure 2.2. As vegetative cover is lost, rainfall runs off instead of being intercepted, which increases the speed of water delivery to the channel. This alteration of the rainfall-runoff relationship typically leads to a wider stream channel, as the channel capacity needed to contain the increased peak runoff is increased (Dunne & Leopold, 1978).
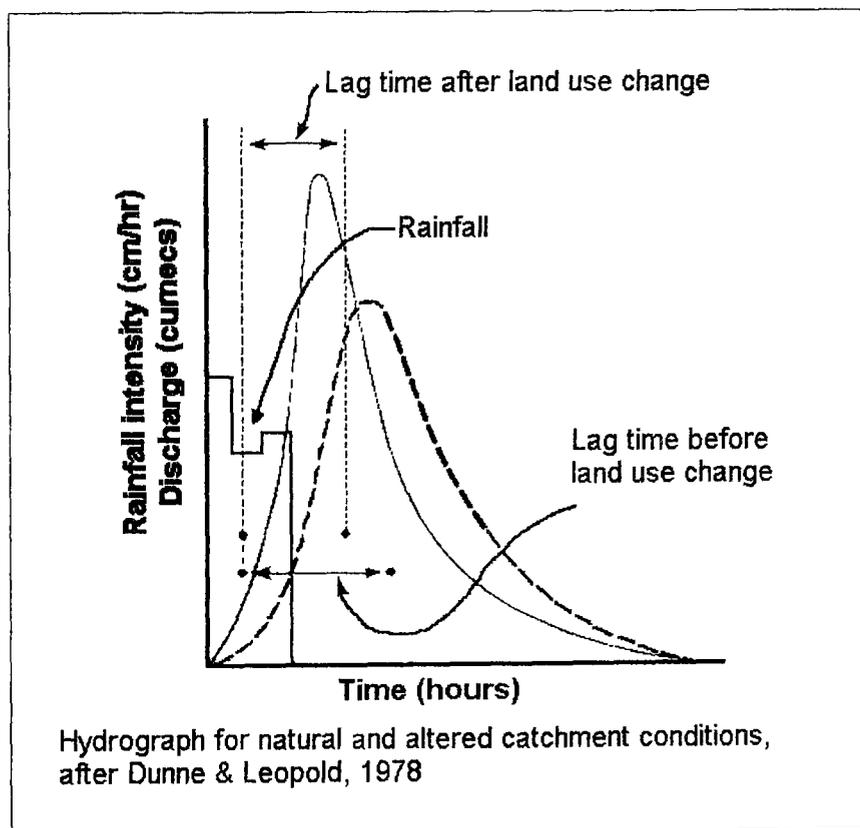
Figure 2.2. Hydrograph showing runoff discharge curves for undisturbed and altered catchment conditions.

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Sigafoos (1964) used botanical evidence to evaluate floodplain history. Sigafoos described methods by which features of woody plants such as scars, growth rings, plant form and orientation, and sediment layers above root tissues can be used to date floods, reconstructed with the hydrologic record, in his study for the Potomac River, USA. Botanical evidence can also be used to locate geomorphic features of floodplains. A sequence of tree growth was given from a single tree established during low flow periods, then flooded to inundation where the top branches were broken off, the tree was pushed over, and subsequently resprouted; these formative processes are reflected in the damage history. Partial burial by sedimentation or sequences of scour and burial can compound the difficulty of correctly interpreting field evidence. In response to overbank flows, the botanical and sedimentological record is complex, especially for floodplains where storage and release of alluvial materials is dynamic. The floodplain, its vegetation and the flow regime are in dynamic equilibrium with each other under 'natural' (non-human-impacted) conditions. Sigafoos suggested that floodplain vegetation may concentrate overbank flows (into small channels, depending on plant spacing), and potentially can increase both the rate of sedimentation and the retention of deposited sediments.

The dominant geomorphic processes modifying a floodplain are determined by the flow regime, the sediment regime and the floodplain roughness (which may include vegetation). Sigafoos noted that forested rivers tend to migrate more slowly than rivers where the floodplains have been cleared by forest practices, agriculture or urbanisation. Although Leopold and Wolman (1957) are cited as reporting that forested river banks are relatively stable because they are composed of cohesive material bound by heavy roots, Sigafoos does not explore the mechanisms whereby trees influence sedimentation or bank stability. This approach to the use of botanical evidence on floodplains may be primarily for the purpose of extending hydrological records either back in time or to ungauged stream reaches. The report gives useful data on riparian plant anatomy, physiology and geo-ecology, which are used in the mapping process to

reconstruct past events (Sigafoos, 1964). This thesis seeks to describe some of the processes involved, to link the physical relationships among plants, geomorphic features and hydrological regime.

2.2.1 Riparian vegetation, overbank sedimentation and scour processes

Sediment deposition in riparian corridors occurs when flow velocity and energy of sediment-laden water is reduced and sediments drop out of suspension (Davis *et al*, 1995). Generally, under conditions of flow, dense vegetation acts as a filter to flowing water, and the boundary layer of the "no-slip condition" is increased in height from the bottom of the water column upwards (for a fuller explanation, see section 3.1 and Figure 3. 1). Variations in vegetation type, spacing among plants, age or life stage and density of stems can have significant influences on actual roughness values for various stage (water elevation) heights (Klingeman & Bradley, 1976). The primary zones of sedimentation from floodwater in the river corridor are considered to be:

1. point bars within the channel,

2. natural levees, typically parallel to the channel, and

3. depressions within the floodplain, such as oxbows, where flood waters collect.

The primary effect of vegetation on sediment trapping is to induce deposition by increasing resistance to flow. Vegetation is most effective at increasing sedimentation of coarse silt to coarse sand fractions in floodwater, since fine silt and clays have long settling times and are readily resuspended by water movement (Gibbs *et al*, 1971).

According to Davis *et al* (1995), silts and clays settle out of still water in depressions where vegetation has little effect other than to minimise wind movement of the water surface. Sediments in surface runoff from adjacent uplands are filtered out through stems, coarse woody debris, and leaf litter as

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surface waters pass through the riparian vegetation buffer (Lowrance *et al*, 1984).

Plant stems present resistance to flow that is proportional to the stem cross-sectional area. In general, the greater the stem size and density, the greater the resistance to flow (Li & Shen, 1973). When vegetation is sparse, plants have little effect on flow velocity, but increasing the density does not necessarily proportionately or uniformly reduce flows (Klingeman & Bradley, 1976). Very dense stems usually result from multi-stemmed woody shrubs, from tussock-forming grasses or other herbaceous species (e.g., reedmace *Typha*, hairgrass *Deschampsia*). These clumped stems often collect organic and mineral matter around their bases, forming dense, raised mounds. Water does not easily flow through these mounds and thus tends to flow around the mounds' surface (Kadlec, 1990). The water flow may be channelled; the cross-sectional area of the flooded area then becomes less than predicted for shallow floods based on stem cross-sectional area alone. Sedimentation thus does not occur uniformly throughout the vegetated floodplain (Davis *et al*, 1995).

Flow patterns around riparian vegetation are also affected by the structural rigidity of the plants (Rahmeyer *et al*, 1996). If stems are uniformly distributed and uniformly rigid, flow velocity is uniformly reduced and sedimentation is evenly distributed. If, however, stems are deformed by flow, erosion and sediment transport may be increased under the bent crowns of the vegetation. Contrasted with grass stems, flexible woody stems increase the depth of the boundary layer for non-submerged flows. These stems may continue to deflect shear forces from the boundary for submerged flows, but this differential in flow resistance is not well understood. (See also Chapter Three, sections 3.1.2 and 3.1.10.)

2.2.2. Floodplain formation processes and vegetative influence on sedimentation

Floodplain form reflects the interdependent interactions between a river and its floodplain (Wolman & Leopold, 1957). The dominant processes involved in floodplain formation are complex, reflecting a continuum of landscape processes. Sediment deposits can reside in long term floodplain storage when the channel migrates away from a floodplain deposition zone (Wolman and Leopold,1957).

According to Davis *et al* (1995), rates of deposition in riparian areas are related to stream gradient, stream power, percent riparian wetland, hydroperiod, and land use. Data from the US Geologic Survey document rates of deposition on floodplains for large eastern US rivers ranging from 0.24 to 3.47 cm/ flood (Wolman & Leopold, 1957). Volume and type of deposition is related to the local resistance to flow, water stage height, flow duration and suspended sediment load. Typically, floodplain sediment depths vary with distance in the longitudinal direction from the headwaters at the catchment scale, and in cross-section across the floodplain by topographic elevation and distance from the channel, with variations in the suspended sediment concentration in flood waters, and in the sediment- hydrological response throughout the year (Davis *et al*, 1995). Dense, flexible plant stems such as turf grasses or sods will induce the greatest sedimentation rates (Hemphill & Bramley, 1989), but can withstand lower velocities than woody stems. Large woody, rigid stems can induce significant scour during floods (Thorne, 1990, Davis *et al*, 1995).

2.3 Vegetation influences on bank erosion

Vegetation, especially plants with flexible stems, influence overbank flows, sedimentation and scour patterns in complex ways. The following research has revealed several aspects of this mediating role of vegetation in bank erosion.

Murgatroyd & Ternan (1983) documented bank erosion rates on an acid moorland stream in Devon, England, which was planted to an exotic coniferous plantation. They showed that shading by mature, exotic spruce trees caused the

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suppression of native grasses and heathers, with attendant loss of the fibrous root network in the cohesive bank soil profile. Loss of the sod cover increased bank erosion rates and channel widening. Their recommendations for Devon forestry programmes planting conifer monoculture plantations included allowance for a grass buffer to reduce sedimentation to downstream reservoirs (Murgatroyd & Ternan, 1983).

In Alberta, Canada, Smith (1976) performed a series of experiments on an anastomosed river, to determine the effect of vegetation roots on bank erosion and sedimentation. Floodplain deposits were primarily silts, and the vegetation type was meadow grass and scrub willow. Using an erosion box containing a sample of vegetated bank material, and erosion pins, Smith made three estimates of bank erosion rates. He measured soil particle loss by weight/unit time for 1) bare silt banks, 2) silts with 16-18% root reinforcement (by volume) and 3) the latter reinforced silt soil with an additional 5cm of surface root matting. Smith found erosion declined by 600 times with the addition of 16% root reinforcement, and by 20,000 times with the addition of the 5cm root mat. These herbaceous and woody roots tend to accumulate over time, and have accumulated floodplain sediments greater than 7m thick, owing in large part to the cold climate in which low bacterial activity does not decay roots easily in the soil matrix. Thus the presence of meadow vegetation is largely responsible for the significant bank stability of this braided silt stream system (Smith, 1976).

Dunaway et al (1994) created 'in-stream flume' conditions to study the combined effects of soil cohesion and plant root interlocking on bank erosion rates, segregating particle erosion processes from mass wasting. Noting that clay soils have the greatest cohesion and lowest root densities, they attempted to sort out the effect of the soil-root combination. A regression analysis study was used to create a soil erosion model. Effects of groundwater level variation were not considered. They found that natural plant communities are not independent of soil type, and percent silt-clay is a strong determinant of the erosion rate. As clay increased, erosion increased, probably for the influence of the clay soil texture to decrease available soil oxygen and thus root growth (Dunaway et al, 1994). This

study highlights the need to consider above-ground hydraulic forces (erosive forces) and below-ground geotechnical processes (erosion resistance) simultaneously in quantifying vegetation effects on river bank processes.

Soil texture, soil moisture and root growth interactions govern survival, stem and leaf growth of plants in general, and for willow in particular (Amarasinghe, 1992). Shields *et al* (1998) identified soil texture and moisture gradients controlling willow (*Salix nigra*) post survival in Mississippi, and found that biomass was greatest for willow post cuttings planted in silty sands at moderate elevations (above groundwater table). Survival was low in sandy gravels at very low elevations, and for sands and gravels at higher elevations. They also found that biomass declined as soil cohesion (clay content) increased (Shields *et al* 1998).

2.3.1 Influence of vegetation on channel form for small streams

Zimmerman *et al* (1967) compared channel width by drainage area for small streams and varying types of vegetative cover in northern Vermont on the Sleepers River basin. On steep granitic catchments for zero and first order streams with dense forest cover, width did not increase in the downstream direction until a threshold occurred at a drainage area of 0.5-2.1 km². Above this threshold, the mean channel width for this drainage area was narrower (averaging 1.5m less) under sod than under forest cover, regardless of the drainage area. Downstream of this threshold, channel width increased in response to increase in discharge, but width variability also increased. A second threshold occurred at 10 –15 km², beyond which the influence of vegetation became increasingly marginal in relation to channel width. The influence of vegetation on geomorphic processes was therefore more pronounced in small stream channels than in larger channels downstream.

Two important components of these effects are extensions of the root network, and formation of organic debris dams. Roots may armour the banks or indeed the channel itself. Channel width increased less under sod than under forest

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geomorphic surfaces and vegetation patterns at reach scale is shown in Figure 2.3.

Conceptual diagram of forested floodplain and geomorphic features

Influence of allogenic processes

General characteristics of natural alluvial corridors. Along large European rivers, these corridors were typically up to 10km wide. From Petts, 1990.
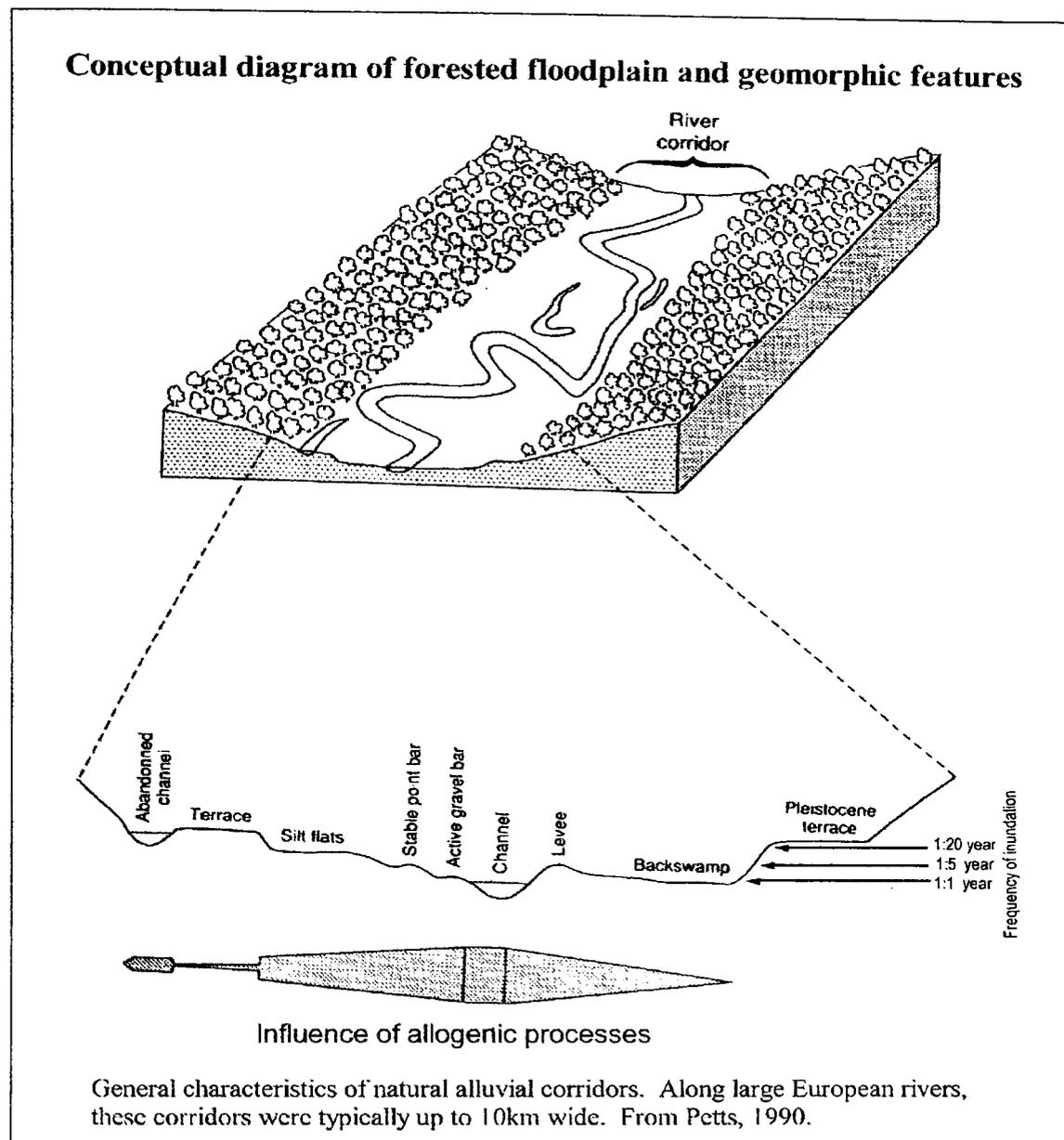
Fig.2.3. Main channel influence on floodplain geomorphic surfaces and floodplain vegetation patterns, from Petts (1990).

This diagram shows the main channel as the dominant force in floodplain formation dynamics, where sufficient stream power is available for the stream to shape its own bed and banks. Stream power is available during overbank flow distributed across the floodplain in diminishing force as the distance from the main channel increases.

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cover, despite differences in drainage area of several square kilometres, and bank material consolidated by a dense grass root network behaved more like cohesive sediment than banks held by tree root networks.

In small streams, vegetation appeared not only to influence channel roughness and the shear strength of the sediment, but also actively to determine the mean and extreme channel dimensions, in particular channel width. However, vegetation influence on bank roughness decreases in the downstream direction; vegetation influence on bank erosion rates has greater variability on larger streams than smaller ones.

2.4   Plant ecological relationships with fluvial geomorphic processes

Numerous studies have examined the relationships among topography, sediment type, groundwater level fluctuations and subsurface drainage, and flow regime in explaining floodplain vegetation ecology and distribution (see for example the work and extensive bibliography in Malanson, 1993). Temperate alluvial forests have been described in geomorphic detail by Everitt, (1968), Swift (1984), Patou & Decamps (1985), and Dister *et al*, (1990). These descriptions are yet to be fully supported by detailed analyses of the processes creating the particular landforms and ecology (Petts, 1990).

At the macro-level, flood history and the catchment sediment transport regime determine floodplain geomorphic surfaces, both relictual and contemporary, which can support varied and complex interactions among the plant communities and geomorphic processes, as described in Petts (1990). At a meso-level, floodplain vegetation develops in response to reach-scale geomorphic conditions, and the condition of vegetation on banks and floodplains in turn influences reach geomorphic processes. These relationships have been described in terms of bank resistance (Thorne, 1990), channel morphology (Zimmerman *et al*, 1967) sediment entrainment thresholds (Davis *et al*, 1995), and sediment deposition patterns (McBride & Strahan, 1984). An idealised set of relationships among

Floodplain plant species are adapted to withstand varying inundation, shear forces, soil moisture regime variation and burial by deposition as a reflection of their preferred floodplain location, with respect to distance from the main channel, as shown in Figure 2.4, after Sparks (1998).

2.4.1 Plant community distribution on a large floodplain river

On natural floodplain rivers, the distribution of plant communities is controlled by variations in topographic surface, depth to groundwater, soil texture and moisture regime, and flood history (Sparks, 1995). Topographic variation in channel and floodplain geomorphic surfaces has been shown to be key to the habitat niches needed for biodiversity conservation in riverine landscapes, as illustrated in Figure 2.4 (Sparks, 1995).

Representative cross-section of the Illinois River- floodplain ecosystem. The floodplain is seasonally inundated and includes permanent and temporary lakes and ponds. Land forms, such as natural levees, sloughs and islands are created by processes of erosion and deposition, primarily during floods. The vertical scale and channel width are exaggerated here; the floodplain is typically 2.5-5km wide along the middle and lower Illinois River. Bluffs are typically 30m high. Main channel occupies only 3-8% of the total floodplain width. From Sparks (1995).

Figure 2.4. Idealised natural topographic variation of the channel-floodplain geomorphic unit, after Sparks, (1995).

Topographic complexity is clearly important to maintain those ecological niches needed for the floodplain forest complex.

Temperate floodplain plant communities across the northern temperate zone have a remarkable similarity in genera (the taxonomic level above species), especially for the dominant tree and shrub genera, while, as an ecosystem, showing high

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diversity in plant species and in faunal composition (Harper & Ferguson, 1995).
Numerous studies have shown that distinct plant community associations are
found on specific geomorphic landforms, and these associations may be found no
where else (Osterkamp & Hupp, 1984). Plant community structure is strongly
influenced by flood hydraulics (Petts, 1990, Sparks, 1995). Recovery from flood
damage depends on available propagules from upstream sources, so the
longitudinal continuity of plant communities along a river corridor is a key factor
in natural recruitment or re-establishment of plant species populations and
subsequent plant succession.

An idealized diagram of temperate floodplains, Figure 2.5 illustrates the
succession of riparian to floodplain forest species.
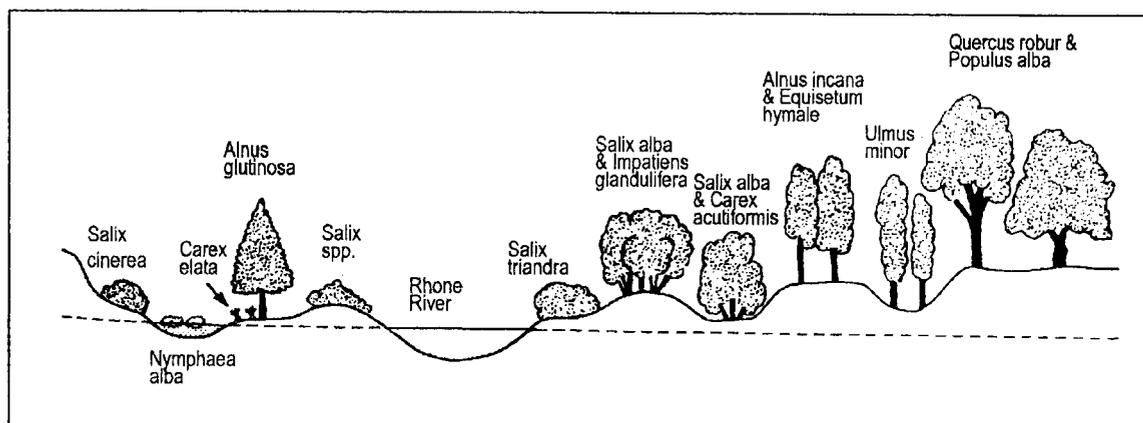
*Figure 2.5. Generalized cross-section across the Rhone alluvial corridor,
France, showing topographic variation of the floodplain in relation to
groundwater levels, after Pautou & Decamps, (1985).*

Everitt (1968) dated the ages of floodplain forest by coring trees on various
geomorphic surfaces, and found that *Populus* showed growth classes in even-
aged narrow stands; thus the unmanaged floodplain forest is a living record of
channel migration across the floodplain. This reflects the germination
requirements of *Populus*, which include seed contact with fresh mineral soil under
high light conditions, with relatively constant moisture and only a gradual draw-
down of subsurface moisture supply (Bradley & Smith, 1986, Friedman. 1993).
These conditions typically occur for a short time in late spring after seedset, after
spring floods in the Midwest and western north America, in relatively narrow

bands along alluvial features of riparian corridors, shown in Figure 2.6.
Sequential bands of willow and cottonwood seedling establishment events follow
meander migration across the floodplain, and play a role in floodplain formation
geomorphic processes.
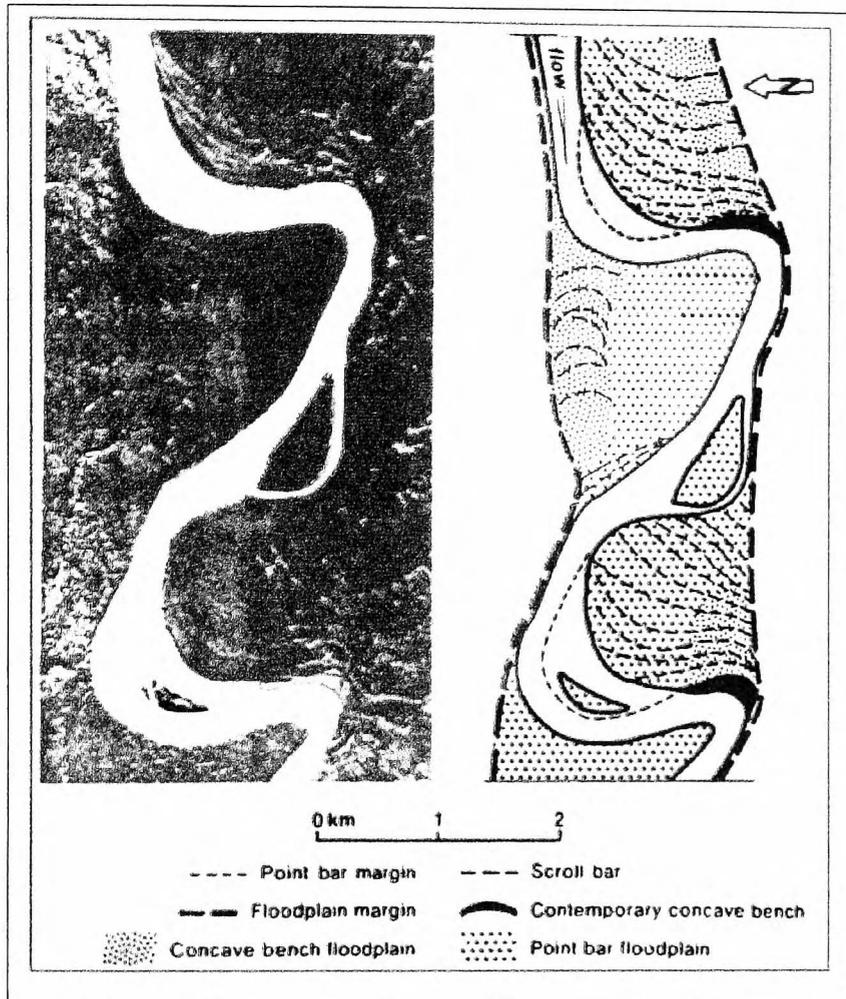
Figure 2.6. Arcuate bands of floodplain trees showing meander history, age classes and floodplain development (Gurnell, 1995).

Shading is a major factor in plant community succession, well documented in
plant ecological and forestry literature (Botkin, 1990). Pioneer species such as
sandbar willow *Salix exigua* require full sun to germinate and mature (Soil
Conservation Service, 1993) stabilising sediments on point bars. Over time, these
landforms become the germination substrate for secondary species such as oaks
Quercus, (many spp.), California bay laurel *Umbellularia californica*, or other
floodplain trees. Plant succession typically drives a temporal process whereby

pioneer *Salix* species are replaced over time with other genera whose seedlings are shade-tolerant (Botkin, 1990).

2.4.2   Natural plant recruitment processes on floodplains

Bradley and Smith (1986) observed two populations of Plains cottonwood (*Populus deltoides var. occidentalis*) on the Milk River, Alberta and Montana, for age, distribution and density on river meander lobes and mid-channel island margins. They observed patterns of cottonwood seedling recruitment and floodplain distributions upstream and downstream of Fresno Dam, Montana. Bands of cottonwood trees could be found in arcuate curves, reflecting germination on the fresh substrate of point bars on an actively migrating channel (as in Figure 2.6). Their research showed that, in Alberta, seedlings survive on point bars at the time of year when the daily maximum flows attained a stage equal to or greater than the 2-year return flood, based on the annual flood series, during the period of seed dispersal, June 1-July 10.

Below the dam in Montana, flow regulation reduced flow magnitude and frequency, as well as the suspended sediment transport rate, sedimentation on point bars and rates of meander migration. There cottonwood seedling survival was greatly diminished for at least 25km downstream. A critical elevation on point bars was identified where seedling roots can maintain contact with falling groundwater levels, and they avoid scour or inundation by subsequent flows. This elevation was observed at 0.5-0.8m above mean river level. Salicaceous seedlings (*Populus* and *Salix*) can withstand up to 1.5m sediment aggradation in the first ten years of growth, with an average of 0.16m/year observed (Bradley & Smith, 1985).

McBride and Strahan (1984) documented vegetation-geomorphic interactions on an intermittent stream in northern California, and showed relationships between sediment particle size and tree species for naturally recruited vegetation. Strong links to successful tree seedling germination have been identified by several authors among the following factors;

- distance from the active channel,

- location in the channel planform,
- sediment particle size and
- depth to groundwater.

Active bank features such as riffle bars are sufficiently mobile to inhibit the development of successional stages beyond the early pioneer stage, preventing trees from becoming established on these geomorphic features. Sapling stands established on point bars often captured coarse sediments on the upstream end of the stand, with sediments becoming finer in the downstream direction. The increasing height of the bars, created iteratively by sapling growth, inundation and resulting sedimentation, contributes to the trapping of finer-sized particles, leading to more favourable soil moisture development for plant growth, and the subsequent germination and establishment of other riparian species (Bellah & Hulbert, 1974). This process clearly influences channel and floodplain morphological evolution.

Early seral (pioneer) stage plants with high requirements for sunlight such as *Salix* species are typically shaded out by alder and poplar saplings which grow in the resulting fine sediment around willows (McBride & Strahan, 1984). These can be replaced or succeeded by walnut, box elder, bay and oak on more mesic terraces. Distinct patterns of floodplain forest types with significant variations were observed on Dry Creek during this study on banks, terraces and swales. Floodplain forest is a diverse, highly dynamic plant community type because of the tendency of the channel to migrate across its floodplain (McBride & Strahan, 1984). These plant ecological dynamics reflect variations in discharge, groundwater regime and the sediment transport regime of the river and its catchment system.

Natural vegetation recruitment on northern California streams has been slow in recent decades (Lisle, 1989), but the 'narrow ribbon' type of riparian tree establishment became a common feature of many West Coast USA streams during the drought of 1987-92 (Brown, 1993).

The relationships between flooding, seed germination and establishment for black poplar, a member of the willow family, is described by Bradley and Smith, (1986), and by Fenner *et al*, (1985); where regulation of flow regime by damming had a significant negative effect on seedling survival and few freshly deposited sediments were made available post-flood. Seeds of the willow family Salicaceae typically are small, wind or water dispersed 'fluffy' seeds with little endosperm and a short period of seed viability. Seeds of Salicaceous species require moist mineral soils with sufficient drainage to permit oxygen exchange with root hairs; the conditions typical of sandy or gravelly point bars and floodplain terraces following spate or flood events (McBride & Strahan, 1984). Research indicates that willow and poplar seed germination, and indeed riparian genera generally are sensitive to alterations of the hydrologic regime (Malanson, 1993). Seedling survival to the sapling stage is strongly influenced by the depth, duration and frequency of subsequent flows, and seedlings are easily scoured from alluvial sediments below the stage height of the annual or greater flood (Fenner *et al*, 1985).

On largely unmanaged floodplains, a wide range of diverse plant and animal species occur, often in distinct microhabitat niches (Dister *et al*, 1988). (See Figure 2.5). Small scale variations in topography, groundwater level and sediment type can have pronounced effects on root zone aeration, a factor which drives plant succession. Remnant geomorphic surfaces reflecting sediment deposition history may support distinctive plant species assemblages, and survival rates are often controlled by the frequency of inundation on a given surface (Pautou & Decamps, 1985). Thus any alteration in hydrologic regime is likely to have profound effects on downstream vegetation patterns.

Seed dispersal mechanisms are another factor in riparian plant species distribution, which may include water, wind, rodents or birds, or mammals (Gurnell, 1995). This concept, called dispersal spectra or assemblage of dispersal types, suggests that coexistence of species may be due to their sharing of dispersal traits rather than to other traits such as physiological tolerances or requirements (Malanson, 1993). Riparian corridors function as active conduits

for the movement of many species, such as *Salix* seeds and salmonids, or more passively for animal migration routes (Malanson, 1993). Forman and Godron (1986) identified width of the corridor as the most important feature for species dynamics, but connectivity between channel and floodplain, sinuosity and network pattern also play a role. Wildlife habitat usage patterns are complex, and linkages between valley and upslope are important for many species.

Studies of plant establishment on wetlands in the Willamette Valley, Oregon have demonstrated that, in addition to the physical parameters driving plant community succession such as flow and sediment transport regime, interactions among plant and animal species are important in native plant establishment and survival (Davis *et al*, 1995). Examples of interactions among beaver and riparian trees are simple illustrations of this principle.

The natural range of variation of flow regime has been demonstrated to be a controlling factor in riparian plant community establishment and development (Petts, 1990, Malanson, 1993, Gurnell, 1995). On regulated rivers and streams, flow regime variation (or lack of it) is an important factor to consider in interpreting plant species distribution and plant community structure. The flood pulse concept has been shown to describe well the periodic nature of extreme events and their importance to both physical and ecological functions of the floodplain ecosystem (Junk *et al*, 1989).

2.4.3 Effects of flooding on floodplain forest ecology

The flood pulse is a major force shaping geomorphic features in floodplains of large rivers (Junk *et al*, 1989, Bayley, 1995). Flow regulation eliminates these flood pulses, minimising flood peaks, reducing sediment available to transport and the stream power needed to transport sediments downstream (Newson, 1992). The loss of flood pulses owing to river regulation has been shown to have profound impacts on the structure and function of riparian and floodplain forest ecosystems (Molles *et al*, 1998, Petts, 1990).

On the Rio Grande in New Mexico, floodplains cut off from flooding for 50 years were identified as supporting senescent forest structure by the high volumes of organic debris on the forest floor, and the invasion of exotic woody species such as *Tamarisk* (Molles *et al*, 1998). 10ha of floodplain were experimentally flooded over three seasons simulating the historic flood regime, and the forests were monitored for biological, physical and geochemical responses. Molles *et al* (1998) developed a model for testing theories of floodplain ecosystem restoration, using patterns of ecosystem reorganisation. They developed a model in which three phases were identified in the restoration-by-flooding process:

Phase One	Initial disconnected state	Low nutrient cycling	Declining biological productivity
Phase Two	Reorganization in response to flooding	High, rapid rate of nutrient cycling	Disturbance followed by rise in biological productivity
Phase Three	Steady-state	Moderate level of nutrient cycling	Highly productive native community, high connectivity

After Molles et al (1998)

Molles' work examined the stimulation of productivity through biochemical pathways, and showed that below-ground biomass and productivity were greatly stimulated by flooding. As different groups of organisms 'recover' through the phase two reorganisation period at different rates, the timing of flood frequency (months to years) will 'restore' biological groups at different rates (Molles *et al*, 1998). These differential recovery periods will be a subject of much riparian research in the coming decade, and the results will help to manage public expectations of riparian 'restoration' efforts.

Plant communities become established on landscape surfaces created by geomorphic processes (Hughes, 1997), and the resulting plant communities in turn influence the fluvial dynamics of those surfaces (Gurnell, 1995). Describing the evolution of mid-channel bars, Hooke (1986) demonstrated that the typical

herbaceous vegetation which germinates on these bars increases the deposition of fine sediments on these features.

Variation in discharge is closely related to the variation in channel and floodplain morphology, as suites of organisms are adapted to a range of inundation preferences. The variability of morphological features is key to the biodiversity of floodplains. However, the question of the role of vegetation in development of this variability remains uncertain, particularly related to the balance of forces influencing erosion, transport and deposition at micro, meso and macro scales. Gurnell (1995) reviewed a substantial body of literature describing landforms and hydro-geomorphic processes at the scales of hillslope – floodplain types and their vegetation, hydrological regime relations among topography, soil moisture and water table, flooding disturbance and vegetation response, and fluvial geomorphological disturbances, river bank(form and process), river planform change with associated vegetation and floodplain landforms.

2.4.4 Influence of groundwater regime

Many studies have shown that the variation in the groundwater regime has a strong controlling influence on plant establishment and survival (Kondolf & Curry, 1984, Patou & DeCamps, 1985, Gurnell, 1995, Kondolf, 1995). Gurnell (1995) reviewed extant literature documenting effects of groundwater regime on plant species distribution and plant community structure in riparian corridors and floodplains for many environments. She showed that in headwater streams, flooding disturbance and hillslope geomorphic processes are often more important for defining the riparian character than simple topographic moisture gradients.

Groundwater abstraction had significant impacts on riparian vegetation die-off on the Carmel Valley, California, which resulted in increased rates of bank erosion in the vicinity of wells (Kondolf & Curry, 1984). The authors reported that groundwater draw-down to 10m depth moved the water table below the root

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zone of riparian willows on this alluvial river, with resulting decline and death of riparian trees.

Patou & Decamps (1985) reviewed European research on alluvial forest ecosystems related to the presence of the watertable. Extensive data collection on the Upper Rhone River documented relations between plant community type, floodplain topography, soil type and depth to groundwater, showing heterogeneity to be a primary feature of floodplain forests on a gradient from semi-aquatic wet meadow to streamside forest to transitional floodplain forest to upland hardwood forest. Patou & Decamps (1985) note that the water table contribution to vegetation depends on a number of variables; average depth, amplitude of fluctuation, vertical grain size distribution of the various (topographic) levels, existence of discontinuities (sandy or clay layers), and the density and penetration of the fine root fibres into the soil matrix. Thus groundwater elevation and seasonal fluctuations are primary factors in floodplain plant ecology, but these influences are modified by other factors such as soil moisture regime, soil texture, topographic elevation and anthropogenic activities.

2.4.5   Riparian woody species and mycorrhizal fungi

Root-fungal associations have significant implications for the existence and function of floodplain vegetation in mediating flows and sediment transport. The soil rhizosphere is that matrix of mineral particles aggregated with organic matter, fungi, bacteria and other micro-organisms, which is capable of supporting plant life.

Of particular interest to the new science of ecological restoration is the role of mycorrhizal fungi in plant response to stress and nutrient requirements (Ingham & Molina, 1991). Once thought not to be significant in wetland and riparian ecosystems, mycorrhizal fungi have now been shown to affect both obligate and facultative wetland plant hosts, especially during periods of drought, predation or nutrient loss. There may yet be greater significance for the roles of mycorrhizae in the plant ecology of floodplain ecosystems. These roles could include the

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enhanced ability of plant, especially woody, roots to bind alluvial sediments into soil particles, for example in increasing cohesion and shear resistance of bank sediments, reducing bank soil erodibility (Thorne *et al*, 1998). In hillslope forests, the component of soil fungi has been shown to be critical in the establishment and survival of tree species (Perry & Amaranthus, 1990). For floodplain forests such as the Mattole estuary (and many thousands of miles of western American streams) where soils have been eroded and lost, natural recruitment of forest cover has, in many places, been severely compromised. One potential source of assistance in recovering this plant community is in identification and cultivation of the soil micro-floral associations without which seedlings have poor survival and establishment (Perry & Amaranthus, 1990).

Watling (1992), examined fungal relationships for British willow species for arborescent, shrub, alpine prostrate and herbaceous *Salix*. Mycorrhizal fungi are grouped as endo- (internal), ecto- (external) mycorrhizae, or vescicular-arbuscular mycorrhizae (VAM). Many ecto-mycorrhizal fungal species are commonly recognisable mushrooms, for example *Russula, Lactaria,* and *Boletus* species (Allen, 1991).

Fungal genera are commonly grouped as suspected (or known) mycorrhizal species, parasitic taxa (those which derive energy from a host without benefit to the host) and saprotrophs (those fungi which derive their energy from the decomposition of dead plant tissues). Recent research has indicated that saprophytic fungal growth on woody plants often follows decay of wood tissues, (by saprophytes) rather than causing it, especially in mechanical wounds and tissues killed by changes in water regime (Arora, 1986). Mycorrhizal fungi are often associated with habitats rather than distinct tree species, but some *Salix* species are associated only with specific fungal genera and species (Watling, 1992). The frequency and variation of infection seems to be highly variable in many plant species; some plants are said to be facultative (non-obligate) in their relation to a fungal partner.

The riparian tree species of *Populus, Salix* and *Alnus* can be either ecto-mycorrhizal or VAM infected (Fitter, 1989). Mycorrhizae assist plants in uptake of nutrients, especially phosphorus, but several studies have found infection rates of ecto-mycorrhizae to be generally low in acidic wetlands (Fitter, 1989). Willows on Michigan peat wetlands were shown to be ecto-mycorrhizal, and the addition of phosphorus increased infection intensity on willow roots for both wet and mesic sites up to a threshold for P saturation beyond which infection declined (Marshall & Pattullo, 1981). Infected roots may have low biomass, reflecting that several functions of roots may be subsumed by the fungal partner (Fitter, 1989).

Plants appear to vary in their need for (or benefit from) mycorrhizal infection, perhaps by season, such as when, during flowering or fruiting, demand for phosphorus increases, infection rates may increase (Fitter, 1989). Seedlings appear to be infected more often than mature plants.

Inoculation of roots by mycorrhizal spores in alluvial soils depends on availability of source spore material as well as suitable environmental conditions. Because floodplain alluvium is often highly mobile sediment, inoculation of new trees and their roots could be delayed where few trees have become established. These root associations are likely to be significant in the development of floodplain soils where vegetation plays an influential role in stabilising alluvial bank sediments, such as the glacier river conditions described by Smith (1976). The presence of mycorrhizae on roots extends root penetration into the sediment matrix, and increases soil particle cohesion by exudation of sticky polysaccharides and carbohydrates to aggregate particles into peds or clods of soil (St. John, 1990).

The presence of inoculum is a critical determinant in re-establishment of the rhizosphere (Perry & Amaranthus, 1990). More research is needed to identify the organisms which can assist floodplain soil development, and whether and how mycorrhizae and other micro-flora can be used to assist the floodplain revegetation processes.

As greater areas in floodplain forest are recovered to native vegetation, the ability of these streamside woodlands to capture sediments during overbank flows will increase. Greater stability of floodplain sediments owing to the presence of woody vegetation would encourage development of soil horizons and greater biological activity within those young soils; increased area in tree cover would provide more fungal refugia for spores which can inoculate new trees, shrubs and grasses. This reciprocal relationship represents a feedback loop which is easily set back under current, deforested conditions. Great potential exists to encourage the development of native plant communities on alluvial rivers using locally native mycorrhizal inoculum from neighbouring well-forested areas. Use of mycorrhizae on roots of nursery stock has been demonstrated to be effective in increasing survival and growth of container-grown native plants used to re-establish native plant community processes (St. John, 1990).

2.5   Effects of large woody debris on river channel morphology and processes

At meso and macro scales, both living and dead wood play important roles in landscape ecology, contributing a large part of the river's carbon cycle supporting the trophic web (Harmon *et al*, 1986). Much evidence exists to demonstrate that, prior to the Industrial Revolution, floodplains on larger rivers were extensive networks of channels and were either heavily forested or vegetated with trees, shrubs, grasses and other wetland species (Petts, 1990). Large downed tree snags in channels have been recognised as having important contributions to inchannel processes (Hickin, 1984, Keller & Tally, 1979), to channel stability (Keller & MacDonald, 1995, Wallerstein, 1999), and to many ecological and geomorphic processes (Harmon *et al* 1986, Gregory, 1990). Large volumes of coarse woody debris (CWD) have been removed from river channels after the invention of the internal combustion engine, documented by Seddell & Frogatt, (1984) for the Willamette River, Oregon, for the Rhine River by Dister *et al*, (1990), and for the Mississippi by numerous authors, especially Shields &

Nunnally (1985). Geomorphic consequences of organic 'debris' removal were documented by Gregory (1990).

Gippel *et al* (1995) developed a classification for debris jam types, used to predict debris jam formation and hydraulic criteria for jam stability. Debris jam patterns found on natural rivers were modelled in the flume to determine debris drag coefficients and their effect on water stage elevation or afflux. Debris alignment was found to be a significant factor in the hydraulic drag induced by the jam; spacing is important as is the percent blockage of the channel. Wake interference acts to reduce the hydraulic effect of debris so that, if spaced within two diameters, multiple in-line items of debris have no more effect on afflux than single items (Gippel *et al*, 1995). Shields and Gippel developed a method for calculating the drag and roughness factors for debris dams on river channels, to demonstrate the effects of dam removal on decreasing flow resistance (Shields & Gippel, 1995). Significant progress has thus been made on understanding the effects of woody debris on hydraulic performance under natural river conditions; preliminary guidelines now exist to assist river managers in integrating large wood structures into river management practices.

Geomorphic and hydraulic effects of coarse or large woody debris (C/LWD), or more simply "large wood", are important influences on channel and floodplain-forming processes, linking the terrestrial ecosystem with the aquatic ecosystem (Harmon *et al* 1986, Gregory, 1990). Large wood is especially significant on alluvial streams and sand-bed rivers where few hard points exist to provide strong controls on channel morphology (Wallerstein, 1999). Forested streams and rivers revegetated with trees will eventually produce significant amounts of large wood, so that the longer-term effects of dead wood is an important consideration in the revegetation process.

Trapping of large wood on floodplains by floodplain roughness elements such as live and dead trees can be beneficial to many wildlife habitats, both as shelter sites and for food and carbon sources. Floodplain and river channel large wood increases channel stability, and increasingly has been shown to be perhaps the

most significant structural elements for channel stability in both cohesive and alluvial streams (Harmon *et al*, 1986, Gregory, 1990). Large wood can decrease channel flood capacity for constricted channels in urban areas, unacceptably increasing flood risk unless greater area of floodplain is made available for floodwater occupation. This is true for all scales, physical and temporal; the recruitment of large wood and the interactions of large wood in channels and on banks is a significant factor over a range of time periods in the recovery strategy for streamside forests. However, it is likely that emphasis on planning at a catchment (watershed) scale is needed to incorporate this element of the revegetation strategy, which may not be so favoured at the reach or site scale.

2.6 Floodplain classification according to energy regime

An appropriate classification of floodplains, like river channel classification schemes, may be helpful in identifying the dominant processes driving geomorphic formation and change. Such an approach can be very informative in clarifying the geomorphic regime potentially being considered for riverine or floodplain rehabilitation, in the absence of which serious errors of judgement can be made based on incorrect understanding of large-scale processes.

A genetic floodplain classification system has been devised by Nanson & Croke (1992), based on energy conditions, sediment regime and geomorphological features. The term 'genetic' refers to an approach which emphasises the dominant, contemporary processes by which the landforms originate or have their genesis, including the range of variation in the climatic regime.

Connectivity between the river, the riparian corridor and the floodplain is illustrated below:

> An alluvial channel adjusts its hydraulic geometry and builds a surrounding floodplain in such a way as to produce a stable conduit for the transport of water and sediment. The active boundary of the channel is usually where the floodplain is being constructed or eroded, although during large floods this activity can extend across much of the floodplain surface. (Nanson & Croke, 1992, p.459.)

In this classification, floodplains are divided into non-cohesive and cohesive classes, with high and medium energy subclasses for non-cohesive systems, and low-energy subclass for cohesive floodplains. In relating form to process, the erosive power of the stream is related to resistance by the primary parameter shear stress. Unfortunately, few floodplain studies provide sufficient hydraulic data (notably flow depth or hydraulic radius of flow on the floodplain during flood flows) from which to calculate shear stresses across the floodplain.

Many more studies provide slope and discharge data from which gross stream power can be computed, the parameter defined by Bagnold (1966) as:

$$\Omega = \gamma Q S \qquad\qquad\qquad Eq. 2.1$$

where γ is the specific weight of water, Q is the discharge and S is the channel slope.

While gross stream power is a useful measure of the total energy and total work done by the river at any point along its length, it is power per unit of the channel wetted perimeter (channel width) which is diagnostic of the power available to erode and construct individual landforms.

Termed 'specific stream power' by Bull, (1979), this is defined as:

$$\varpi = \Omega / W \qquad\qquad\qquad Eq.2.2$$

where W is the average width.

These equations are intended to give average estimates of energy conditions of the stream from regional data, rather than to predict erosive force at a specific location on the stream. However, according to Brookes (1988), there is a threshold of 30watts m^{-1} above which lowland rivers become unstable.

Erosional resistance is measured in Nanson & Croke by distribution of sediment size. Vegetation parameters are not accounted for in floodplain resistance factors, a factor not uncommonly overlooked in traditional fluvial geomorphic studies (note, for example, the lack of mention of vegetation hydraulic parameters by Dunne & Leopold, 1978).

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Dominant floodplain depositional processes involved in accumulation or accretion of surfaces include;

1) lateral point-bar accretion,
2) overbank vertical deposits,
3) braid-channel deposits accreting from channel migration on previously active braid bars and river bed,
4) oblique accretion or inner accretionary bank deposits,
5) counterpoint accretion (formed of suspended sediments and organic matter in the within channel bench on the upstream limb of the convex bank of tightly curving bends) and
6) abandoned-channel accretion.

Floodplain classification systems, such as the Nanson & Croke model, can be helpful in identifying dominant processes driving the system, as an aid to the recovery of landscape scale ecological and geomorphic processes. Without such a framework or the use of a threshold value for ω, assessment of the hydraulic and geomorphic conditions of the floodplain can be a matter of guesswork, a higher-risk undertaking when prioritising river rehabilitation efforts.

2.7   Anthropogenic influences on floodplain plant communities

Less amenable to predictive modelling is the influence of human activity on the riparian and floodplain vegetation distribution. Such influences as catchment-scale land use change, clear-cut logging, road construction, slash burning, extensive grazing and arable agriculture can significantly affect rainfall infiltration, absorption, runoff, soil erodibility and the catchment sediment yield (Dunne & Leopold, 1978, Mattole Restoration Council, 1995). Smaller scale influences may include reach or site level removal of riparian vegetation and the introduction of grazing herbivores such as cattle and sheep (over 1000 references on this subject; see USFS Riparian Bibliography, Markuch, 1993). Research into the cumulative effects of land use change and the resulting change in sediment and runoff response may be very helpful for catchment (watershed) planning in identifying impacts to the river and floodplain corridor, and in identifying relevant responses for land and river management practices (Reid, 1993). A great deal of

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research has gone into this subject of interrelated processes at the watershed or catchment scale in the recent decade, some of which is summarised by Naiman (1992). The journal Regulated Rivers, in publication since 1984, is devoted to documenting anthropogenic influences on rivers and fluvial ecology and their remediation.

Although many river rehabilitation researchers and practitioners have now recognised the ecological and geomorphic need for and benefits of riparian and floodplain vegetation recovery (Petts, 1990, Malanson, 1993, Flosi & Reynolds, 1994), appropriate methods leading to effective recovery and the management consequences of such revegetation are still not well understood.

In some rural areas owned by the USDI Bureau of Land Management (BLM), the BLM has adopted a policy of reducing grazing pressure to assist vegetation recovery, with programs in some areas implementing modest structural measures such as fencing of riparian areas (http://www.blm.gov/riparian, 1998). Enforcing such policy changes has often been challenged politically, and heated debates take place every year in the Western States over grazing rights and grazing fees, while feral cows regularly invade wilderness zones and other public lands in excess of the official levels of animal use months (AUMs) (Ferguson, 1983).

In the UK, grazing animals are sometimes used to reduce weed growth in channels and along river banks, while farmers often manage the timing and intensity of grazing on grass-lined river corridors. Limited cattle 'poaching' or trampling or banks of engineered channels is considered to be potentially beneficial to wildlife, creating habitat diversity (RSPB, 1994). Animal stocking is preferred after July following the bird nesting season, and efforts are made on conservation areas to prevent overgrazing degradation of wildlife habitat (RSPB, 1994). Tree growth along river banks and floodplains is very limited along UK rivers and streams; typically a narrow fringe of trees may be permitted along one side of a stream to maintain access on the other side of the river for river maintenance operations such as dredging (Holmes, 1994). However, more liberal regimes have been exercised, recognising that a 15-20 year return period for

dredging allows willow and alder to be readily removed for desilting, in the knowledge that regrowth will be rapid (Gardiner, pers. comm, 1999).

Such 'external variables' as grazing animals, vandalism, drought, unpermitted or poorly planned development, often compound the complexities of working to revegetate streambanks under field conditions. Typically, only some of these impacts can be anticipated. Fencing may be cost effective when used as a precautionary measure, when the option of controlling animal movement or removing the animals is unavailable. Where cattle cannot be prevented from grazing along streams, fencing can sometimes be a critical element to determine the success or failure of riparian vegetation recovery.

In more populated areas, high demands are made on riparian areas, and revegetation strategies often face substantial obstacles in implementation. Increasingly, riparian revegetation will be integrated into river engineering and management practices for multiple purposes, such as for water quality (Lowrance *et al*, 1984), bank protection, (Thorne *et al*, 1998), fishery habitat (Sedell & Beschta 1991), erosion control (Schultz *et al* 1994), and flood defence within a catchment context (Gardiner, 1995a, Philip Williams & Associates, 1996).

Greater understanding of the influence of woody vegetation on fluvial processes enables land managers better to utilise forest and herbaceous vegetation on stream banks (Elmore & Beschta, 1988). Riparian vegetation management is being incorporated into integrated river system management, allowing for human settlement, human interaction with the floodplain, and the conservation of fish populations and other, increasingly pressing biodiversity and landscape preservation needs (Gardiner, 1991). In the 1990s, both the US Army Corps of Engineers and the UK Environment Agency have called for control of development in the floodplain as a primary strategy for flood hazard management (IFMRC, 1994, Environment Agency, 1997).

Floodplain management and development control are necessary precursors, especially in urban or developing areas, for the change in both philosophy and practice of river management needed to enable inclusion of geomorphological and

ecological criteria, and to make possible affordable flood hazard protection for urban areas (Dister *et al*, 1990, Gardiner, 1994, PWA, 1996, Okuma, 1997). The role of floodplain management planning is changing the management and perceptions of flood impacts (Penning-Rowsell & Tunstall, 1996).

STRATEGIES AND TOOLS FOR FLOODPLAIN MANAGEMENT

Strategy A. Modify Susceptibility to Flood Damage and Disruption
1. Floodplain Regulations
2. Development and Redevelopment Policies
3. Disaster Preparedness
4. Disaster Assistance
5. Floodproofing
6. Flood Forecasting and Warning Systems and Emergency Plans

Strategy B. Modify Flooding
1. Dams and Reservoirs
2. Dikes, Levees and Floodwalls
3. Channel Alterations
4. High Flow Diversions
5. Land Treatment Measures
6. On-site Detention Measures

Strategy C. Modify the Impact of Flooding on Individuals and the Community Information and Education
1. Flood Insurance
2. Tax Adjustments
3. Flood Emergency Measures
4. Post-flood Recovery

Strategy D. Restore and Preserve the Natural and Cultural Resources of Floodplains
1. Floodplain, Wetland, Coastal Barrier Resources Regulations
2. Development and Redevelopment Policies
3. Information and Education
4. Tax Adjustments
5. Administrative Measures

From the "Galloway Report"
Interagency Floodplain Management Review Committee, (1994).

Table. 2.1. Strategies and tools for floodplain management, from the USA.

This concept is well expressed in the modern German approach to river management in the phrase "Mehr Raum für die Natur", meaning "More room for Nature" (Binder *et al*, 1994). This approach provides guidance to allow for a wider river corridor in order to integrate geomorphological functions and ecological benefits into river management (Binder *et al*, 1994, Wasserwirtshaft in Bayern, 1990). The design of new channels which include vegetation need to take into account the racking of debris on trees during flood events, and allowance for the increased roughness and backwater effects caused thereby. In practical terms, land use must be planned and co-ordinated to allow a wider, unobstructed river corridor, connected longitudinally, which permits transport of storm water, sediment, debris and the migration of fish and wildlife. This strategy for river engineering is essential for the multiple functions and benefits of riparian vegetation to be achieved in modern river management.

Progressive though these developments are in the USA, the UK and Europe, tangible recognition of catchment influences on flood risk management has yet to emerge in policy-making among major organisations responsible for flood defence or so-called "flood control" in America. Floodplain management and flood risk management depend on co-ordination within a catchment context to achieve effectiveness (Gardiner, 1996), because reach-scale benefits may be overwhelmed by cumulative effects and processes (Reid, 1993) within the catchment. Within the wider (and longer) river corridor, many more options become possible for reconnection of the stream channel to the floodplain. Integrated catchment planning and management, as the way forward, needs the support of the local community as well as policy and legislation (Gardiner, 1997, Young, 1997).

2.8   The role of 'buffer zones'

The increasingly popular concept of "buffer zones" along riparian banks addresses the appropriate use of trees, shrubs, grasses and emergent vegetation for multiple benefits, especially improvement of water quality through retention

of nutrients and sediment within the buffer zone (Haycock, *et al*, 1997). Buffer zones and buffer strips are coming into greater application within agricultural areas in the USA and Europe. One such example was developed at Iowa State University for use in the Midwest, called the Multi-Species Riparian Buffer Strip (MSRBS) system (Figure 2.7). These buffer zones offer potentially significant reduction of nutrient and sediment pollution from agricultural fields to streams (Schultz *et al*, 1994).

Multi-species Riparian Buffer Strip
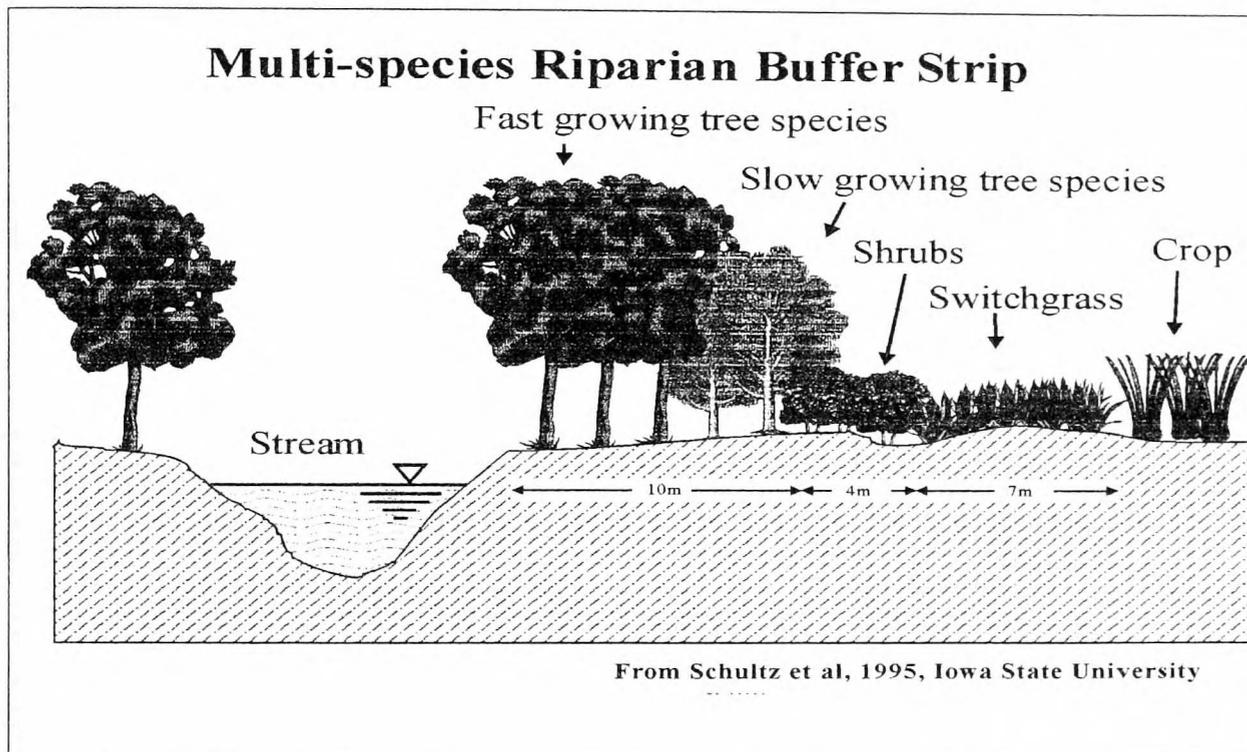
Figure 2.7. The Multi-Species Riparian Buffer Strip (MSRBS) system for agricultural land uses, from Schultz et al (1994).

In the MSRBS agricultural model, three zones between the stream and the crop field are defined, with minimum widths at 10m for zone 1 containing trees, zone 2 at 4m. minimum width containing shrubs, and zone 3 at 7m. a zone of grasses for ease of maintenance. Widths are varied based on site conditions and constraints, but the goal is a buffer of approximately 21m on each side of the stream. Longer term functions of the buffer for sediment retention, and maintenance criteria of the MSRBS system are still in the developmental stage (Schultz *et al*, 1994).

Buffer systems in MSRBS are designed on a site-by-site basis for multiple criteria, including sediment filtration and retention, nutrient and chemical

processing, streambank stability, enhanced instream environment, wildlife habitat, water storage and groundwater recharge. To reduce nitrogen effectively in surface and ground water, plant roots must be in contact with high water tables or sufficient unsaturated flow for a sufficient length of time, thus the hydrology of buffer zones is critical to the success of processes such as denitrification (Gilliam *et al*, 1997). Extensive research is now taking place in this field to determine nutrient cycles and fates, effects of hydrological regime, and monitoring buffer zone design to specific soils and regional requirements.

Protection of the riparian corridor from livestock grazing and trampling is often an essential key to re-establishment of multiple functions of the stream ecosystem, and numerous researchers have addressed the questions of management of herbivore pressure within the riparian zone. Elmore (1992) suggests that grazing is compatible with riparian recovery from past abuses, but needs to be managed carefully to ensure that seed, stem, root and shoot regeneration are not damaged by excessive or unseasonal herbivore pressure. He has identified ten grazing rotation strategies and their potential effects on riparian plant community recovery (Elmore, 1992).

On an intermittent stream in coastal California, Smith (1988) found that riparian tree recruitment was absent during 70 years of intensive grazing. When cattle were removed but some trespass cattle continued to browse the stream, stem growth and riparian recovery was very slow, and Smith argued that riparian grazing may not be compatible with long-term sustainability of the stream ecosystem (Smith, 1988). This incompatibility has been recognised by the US Government, and has resulted in actions such as purchasing the grazing rights to 19,830ha in an Idaho national forest from an rancher of long standing, in order to protect salmon spawning habitat (Oregonian, 1999).

Widths of the Buffer Zone

The question of buffer width has generated a good deal of discussion in several different fora, such as in forestry (for example, Ice *et al*, 1988), in agriculture for

water quality control (Haycock *et al*, 1998, the Bufferzones internet discussion list bufferzone@listserve.vt.edu), in rural areas for wildlife habitat (Ledwith, 1996), and in urban areas for storm water management (King County, 1992). Width dimensions are difficult to determine from a formula or prescription, as site characteristics vary greatly by stream order, location in the catchment or distance from watershed, discharge, sediment transport regime, groundwater regime, elevation and topography. Criteria for buffer width will vary among different functional requirements, such as water quality, sediment and erosion 'control' or bank stability, navigation, flood defence, fisheries, wildlife habitat, etc. Substantial challenges await river managers in the near term and in future as multiple functions are integrated into buffer zone management.

Recommended widths for buffer zones continue to be debated as these determinations may have substantial effects on economic activities within the river corridor.

For the Northeastern USA, forested buffer widths are recommended by the American NGO River Network as an expression of the regional slope:

Buffer width in m. = 4 x (percent slope) + 15m.

A study in Vermont showed that 90% of the streamside flora are found within 30m. of the water interface zone. Reptiles and amphibians in the Northeast use 30-60m. of habitat within the forested riparian buffer (Peterson & Kimball, 1995).

This formula causes the buffer width to be wider in the upstream areas, with no increase for drainage area in the downstream direction. For example, on a mountain stream of slope = 4%, the buffer width would be (4*4) + 15m = 31m. On the valley floor, slope may decrease to 2%, yielding a buffer width of 23m. Thus in this arithmetic model, as slope decreases, the buffer width would also decrease, but in fact the floodplain width normally increases in the downstream direction. For the forested Northeastern USA where the target is conservation of wildlife habitats, this formula would appear to be conservative in upper catchment areas and a poor predictor of wildlife habitat needs for larger streams.

Width of the buffer zone will continue to be a subject of heated debate, as development pressures collide with multi-objective natural resources issues in public fora. Numerous demands exist for prescriptive formulae to determine adequate buffer widths in the logging industry, for housing developments, for mineral extraction along rivers and wetlands, for waste disposal issues, transportation and a host of other pressures. No single approach can provide adequate solutions to this problem, as geomorphological details at the reach and site scale highlight the need for consideration of the unique site and reach-scale features. Although land-use decisions are typically made in the political arena, there is much scope for the continued and increasing contributions from scientists in providing adequate land area for multiple criteria in land use planning and implementation.

2.9   Conclusions

The ecological values, the distribution and structure of riparian and floodplain vegetation are governed strongly by the geomorphic and hydrologic conditions of the stream and its floodplain. These plant communities have been shown to have significant effects on fluvial geomorphic processes, and dynamic links between fluvial and plant ecological processes have been identified.

The relationship of vegetation to fluvial geomorphic process is reasonably well described. For river management, the challenge is therefore to understand the mechanics of these relationships so the effect of intervention in these processes can be reasonably well predicted. River restoration by any means, from 'benign neglect' to the use of live vegetation for bank stabilisation and fish habitat, will bring change to the anthropocentric system as the vegetation grows. Prediction of likely change is needed to satisfy regulatory concerns over hydraulic performance, and societal concerns over the impacts on riparian land use.

Increasing understanding of human impacts to river systems offers substantial breadth of opportunity for changing land management paradigms and land use practices. Rural and urban people differ somewhat in the demands made on

riparian plant communities, affecting the allowable channel and floodplain width. The potential multiple benefits available for recovery of streamside native plant communities have been described, along with the challenges facing land managers for the integration of these multiple goals.

In Chapter 3, the engineering criteria for streamside vegetation are explored, to set the framework for understanding how river management theory and practice can be enhanced to facilitate the recovery of streamside plant communities within a fluvial geomorphic paradigm.

Chapter 3: Engineering considerations of streambank and floodplain vegetation

A fundamental concern of the flood management engineer is the problem of roughness associated with streamside vegetation, which may increase flood risk in moderate events by reducing the effective hydraulic capacity of smaller streams. This concern has been a primary motivation for the removal of streamside plants, especially trees, where development places constraints on the width of the river corridor. Vegetation influence on reach roughness for natural channels has been addressed by several authors, such as the classic works by Ree (1949), Chow (1959), Barnes (1967), Arcement & Schneider (1989), and in German by Rouve *et al* (1987), and DVWK (1991).

Flood defence arose out of the paradigm of land drainage, where water is regarded as a waste problem to be disposed of, removed from the land as quickly as possible to make land 'safe' for agriculture and development (Newson,1992). Under this paradigm, woody vegetation is a problem causing excess channel roughness, inhibiting the engineer's ability to remove flood water safely. Indeed, this approach to flood defence engineering has been so effective that few wetlands remain today in England, Europe, much of the mesic United States, and elsewhere (National Research Council, 1992, Newson, 1992). With the loss of wetland storage and groundwater recharge, water shortages and downstream flood hazards are becoming more increasingly common in industrialised countries (Newson, 1992).

A process of rethinking the purpose of flood defence and river engineering is needed, to allow surface waters to be regarded as a resource (Gardiner, 1995), where streamside vegetation can be valued for its ability to reduce flood water velocity, and to reduce flood hazard and damage, among other benefits (Williams, 1990). Modern engineering is shifting from the traditional, single-function approach to a multiple purpose strategy, incorporating ecological and environmental benefits into river management (Gardiner, 1991). See, the flood management strategy given in Table. 2.1, *Strategies and tools for floodplain management, from the USA,* illustrating new approaches for flood defence in the USA.

3.1. Vegetation and river hydraulics; the state of our knowledge

Knowledge of the hydraulic effects of woody riparian vegetation in overbank flow falls within three categories; theoretical derivation, flume studies and field experience (Davis *et al*, 1995). Much work has been carried out to determine hydraulic roughness values for various types of channels with aquatic vegetation in-channel (Kouwen & Unny, 1973, Dawson & Charlton, 1988) and for vegetation on channel banks (Arcement & Schneider, 1989, Masterman & Thorne, 1994). The behaviour of flow through grasses has been studied since the 1950s, and was characterised for various flow depths and grass species (Ree, 1949, Ree & Crow, 1977). German research beginning in the 1970s addressed the problem of flow through channels with vegetated floodplains, and has modelled such problems as the turbulent exchange between channel and floodplain (Pasche & Rouve, 1985, Nuding, 1994). Sedimentation resulting from flow through rigid, emergent vegetation has been modelled in flumes (Li & Shen 1973, Tollner *et al*, 1976); the utility of the Tollner *et al* model is examined for its application to the field data from flow through flexible emergent vegetation in the field research (Chapter 6) for this thesis.

As confirmed by Thorne *et al* (1998), the contemporary situation is that no large, quantitative data sets exist from which to derive predictive capability of vegetation influence on channel hydraulics, especially that capability which can be applied under the conditions encountered along natural streams and rivers. Theories from which flow behaviour through woody vegetation could be predicted are hampered by the lack of field data, and a growing research effort has been directed in this topic area (Gerstgraser, 1999). The engineering framework in which the research for this thesis occurs, and for supporting or closely related topics, is examined in this chapter.

Micro-scale considerations:

3.1.1 An introduction to theoretical hydraulics and vegetation

The equations examined in this section support the theoretical hydraulics used in this thesis, and underpin the choice of analytic methods (Chapter 6) used and the findings. Chapters 3 and 6 therefore involve discussion of the principles of hydraulics, to identify strengths and weaknesses in analytic and design tools available to predict vegetative roughness of flexible emergent woody plants, the shrub forms of riparian plants.

The foundations of theoretical hydraulics were derived from laboratory flume experiments over the recent 200 years, beginning with the study of flow in canals by the French engineer A. Chezy in 1775. Chezy formulated the equation to predict flow velocity as:

$$V = C\,(R*S)^{1/2} \qquad \text{Eqn. 3.1}$$

$$C = \sqrt{\frac{\rho g}{\alpha}} \qquad \text{Eqn 3.2}$$

where:

    V = mean velocity

    C = Chezy coefficient for roughness,

    R = channel hydraulic radius (area divided by wetted perimeter)

    S = slope of the channel

    α = a roughness coefficient

Chezy's C has units of m$^{1/2}$/s, and varies from about 30 in small, rough channels to 90 in large, smooth channels (Gordon *et al*, 1992).

Chezy's equation was modified in 1891 by an Irish engineer, R. Manning who wrote the equation in the form (shown here in SI units), using *n* for the roughness coefficient (Henderson, 1966):

$$V = 1/n\ R^{2/3}\ S^{1/2} \qquad\qquad \text{Eqn. 3.3}$$

or

$$Q = 1/n\ A\ R^{2/3}\ S^{1/2} \qquad\qquad \text{Eqn. 3.4}$$

Where:

Q = channel discharge in $m^3 s^{-1}$

A = channel area (width * depth)

Chezy assumed that the channel dimensions (slope, depth and hydraulic radius) were uniform, and that flow was carried at a constant rate in the channel (Newbury, 1995, Chow, 1959), an assumption which generally does not hold for natural stream channels.

The Manning equation was developed to describe rough turbulent flows over surfaces having discrete, rigid, small-scale roughness elements (Manning, 1895, Smith *et al*, 1990). According to Smith *et al*, (1990), the use of $R^{2/3}$ rather than the theoretically correct $R^{1/2}$ results in a roughness coefficient n which is constant for a particular surface; however, when the equation is applied to flows over surfaces with large or flexible roughness elements or mobile beds, n becomes a variable, largely dependent on flow depth (a surrogate for radius on large channels and floodplains) and velocity.

In two major equations for roughness, the Chezy formula and Manning equation, the parameter hydraulic radius is used to evaluate resistance of bedforms and obstructions to flow. Based on the formula for area equal to width times depth, (Eqn. 3.5) and wetted perimeter equal to width W times twice the depth (Eqn. 3.6), hydraulic radius R is defined as area A divided by wetted perimeter P (Eqn. 3.7).

$$A \equiv W * D \qquad\qquad \text{Eqn. 3.5}$$

$$P \equiv W + 2D \qquad\qquad \text{Eqn. 3.6.}$$

$$R \equiv \frac{A}{P} \cong D \qquad\qquad \text{Eqn. 3.7.}$$

For wide rivers and in open channels, as width becomes much greater than depth, the perimeter P becomes roughly equal to W (Eqn. 3.6). In larger natural streams,

for computing radius R, the width terms in numerator A and denominator P (Eqn. 3.7) cancel each other, leaving hydraulic radius R roughly equal to depth D, so depth may used as a surrogate for hydraulic radius. This is applicable to computation of floodplain flows, where there is often no well-defined perimeter or edge to the flow. For the analysis of sedimentation and for roughness computed from the velocity profile, depth is an acceptable parameter for the expression of radius (Dingman, 1984).

The Manning equation is routinely used by engineers to compute either velocity or discharge for natural streams (Henderson, 1966, Barnes, 1967, Freeman *et al*, 1996). A large body of experience exists relating to the estimation of n values where calibration is not possible (Smith *et al*, 1990). The Manning equation is the most widely used method in America to predict either velocity or discharge for channel design. The Darcy-Weisbach equation (Eqns 3.8, 3.9) is favoured in Europe and Australia (Rouve *et al*, 1987, Smith *et al*, 1990) to compute bank resistance to flow. It is recommended by some authors for being non-dimensional (Dingman, 1984) and having a sounder theoretical basis (Knighton, 1984). This equation relates slope to flow energy and is a ratio of velocity to hydraulic radius (Dingman, 1984).

The equation for the Darcy-Weisbach friction factor f_D is:

$$S_e = f_D \left(\frac{V^2}{8gR} \right)$$

Eqn. 3.8 or

$$V = \left(\frac{8gS_eR}{f_D} \right)^{\frac{1}{2}}$$

Eqn. 3.9

where:

S_e = energy slope (m)

g = gravitational constant (9800 N/m^2)

R = hydraulic radius (m)

For a flow carrying sediments, the components of resistance are: grain or surface roughness, form roughness, channel irregularities, and suspended material in the flow (Knighton, 1984). Resistance can be separated into skin, free surface and form

resistance (Masterman & Thorne, 1994). Bank and floodplain vegetation would be a component of form roughness for its influence on the boundary layer, however this dimension of hydraulic roughness is poorly defined (Masterman & Thorne, 1994). This cumulative nature of resistance is reflected in the value of the three coefficients described, thus 'n' or 'f' will rely on sinuosity as well as cross-sectional roughness. This characteristic makes field estimation more a matter of experience than of calculation.

The Darcy-Weisbach friction factor f is used primarily in hydraulic research, and has been applied to field engineering in channel design (Smith et al, 1990, Masterman & Thorne, 1994, Gippel, et al, 1995), but has not been used in practice to calculate vegetation effects on roughness in field conditions to the extent as has the Manning equation.

3.1.2. Boundary layer theory and boundary layer effects

The boundary layer theory states that the flow at the boundary or bed of the channel has a laminar layer of undefined molecular thickness which exists in the 'no-slip' condition (Dingman, 1984). From the boundary of the channel bed, the flow of water over the bed increases in speed as it increases in depth, on a logarithmic function (Figure 3.1.)
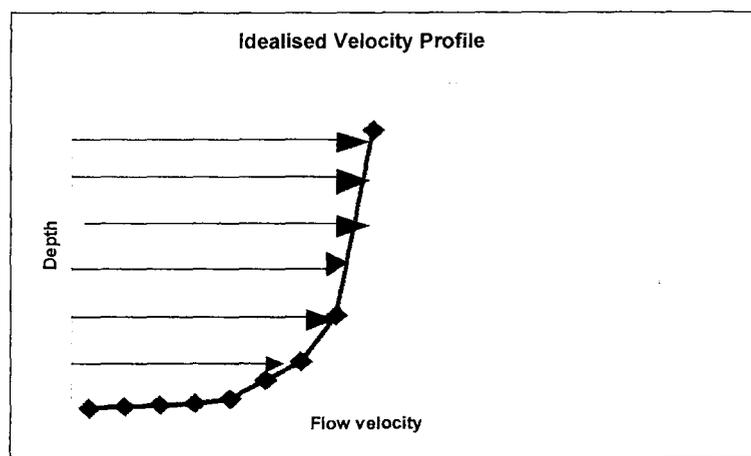
Figure 3.1. An idealised logarithmic velocity profile, showing the boundary layer.

The terms 'rough' and 'smooth' have precise meanings in hydraulics, related to the concept of flow over the boundary layer (Gordon *et al*, 1992). At the outer limit (water surface), the fluid speed matches the 'free stream velocity', i.e. that speed which would exist if the boundary were not there (Gordon *et al*, 1992). Boundary friction is transmitted through the flow, and flow velocity near the boundary governs the ability of flowing water to 'entrain' sediment into the water column (Dingman, 1984). Height of the 'roughness elements' on the bed, whether these are sediment particles such as sand, gravel or boulders, plant stems or other obstructions to flow, influences the thickness of the boundary layer and the ability of the bed to retard flow velocity (Kouwen *et al*, 1969).

Like all fluids, water is viscous, meaning that molecules have a certain stickiness. The coherence of a viscous fluid is disturbed when the flow encounters an object, which causes separation of the flow. The viscosity of water flowing over a rough surface generates turbulence, which expresses its chaotic behaviour in eddies. Turbulence acts analogously to viscosity to retard boundary-layer flows (Dingman, 1984). Eddies dissipate energy, and often can be observed translating upstream.

Eddy viscosity ε is a friction within the flow that results from the vertical circulation of turbulent eddies, and is proportional to the rate of vertical momentum transfer via turbulent eddies (Dingman, 1984). In water, ε is governed by temperature, solute density and dissolved and suspended sediment (Gordon *et al*, 1992). Eddy viscosity is a dimensionless parameter used to predict boundary shear stress τ in the Eqn. 3.10:

$$\tau = \varepsilon \frac{dv}{dy} \qquad \text{Eqn. 3.10}$$

where v = velocity (m/s)
$\qquad y$ = distance in y direction (m)

As discussed in Dingman (1984), Prandtl (1925) showed that in turbulent (natural) flow, the turbulent forces far outweigh viscous forces, but act to resist the flow in the same way viscosity does (Dingman, 1984). Prandtl was the first to develop a

formula (Eqn. 3.11) for the velocity profile in turbulent flow using the eddy viscosity factor:

$$\varepsilon = \rho l^2 \frac{dv}{dy}$$ Eqn. 3.11

where ρ = water density (kg/m^3)
      l = length (m)

Viscosity is related to the speed at which natural water flows, through the use of the dimensionless Reynolds number **Re.** The Reynolds number (Eqn 3.12) characterises the degree of turbulence in open channel flow, and is a ratio between inertial forces and viscous forces (Shapiro, 1966). Put another way, it is a dimensionless ratio of the product of the average velocity (m s^{-1}), hydraulic radius (or some characteristic length or depth in m) and fluid density (kg m^{-3}) divided by dynamic viscosity v (N*s m^{-2}), as shown in Eqn 3.12 (Dingman, 1984).

$$\text{Re} = \frac{VL\rho}{\mu}$$ Eqn. 3.12

where V = velocity (m s^{-1})
      L is the characteristic length (m)
      μ = kinematic viscosity (m^2 s^{-1})

Viscosity is a fundamental property of water relating the 'thickness' and resistance of flowing water. It is a function of temperature which can be altered by the presence of dissolved solutes. For this exercise, the role of solutes in altering viscosity was ignored, although solute concentration may have a minor role in affecting flow resistance on a natural floodplain.

Reynolds number expresses laminar flow for **Re** <500 (10^2), transitional for 500 < **Re** < 2000, and is fully turbulent for **Re** > 2000 (10^3) (Gordon *et al*, 1993). For the Tollner *et al* (1976) flume study, **Re** ranged from 100-3000. Nearly all flows in nature are fully turbulent, an important feature to simulate in flume studies on open

channel flows. The Reynolds number is used, among many other things, to compute the turbulent flow conditions under which suspended particles settle out of a water column (Tollner *et al*, 1976).

Vegetation on the floodplain acts, in many ways, as any other roughness elements, increasing the effective roughness height of the boundary layer, displacing the zero plane of velocity upwards away from the bank, and increasing flow resistance. This has the effect of reducing the forces of drag and lift (and their surrogate, boundary shear stress) acting on the bed or bank surface (Gordon *et al*, 1992). At the boundary, friction or shear stress τ_o is zero, but increases as a function of the channel slope and hydraulic radius or depth (Eqn.s 3.13 and 3.14).

The fundamental equations for critical shear stress are:

$$\tau_o = \rho g R S \qquad \text{Eqn. 3.13}$$
or
$$V = \sqrt{\frac{\rho g}{\alpha} R S} \qquad \text{Eqn. 3.14}$$

where τ_0 = Newtons per square meter (N m^{-2})
        R = hydraulic radius (m)
        α = a constant

As the boundary shear stress is proportional to the square of near-bank velocity, a linear reduction in this velocity produces a squared reduction in the forces responsible for erosion (Gordon *et al*, 1992, Thorne *et al*, 1998). Quantification of this effect is especially difficult in the field, because a natural flow field is non-uniform, turbulent, and varies in each vector (x, y, and z) simultaneously. Because field conditions are highly variable, large data sets will be needed to develop predictive capability. This further highlights the need for co-ordination between laboratory and field research, as attempted in this thesis.

Some of the contemporary work in woody vegetation effects on flow is now no longer focused on reach-scale studies using Manning's '*n*' or Darcy-Weisbach '*f*' friction factor values to represent gross flow resistance, but on characterisation of

the effective roughness height and form drag effects exerted by stems on near-boundary turbulent flow structures (Masterman & Thorne, 1994). While this new approach, based on boundary layer theory, is still in its early stages, it has potentially profound significance for river engineering where incorporation of bankside vegetation is emphasised.

For example, detailed laboratory studies employing numerical modelling of velocity profiles, drag forces and turbulence have been conducted recently in Japan, the USA and Israel (Shimuzu & Tsujimoto, 1994, Garcia, 1996, Naot *et al*, 1996). The results may 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 from bedforms, for submerged or emergent vegetation. Vegetation simulation in these models has used either herbaceous or grass resistance which flattens when submerged, or rigid cylinders of constant resistance.

3.1.3   Retardance of near-bank velocities

The theoretical and empirical work on vegetation and flow resistance undertaken by Kouwen at the University of Waterloo, Canada (e.g. Kouwen & Unny, 1973; Kouwen & Li, 1980), 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.

This finding has profound implications for the direction of research, implying greater emphasis on more qualitative descriptions of natural phenomena and 'lumped-parameter' characterisation of the reactions between flow and flexible vegetation.

The amount of bending depends on the roughness of the stem and bark, 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 (Davis *et al*, 1995). The vertical velocity distribution may remain approximately logarithmic throughout, although this is not certain. The major effect of stem bending would be to move the virtual origin of the velocity distribution (the height above the bed at

which the velocity goes to zero) progressively nearer the boundary as bending increases (Davis *et al*, 1995). The effect of the plant body in shielding the boundary layer would depend on the distribution of stems in the flow, and is important in dense aquatic vegetation stands (see Dawson & Charlton, 1988).

From the development of drag theory, 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 (Thorne, 1990). 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
  - ◆ plant type,
  - ◆ plant height and
  - ◆ vigour
- channel geometry cross-section, and
- channel 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 (Masterman and Thorne, 1994, Thorne *et al*, 1998).

3.1.4 Drag and roughness in flow through woody vegetation

Drag is the force exerted on an obstruction by the flow, composed of lift or pressure force and friction force, causing either entrainment of a particle into flow or a deformation of the obstacle at the threshold of resistance, (Shapiro, 1966), shown in Figure 3.2.
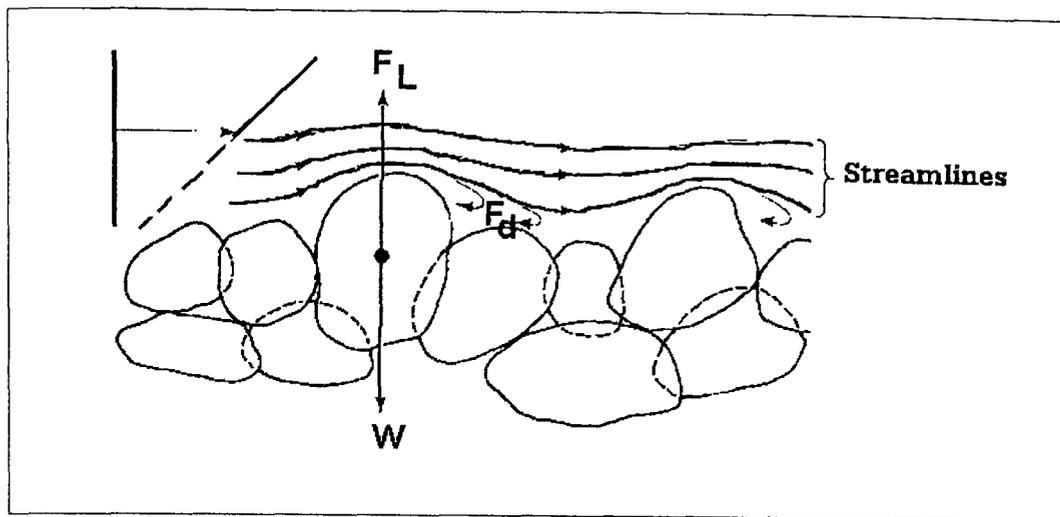
Figure 3.2. Forces of lift and drag on a particle on a streambed; Fd is the drag force, FL is lift force, w is weight (gravitational force). Velocity gradient line is shown on left.

At high Reynolds number conditions, drag is proportional to velocity times density times size, and increases as a square of the speed (Shapiro, 1966, p103).

$Drag \equiv speed^2 \times density \times size^2$ Eqn. 3.15

According to the simple proportionality in Eqn. 3.15, drag force increases as a square of the size of the obstruction. However, the property of relative flexibility of the obstruction to flow is not accounted for here.

For some engineers, measures of drag force on the bed and banks are preferred to a roughness value, because use of the Manning's n value is largely based on an educated guess as to the correct value. However, a large empirical basis now exists for the use of n values, even if these values may be imprecise (Thorne *et al*, 1998). Sensitivity analysis could be applied to derive confidence limits to applications of the Manning formula.

Prior to the 1970s, most studies relating flow and vegetation focused on grasses, and to the change in boundary layer height under uniform flow with submerged vegetation. Based on the PhD research of Petryk, Li & Shen (1973) published an analysis of vegetation flow resistance using rigid, non-submerged cylinders. The analysis was intended for comparison of the relative effects on sediment yield for various combinations of spatial patterns for tall vegetation (modelling the hydraulic

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effects of various floodplain forestry methods). This model is difficult to apply under field conditions because it depends on accurate characterisation of such parameters as wake width and length, on which almost no field data exist, because data collection would involve measuring the flow in plan view.

Theoretical calculation of the drag coefficient is based on the average flow velocity, the cylinder diameter and cylinder Reynolds number. Calculation of the wake width and decay length was made for a single cylinder, then for multiple cylinders to compute the velocity distribution in the wake pattern. 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, wake width and length, then computing the mean drag coefficient for each cylinder at varying depths.

Results from Li & Shen (1973) (see also section 3.19, Effects of vegetation spacing on roughness and flow) 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. Thus reduced drag among the staggered pattern leads to reduced sediment transport and increased deposition. The average boundary shear stress was not sensitive to variation in discharge or sediment size, but was sensitive to slope and variation in vegetation (cylinder) diameter.

3.1.5   Hydrodynamic modelling of turbulence in vegetation
One of the important effects of riverbank woody vegetation on the near-bank flow field is to influence turbulence. The field of theoretical hydraulics, based on the calculus of fluid mechanics, is expanding rapidly in the 1990s, with contributions from numerous workers around the world in several closely-related disciplines. Much of the numerical modelling work being undertaken at present addresses the complex nature of turbulent flow.

On a foundation of hydro-dynamics laid in the 1980s, computer-based hydro-dynamic modelling in the 1990s extended the development and application of numerical three-dimensional turbulent flow in a compound open channel. A large body of research has been developed in this field, and work on the special case of the compound channel with a vegetated floodplain has been addressed by Tsujimoto & Kitamura (1992), Naot *et al* (1996) and Garcia, (1996), among others.

Most of the work reported thus far has been undertaken in one- or two dimensional-analysis, because this is easier to compute. Several workers have approached the problem of vegetation influence on flow and sedimentation from the three-dimensional analysis, using the calculus-based k- ε turbulence model (Pasche, 1984, Shimuzu & Tsujimoto, 1994, Garcia, 1996, Naot *et al*, 1996).

Shimuzu & Tsujimoto (1994) modelled flow and suspended sediment in a compound channel with emergent vegetation. In careful field work, primary and secondary flow components were identified, with transverse gradients of sediment concentration modelled both in the flume and numerically. Emergent vegetation was modelled in a channel with and without a floodplain. Without floodplain (i.e. in the main channel,) the zone of sand deposition appeared in the vegetation zone, with its location and lateral distribution varying with vegetation density. As density (uniformly) increased, an area of sand deposition appeared in a narrow band near the boundary of main channel.

Without the presence of vegetation on the floodplain, sediment deposited widely across the floodplain. With vegetation in the model at the riparian margin, sand deposited at the zone near the main channel. With vegetation on the floodplain, secondary flow vectors move toward the floodplain-channel edge. With a narrow band of non-submerged vegetation on the floodplain, the flow promoted erosion of the non-vegetated areas of the floodplain (Shimuzu & Tsujimoto, 1994).

Tsujimoto constructed several flumes with herbaceous annual plants for submerged flow on the floodplain of the R. Kakehashi, Japan. Flume dimensions were 18m long, 1.3m wide and 0.75m deep, sunk 20cm into the bed. An electromagnetic current meter was suspended from a gantry, and water was pumped through the

flume to simulate floodplain flows. Time-averaged velocity measurements were taken, and turbulence characteristics were obtained to investigate the flow structure within and over the vegetation layer. Referring to Figure 3.3, (mean velocity distribution, turbulence intensity and Reynolds-stress distribution over vegetated floodplain), intense momentum transfer was observed between the vegetated part of the depth profile and the flow above the vegetation.
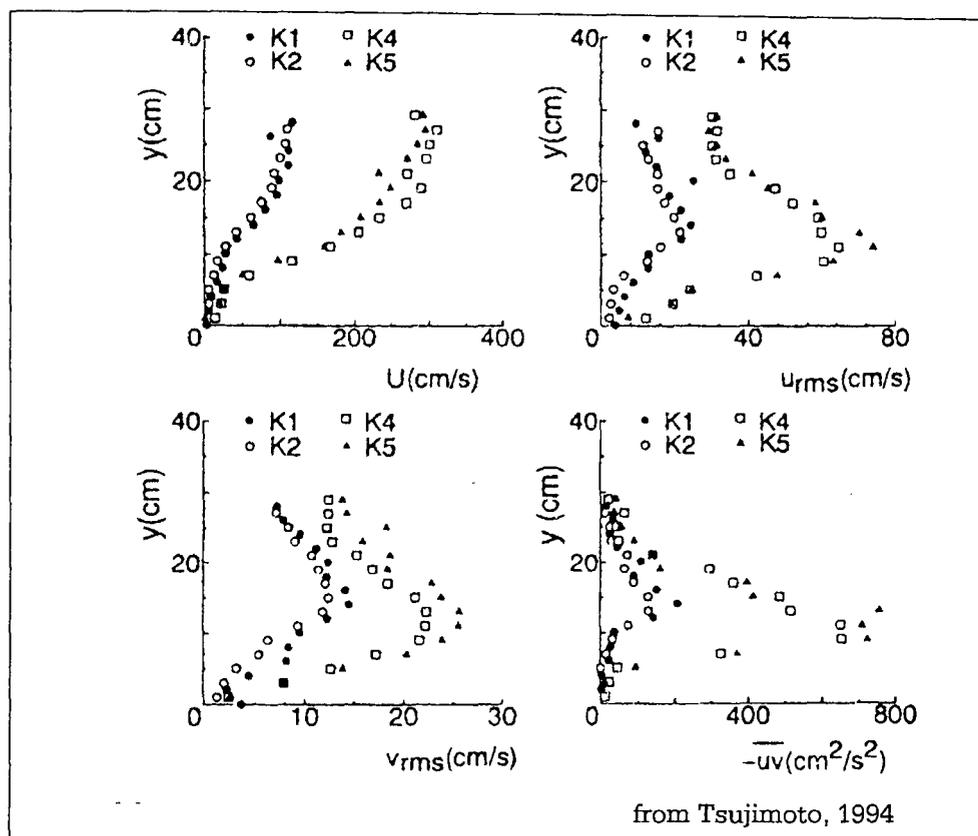
Figure 3.3. Mean velocity (u) distribution, turbulence intensity (v) and Reynolds-stress (-uv) distribution over vegetated floodplain, from Tsujimoto (1994).

Using a drag term rather than roughness value, the effect of vegetation on turbulence was then analysed using a κ-ε model to predict flow structure, bed shear stress and erosion resistance (Tsujimoto, 1994). Tsujimoto's velocity profiles repeatedly show a flexure of the middle of the profile, as velocity appears to be attenuated at the boundary and near the water surface (see also Figure 6.5, Mattole velocity profile 4).

The calculus-based, hydro-dynamic approach models the components of turbulent flow structure in three dimensions, longitudinal, lateral and vertical. A feature

shared by the work of Tsujimoto (1994), Naot *et al* (1996) and others is the use of three groups of equations;

1) three momentum equations plus the continuity equation govern the mean flow;

2) two transport equations for energy and dissipation represent the intensity and scale of turbulence, and

3) a set of algebraic equations to describe the anisotropy (different properties in different directions) of turbulent stresses (Naot *et al*, 1996).

Introducing vegetation into turbulent flow results in additional drag forces, additional production of turbulence energy and interference with the turbulence length scale and anisotropy.

Naot *et al* (1996) observed that the universal logarithmic velocity was no longer adequate to describe flow through a vegetated domain, and that a new velocity profile and new wall functions (for flumes and channels with distinct edges) should be formulated. They suggested modifying the logarithmic velocity profile to more irregular shapes based on an anisotropy matrix, where different vectors compute stress for different directions. Their results from the numerical model are compared with experimental flume data for 5 cases of floodplain vegetation density. In the physical model, vegetation was simulated as round vertical rods, randomly distributed. The flow meter used is the laser Doppler anemometer (LDA), which is capable of measuring subtle changes in flow vectors in 3 dimensions. Drag coefficients vary by vegetation density expressed by Reynolds number, ranging (in the flume work) from about $C_D = 0.5 - 1.15$ (Naot *et al*, 1996).

Results indicated that an increase in vegetation density homogenised the flow and attenuated velocity in the 'streamwise' direction. Discharge was displaced from the vegetated domain into the clear main channel, and the 'wall effect' at the edge of the vegetated domain developed a free shear layer, increasing momentum exchange between floodplain and channel. This led to an increase in the effects of secondary currents in the main channel. During floodplain flow, at some distance from the flume wall, the velocity profile changes from a logarithmic distribution to a uniform

velocity distribution (see also Figures 6.6 and 6.7, comparison of profiles for bare and vegetated floodplain surfaces).

Owing to the partial blocking of the flow through the vegetated zone, a free shear layer is formed in the channel adjacent to the edge of the vegetated domain. The authors note that as vegetation density increases, floodplain flow attenuates, discharge decreases and energy is gradually attenuated. Flow is homogenised as density increases. In the physical model, flow is nearly blocked for N > 32, (in contrast with flow at the study site, where N > 40 was computed, and flow penetrated the vegetated domain, as shown in Figures 6.5 and 6.7). The hydrodynamic behaviour of the compound channel with a vegetated floodplain depends, in the model, on two vegetation parameters, the shading factor (similar to the wake length in Li & Shen (1973), the degree of hydraulic 'shade' one rod casts on the next) and the reference length, which characterises the vegetated zone structure (an empirical parameter). Again, spacing or plant architecture has a profound effect on the hydraulics of flow through the vegetation zone.

The results from the turbulence model contrast with that for velocity. Turbulence decreases with increasing vegetation density (Naot *et al*, 1996) (see Figure 6.16 for vegetation density influence in the Naot *et al* model).

This study was formulated for the range of Reynolds numbers $\mathbf{Re} = 10^3\text{-}10^4$. Because flows in large natural streams can be far more turbulent ($\mathbf{Re} > 10^{4)}$, further study to extend this model into the higher Reynolds numbers would be very helpful to progress prediction of floodplain revegetation consequences. Additional work adding suspended sediment to the model would further enhance simulation of fluvial processes on natural, vegetated channels for flows carrying sediments.

3.1.6   Summary of the section on micro-scale hydraulics

This section, examining the theory of small-scale hydraulic behaviour, provides an essential foundation for any analytic work to understand the effects of vegetation on fluvial geomorphic processes. These foundations were laid over the last 200 years, and the application of these theories has led to substantial modification of river

channels, mostly toward simplification of channel geometry in order to improve predictive capability. Thus, to be able to change existing river management paradigms, the preceding history and theoretical development must be understood and integrated.

Some material is included in the following sections for comparative purposes, for example to illustrate why hydraulics of flow through grassed channels will be insufficient for predicting or modelling flow through forested floodplains. The original intent of this inquiry was to find a numerical model, empirical or not, which could be used to analyse the hydraulic consequences of a soil bioengineering project for riparian revegetation and fish habitat recovery. In the light of the paucity of available literature on this subject, a major part of the research was then directed toward 1) understanding and 2) critiquing the existing equations and models, developed from flume research, in the light of the field data.

This section, and those that follow, also help to identify those gaps in knowledge which will be needed as fluvial geomorphic and hydraulic research recognise the need to incorporate woody vegetation along streambanks and floodplains.

Macro-scale considerations; Vegetation hydraulics in interactions among channel and floodplain

3.1.7 In-channel vegetation roughness values

The empirical study of roughness in natural river channels by Barnes (1967) has provided a database for varying roughness factors. Photographs with calculations show roughness values for channels in a manual, to assist the practising engineer with the correct roughness determination. The Barnes' manual applies the Manning equation to natural streams, although the equation was developed for conditions of uniform flow in irrigation channels, in which the water-surface profile and energy gradient are parallel to the streambed, and the area, hydraulic radius and depth remain constant throughout the reach. This method computes flow only for the water in-channel, ignoring the complication of flow on floodplains and the potential

momentum exchange between channel and floodplain. Barnes' method does not directly address the roughness factor contributed by bank or floodplain vegetation, although it may be said to be factored into the empirical derivation of the equations.

Primary variables in the computation of roughness are in-channel morphology (width, depth, area, hydraulic radius), measured average velocity, bed and water surface gradients, flood stage height, degree of meander curvature, slope of banks and sometimes includes bed particle size (Barnes, 1967).

Hemphill & Bramley (1989) reviewed the role of vegetation on river and canal banks, as a practical guide for the river manager. Methods for the use of trees and shrubs are given in text and construction diagrams. Useful guidelines are summarised in this work, for hydraulic and geotechnical evaluation of vegetative effects on streambanks. Valuable design criteria are presented in this work. However, only the work on grasses and grass-lined channels and banks includes a discussion of hydraulic roughness, further indicating the need for research into the hydraulics of woody plants for riparian and floodplain conditions.

According to Davis *et al* (1995), there are five approaches to the computation of flow resistance, ; those based on:

- direct measurement (Thorne, 1998),
- a more indirect, analytical solution (Cowan, 1956, Petryk & Bosmajian 1985);
- handbook methods (Chow, 1959, Barnes, 1967),
- effective area techniques (Masterman & Thorne, 1992) and
- atmospheric sciences methods.

While direct measurement may hold the best promise of accuracy, in practice obtaining hydraulic parameters for the full range of flows is seldom possible (Davis *et al* 1995). With the now extensive development of theory and laboratory flume data and modelling, analysis of a wide range of field measurements represents the next substantive contribution to this growing field. This thesis reports on the use of the direct measurement method.

3.1.8 Channel flow regime

The dimensionless Froude number **Fr** is an important criterion for flow classification. Traditionally, a micro-scale characterisation of flow regime refers to the turbulent status or condition of the combined effects of viscosity and gravity (Chow, 1959) based on the Reynolds number **Re** scaled between 1-50,000 (Eqn. 3.5). Developed by the English hydraulician W. Froude (1810-1879), it is used to characterise flow regime, shown as equation 3.16.

$$Fr = \frac{V}{(gY)^{\frac{1}{2}}} \qquad \text{Eqn. 3.16}$$

where V = mean velocity (m/s)

g = gravitational constant ($9.81\,\mathrm{m\ s^{-2}}$)

Y = flow depth (m)

For **Fr** < 1, flow is subcritical, wave velocity exceeds the flow velocity, or a wave caused by an obstruction can travel upstream. When **Fr** = 1, the flow is termed 'critical'. When **Fr** > 1, waves cannot propagate upstream, and flow is in the supercritical regime, also called rapid, steep or shooting flow. (Dingman, 1984).

Four states are known to exist;
- subcritical laminar, where **Fr** < 1 and **Re** <500
- subcritical- turbulent, where **Fr**<1 and **Re**>500
- supercritical laminar, **Fr** >1 and **Re** < 500
- supercritical- turbulent, **Fr** > 1 and **Re** > 500

Flow states are characterised to determine conditions of flow erosivity, turbulence and critical thresholds of failure for channel designs (Chow, 1959). Such flow conditions govern processes of sediment entrainment, transport and deposition, channel morphological processes and countless habitat niches for aquatic organisms (Gordon *et al*, 1992).

Working at a macro-scale in the complex interactions among main channels and their floodplains, the effects of woody vegetation placement in channel planform may be impossible to model precisely (Willets, B., pers. comm, 1996), yet there are some

large-scale features of the flow interactions at the scale of channel and floodplain which are well understood.

Based on the flume studies at HR Wallingford, channel flow regimes have been characterised for compound, meandering channels with a relatively 'natural' cross-section (Ervine *et al*, 1994). Flow structures were observed using dye flow visualisation, a miniature propeller current meter and the advanced current meter technology laser-doppler anemometry (LDA), which can measure flows simultaneously in longitudinal and transverse vectors. Vertical velocity vectors were not measured in this study. Velocity components are subdivided in longitudinal vectors (downstream component), and transverse vectors (parallel to flow) which were observed to flow at 20-30% of the longitudinal velocity. In this 56m. long flume, floodplain roughness simulating trees was modelled using cylindrical rods located on the flat floodplain.
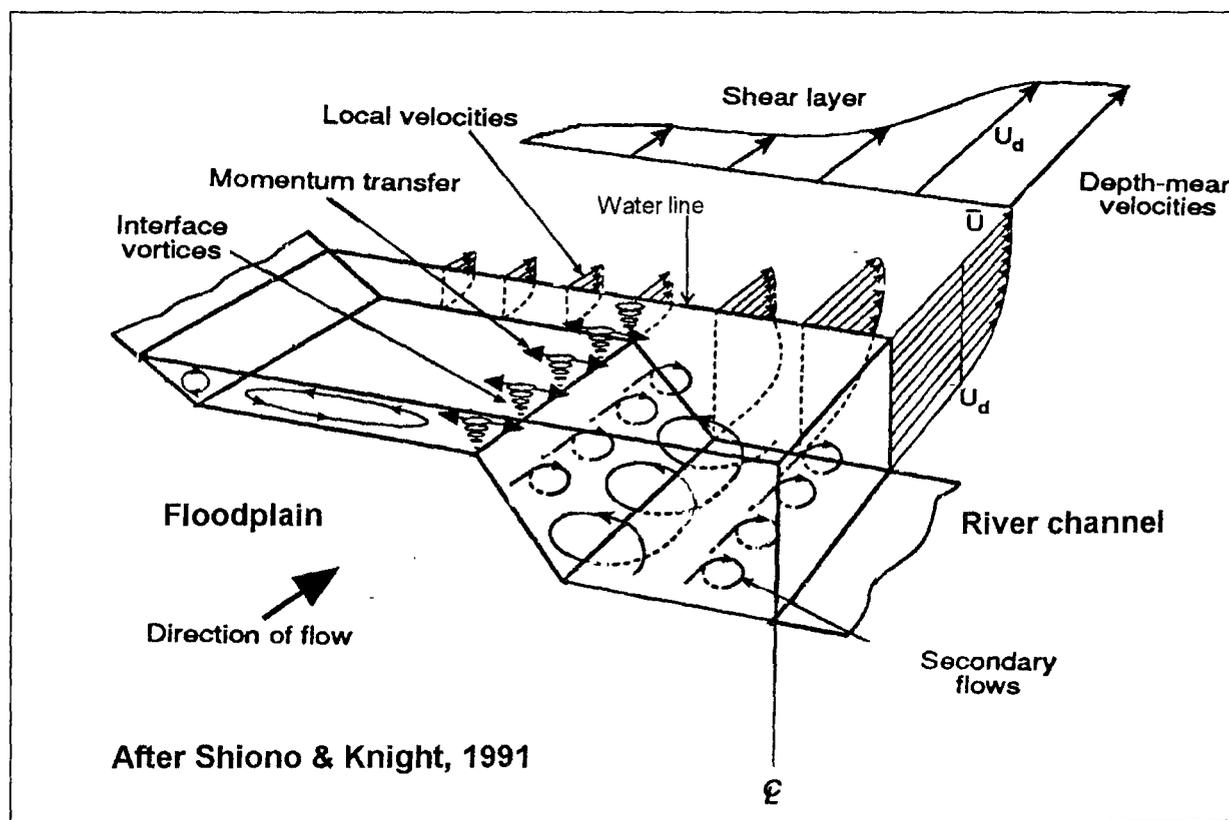
Figure 3.4. Flow processes in a straight compound channel, with no floodplain roughness elements, after Shiono & Knight, (1991).

In Figure 3.4, U is velocity, and C_L is the centre-line or thalweg. Important features for riparian vegetation include the vortex eddies occurring at the channel floodplain interface, and helical flow occurring along the submerged bank slope.

The major flow features observed on a curved channel interacting with a straight floodplain include:

- Accelerations and decelerations caused by bedform resistance;
- Transverse (across floodplain) pressure gradients;
- Secondary cells at the channel bend rotating in the direction opposite to inbank flows;
- Intense crossing-over region mixing of faster (channel) and slower (floodplain) flows;
- Vigorous expulsion of main channel water downstream of each bend apex;
- Plunging of the floodplain flow (returning) into the main channel.

This study found that flood water escaping from the channel accelerates upon entering the floodplain, and the flow depth there on the floodplain is locally reduced (Ervine *et al*, 1994).

Clearly, the hydraulics developed on bare soil banks will cause erosion, particularly where accelerations are involved. Riparian vegetation acts to dampen these effects. Thorne (1990) suggested that use of average velocity as a predictive parameter may present a misleading picture. Scour often occurs across floodplains where instantaneous peak velocities accelerate flow in 'burst and sweep' patterns, where instantaneous velocities can exceed the average velocity by 3-4 times (Thorne, 1990). The instantaneous maximum velocity increases the threshold of resistance needed to which vegetation must be adapted, or be scoured from place during flood. The entropy balance between the forces promoting order and disorder determines the stability of the river bank.

3.1.9   Grass-lines swales and channels

The early vegetation hydraulic research of Ree (1949) is reported here because it gives an historical context for the more recent work on emergent stems. Ree's work

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was carried out at the Stillwater Laboratory in Stillwater, Oklahoma in flume models at the scale of 1:1, and focused on grass-lined channels and swales. This work laid a foundation for much of the subsequent flume and field research on flow through submergent flexible vegetation, and has been applied for many years in hydraulic research on vegetation, by the agricultural engineering industry to reduce pollution from farms, and by the engineering industry in construction erosion control technology.

The work was conducted in a series of outdoor flumes varying in width from 1-12 m., and in length from 30-150 m. Slopes varied on the site up to 10%, and discharges ranged from 3×10^{-4} cms to 5cms. The channels were lined with Bermuda grass sod varying from less than 5 cm in length to more than 75cm, in summer (live) and winter (dormant) conditions. Velocity was measured using a Pitot tube across the channel to compute non-uniform velocity distribution curves. Figure 3.5. shows the deflection of the boundary layer in flow over a grassed channel.
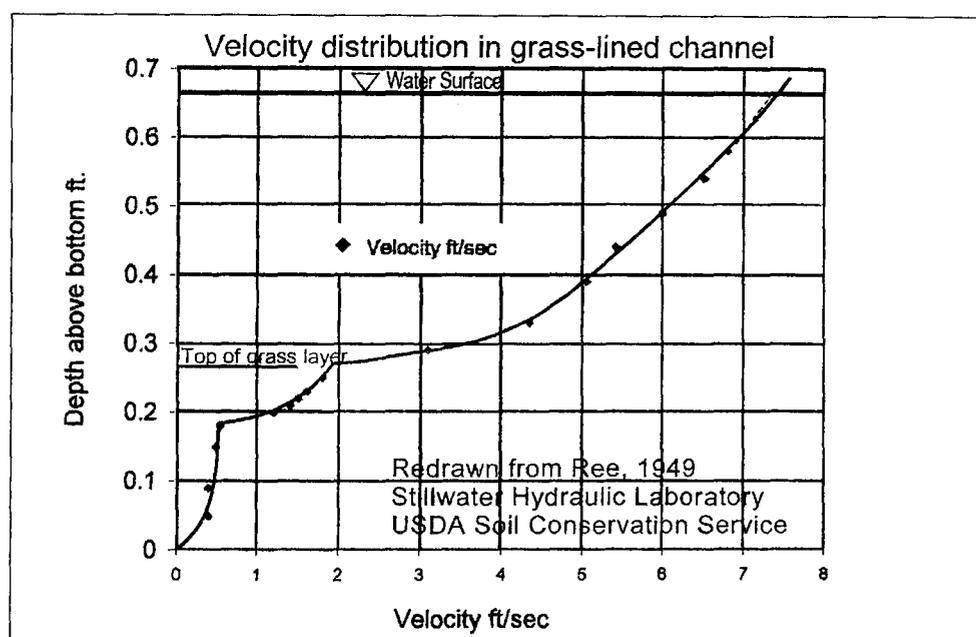
Figure 3.5. Velocity distribution in a grass-lined channel, after Ree (1949).

Roughness was computed as Manning's n values for several vegetation conditions. The author's states that the n values varied from 0.02 to 0.6 for one vegetation type in a single channel over different depths. The roughness curve rises steeply for non-submerged grasses, but as flow depth increases and the grasses are submerged,

Ree's *n* curve approaches a level value. Classes of vegetal retardance are given for the product of *n*-VR (velocity times radius) to average the parameters of slope and depth, reducing the range of *n* values to just five classes. All five classes are composed of grass genera varying from sods (highest retardance value) to clumping grasses (lowest values). Reduction of scour forces (to decrease erosive force) against the bed was noted as the most important property of the grass-lined channel.

A critical design capacity of 4.2 cm s^{-1} was achieved in May with uncut grass; if grass was cut or burned the channel capacity was increased but permissible velocity was exceeded, permitting scour of the bed. If the grass was grazed very short, critical velocity was reached at 2.2 cm s^{-1}, and if burned, at only 0.56 cm s^{-1}. According to Ree, use of sub-optimal (plants giving incomplete surface coverage) grass species in the grassed channel reduces the critical threshold (shear) velocity necessary for sediment entrainment (Ree, 1949). Much work has followed on after this research to develop effective grass/sod installation and maintenance techniques for use in the erosion control industry, as has been reported frequently in the International Erosion Control Assn. Journal since 1988.

3.1.10 Effects of vegetation spacing on roughness and flow

Li & Shen (1973) examined drag and wake effects for single and multiple cylinders in non-submerged, open-channel flow and the effects of multiple cylinder spacing on hydraulic parameters. Detailed investigation of the flow regime around a single cylinder developed computation of a drag coefficient, from which the wake spread and decay could be computed. From the single cylinder case, a method of wake superposition is presented in open channel flow with multiple cylinders. Important parameters are the size and spatial distribution of cylinders, discharge, bottom slope, channel width, local drag coefficient and the depth of flow.

The authors assumed that cylinders are distributed in such a manner that uniform flow could be achieved in an open channel, that channel slope is uniform (although its effects are negligible), that boundary shear stress was uniformly distributed over the entire bed, and that the wake from each cylinder decays independently of the

cylinders upstream and downstream (in order to estimate the approach velocity for each cylinder). The model is applicable based on the assumptions of subcritical flow. In a series of experiments, the cylinder drag coefficient was found to be $C_d =$ 1.2 - 1.4.

Using a series of geometric arrangements (bare, uniformly spaced, parallel, perpendicular, and several staggered arrangements) for rigid emergent cylinders in a flume, Li & Shen developed some qualitative comparisons on effects of vegetative spacing on sedimentation patterns.

The authors concluded that:

a) groupings have a significant effect on retardation of flow rates,

b) staggered groups of vegetation perpendicular to flow are the most effective at reducing sediment yields and

c) blocks of vegetation perpendicular to flow were the next most effective.

The model predicted that vegetation diameter has a strong influence on boundary shear stress, suggesting that trees would become more effective on sediment yield as the trees grew larger. However, their model used only rigid emergent cylinders, so this model could not test the effective sediment yield from flexible stems. This model was not used in the present research programme because of the number of parameters which could not be measured in the field, such as wake width and length, from the Mattole baffle layout (see section 5.1.1 construction design).

This research could be continued in a programme combining flume with field experiments, to improve the correlation between the sediment trapping capability of various vegetation groupings. Perhaps the greatest challenge of the Li & Shen model for implementation in the field is the reliance on the wake width and length, which would have to be determined in plan view. During a flood on a floodplain, this view could be achieved perhaps on a clear-span bridge, a floodplain gantry or from a tethered low-elevation balloon.

The spacing of trees or shrubs along the channel and floodplain has a strong influence on the hydraulics of flow through the vegetation stand. Single trees or small groups of trees act as impediments to the flow, that can generate large-scale

turbulence and severe bank attack in their wakes. 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 (Thorne, 1990). For trees to be effective in reducing flow attack on the bank, they must be spaced sufficiently closely that the wake zone generated by one tree extends to the next tree downstream, preventing re-attachment of the flow boundary to the bank in-between.

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 (Thorne, 1990).

Large stands of vegetation may act to suppress the meso- and macro-scale eddies shown in Figure 3.4, which will further reduce the erosive attack of the flow on the bank. The actual mechanisms by which this process occurs are not yet well understood. While grasses and other herbaceous plants are effective in protecting the soil surface at low velocities, their influence on flow decreases as velocity increases, and may be eliminated once the plants are flattened by fluid drag forces (Davis *et al*, 1995). Stiff woody stems, by contrast, continue to retard flow up to very high velocities, but in isolation or small groupings may generate serious local scour through convective acceleration of flow around their trunks and through eddy-shedding. The effects of spacing between plants and the architecture or structure of plants are crucial to their effect on the flow field during a flood.

Flexible woody stems at or near the water margin may offer greater bank protection than herbaceous bank colonisers, when the above ground and below ground effects are considered together. The density of vegetation and its continuity from water margin to top of bank are likely to be important, as well as the continuity of vegetated banks and floodplains in the longitudinal direction within the channel/floodplain geomorphic context (Thorne, 1990).

The scale of fluvial processes and vegetation effects must also be considered. For example, fallen trees on a small river can divert the flow and may generate

significant scour of the bed and opposite bank, processes less effective on large rivers (Thorne, 1990). As stream order increases in the downstream direction (see section 2.3.1), 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 dis-benefit by many river engineers. This engineering view is based on the assumption that by increasing roughness, bank vegetation significantly reduces channel capacity, thereby promoting flooding. While this may have some validity where rivers have been channelised and confined in urban areas, there is a growing body of evidence which supports the view that removal of riparian trees and shrubs increases bank erosion and channel instability, aggravating the actual damages caused by flooding (Thorne, 1990, Swanson, pers. comm, 1998). Such a loss of bank stability would increase the effort required for channel maintenance (Holmes, 1994). However, bank vegetation has often been removed to increase channel conveyance, despite the repeated observation that standing vegetation will trap floating debris and prevent it from accumulating at potentially more vulnerable constrictions such as bridge piers.

For most natural channels at high in-bank flows, the contribution of bank roughness to total channel resistance is small (Thorne, 1990). 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 (an increase in the width-to-depth ratio), siltation and aggradation of the bed by sediments derived from bank erosion, and a reduction in both the area and hydraulic efficiency of the channel cross-section.

Following bank vegetation removal, desilting or capital dredging are often required more frequently to restore and maintain channel depth and conveyance to pre-bank

clearance levels (Masterman & Thorne, 1992). Where fiscal accountability and ecological criteria are required of river managers, there is a strong need to re-examine maintenance operations in light of the economic benefits of riparian trees to bank and channel stability (Holmes, 1994), in addition to the suite of other benefits outlined in Chapter One.

These observations illustrate that riparian vegetation offers a wide range of hydraulic benefits that were not included in the post-industrial engineering paradigm. Greater use of the geomorphic context and allowed interactions among natural channels, their floodplains and vegetated banks requires more detailed analyses of physical processes at multiple scales and a shift in practice. In this new paradigm, the use of woody vegetation for river bank protection on constrained channels will require greater technical skills of river managers, but offers rich and numerous added benefits. This is the direction in which the present research is leading.

3.1.11 Roughness computation methods for aquatic vegetation

Much of the research in recent decades draws upon the work of Kouwen and colleagues at the University of Waterloo, Canada. Kouwen & Unny (1973) developed an index of plant resistance based on stem stiffness, which has been cited widely (i.e. by Thorne, 1991). A composite parameter mEI is used to quantify plant resistance. Parameters include the number of roughness elements per unit area (roughness density) m, times the modulus of elasticity of the roughness material E, and the area moment of inertia or cross-sectional area of the stem(s) I (Kouwen and Unny, 1973).

E is the modulus of elasticity, a measure of the degree to which a material can flex and deform plastically while able to return to its original shape. It is measured for various materials by standard engineering tables, but has been applied relatively recently to vegetation by Kouwen and from work done at the Army Corps of Engineers Waterways Experimental Station (Freeman et al, 1996). Kouwen and Unny measured E by dropping a board from a defined height onto the vegetation, such as grass, and measuring the deflection of the stems. This process is a surrogate

measure for the stem deflection by the lateral shear force of flowing water. It's unclear whether this method would apply to tall, brushy willows or other woody vegetation types, and further research would progress understanding this important area.

Kouwen *et al* (1969) examined flexible roughness in vegetated channels, simulating the hydraulic role of aquatic vegetation (grasses, reeds, etc.) in streams and irrigation ditches. Based upon the assumption of the semi-logarithmic velocity distribution laws in open channels, this assigns the roughness element concentration to an equivalent sand grain size k_s. The ratio of average velocity to the shear velocity is a function of the deflection parameter and the height of the boundary layer. As vegetation deflects the flow from the boundary, (assuming uniform vegetation density) the height of the vegetation (in submerged flow) forms the lower boundary of the velocity profile.

In submerged flow, this roughness element shifts the lower boundary of the logarithmic velocity curve upward by the height of the roughness element. Kouwen carried out experiments in a small tilting flume to measure flow retardance by styrene strips under uniform flow conditions. Results are expressed in terms of the deflected height k_s and Manning's n for a given depth, slope, average velocity, slip velocity and hydraulic radius. Deflected height of the flexible roughness elements was estimated visually by noting the height at which the roughness appeared to be situated most of the time, an unrepeatable operation under most field conditions!

Kouwen *et al* (1969) list typical density values and plant hydraulic resistance values for several aquatic vegetation types such as *Elodea, Potamogeton, Alisma, Callitriche* and *Glyceria*, (data from the Netherlands) which deform predictably under the three flow regimes of negligible flow; slow flow when the vegetation undergoes a waving motion; and fast moving water when the plants bend over entirely.

This approach improved upon the standard method of computing roughness n as a function of average velocity U times the hydraulic radius R, by expressing relative roughness as y_n/k. In this way, roughness is related to the relative height of the

submerged vegetation; and the familiar drag coefficient C_D can be related to the number of stems per unit area, the vegetation density. This work could form the basis of extending roughness values for flexible and rigid woody stems during various flow regimes, with a combination of laboratory and field work. The Kouwen method has been applied to in-channel flow vegetation roughness, and has been extended by flume and field research in the UK and in the USA.

Aquatic vegetation habitats and species composition is relatively well documented for British rivers (Haslam 1978), and for hydraulics of flow through aquatic vegetation (Dawson & Charlton, 1988). Flow resistance of aquatic genera has received substantial research attention, owing to the very practical problems in English rivers (and elsewhere) of predicting and controlling aquatic plant influences on navigation channels and drainage ditches (Dawson & Charlton 1988). More recently, research has begun to distinguish between the resistance factors for different types of river bank and floodplain vegetation. Herbaceous grasses offer weak resistance to flow and deform under flow pressure in different ways than the flexible stems of young willow shoots, brushy woody plants or stout tree trunks (Davis *et al*, 1995).

3.1.12 Non-submerged vegetation effects on hydraulic roughness

Petryk & Bosmajian (1975) developed a model for predicting Manning's n values as a function of flow depth and vegetation characteristics. They developed a method of computing roughness values for rigid, emergent vegetation. Their method was to segregate vegetation roughness from bed roughness, assuming uniform or gradually varied flow and non-submerged, non-bending vegetation. Key parameters are

- flow depth d
- length of reach, l
- wetted perimeter, P
- hydraulic radius, R
- approach velocity, v
- plant area in the direction facing flow, A_i
- stem density,
- gradient, S_0 and

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- a computed vegetation area factor.

This vegetation area factor is an expression of density, proportional to vegetation area divided by the total flow area. The factor uses a drag coefficient of 1.0 (compared with Cd =1.2 in Li & Shen (1975)) in the Eqn. 3.17:

$$density = \frac{C_d \Sigma A_i}{AL}$$ Eqn. 3.17

where C_d is the drag coefficient for the vegetation, A_i is the projected area of the ith plant in the streamwise direction, A is the cross-sectional area of flow, and L is the length of reach under consideration. A drag coefficient equal to unity was assumed for vegetation density, used in the computation of vegetation roughness based on the frontal area of all stems presented to flow, channel area and length of the reach being considered.

Using Imperial units, the model shown in Eqn. 3.18 for computing vegetation roughness n_b is:

$$n = n_b \sqrt{1 + \frac{C_d \sum A_i}{2gAL}\left(\frac{1.49}{n_b}\right)^2 R^{\frac{2}{3}}}$$ Eqn. 3.18

where n_b is the bed roughness, and n is the vegetation roughness, R = hydraulic radius (R=Area/ Wetted Perimeter, or on wide rivers and for flow over floodplains, R ~ flow depth). The vegetation roughness n value is mathematically derived from the Manning's n_b value for bottom roughness without vegetation.

Roughness values are computed for vegetation types by flow depth and density, as summarised in Table 3.1.

Vegetation type	description	Flow depth (ft)	Veg. Density (plants ft^{-1})	Manning's n
Wheat	Uniform distribution	0.5-3.0	0.03 – 0.7	0.105 – 0.124
Sorghum	Uniform distribution	0.5 – 2.2	0.09 – 0.16	0.04 – 0.105
Weedy brush in dredged channel	Dense foliage in summer	2 - 12	0.05 – 0.07	0.064 – 0.16
Irreg. channel w/ large trees	Dense foliage in summer	4 – 12.3	0.015 – 0.047	0.053 – 0.143
Valley bottom w/ dense forest	Even channel, . w/ down logs	2.6 – 11.2	0.024 – 0.033	0.08 – 0.17
Channel w/ bushy willows, weeds	obstructed by trees, dense summer foliage	3.9 – 10.2	0.028 – 0.037	0.064 – 0.104
Sample flood plain vegetation	Variety of trees & shrubs	1 – 20	0.064 – 0.075	0.05 – 0.354

Table 3.1. Vegetation roughness values after Petryk & Bosmajian (1975).

The units used, number of plants ft^1, make the data difficult to compare with other authors or standard methods. Plant ecological research methods have for many decades reported plant density in terms of number of plants per unit area such as m^2, rather than per lineal foot, thus this unit (ft^{-1}) is not dimensionally comparable to standard methods. A linear interpretation of vegetation density using units of ft^{-1} may be simpler to measure, but is not capable of representing adequately the density of stems interacting with overbank flows.

Computation of the vegetation roughness n value is based mathematically on the n_b value for the bed roughness, so that in this model, vegetation roughness is a function of bed roughness. They note that the n value increases with depth in rivers with vegetated floodplains, which in reality depends on the architecture of the vegetation. Large trees with single stems, for example, would present a constant, relatively high roughness value over varying flow depths while clumping rushes are very dense near base levels and can be dispersed and fine textured above 0.3m, which would present a lower roughness value at higher stage values.

They found 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 approach may be enhanced once it can be related to contemporary work on drag coefficients; a lead undertaken in Davis *et al* (1995). A field evaluation of the Petryk & Bosmajian (1975) model is used in the analysis of this thesis' field data to segregate vegetation roughness from bed roughness based on the Manning equation (Eqn. 3.6) in Chapter Six.

Arcement & Schneider (1989) examined hydraulic roughness on floodplains, with special emphasis on heavily wooded or forested floodplains. They suggested that the effects of vegetation on roughness depend on:

- depth of flow,
- percentage of the wetted perimeter covered by the vegetation,
- density of vegetation below the high-water line,
- degree to which the vegetation is flattened by high water, and
- alignment of vegetation relative to the flow.

Rows of vegetation parallel to flow, such as the narrow band of willows or alders often seen surviving drought periods along Western stream margins, may have less effect on roughness than rows of vegetation perpendicular to flow. This observation was also made by Li & Shen (1973).

Arcement and Schneider present three methods for computing floodplain roughness values. The first is a modified version of the arithmetic Cowan method, discussed in this section (Cowan, 1956). The second is an indirect method computed from flow and survey data based on Petryk & Bosmajian (1975), and the third is a direct mapping technique.

The Cowan method, also given in Chow (1959) p. 109, segregates roughness values into five discrete elements, given in equation 3.19:

$$n = (n_0 + n_1 + n_2 + n_3 + n_4) * m_5 \qquad \text{Eqn. 3.19}$$

where:

n0 = channel material, values from 0.020 for earth to 0.028 for coarse gravel

n1 = degree of irregularity, values from 0.000 for smooth to 0.020 for severe
irregularity

n2 = variations of channel cross-section, from 0.000 gradual to 0.015 alternating
frequently

n3 = relative effect of obstructions, from 0.000 for negligible to 0.050 for severe

n4 = vegetation, from 0.00 for little (low) to 0.05-0.100 for very high, and

m5 = degree of meandering, from 1.000 for minor to 1.300 for severe

Table 3.2. Basic elements of the Cowan method of computing floodplain roughness.

The Cowan method was developed for in-channel roughness, and was modified by the authors for floodplain features. A range of *n* values for vegetation is given in Table 3.3. for vegetation on floodplain terraces, where flow will encounter plants of varying stiffness and density during floods. For vegetation on floodplains, surface irregularities, obstructions, and vegetation modify the base value for the floodplain's bare sediment surface.

In the modified Cowan equation for floodplain roughness, the variation of floodplain cross-section is given a value of 0.0, (not applicable), and the degree of meandering (*m*) is given a value of 1.0. These values are summed arithmetically, to yield a first estimate of potential floodplain roughness.

Floodplain conditions	n value	Example
Small	0.001 - 0.010	Dense growth of flexible turf grass, such as Bermuda, or weeds growing where average depth is at least 2 times the height of the vegetation; or supple tree seedlings such as willow, cottonwood, arrowweed, or saltcedar growing where the average depth of flow is at least 3x the height of vegetation
Medium	0.011-0.025	Turf grass growing where the average depth of flow is from 1-2 times the height. of vegetation; or moderately dense stemmy grass, weeds, or tree seedlings growing where the average depth of flow is from 2-3 times the height of vegetation; brushy, moderately dense vegetation, similar to 1-2 yr. old willow trees in the dormant season.
Large	0.025-0.050	Turf grass growing where the average depth of flow is about equal to the height of the vegetation; or 8-10 yr old willow or cottonwood trees intergrown with some weeds and brush (none of the vegetation in foliage) where the hydraulic radius exceeds 0.6m; or mature row crops such as small vegetables, or mature field crops where the depth of flow is at least twice the height of the vegetation.
Very large	0.050-0.100	Turf grass growing where the average depth of flow is less than half the height of the vegetation; or dense to moderate brush, or heavy stand of timber with few downed trees and little undergrowth where depth of flow is below branches, or mature field crops where depth of flow is less than the height of the vegetation.
Extreme	0.100-0.200	Dense brushy willow, mesquite and saltcedar (all vegetation in full foliage), or heavy stand of timber, few downed trees, depths of flow reaching branches.

Table 3.3. Adjustment values for factors that affect floodplain roughness, from Arcement & Schneider (1989).

The second method evaluates floodplain vegetation resistivity, following Petryk & Bosmajian (1975). Parameters needed are a boundary roughness value n_o, a bedform roughness n_2, and hydraulic radius $R^{4/3}$. This approach relates these parameters to the vegetation resistivity in Eqn 3.20.

$$Veg_r = \frac{C_* \Sigma A_i}{AL} = \frac{(n^2 - n_o^2)2g}{(1.49)^2 R^{4/3}}$$

Eqn. 3.20

An effective drag coefficient C_* is selected from a curve table for drag C_* and hydraulic radius R. Note that n_0 is the base boundary roughness coefficient,

excluding the effects of the vegetation. The selection of n_0 has a large mathematical effect on the computation of the vegetation roughness value. Arcement & Schneider do not indicate that the final vegetation roughness value achieved by the Petryk & Bosmajian method is strongly influenced mathematically by the selection of the base n_0 value.

The direct mapping method of vegetation density described by Arcement & Schneider applies to heavily wooded floodplains, where tree diameters can be directly measured and mapped onto a grid. Direct mapping of floodplain vegetation quantifies the vegetation area a_i presented to the flow, which is summed to the value Σa_i. Vegetation density is computed using Eqn 3.21:

$$Veg_d = \Sigma_{ai} \Big/ AL = \frac{h\Sigma n_i d_i}{hwl} \qquad \text{Eqn. 3.21}$$

where $\Sigma n_i d_i$ = summation of the number of trees multiplied by tree diameter
h = height of the water on flood plain,
w = width of the sample area, and
l = length of the sample area.

Mapping the vegetation gives the added benefit of getting the engineer out onto the floodplain, observing site conditions, which direct perception is always informative.

The combination of field survey for vegetation density and the computation by the Petryk & Bosmajian method could be helpful under circumstances such as where bridge footings are being placed in the wooded floodplain, so that the two n values could be compared for a best estimate. The direct mapping method by Arcement & Schneider, if applied with care, could give reasonable estimates of floodplain roughness for bed, vegetation, obstructions, and surface irregularities, assuming experience on the part of the practitioner.

Arcement & Schneider suggest that, for wide, deep channels (having small width-depth ratios) with little or no in-channel vegetation, the hydraulic effect of bank vegetation is likely to be small, and give a maximum value of about 0.005. (see also Masterman & Thorne, 1992).

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Klassen & van der Zwaard (1974) modelled a vegetated floodplain for two main rivers of low gradient (the Rhine and the Meuse) in the Netherlands, to determine roughness coefficients in order to predict stage heights for large floods. Two types of vegetation, dense agricultural hedges and orchards, were treated using field data and a flume study (flume dimensions 3m wide x 3m deep x 7-m long). In the flume, flow through hedges was simulated, then organic debris was simulated as hay was added to the hedges, to observe the change in discharge over the floodplain.

For the orchard model, a smaller flume was used on a scale of 1:10 (3m wide x 20m long). Model velocities were scaled using the Froude-scale law. Eight spacings were tested in the flume using 1 baseline treatment, 3 parallel and 4 staggered patterns. Model data were analysed using a modified Chezy formula, to calculate the change in stage height with varying roughness. Drag coefficients varied from 0.8-1.65.

Results of the tests indicated no detectable difference in drag values for staggered vs. parallel spacing of trees. Comparison of the bare floodplain with a vegetated one showed slight increases in computed water levels, but the vegetated condition indicated higher velocity in the main channel. Their results also showed that removal of all hedges would decrease the water slope by 15%, and would decrease the mean velocity in the channel. Their analysis lead to the conclusion that, if river-works in the floodplain would have an unfavourable effect on discharge, then this could be compensated by the removal of (floodplain) vegetation (Klassen & van der Zwaard, 1974). This approach to hydraulic analysis and river engineering, considering river modification and flood dynamics without taking into account fluvial geomorphology, sediment transport, hydrology, stream and floodplain ecology or climatic effects of river engineering, is fortunately considered today an outdated paradigm by modern river engineers.

Flow patterns around riparian vegetation are affected by the structural rigidity of the plants (Rahmeyer et al, 1996). If stems are uniformly distributed and uniformly rigid, flow velocity can be uniformly reduced and sedimentation evenly distributed.

If, however, stems are deformed by flow, erosion and sediment transport may be increased under the bent crowns of the vegetation, possibly owing to the phenomenon of instantaneous scour (Rahmeyer *et al*, 1996). Thorne *et al* (1998) reported that bank material detachment and entrainment usually occur during turbulent sweeps, when velocities and stresses may, for short duration periods, attain values triple the time-averaged mean (Jackson, 1976; Leeder, 1983), throwing into question the common field practice of using the mean velocity (at 6/10ths depth) to characterise roughness and resistance in the flow field, (Thorne *et al*, 1998). Vegetation, especially if erect but flexible, may damp local turbulence and so reduce the magnitude of instantaneous velocity and shear stress peaks (Thorne, 1990).

Flow patterns are affected by the shape and spacing of the roughness elements. Fluid flow, whether wind or water, over a rough surface generates a wake, which increases turbulence within the roughened, non-laminar boundary layer (Wolfe & Nickling, 1993). Flexible vegetation interacts with the mean flow velocity by extracting momentum from the flow through movement of the stems. According to Wolfe & Nickling (1993), flexible vegetation produces turbulence in the form of wakes behind the obstacles, breaking down large-scale turbulent eddies into smaller scale motions (Wolfe & Nickling, 1993). At the tops of the vegetated layer, the velocity profile changes abruptly as a result of the considerable shear produced by the roughness elements. (See the velocity profile, Figure 3.5, from Stillwater Laboratory, 1949).

Freeman *et al* (1996) studied hydraulic resistance of shrubs in flood control channels, and simulated overbank flows through natural vegetation using both a large and a small flume. They developed an empirical model to predict Manning's '*n*' values for submerged and emergent plants on engineered floodplains of flood control channels, for use in predicting conveyance in channels with vegetation growth.

For plants partly submerged or emergent, the prediction equation 3.21 is:

$$n_{veg} = 0.0393 \left(\frac{EI}{\rho V^2 A^* H^2} \right)^{0.216} \left(MW_p \right)^{0.246} \left(\frac{H'}{D_s} \right)^{0.547} \qquad \text{Eqn.3.21}$$

where n_{veg} = Manning's n value for vegetation
Ds = diameter of stem
M = plant density
V = average velocity
H' = (average) height of leaf mass
E = modulus of elasticity
I = area moment of inertia of plant stem
A = effective plant area
H = plant height (= Y_0 if unsubmerged)
W_p = width of leaf mass
Y_0 = depth of flow

Complexities encountered in field evaluation of the models required adjustments of the resultant n values, to account for such factors as base n values, floodplain roughness, additional roughness from understory plants, and other adjustments specified in Cowan's method (see section 3.1.11). The authors reported difficulty in locating vegetated floodplain field sites which could be entered during overbank flows, and exceptional difficulty with the actual field data collection process. Resulting n values are reported in Table 3.4.

In the non-submerged equation, plant height was taken to equal the flow depth. These authors also called for additional field sites to verify the flume results (Freeman et al, 1996).

Manning's n values for field sites						
Site	Density #/m^2	Stem diam. (cm)	Water depth (m)	Veg type	Field n value	Eqn. 3.26 n value
Big Wood R. channel margin	10.05	2.2	0.51	Willow	0.11	0.08
Henry's Fork site 1	10.76 9.41	2.16	0.34	Willow & rose	0.18 0.14	0.12 0.11
Henry's Fork site 2	9.23	2.54	0.39	Willow & rose	0.14	0.12
Cottonwood R. channel margin	218	2.08	0.29	black willow	0.33	0.24
Cottonwood R. floodplain	59.2	1.88	0.29	black willow	0.14	0.15

Table 3.4. Field and predicted Manning's n values from Freeman et al (1996).

The authors note that Eqn. 3.21 tends to under-estimate roughness values compared with those values measured in the field.

Smith *et al* (1990) considered the hydraulics of overbank flow for the Australian practice of strip cropping along floodplains. The authors identified a need for an adequate hydraulic description of flow through emergent vegetation based on soil conservation methods for erosion control. They a constructed a flume with 2 channels 20m long, 2m wide and 0.6m deep, filled with native soil and sown to common crop plants such as maize and sorghum, to provide controlled flows under simulated local floodplains conditions. They compared hydraulic behaviour using two models; the Manning equation (Eqn. 3. 3) and a depth-discharge equation (Eqn.3.22) based on the Darcy-Weisbach equation (Eqn. 3.5).

Their analysis of the vegetation roughness used data from Ree (1949), Kouwen & Unny (1973), Ree & Crow (1977), and Temple (1982), as well as Australian data. They suggest that the Manning approach is flawed because the equation results in a roughness coefficient n which is constant for any particular surface, however when the equation is applied to flows over surfaces with large or flexible roughness elements, such as vegetated surfaces, n becomes a variable. Their analysis showed

that the Manning equation does not yield an unique value for each set of velocity–radius (n-VR) products (see Section 3.1.10) . Because the VR product can be equal for either a shallow rapid flow or a deep, slow flow, the theoretical basis for this model is flawed, and they discontinued using it.

Their preferred flow equation is based on the theoretically correct Darcy-Weisbach equation using the depth-discharge equation 3.23:

$$q = aS_f^b y^c \qquad \text{Eqn. 3.23}$$

where q is the discharge per unit width of flow, S_f is the energy or friction slope, y is flow depth. a is a coefficient and b and c are fitted exponents from empirical data for flow through crop plants maize, sorghum, wheat and other grasses. Distinct regression equations grouped by slope were derived for submerged and nonsubmerged flow (Figure 3.3). Application of the Smith *et al* (1990) model for woody emergent floodplain vegetation would depend on adequate field and laboratory research to develop the coefficients a, b and c for a relevant range of floodplain vegetation conditions. Lacking these coefficients, the Smith *et al* (1990) model was not applicable for this thesis analysis, but the potential value of developing this approach is recognised.

Work in the Netherlands on floodplain forest (RIZA, 1997) identified that the area of stems exposed which create hydraulic roughness varies with the age of the forest. Dutch research has expressed hydraulic roughness as a function of the density of stems presented to flow, in units of m^2/m^2. Young willow forest presents much higher surface area to flow than does old willow forest or ash-elm forest. Partially submerged vegetation has higher flow resistance than plants completely submerged. The authors noted that, on the very wide European floodplain rivers, the location of the floodplain forest in relation to the channel (i.e., the foreland near the main channel) plays an important role in the degree of hydraulic roughness. Floodplain forest in the floodplain foreland has a greater effect on flood stage levels than forest further back from the main channel. Dense forest cover near the dikes improves wave attenuation and reduces wave erosive force against the dikes (RIZA, 1997).

3.1.13 Vegetation hydraulics in channel-floodplain interactions

A manual published by the German Association for Water Science and Construction (Deutsche Verband für Wasserwirtschaft und Kulturbau- DVWK (1991) illustrates the German hydraulic conceptual division of a river channel and floodplain into distinct roughness regions, with the role of vegetation included in channel-floodplain interactions. This conceptual model has guided contemporary hydraulic research in Germany to develop a theoretical foundation for the recovery of streamside vegetation which must accompany river and floodplain rehabilitation, to compute vegetation effects on flow capacity.

This approach is based on earlier research into the 'two-stage channel' Fig. 3.6.a, (see Wark *et al*, 1994), which has been shown by laboratory investigation at HR Wallingford, UK, to be more efficient at carrying design flood flows than a simple rectangular 'box' channel.

The interaction effects between channel and floodplain flows during floods are complex; compounded with the addition of vegetation of varying dimensions to the banks. Turbulent exchange is an important property of such interactions, because the chaotic patterns make numerical modelling of flows with vegetation very difficult on any scale larger than a few centimetres.

A conceptual model developed in Germany has assisted hydraulic research in identifying regions of interactions and the role of bank and floodplain vegetation on flood flows, referring to Figure 3.6.

Interaction   Interaction   Interaction
zone 3   zone 2   zone 1

I   II   III   IV   III   II   II   III   IV

Qualitative representation of cross-section partition in various discharge regions for three examples of articulated profiles (half-side examples).
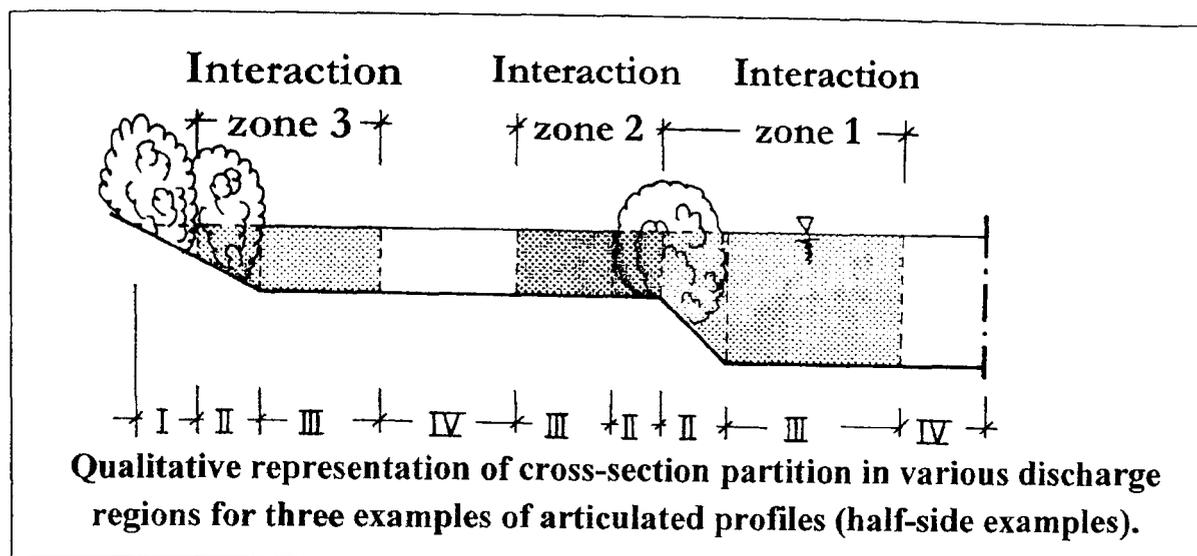
Figure 3.6. Regions of coherent flow structure between channel and floodplain flows, showing non-submerged vegetation influence on turbulence exchange in the cross-sectional velocity profile, from Pasche (1984). See text for explanation of regions.

Macro-turbulence exchange is generated by channel form at the boundaries between thalweg, bank slope and floodplain. Vegetation placed at the 'separation wall' between channel and floodplain reduces velocity and causes eddy shear stress in region II. Region I is the zone where resistance to flow is only from vegetation and the bed surface, flow velocity is negligible and turbulence is very high. In regions II and III, the resistance to flow comes primarily from 'macro-turbulence' elements of channel form and the interaction between the vegetation zone 1 and free-flowing water. Region III is open channel flow influenced by turbulent exchange with high velocity flow. Region IV is uninfluenced by vegetation resistance, and supports relatively smooth, high velocity open channel flow.

The interaction zones identified in the flume appear to have characteristic turbulent momentum exchange such as eddy shedding vortices where a shear force develops between regions of slower and faster moving water (DVWK, 1991).

Pasche & Rouve (1985) investigated flow characteristics in non-submerged floodplain roughness using dye visualisation techniques. On a two-stage channel with cylindrical rods on the floodplain, they observed an intensive vortex shedding at

the interface between channel and floodplain, sometimes called a 'hydrodynamic wall'. The resistance due to this momentum exchange is considered by subdividing the channel into different sections, regarding the turbulent shear stresses as apparent wall shear stresses.

Pasche & Rouve carried out field tests of their model on a channel with a line of willow bushes at the floodplain margin. Their model considered the flow resistance in each of the four subdivisions shown in Figure 3.7.
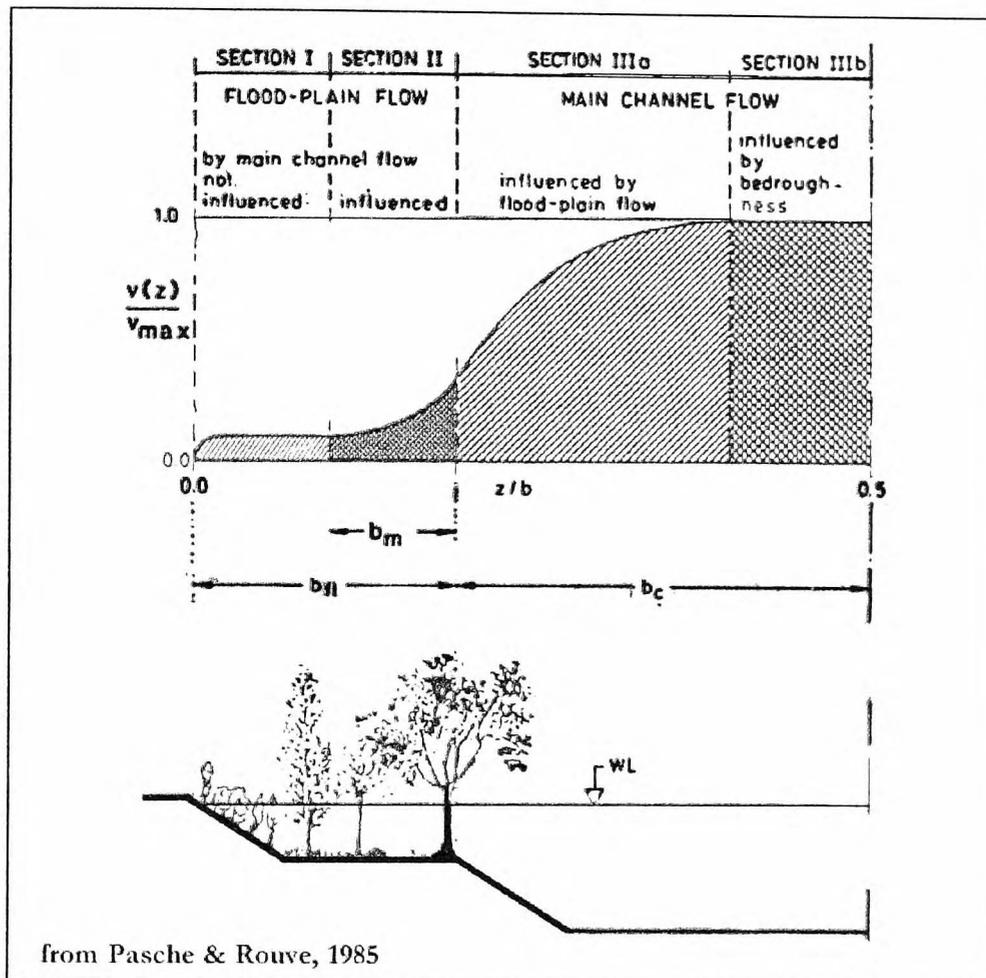
Figure 3.7. Compound channel subdivided into different flow sections. The curve above is the ratio 'average velocity/ maximum velocity'. From Pasche & Rouve (1985).

In Figure 3.7, v is velocity, z is the transverse dimension, b is a width parameter, b_{fl} is the floodplain width, b_c is channel width, b_m is a co-operating width, W_L is the water line. The graph above illustrates a typical velocity distribution across the floodplain and channel, and also shows how bedform roughness influences velocity distribution across the channel.

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For the floodplain section not influenced by main channel flow, Pasche & Rouve observed rather constant velocities on the floodplain, varying with the density of the vegetation (Figure 3.6). The width of the vegetation zone and the bank slope are of only minor importance in compound channels with vegetatively roughened floodplains, but the bedform effect of the channel (side) slope has considerable importance for flow resistance. The Pasche & Rouve (1985) model predicted, for shallow floodplain flood depths, that the momentum exchange between channel and floodplain has a significant reduction effect on overall discharge in compound channels with non-submerged floodplain roughness. They concluded that for high vegetation densities, the friction factor λ can be actually increased by reducing the width of the wooded floodplain. This suggests that 'narrow ribbon' type revegetation patterns, such as the willow spiling or live woven woody fence bank protection, may have higher friction values than wider vegetative treatments which include the width of the bank and floodplain.

The work of Pasche & Rouve represents some of the earliest efforts on the hydraulics of vegetation (buffer) zone width. This work had a strong influence on the development of the present research, and aided the conceptual model relating field data collection to flume modelling of flow through a channel with a vegetated floodplain.

3.1.14   Vegetation effects on flood wave attenuation

Wave attenuation is an important function of either herbaceous or woody vegetation on the river banks and lake shores (Markle, 1979, van Splunder, 1997). Research on large, lowland alluvial rivers, such as the Rhine in the Netherlands and the Mississippi has demonstrated that vegetated groin structures significantly reduce wave-induced bank erosion (van Splunder et al, 1994).

A flume study carried out at Vicksburg Mississippi for the Army Corps of Engineers tested wave attenuation for geometrical spacing of trees with and without branches. The results of this study demonstrated that it is the tree branches which are the most effective component at reducing wave attack against river banks during floods, with

an average wave attenuation at a minimum of 15% with branches compared with an average of less than 9% without branches, (Markle, 1979).

Wave attenuation effects of floodplain forest have been studied extensively on floodplain rivers of the Netherlands (RIZA, 1997). Floodplain forest decreases both the speed of the current and the height of the waves, but may increase the height of the water surface during floods. Wave attenuation is a result of the loss of energy owing to the bending of flexible willow trunks under the influence of the waves, and the creation of turbulence behind them. The mechanisms of vegetation attenuation of waves are not well understood, but important factors identified include the height and width of the forest, stem or trunk density and diameter, water depth, wave height and distance travelled. Increasing stem density can be managed by cutting or coppicing willows to maintain the young, flexible stem condition. Grazing on the floodplain typically reduces stem density (RIZA, 1997).

3.1.15   Computation of flow resistance for vegetated banks

Masterman & Thorne (1994) developed rational flow resistance equations based on the Colebrook-White equation using the Darcy-Weisbach friction factor f, which characterises the distribution of boundary shear stress. The Colebrook-White equation is expressed in Eqn. 3.24:

$$\frac{1}{f} = a + c \log\left(\frac{R}{K}\right) \qquad\qquad \text{Eqn. 3.24}$$

where K is a roughness height, R is the hydraulic radius, c is a coefficient derived from the von Karman constant usually taken to be 0.4, and a is a coefficient determined by the cross-sectional shape of the channel.

Oplatka (1996) developed an equation for computing resistance of woody vegetation for the measurement of soil bioengineering constructions. Using 5-year old willows growing along a navigation canal, a series of flume experiments were conducted velocity measurements were made over a range of flow depths, 0.8m to 1.6m. Detailed measurements were made of the plant characteristics: species, height, width, age, number of stems greater than 8mm, stem volume and dry weight.

Degree of bending was measured for stems, which was dependent on flow velocity. Oplatka noted that the drag coefficient for resistance of flexible woody stems is dependent on flow velocity. Willows were partially submerged or not, in the flume with varying flow velocity, to measure the deformation of stems and the resulting flow retardance. Flume velocities varied from 1 to 4 m s^{-1}.

Stress resistance for plants is given in Eqn. 3.25.

$$S_W = C_D \times A \times \rho \times V^2/2 \qquad \text{Eqn 3.25 where}$$

S_W = plant shear resistance (kN)
C_D = drag coefficient
A = plant stem surface area (m^2)
ρ = water density (kg m^{-3})
v = velocity (m s^{-1}).

From the graph of a relationship between C_D * A and velocity by flow depth, values for C_D * A can be obtained. This work appears to be at the leading edge of engineering computation of vegetation resistance. Because Oplatka's velocity data do not extend below 1 m s^{-1}, the assumptions of the model are challenged by the application of the present research data below the threshold of lowest velocity. Nonetheless, this is attempted in Chapter Six to obtain estimates of the shear resistance of the vegetation structures in the present research.

Masterman & Thorne (1994) used the theoretical work of Kouwen to express resistance of vegetated banks, based on the formula for shear resistance given in Eqn. 3.13. Their approach divides resistance for bed and bank into sub-areas, taking into account roughness height based on stiffness for flexible vegetation and depth of flow, and using a wake correction factor (to velocity) for emergent, non-bending vegetation. Effects of the vegetation wake on velocity can be incorporated into calculation of the discharge capacity at a cross-section. Masterman & Thorne developed a series of algorithms for computing discharge in gravel-bed rivers with vegetated banks.

Reductions in channel capacity (discharge) are computed as a function of the width-depth ratio, and the vegetation stiffness. The results of their numerical simulations

indicate that the hydraulic effects of bank vegetation decline rapidly as width-depth ratio increases. That is, as rivers become wider, the flow is influenced decreasingly by floodplain and bank vegetation, even trees. This has significant consequences for large river management, where even large trees may have a relatively small influence on high-magnitude flood flows. This logical finding shifts the burden of managing trees on large floodplains from the direct effects of tree roughness on stage levels, to managing the consequences of large woody debris during floods, and in particular, ensuring adequate clearance during flood stage for river crossings (Williams, 1990). On smaller channels and on space-limited urban creeks, large trees and shrubs near the water margin are likely to have a greater influence on flood risk (Masterman & Thorne, 1994). This method is derived from theoretical relationships and mathematical models, and could be furthered with additional field applications. The model has potential to be helpful in progressing the incorporation of vegetation into engineered channel and floodplain design.

Considering the significant advances made in hydraulic engineering in the 1990s owing to high-speed and high-memory, computer-based 3-D mathematical modelling, computation of woody vegetation influence on overbank flows remains dependent on verification by physical models and field data. In 1997, physical modelling was as yet unable to predict flow behaviour for overbank flows in compound meandering channels with channel-floodplain interaction for sediment bearing streams with vegetated boundaries (Ervine, pers. comm. 1997). The resistance values of flexible woody stems such as shrubby plants or those created by the traditional European coppice method of willow pruning are presently beyond computation, but would appear to offer much promise in river bank management, for both hydraulic and geotechnical considerations.

A practical problem arises from the fact that most hydraulic computation methods applied to natural river conditions are based on a relatively small number of physical (or flume) models of river process. Some field verification of flume models has been carried out using naturally occurring plants (Freeman *et al* 1996). But the natural river conditions which best support a diverse and healthy ecosystem are at present too complex to model, and few studies of open channel hydraulics have been carried

out on vegetated natural rivers and flow through their floodplains. Thus, recognition of the importance of vegetated riparian corridors and floodplains has generally not been accompanied by concurrent laboratory and field research into the hydraulic performance of these complex systems. The result is that design engineers can be most reluctant to incorporate vegetation into their channel or revetment design, because of a lack of design guidance.

Field-based fluvial geomorphic research is steadily addressing this gap between hydraulic theory and laboratory research on the one hand, and field-based research on complex landscape-level and smaller scale processes on the other. The present study addresses a component of this research gap by testing flume-derived models with field data, addressing the current lack of information on woody vegetation influences on overbank flow structure and sedimentation responses to flood flows on vegetated streambanks and floodplains.

3.1.16   Flume research and the problem of scale effects

With the growing demand internationally for more natural looking rivers, many workers have recognised the need for hydraulic research at the scale of 1:1 to enable better prediction of the effects of various vegetation regimes. UK researchers have called for a vegetated flume facility on a scale of 1:1 (Thorne *et al*, 1998), but greater multi-functional and institutional support will be needed for this approach in hydraulics research. In Vienna, Austria on the river Wienfluss, the Institute for Soil Bioengineering and Landscape Planning (Universität Wien Institut für Bodenkultur, Institut für Landschaftsplanung und Ingineurbiologie) have, for the first time, tested the performance of several soil bioengineering construction methods for controlled release discharges, with estimates of bank shear stress and computed thresholds of failure for 'soil bioengineered' structures (Gerstgraser, 1998).

Flume research in Switzerland has tested the shear strength of willow stems in engineered canals and their applications is soil bioengineering structures, with the goal to inform engineering design practice (Oplatka, 1996).

Klumpp & Falvey (1988) simulated the roughness of sparse mesquite trees on an engineered channel in a flume study at a scale of 1:30. The flume roughness elements were plastic trees "similar in texture to mesquite trees". Roughness data were analysed using the Darcy-Weisbach friction factor f to obtain an equivalent sand grain roughness k_s for use in the Colebrook-White equation. The momentum equation was used to solve for k_s. After testing the effects of roughness on discharge in the channel, they computed that the presence of the mesquite reduced effective discharge about 6% for Q>2.7 x 10^4 m^{3}s^{-1}. Their test for roughness did not look at vegetation effects on flow patterns, or the possibility that vegetation influences could have beneficial effects on overall flow patterns in the engineered channel, directing regions of high and low velocity and turbulence zones.

Dynamic similitude is the principle on which all physical modelling is based (Shapiro, 1966). This is in contrast to geometric similitude, or the reproduction of some single dimension of size, for example a ratio of length and width. Scale models of airplane wings or dam spillways are usually geometrically similar to the full-scale structure. Dynamic similiarity makes use of the ratio of forces, such as density (fluid inertia) and viscosity (fluid frictional resistance to distortion). The Reynolds number (Eqn. 3.9) is a relationship between density x speed x length, divided by viscosity, which gives an expression of the inertial forces to the viscous forces. This expression yields a ratio of forces not dependent on geometry, which thus can be represented at smaller or larger scales than the original scale.

However, as the scale becomes smaller, the influences of weaker forces, gravity, viscosity and surface tension become relatively greater than at 1:1 scale. Fluid viscous forces are the attractions of water molecules for each other, which are especially important when characterising the height of the boundary layer, as water molecules adhere tightly to the boundary layer and flow with increasing velocity as distance from the boundary increases (Figure 3.1). In the flume, this height is exaggerated in proportion to the rest of the water column. Typically the range of turbulence generated in the flume is much lower than turbulence found in natural streams, on the order of **Re** = 10^2-10^3, as compared with a natural stream **Re** > 10^4.

In attempting to model both the geometry and dynamics of overbank flow through roughness elements on a floodplain, a necessary distortion is introduced as the vertical dimension differs from the horizontal (typically with ratios such as 1:10 vertical and 1:50 horizontal). While such exercises can be very informative by allowing, for example, a plan view of flow behaviour, caution must be exercised that the results are not taken into application too specifically. Interpretation is therefore as much a matter of understanding as of computation. This distortion effect is why, for fluvial geomorphic flume research, the flume model should be tied as closely as possible to field conditions, to minimise distortion effects and to enhance the reliability of the flume results. Strong links between field and laboratory research have substantial potential to progress understanding of complex flow behaviour.

3.2   Vegetation in models of sedimentation processes

The following discussion represents a narrow range of the possible topics for consideration, relevant to the present research.

3.2.1   Thresholds of sediment transport and entrainment

Much theoretical and empirical work has been devoted to the identification of thresholds of sediment entrainment, transport and deposition (Yang, 1996). Theoretical relationships among fluid properties and suspended sediment properties of size, shape, surface roughness and density are reasonably well defined from extensive laboratory and field research. These relationships inform understanding of such processes as channel stability criteria, fluvial landform evolution, sediment recruitment rates and a host of fluvial processes.

Yang (1996) presented criteria for critical water velocities and the mean sediment size a flow is capable of transporting, from Vanoni (1975), shown in Figure 3.8.

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Critical water velocities for quartz sediment as a function of mean grain size (Vanoni, 1977).
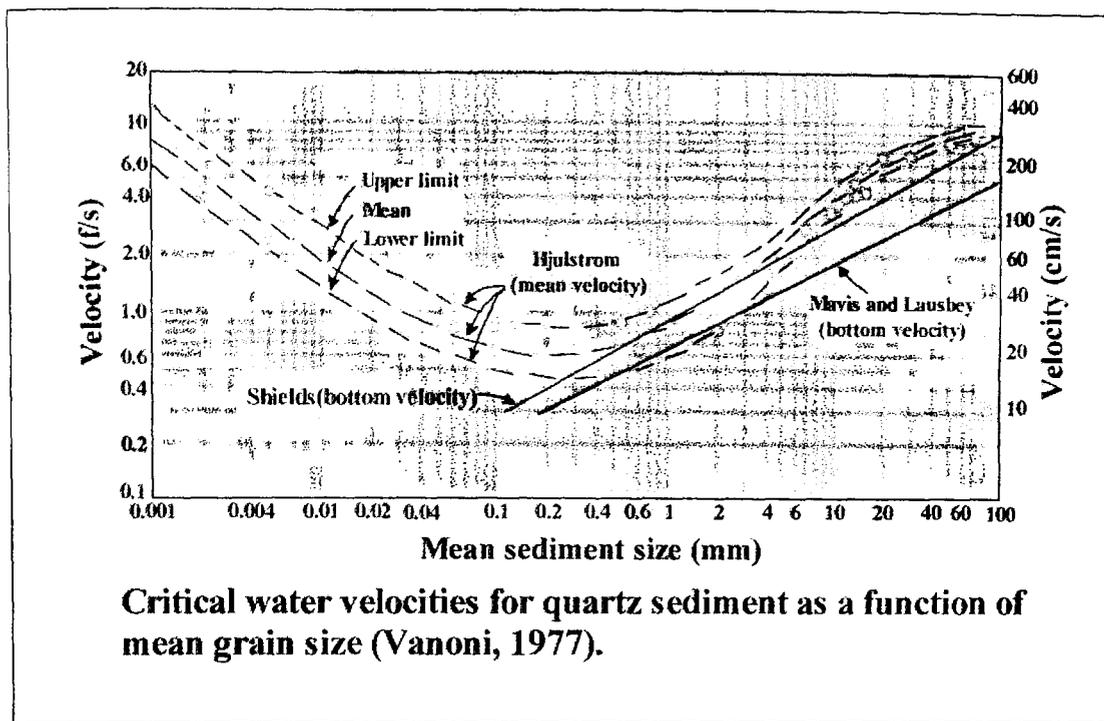
Figure 3.8. Vanoni diagram for entrainment thresholds for sediments by mean particle size, from Yang (1996).

These data can be used as guidelines for estimating the capacity of water to move sediments by size classes. Such information is fundamental to prediction of sediment transport rates and recruitment rates of sediment (such as gravel) based on flow velocity.

3.2.2   Parameters in sedimentation modelling of vegetated flume channels

Ree (1949) had showed that the hydraulics of flow through submerged and non-submerged vegetation differs significantly. Tollner *et al* (1976) developed a sediment trapping function to address the hydraulics of sedimentation in emergent vegetation, which has been applied to the field data in this thesis.

The Tollner *et al* (1976) model was developed from flume experiments using rigid, non-submerged cylinders and uniform sediments composed of small glass beads. In the flume, they observed the capacity of rigid, non-submerged vegetation, (simulated with iron nails), to filter suspended sediment. The cylinders were placed across the

entire width of the flume channel, so no edge or backwater effects would have been detectable for the empirical model.

To explain the detail following, the critical physical parameters used in the model are given:

- channel slope
- discharge or flow rate
- particle size
- particle fall velocity
- suspended particle concentration
- characteristic spacing of the vegetal filter media
- channel length.

The particle fall velocity (the speed at which a sediment particle falls out of suspension) is based on a uniform (spherical) grain size (glass beads), the channel length, flow velocity and depth, and a Reynolds turbulence index, an increase of which would increase the probability of particle suspension. Turbulence is represented in the model in the parameter Root Mean Square (RMS) of the Reynolds Number (Eqn 3.12).

The Tollner *et al* (1976) empirical model formula is given in Eqn. 3.26 as:

$$\frac{Si - So}{Si} = Exp\left[-1.05 * 10^{-3}\left(\frac{VsRs}{v}\right)^{0.82}\left(\frac{V_m L_T}{V_s d_f}\right)^{-0.91}\right] \qquad \text{Eqn. 3.26.}$$

Symbol	Definition	Units
S_i	Sediment input concentration	(g sed./ g H20)
S_o	Sediment output concentration	(g sed./ g H20)
V_s	Mean flow velocity	m/s
R_s	Spacing hydraulic radius	m.
v	Kinematic viscosity	(m^2/s) $v=\mu/\rho$, where
μ	dynamic viscosity	$(N*s/m^2)$
ρ	fluid density	$(kg/m^{2)}$
V_m	Particle settling velocity	(m/s)
L_T	Section length (of channel bank)	(m)
d_f	Flow depth	(m)

The coefficient and the first term together formulate the Reynolds Turbulence Index, and the second term formulates the particle fall number N_f (Tollner *et al*, 1976).

Three 'filter' spacings were used in the flume (210cm x 13.5cm x 10cm), and particle size and sediment concentration were varied. Particles were kept in suspension with an agitator at the flume inlet to maintain uniform concentration. Flow depth was sampled with stilling wells along the flume, and uniform flow was maintained.

In tests with larger beads on lower slopes, deposition built up rapidly at the inlet point; there the surface slope increased, but little of the material moved as suspended flow, only as bedload. Tests on the smallest beads produced lower trapped fractions overall, and the depth of deposited material decreased uniformly with distance from the inlet, effectively increasing channel slope. Medium sized beads produced intermediate results. A linear regression model was created from the observed results for the percent trapped sediment on particle fall number and the Reynolds turbulence index. The fraction trapped was found to be a function of the media spacing, flow depth and velocity, sediment concentration, particle size, and channel length.

This model is used to analyse the field sedimentation data in Chapter Six, to estimate quantitatively the sediment filtration capacity of the Mattole siltation baffle structures. Such an engineered revegetation application offers an opportunity to test the accuracy of the laboratory-derived model under field conditions, where parameters such as mean velocity, particle concentration (in flow) and vegetation stem density can be difficult to measure accurately. Results could be helpful in increasing the ability to predict the potential volume of fine and coarse sediments which could be kept out of stream channels with revegetated floodplains.

3.3 Sediment deposition among vegetation during overbank floodplain flow

Abt *et al* (1994) developed a quantitative measure of the influence of herbaceous vegetation on sediment deposition, entrapment and retention of fine sediments on

lower order streams in mountainous areas. In previous studies, Abt had identified that the length of the leaf blade had a strong effect on the amount of sediment deposited, such that as the leaf blade length increased, sediment deposition during transport decreased. The authors constructed a meandering flume to simulate stream conditions for the US intermountain area, and conducted four test series. The first test series measured sediment deposition areas in the flume with no vegetation. A second series evaluated the enhanced sedimentation with submerged grasses present; a third series examined the sediment retention during flushing flows with submerged grass present, and a fourth series tested the effects of leaf blade width on sedimentation.

The first series identified the inside meander bend location where sediment deposition occurs naturally. In all other planform locations, the presence of grass had a positive effect on sediment deposition and retention for all flow conditions. Shorter leaf blades enhanced deposition significantly more than longer leaf blades, apparently because the longer blade flattens more easily, armouring the bed against sediment entrapment. The wider corn leaf blades captured and retained less sediment than the Kentucky bluegrass in the other trials (Abt *et al*, 1994).

Brown & Brookes (1997) measured rates of sedimentation from overbank flow on leaves of floodplain plant species. They noted that flood sedimentation is difficult to quantify, that sediment concentration is dependent on the distance from the channel and that fresh deposits are often eroded by subsequent flood events. They observed that herbaceous species such as nettles (*Urtica dioica*) appear to 'scavenge' fine sediment particles from the water column by a mechanism of fine leaf hairs, and in experimental work showed that these deposits occur on leaf surface without respect to depth. They hypothesised that leaf surface modifications may have evolved to increase retention of phosphorus, which is typically bound preferentially to sediment particles. In densely wooded floodplains with high overbank velocities, overbank deposition on leaves was not found, suggesting that macro-roughness elements may prevent overbank deposition of fines and may instead favour overbank scour. The

few data sets on vegetative influence on overbank sedimentation and scour processes indicated to the authors that factors such as biomass and structural diversity may be significant in vegetative controls on overbank sedimentation and scour processes (Brown & Brookes, 1997). Because "real-world" data are both difficult and expensive to gather, such data sets tend to be small. Real data posses great potential valuable in progressing scientific understanding of real-world processes.

3.4   Geotechnical effects of woody vegetation on banks and levees

Woody riparian (not necessarily floodplain) plants have a controlling influence on bank stability of alluvial rivers. Hupp and Simon (1986) demonstrated channel widening rates of up to 2.4m/year for straightened, dredged rivers in Tennessee, using dendro-ecological and dendro-geomorphic analysis of riparian vegetation. Once active mass-wasting is relatively stabilised (the channel begins to recover from dredging/straightening), germination and establishment occurs rapidly. Riparian vegetation enhances sedimentation and tolerates sediment accretion by infiltrating fresh sediments with new root mass. Subsequent growth following burial initiates root cell growth among stem tissues, and excavation of buried stems can provide botanical evidence of channel evolution processes. They showed that widening occurs predominantly by mass wasting of banks, and that riparian vegetation ameliorates bank erosional processes. In their study, the most unstable reaches were those largely devoid of bankside vegetation (Hupp & Simon, 1986).

Amarasinghe (1992) showed that the presence of plants on the banks of lowland British channels with cohesive sediments significantly affected bank stability, primarily by roots increasing the shear strength and particle cohesion of soils. Grasses and herbaceous plants have average root depths typically less than 1m, and grass roots are most effective at increasing bank stability when the slip surface is less than 1m deep (Amarasinghe, 1992). Using native vegetation for stabilising river banks is a design process dependent as much on the soil medium and groundwater levels as on the surface environment.

3.4.1   Effects of woody vegetation on banks and levees

Engineered levees have been constructed along many rivers throughout the world. Most have been maintained devoid of vegetation, often to ease the inspection of damage from burrowing animals, but usually to avoid the damage caused by windthrow of large trees. However, where trees have been allowed (usually by increasing the cross-sectional area of the levee) to accommodate windthrow, research has shown some of the beneficial effects gained with tree cover.

Shields & Gray (1992) observed levee root densities by excavating trenches in vegetated levees. Root area ratios (RARs) were computed for herbaceous and woody vegetation types. Root orientation was observed to be important by vegetation type, although influenced by soil moisture and drought regime. Shields & Gray showed that plant roots, both woody and herbaceous roots, effectively bind soil particles and increase soil cohesion, even in sandy soils (Shields & Gray, 1992).

Woody and herbaceous root effects on slope stability were calculated using seepage analysis, circular arc and mass stability analyses. In the standard slope stability analysis, a safety factor of 1 indicates a slope just at equilibrium (Selby, 1993). Without roots present, safety factors for slopes were found to be less than unity on critical shallow failure arcs. With roots present, safety factors ranged from about 1.2 to 16.5, with root influence greatest near the surface declining sharply with depth. Since woody roots have greater strength at depth than herbaceous roots, Shields & Gray, (1992) found that levee maintenance could be improved by allowing woody shrubs and small trees to grow on the riverside of the levee. They did not address the question of change in plant architecture over time, which would influence ongoing levee maintenance. Temporal change in plant structure would progress toward an increase in above-ground plant mass, potentially increasing the risk of treefall and root-throw (Thorne *et al*, 1998), which could undermine levee integrity, unless preventative maintenance kept the above-ground growth in check without destroying the plants (Holmes, 1994).

These findings further encourage the maintenance of woody riparian vegetation as relatively flexible stems, without a large, high hamper to transmit turning moment to the root mass during high winds or flood flows. Maintaining willow and other

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suitable riparian trees in a coppiced state also encourages extensive root growth and can increase plant longevity and utility.

3.5   Geomorphic channel instability and streamside vegetation

The problem of channel incision is addressed here because it is so critical for understanding vegetation fluvial interactions on many streams around the world. This section does not directly address the field conditions encountered on the study site, but is highly relevant for a large number of stream systems where streamside vegetation recovery may be desired. Relatively little literature exists on the subject, but this represents a field of growing interest internationally.

The problem of incising channels was highlighted at a conference in Mississippi in 1997, called "Incised river channels" (Wang *et al*, 1997). Most streams and rivers in the south-eastern USA, and in numerous regions around the world, have been resectioned, straightened, dredged and cleared of debris, for the purposes of navigation, land clearance for agriculture, bridges and urbanisation. Along much of the Mississippi River system, the geology is alluvial, lacking bedrock outcrops to act as controls on headward migration of knickpoints (the upstream limit of channel incision). Engineered channels in regions lacking a hard rock source for riprap have often incised progressively into the bed material, causing bank erosion on a massive scale (Harvey & Watson, 1986). Many authors have noted that in regions such as the Mississippi, the riparian and floodplain trees and associated large woody debris (LWD) or coarse woody debris (CWD) were historically the only fixed structures in the landscape providing channel stability; when these were removed in the 1800s, whole catchments lost their structural integrity (Roseboom *et al*, 1995). This resulted in mass wasting of hillslopes and massive widening of whole stream systems. The application of geomorphic principles to this pervasive river engineering problem is needed to address root causes rather than merely symptoms (Harvey & Watson, 1986).

A geomorphic approach would include detailed assessment of reach conditions based on channel cross-section and long profile surveys. Sediment supply and

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transport capacity can be estimated from channel capacity data, changes in historic regime and available streampower to transport sediments. Attempts to redress channel incision processes need to address the causes of incision by modifications such as dredging, straightening, widening, deepening, relocation, diking, clearing and snagging (Harvey & Watson, 1986).

A traditional engineering response to incision uses one or several large grade control structures, in an attempt to halt incision and stabilise the grade or slope of the bed. Channel evolution models such as that by Hupp & Simon (1986) illustrate that repair of bank collapse following knickpoint migration needs to address bank stability, especially at the bank toe. Where bank failure is a problem, a structural use of woody vegetation can offer assistance to help recover the channel stability needed to recover geomorphic and ecosystem functions.

The 'Willow Post Method' was developed by Roseboom et al (1995) in the glacial till landscapes of Illinois to address the problem of degrading catchments and incising channels. In the absence of other materials to reinforce banks destabilised by inappropriate engineering works, locally acquired 40-75mm diameter black willow posts have been planted vertically much like fence posts in close rows parallel to the channel, on outside bends and on straight reaches. Often additional materials are used to reinforce the bank toe region. Examples include pre-cast concrete 'Ajax' anchors used in urban settings, or in rural areas juniper trees are wired horizontally onto the bank pointed downstream, to increase roughness at the toe and provide a depositional zone for sediment accretion (Roseboom et al, 1995).

The willow posts have three main functions;

1) to 'pin' the toe region of an unstable bank with successive rows of posts armouring the bank from the stream elevation upward,
2) to provide increased resistance to flow and a zone of sedimentation and/or reduced scour, and
3) to provide tree cover, shade and wildlife habitat along devegetated rivers.

Some of the Roseboom posts do not survive the first or second year, especially in the lowest rows. Larger diameter (100-200mm) posts are often used in the lowest row to provide mechanical protection against ice scour. Behind them, the smaller diameter (40-75mm) sprout and grow dense leafy canopies which also provide shade, valued for ecological reasons. This method is an example of field engineering developed without a strong laboratory or theoretical basis, which has provided a cost-effective and easily implemented solution to a complex, extensive and intractable problem of serious economic proportions.

3.5.1 Limits of vegetation contributions to bank stability in incising channels

Where incising channels cause a lowering of the groundwater table, normal summer water levels can drop below the summer maximum rooting depth for various plant groups, herbs, grasses, shrubs and trees. Vegetative treatments alone cannot redress bed degradation processes (Schiechtl & Stern, 1997). Preparatory works are often needed first to retard or reverse channel incision processes. Methods developed to address bed degradation processes generally take the form of grade control structures, including:

1. Infrequent or solitary massive concrete or earthen weirs constructed completely crossing the channel bed, with bank stabilisation such as riprap;

2. more numerous smaller structures, which may be porous to water flow but not sediment;

3. phased treatments which rebuild the bed elevation over stages of time, using either approach 1 or 2 above.

The incorporation of woody vegetation for bank stability in channel incision problems offers a rich field of future research, as river managers around the world begin to address these problems for economic, flood defence, water resources, social and ecological reasons.

3.6. Conclusions

This chapter has reviewed the basic principles of hydraulic engineering with respect to flow over a surface, flow over obstructions and flow in channels and floodplains. The complex problem of turbulent flow over flexible emergent vegetation is introduced. Hydraulic research has progressed the incorporation of submergent vegetation into flow theory and sedimentation processes. Less well understood is the problem of the flexible emergent flow resistance characteristic of shrubs on streambanks and floodplains.

Significant advances have been made to bring bank vegetation parameters into channel design. Hydro-dynamic modelling research for flows in large natural streams with higher Reynolds numbers ($Re > 10^{4)}$ would be very helpful to progress prediction of floodplain revegetation consequences. Additional work adding suspended sediment to the model is needed to simulate fluvial processes on natural, vegetated channels.

Both hydraulics and geotechnical considerations must be included in the engineering design of river restoration involving riparian revegetation, particularly for bank stability. A geomorphic context is needed, so that critical factors such as channel incision are not neglected in management practices. Vegetative influences at reach or larger scales may appear very different than those observed at small scale, and can be very beneficial to overall reach channel stability.

With the overview given in this chapter, a framework has been set up to evaluate the field and laboratory experiments in this thesis. In Chapter Four, the background for the field study is presented, including the fluvial geomorphic and engineering considerations necessary for setting up a floodplain revegetation project for fish habitat recovery.

Chapter 4:   Background of the case study

4.1. Overview, description of the catchment and study site

The Mattole catchment is located in one of the most remote regions on the northern California coast, known as the Lost Coast. With rugged topography and high incidence of earthquakes and landform dynamics, roads fail frequently, thus this region of California has remained rural and largely inaccessible to the average tourist. Although this region, Humboldt County, is well known for the coastal California redwood forests, *Sequoia sempervirens* is not an important forest species in the Mattole valley. The dominant forests are mixed coniferous and deciduous, with a remarkable species diversity of plants, animals, fish and fungi. Because this area is so remote, the Mattole River was never stocked with hybrid hatchery fish, consequently some of the last remaining stocks of California wild salmonids survive there.

Logging activity came late to the Mattole, but after 1947, over 90% of the catchment (approximately 70,800 ha) was logged in just 40 years, primarily by tractor (MRC, 1995). Tractor logging left a substantial legacy of low-quality roads and increased sediment delivery to the river network. During this period, large-scale channel changes occurred on the mainstem of the Mattole, although few records of historic channel morphology exist.

The decline in fish stocks has been monitored by the Mattole Watershed Salmon Support Group (MWSSG) and the Mattole Restoration Council (MRC) since the early 1980s. Individual and community efforts to improve ecosystem conditions, particularly for the wild salmon species, have inspired numerous projects to recover forest plant species on steep hillslopes, to remove inappropriate old roads and culverts, and to address the extensive problems of loss of streamside and floodplain vegetation (MRC, 1995).

The floodplain revegetation efforts described in this research programme were part of a much larger effort to prevent the extinction of the King, coho, chinook and steelhead salmon in the Mattole Valley, with emphasis on the smolt summer rearing habitat in the estuary. This work is ongoing, and will continue to rely on river restoration efforts involving fluvial geomorphology, engineering hydraulics, fisheries biology and plant ecology to achieve significant remediation of the decline of Mattole salmonids.

The Mattole Catchment
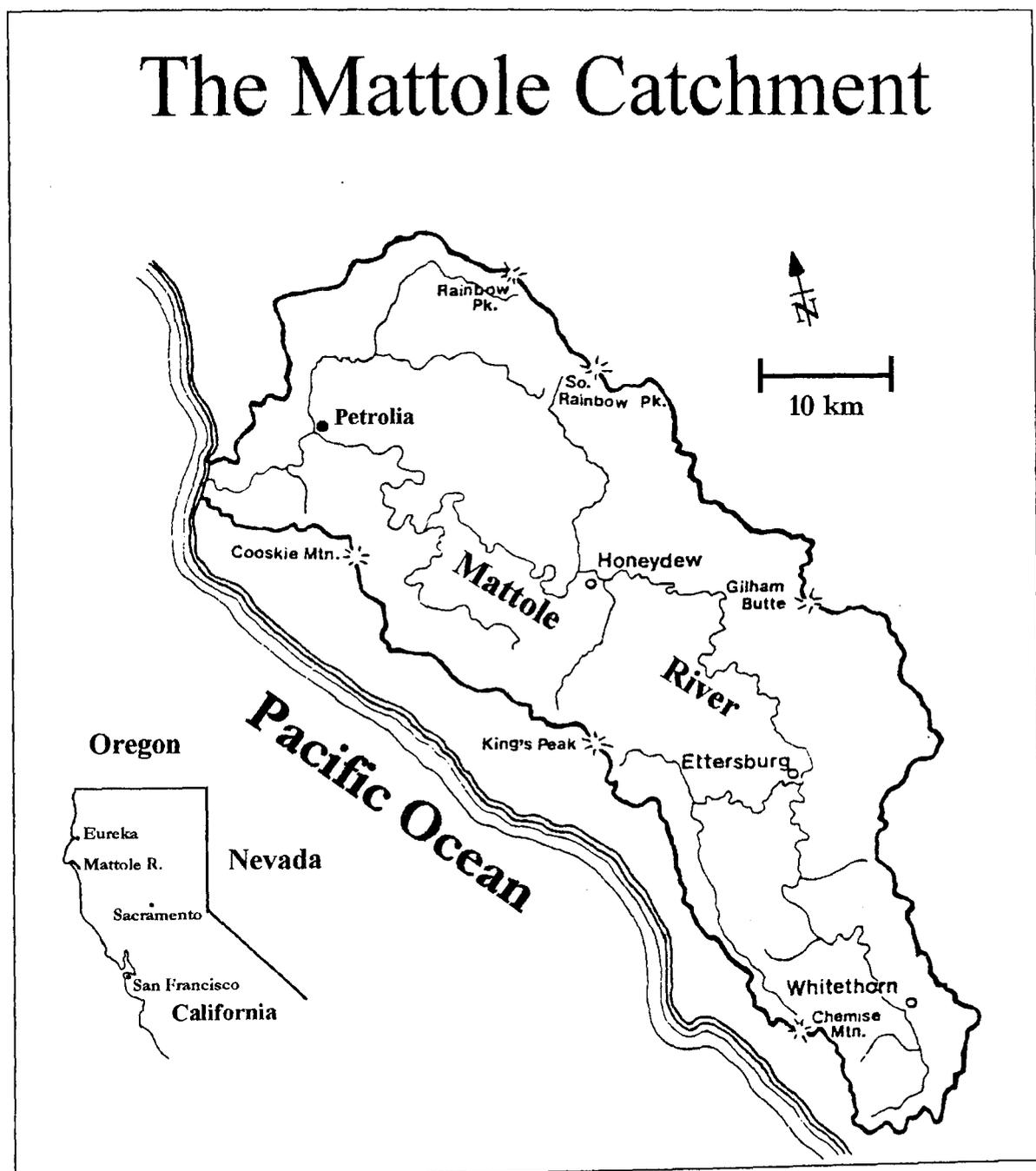
Figure 4.1. Location map and catchment geography for the Mattole River.

4.1.1   Catchment characteristics and geology

The Mattole catchment covers approximately 787km^2 in the northern California Coast Range, originating in Mendocino County and flowing northwesterly into Humboldt County for approximately 100km. The only major village in the catchment, Petrolia, is located approximately 80km south of Eureka and 280km north of San Francisco. The catchment is bounded on the southwest by the King Range, which separates the valley from the ocean. The King Range rises sharply from the strand, creating a rain orographic zone for which the region is justly famous. King Peak receives the highest volume of rainfall of any location in the State of California, shaping a dense drainage network of steep gradient streams flowing north and east to the mainstem Mattole . The inland coastal range on the eastern side separates the Mattole basin from the Eel River drainage.

The catchment is underlain primarily by young sedimentary rocks which are fractured by numerous faults, often incompetent and highly erodible. The dominant rocks are graywhacke sandstone and shales of the Franciscan formation. Most shale beds in this area have undergone much local deformation (Busby *et al*, 1988). Large, north-west-trending shear zones may be connected to the San Andreas fault system. Centred on the active geologic feature known as the Mendocino Triple Junction, where the North American, the Pacific and the Mendocino tectonic plates intersect, the Mattole catchment is a highly fractured region of mixed geologic composition. The Mendocino Triple Junction region experiences some of the most intense earthquake activity on the North American West Coast (MRC, 1995).

The soils formed from this highly erodible parent material are subjected to intense weathering, ranging in depth from < 0.2m in upland areas to 2m in the valley bottomlands (MRC, 1995). Clearing of floodplain lands for settlement in the mid -1800s yielded rich pasturelands which were subjected to intense shear forces during high flows. Since the 1940s, valley

bottomlands in the lower Mattole (lower 8km) have largely supported gravel bars and ruderal (weedy) and early seral plant associations with little or no soil development on alluvial landforms such as side-channel bars and terraces.

4.1.2   Climate and catchment hydrology

The climate of this coastal region is humid mesothermal, with heavy winter rains and coastal fog in summer (Calif. Dept. Water Resources, 1973). Mean annual precipitation is 158cm, with two thirds of this rain falling between November and April. Higher in the drainage basin, mean annual precipitation exceeds 254cm. Strong northwesterly winds are common in the estuary and surrounding coastal region. Average daily temperatures range from 23.8 - 35.0^C in summer, and from 4.4 - 15.5^C in winter, with extremes ranging from -03.8 to 41.1^C (Calif. DWR, 1973.) This semi-Mediterranean type climate produced large, dense canopy forests of mixed conifers and deciduous trees, with legendary runs of king, coho and chinook salmon, steelhead trout and many other plant and animal species (MRC, 1995).

The Mattole River is an unregulated stream, where the natural range of flows is governed by rainfall and groundwater storage within the catchment and on the floodplain. There are few withdrawals of water for irrigation or domestic use in the catchment, and no diversions of water out of the catchment. Precipitation in the basin is strongly influenced by topography, and steeply rising slopes on both western and eastern sides of the drainage basin cause sharp increases in mean annual rainfall, from 127mm/yr at the mouth to 292mm/ yr at the top of Honeydew Peak (MRC, 1995).

The Wilder Ridge rain gauge lies near the centre of the basin at 492m elevation, and receives an average of 300mm/ yr (based on 15 years of record), with occurrence of 250mm daily rainfall on record. Highest annual record for this period is 538mm in 1983, and the lowest rainfall

recorded is 145mm in 1991. The Mattole Valley at Honeydew has recorded some of the highest rainfall found in California (MRC, 1995). High intensity rainstorms occurring on already saturated soils and highly fractured geology set up the conditions for extreme flood and sediment load potential.

The storm hydrograph for a typical annual flood event is shown in Figure 4.2, for the flood of 6-9 Dec 1993, when the peak flow at the Petrolia gauge was $770 \text{m}^3 \text{s}^{-1}$.

Mattole hourly discharge data for storm hydrograph 6-9 Dec. 1993, data from USGS Petrolia gauge, Petrolia, California
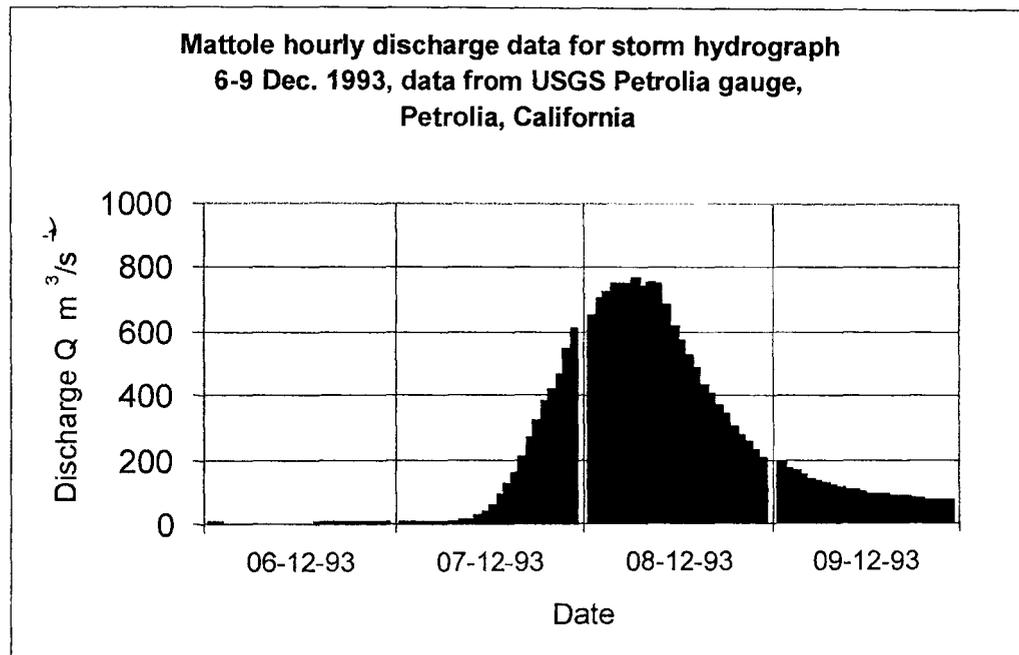
Figure 4.2. Storm hydrograph for the Mattole annual flood 6-9 Dec, 1993.

During the study period 1993-95, a second flood occurred during 6-15 January 1995, calculated to be a 15-year flood event. This flood inundated the entire estuary, and enabled the measurement of velocity profiles for floodplain overbank flow in the vicinity of constructed vegetation. The hydrograph for the 15-year flood is shown in Figure 4.3.

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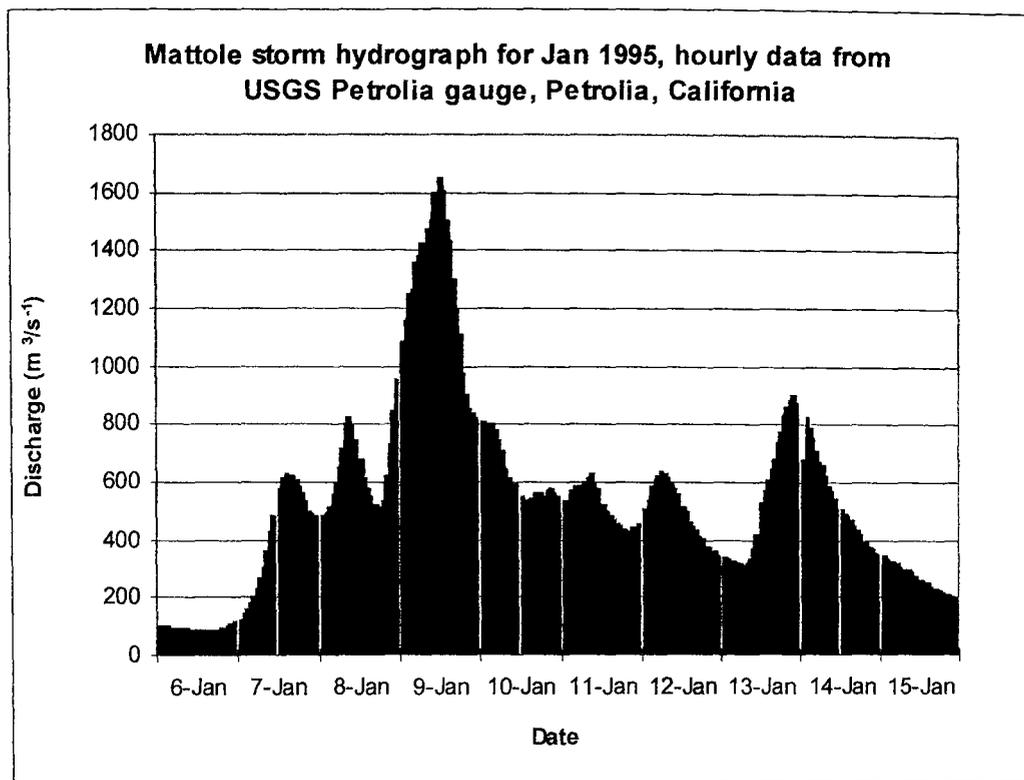
Figure 4.3. Storm hydrograph for the Mattole 15 year flood 6-15 Jan, 1995.

The US Geological Survey (USGS) has operated a stream gauging station on the mainstem of the Mattole river near Petrolia on river kilometre 10.4, in continuous operation since 1951, with intermittent records dating back to the 1930s. Discharge records are continuous at the Petrolia gauge for more than 45 years of record. This gauge accounts for approximately 80% of the catchment by area. Floods in excess of 1500 m^3s^{-1} have occurred at least twice each decade since 1950.

The North Fork Mattole enters the mainstem below the gauge, and contributes an additional 15% by volume to the total flow for the catchment. Average annual discharge measured at the gauge is 570 m^3s^{-1}. Bankfull discharge at Petrolia corresponds to a flow of approximately 850m^3s^{-1}. During the flood of January 1995, water began to occupy floodplain terrace surfaces on the lower Mattole above approximately 540 m^3s^{-1} (see Photo 4.1).

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Peak annual discharges at Mattole gauge near Petrolia

Discharge records for the Mattole gauge extend over 45 years, and include two of the largest floods of memory, 1955 and 1964. Data from the USGS, courtesy of MRC (1995). Peak flows for the study period are in bold, 1993 and 1995.
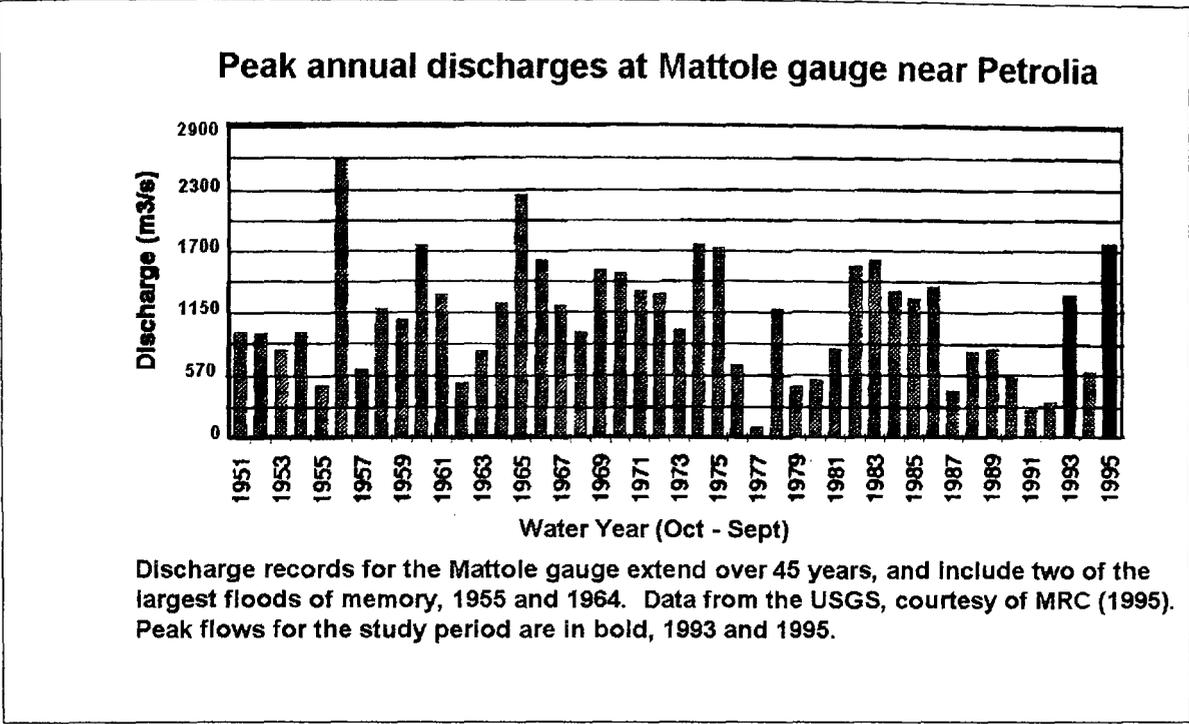
Table 4.1. Annual peak discharge records for the Petrolia gauge, Mattole river.

Photo 4.1. Flood waters begin to fill the Mattole channel near the gauging station at river km 10.4 at Q~540 m^{3}s^{-1}.

Annual Exceedence Probability percent (normal scale)

Plot Symbol Key
* WRC Final frequency curve
o Observed (systematic) peaks
s Historically adjusted peaks
Systematic-record Freq. curve
When points coincide, only the topmost symbol shows.

1.5 year flood

Range of bankfull discharge

2.5 year flood

January, 1995 flood

Recurrence Interval in years

Peak annual discharge in cubic meters per second (log scale)

Table. 4.2. Recurrence interval for bankfull discharge at Petrolia gauge, for a 45-year period of record.

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4.1.3 Valley and estuary geomorphology

The estuary of the Mattole is considered by the MRC to be the lowest 8km of river, from the mouth to the gauging station just upstream of the Petrolia bridge. Below the bedrock constrictions just downstream of Petrolia, the river widens and becomes more shallow. Alluvial bars are formed and destroyed by the annual flood, and the river shifts its thalweg or centreline location frequently. Few hard points exist to resist fluvial entrainment of the alluvial gravels of which the bed is formed, and these hardpoints are typically composed of fractured bedrock. Surface deposits in the estuary are of mixed and unconsolidated alluvium. Bore measurements of alluvial deposits have revealed alluvium depths of greater than 100m (MRC, 1995).

The Mattole Restoration Council conducted an air photo analysis of the thalweg movement and floodplain erosion patterns from 1942-1992, showing the dynamic nature of these geomorphic surfaces.

Taken from an MRC report (1995), Figure 4.4 shows relative pathways of channel migration from 1942-92, with main channel lateral migration occurring across the entire width of the valley floor.

Location and Timing of Floodplain Erosion, Lower Mattole River, 1942-1992

Legend

Extent of floodplain/terrace as it appeared on 1942 photo

Area of 1942 surface eroded between successive photo years

Year of aerial photo in which erosion is first observed

— · — Valley wall (boundary between hillslope and valley bottom)

· · · — · · · Range in which channel has meandered in historic times (meander belt)

— · — · — Extent of vegetated surface in 1992 (i.e. re-established vegetation)

Photo years between which bank erosion occurred

▤ 1942-48	▨ 1970-74		
1948-54	1974-81		
1954-63	1981-84		
▥ 1963-66	▧ 1984-88		
░ 1966-70			

The dark solid line denotes the extent of each floodplain surface as it appeared on the 1942 aerial photo. Thinner lines, with dates next to the area, distinguish surfaces that eroded between that photo year and the preceding one. For example, 48 indicates that the observed changes occurred between 1942 and 1948. The broken line indicates areas where floodplain surfaces have been redeposited, raising their height to the point where perennial vegetation has become established.

Jeffrey Flat

Chambers Bar

Blue Slide Islands

Drewry Flat

Hansen Bar

66
70
74
81

Goff Flat

Pacific Ocean

N

Upper Mathews Flat

Channel Rock Flat

Lower Mathews Flat

Duncan Flat

70

48
64   66   54   48   63
63
70

Alder Forest

Stansberry Flat

This map chronicles the changes in vegetated floodplain areas between 1942 and 1992. It shows the general timing of large changes in the lower river floodplain, and demonstrates how much lateral channel migration can occur in the course of just a few decades. Although the map can only narrow the timing of erosion to a window of a few years between aerial photos, it is possible to make more precise inferences by comparing the map with the historic flood record. (See Fig. 3.7.)

0   1000   2000
Scale in feet

Mattole Restoration Council 1995.
Mapping and aerial photo analysis by Thomas Dunklin

Figure 4.4. Alluvial floodplains of the lower Mattole and their erosion history. Courtesy of T.B. Dunklin, MRC, 1995.

4.1.4 Floodplain classification by energy regime on the Mattole River

Some of the features of the study area, the lower Mattole valley, include the criteria of a medium-energy (streampower ~2-10 $N/m^2 s^{-1}$) stream; confined vertical accretion (gravels >100m. deep) floodplains; semi-arid, non-cohesive, alluvial-filled valley of basal gravels and abundant sand with silty/ sandy and gravelly overburden, relatively flat floodplain surfaces, and catastrophic lateral erosion rates.

According to the Nanson and Croke classification of floodplains (see Chapter Two, section 2.6), the lower Mattole fits the criteria for a B2 wandering, gravel-bed river floodplain with abundant sediment load in a tectonically active area with braided, meandering and anastomosing planform. According to this floodplain type, the landforms associated with this type should include abandoned channels, sloughs, braid-bars, islands and back channels, all of which can be found on the lower Mattole. However, the Nanson and Croke scheme suggests that this floodplain type should be in equilibrium, where sediment inputs equal sediment outputs, which does not currently describe the Mattole. Currently sediment inputs exceed outputs, as shown by the loss of numerous deep pools in the lower Mattole system over decades, measured by the infilling of estuary pools at 3.6m deep in 1991 and 2.9m deep in 1994 (MRC, 1996).

4.1.5 Vegetation of the lower Mattole Valley

The dominant original plant community of the catchment is mixed Douglas fir (*Pseudotsuga menziesii*), tanoak (*Lithocarpus densiflorus*) forest with some other deciduous tree species on hillslopes such as black oak (*Quercus kellogii*) and California buckeye (*Aesculus californica*). Coastal prairie grasslands occur on hilltops and south-facing slopes; northern coastal scrub occurs on slopes and on recently disturbed soils (Barbour & Major, 1988, MRC, 1995). The valley floor originally supported a primarily hardwood riparian forest, most likely consisting of cottonwood or poplar (*Populus*

trichocarpus), ash (*Fraxinus oregana*), alder (*Alnus rubra*), willow (*Salix exigua, S. hookeriana, S. lucida* spp. *lasiandra, S. lasiolepis, S. sitkensis*), bigleaf maple (*Acer macrophyllum*), baylaurel (*Umbellularia californica*), buckeye or horse chesnut (*Aesculus californica*), hazelnut (*Corylus cornuta* v. *californica*) etc., with coniferous elements including Douglas fir and Sitka spruce (*Picea sitkensis*). Photo 4.2 shows an example of native floodplain forest of the lower Mattole.

Photo 4.2. Example of the native floodplain forest of the lower Mattole valley.

A rich flora of shrubs, vines, herbaceous perennials and annuals still exist in remnant pockets, reduced largely by extensive and intensive grazing by introduced herbivores; sheep, cattle and goats. Owing to the regional long dry Mediterranean summers, fire played an important role in the original vegetation ecology, and original forest species must have attained extensive height, canopy and cover.

The original forest cover was clear-cut to gain pasture cover on floodplain alluvial surfaces. Long-time residents remember that five dairies were in operation around the turn of the century (M. Evenson, pers. comm. 1994). It appears that pasture grasses were unable to resist the erosive forces of larger magnitude storms, as these geomorphic surfaces today are primarily gravel bars supporting only ruderal or weedy annual plant species, with some woody species recruitment near the summer channel margins. The topsoils that once supported floodplain forest on the lower Mattole are presumably now somewhere on the continental shelf in the Pacific Ocean.

The sediments into which the willow baffles were placed under this research programme are less than 27 years old, according to a channel configuration analysis of the lower Mattole River, (MRC, 1995, Figure 4.2). These midchannel sediments have supported little woody vegetation during that 27-year period,

although a forest of *Salix* and *Alnus* has developed at the southern edge of the estuary mouth in old river channels and floodplains when the channel migrated northward after 1950 (see Figure 4.2.). However, on mid-channel geomorphic features, environmental conditions are likely to have been poor for the germination and survival of fungal spores. The roots of the baffle willow stems are highly unlikely to have been inoculated with mycorrhizal fungi in the 14-month period in which they were formed, and few sediment particles were observed attached to the roots.

Nonetheless, it is reasonable to anticipate that mycorrhizal associates could play an important role in the development of floodplain soils on overwidened streams in the American West, where so much riparian forest has been lost to human-caused disturbance (MRC, 1995).

4.1.6 Consideration of grazing effects on riparian plants

No protection was given from browsing by cattle, deer or sheep, all of which animal groups exert a considerable grazing pressure on floodplains of the Mattole. In July 1994, some deer browse was observed but the plants overall seemed well able to respond to the level of herbivore pressure at that time. In this catchment in late summer when upslope forage has dried out, farmers typically turn their animals out onto what's known locally as "The Long Pasture". Autumn forage pressure then increases from all grazing animal groups in search of shade, lower temperature and water. By the autumn period of the year, willows, poplars and alders have set their spring growth into woody tissues, although heavy browse will reduce stem circumference growth and can remove riparian shrubs from the grazing area (Elmore, 1992). Where animal pressure is higher, many authors have recommended either exclusionary fencing or control of grazing animals via shepherding and rotation around various pastures in the landscape during the period of riparian vegetation establishment (Elmore, 1992).

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4.1.7 Groundwater regime on the Mattole estuary

Mean annual variations in groundwater levels within the estuary range across 3 m. in elevation, taken from channel cross-section data (MRC, 1995). The range and variation in depth to groundwater was estimated for the Mattole study site based on the variation of flow in the estuary summer lagoon, which varies with tidal influx and mouth closure, but was typically about 1m. below the surface of the midchannel island terrace.

The MRC anticipated that supplemental summer water could be important for the survival of the willow and poplar cuttings, especially during the first year of establishment. Members of the Mattole Watershed Salmon Support Group (MWSSG) conducted an informal experiment to determine the importance of supplemental irrigation for survival of the cuttings. Using a fire hose attached to a portable, submersible pump, river water was supplied a few times during the summer months of 1994 to the baffle trenches at the rate of approximately 340 litres (90 gallons) per row. This application rate was estimated to saturate the sediment profile to the depth of the baffle stems, allowing for the highly porous substrate. Summer irrigation was given twice to the four upstream baffles, and once to the four downstream baffles, leaving the two middle rows as a control. Based on visual observation by MWSSG, irrigation appeared to be highly beneficial; those receiving some summer water had significantly more leaves in early fall than those that received none. Most stems survived the first summer season, and those placed nearer the channel fared visibly better, from visual survey of leaf densities, than those stems furthest away from the water, reflecting the groundwater table gradient and its depth variation (MRC, 1995).

4.2 Study Location

4.2.1. *Rationale for choosing the Experimental Revegetation Site*

Previous studies on the Mattole identified the estuary, the lowest 8km of the river, as a critical summer rearing area for "stocks at risk" salmonid species (Busby *et al*, 1988). The Mattole estuary (see location map Figure 4.2 and Photo 4.3) provides critical summer rearing habitat for native salmonid smolts, which swim to the estuary from their spawning grounds upstream. These small fish hold in the estuary waiting for the autumn rains to swell the river and breach the mouth of the estuary, while increasing body weight in preparation for the journey to deep ocean waters (MRC, 1995). Juvenile salmonids require cool water to survive late summer temperatures in the estuary waters, but shade is lacking now that the floodplain forest is gone.

Photo 4.3. Oblique air view of Mattole estuary from the ocean looking east, with arrow showing project location.

The complex processes by which streambank and floodplain vegetation can be widely re-established are not yet articulated for the variety of conditions encountered on Western American streams. Typically, working with the natural recruitment regime requires a profound understanding of the hydrology and sediment transport regime of the river system, as well as both time and land taken out of resource production (Kauffman *et al*, 1997). Where time, land uses or natural resources are constrained, structural uses of vegetation offer several valid approaches to the revegetation process (Sedell & Beschta, 1991).

Re-establishment of floodplain forest cover was identified by the Mattole Salmon Support Group as a key element in the recovery of salmonid stocks at risk (Barnhart & Busby, 1986). The cumulative conditions of warm estuary waters, the loss of deep cold water pools and fish refugia, lack of shading, intense summer insolation, and unstable shifting banks suggested to many local workers that revegetation of the south bank gravel bars would be a positive trend for fish habitat management. Vegetation

management is a key element in enhancing biological robustness throughout the catchment, along the river corridor and especially in the area of the estuary (MRC, 1995).

For the lower Mattole, the native salmonid fish species and races surviving there are under great survival pressure from many sources, the most important being loss of spawning habitat from logging and road construction in rural catchments, and past practices of over-harvesting in ocean and fresh waters (Naiman, 1992, MRC, 1995). For the local Mattole runs of king, chinook, coho salmon and steelhead trout, the potential time lag is short between recovery or potential extinction (MRC, 1995). To speed up the process of streamside forest cover enhancement of salmonid habitat, an experimental approach was adopted by the Mattole Restoration Council to see whether structural methods of revegetation could be effective in the shorter term (3-10 years) to provide bank stability, shade and tree overhang for fish habitat. Maturation of the planting would provide the earliest shade and, in the longer term, provide desired overhanging branches to the channel for cover, shade and nutrients.

This fifth-order stream supports a highly mobile, braided channel of poorly sorted sediments. The mouth of the estuary lagoon opens on average once to several times per year during storm surges (MRC, 1995). The estuary supports approximately five terraces which function as large midchannel bars or islands during annual and greater magnitude floods.

One such bar, located at approximate distance of 870-1230m from the mouth of the river, becomes inundated on approximately an annual basis. The study is located on this mid-channel alluvial bar on the south side of the active river channel. (Figure 4.5, Map of the Mattole estuary showing project location and estuary forest). The feature is a mixed sand, gravel and cobble terrace with a small amount of natural vegetation recruitment.

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Mattole Estuary: Project Location Map
drawn from WAC air photo 1992

Hillslope forest in drainages

Baffle construction

Pacific
Ocean

137

Lighthouse Rd.

Bear Ck

Landslide-
Photopoint

N

0   325   650
Scale in m

LEGEND

Woody riparian
Sparse annuals
Sediment deposits
Scarp/ landslide

Drawn by N.C. Perala
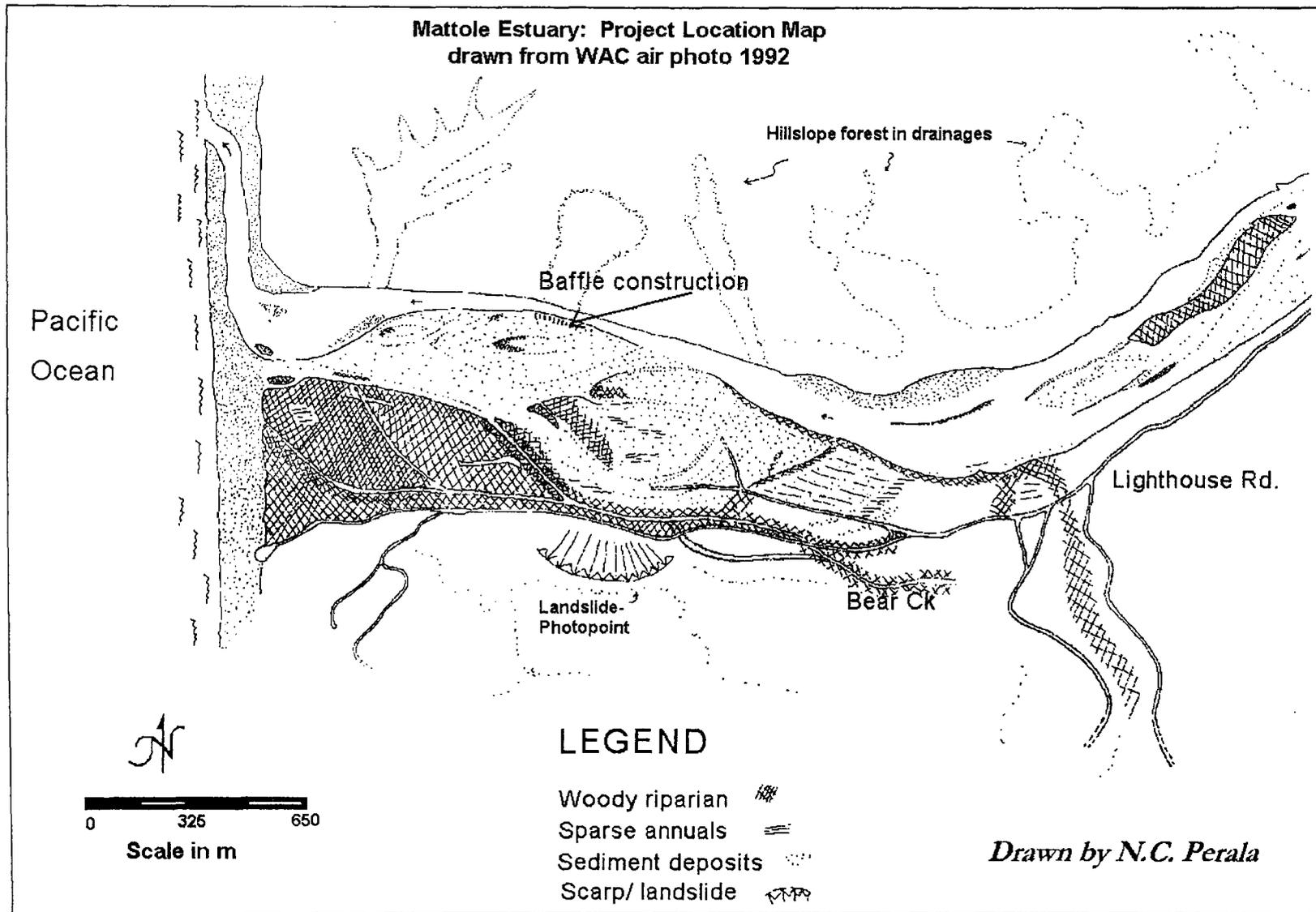
Figure 4.5. Map of the Mattole estuary showing project location and estuary forest, drawn from USGS quadrangle map Petrolia, originally drawn at the scale of 1:10,000

Species found there included shrubs such as willows *(Salix sitkensis, S. exigua, S. lasiolepis, S. hookeriana)*, coyote brush *(Baccharis pilularis)*, the exotic scotch broom *(Genista monspessulanus)*, and annuals such as sweetclover *(Medicago alba)*, and jerusalem oak *(Chenopodium botrys)*.

The channel is just over 275m in width through this section. The mid-channel bar on which the project was sited is approximately 55m wide (north to south), and approximately 360m in length roughly parallel to flow. This reach of the river has a relatively constant slope of 0.002.

This low elevation surface had great likelihood of experiencing overbank flow events during the study period, so that interactions among the vegetation, water and sediment could be observed directly or after major events. Natural recruitment of sitka willow clumps *(Salix sitchensis)* approximately 3-7 year old indicated some degree of bank geomorphic stability, shown in Photo 4.4.

Photo 4.4. Study site before construction Sept. 1993, with existing native willows on coarse gravel terrace.

4.2.2 Experimental use of soil bioengineering to enhance the recovery process of native floodplain forest on the Mattole Estuary

Because of the recognised need for rapid recovery of floodplain vegetation on the lower Mattole estuary, members of the Mattole Restoration Council (MRC) selected an experimental approach to identify potential methods for riparian and floodplain vegetation recovery along the main channel in a catchment of high fluvial dynamics. The discipline of soil bioengineering was identified as a source of appropriate revegetation designs. Funding of $6000 (approximately £3,700) was awarded in 1993 from the USDI Bureau of Land Management (BLM), the major land owner on the lower Mattole estuary, for riparian revegetation in the estuary. Fisheries expertise within the MRC directed use of these funds to the estuary south-side streambanks, primarily for shading benefits and bank stability. BLM

funding made possible the design and construction process described below.

The objective of this construction project was to increase four parameters for better fish habitat (Hunter, 1991);

1. vegetative cover,
2. plant species diversity,
3. bank stability and
4. fine sediment deposition on floodplain surfaces in the Mattole estuary, the lower five miles of the river.

4.3   Research Goals and Objectives

This study addresses a component of the research gap between laboratory flume hydraulic research and landscape ecological sciences progressing the role of vegetation for the many criteria outlined in Chapters One and Two; the current lack of information on woody vegetation influences on overbank flow structure and sedimentation responses to flood flows on vegetated streambanks and floodplains.

The goal of the research is to develop a framework for prioritising strategies for recovery of streambank and floodplain vegetation. Toward this goal, field testing was conducted to assess how woody floodplain vegetation influences overbank flow and sedimentation processes. Analysis of the data uses two widely-accepted flume-derived models to test field performance of flow and sedimentation influenced by vegetation under natural river conditions.

One model by Tollner *et al*, (1976) evaluates the filtration effect of emergent, woody vegetation during overbank flows. The second model by Petryk & Bosmajian (1975) evaluates the effects of emergent vegetation influence on floodplain roughness, segregated from bedform roughness.

Because these and many other models are based on experimental flume research, the need to link field observations with laboratory work was

identified. A flume flow visualisation study was conducted to simulate the conditions observed in the field, to explore how woody vegetation structures on a floodplain affect overbank flow structure.

4.3.1 Field Objectives

Objective 1. Measure the extent and depth of fine sediment deposition for an overbank flood flow influenced by woody vegetation.

Objective 2. Assess the change in floodplain velocity profile owing to the presence of woody vegetation on the floodplain.

4.3.2 Flume Objectives

Objective 3. Simulate field conditions in a laboratory flume, holding the Froude number constant, to observe flow patterns in overbank flow influenced by a porous vegetative filter.

Objective 4. Develop qualitative observation of the effects of a vegetative filter on flow resistance and the backwater effect.

Objective 5. Vary the spacing between baffles to observe flow wake re-entrainment and the distance at which wake re-entrainment occurs.

Objective 6. Vary the placement of the upstream-most baffle from perpendicular to parallel to flow, to observe whether a perpendicular angle or a 60° angle increases the volume of flow onto the floodplain.

4.4   Conclusions

Field conditions on the Mattole estuary were well suited for a field-based geomorphic research programme, linking theoretical and field-based work in fluvial geomorphic processes with floodplain revegetation for ecosystem enhancement. This important site has many projects being carried out to protect natural resources, especially wild salmon, within a catchment management context. Because of previous and ongoing research efforts, the Mattole river catchment is a data-rich environment. On this unregulated river system, natural processes can still be observed relatively unimpeded, as contrasted with urban or highly modified river systems.

Documented baseline conditions on the estuary floodplain enabled quantitative field observations in sediment hydraulics and overbank flow processes before, during and after storm events. Two storm events during the study period made it possible to observe and measure sedimentation responses to a revegetation scheme, and flood flow through the vegetated area.

Subsequent chapters describe the flume study set up to model some aspects of the flow conditions on the Mattole floodplain that were difficult to observe in the field. The laboratory setting was a flow visualisation study designed to enable observations of the hydraulic interactions among channel, floodplain and vegetative filter on the floodplain.

In Chapter Five, the materials and methods used in both field and laboratory research are presented.

Chapter 5   Materials and Methods

5.1.   Field Methods Overview

The US Department of the Interior Bureau of Land Management (BLM) and the
Mattole Restoration Council (MRC) undertook an experimental streamside
revegetation project on the Mattole estuary in autumn 1993, in order to enhance
fish habitat in the estuary. A field survey was carried out by a multi-disciplinary
team of fisheries, geology, fluvial geomorphology, ecology, hydrology, botany and
soil bioengineering interests. The purpose was to determine the best location for
an experimental revegetation project within the lowest 8km reach of the river
(which could inform future floodplain revegetation efforts), and to assess the most
relevant revegetation methods.

The location chosen was on the south side of the estuary, approximately 1.5km
from the mouth of the lagoon, on a mid-channel island. It was sited at the edge of
the main channel to increase riparian shade in the medium term, and to increase
local bank stability. The site exhibited naturally recruited native willows of less
than 10 years age, indicating potential for bank stability. The construction method
and location enabled the creation of natural 'laboratory conditions' for field
geomorphic research and a means to study streambank and floodplain revegetation
processes.

In selecting a relatively uniform mid-channel bar, comparison was made possible
between the overbank flow conditions within a vegetated area and within a bare
gravel area. Placement of the revegetation scheme at the near-water margin (for
the purpose of enhancing fish habitat) increased the likelihood of observing a flood
through the woody vegetation zone on the mid-channel floodplain during the study
period. Although the previous seven years had experienced drought in northern
California, this location had a high probability of experiencing overbank flows at
least once in the study period, because the site was near or just within the
'bankfull' stage height of the annual flood. However, the height of the bankfull
stage was difficult to define precisely because the channel thalweg location shifts

significantly from one major flood to the next, and the USGS staff gauge, where flow records are computed, is located 8km upstream of the project site.

The revegetation method selected is shown in Figure 5.1, the live siltation construction (Schiechtl, 1980) is called Buschbau-traverse in German (Oplatka *et al*, 1996). Locally the method is called the live siltation baffle (Engber, pers. comm., 1993). This method was selected because it was reported to be able to withstand high velocity shear stresses immediately after construction. The structures are designed to facilitate sedimentation during overbank flow, because they have strong geotechnical features for increasing bank stability. This design places relatively large diameter willow *Salix* and cottonwood *Populus* stems approximately 1m or more below ground surface, nearer the groundwater level, which greatly enhances survival prospects.

Refer to Fig. 4.5. (page 137) for the map of the estuary showing the location of the midchannel bar selected for experimental revegetation.

Sedimentation resulting from an annual flood was measured for volume and particle size distribution. The floodplain was entered during a 15-year storm event, and velocity profiles were measured upstream of the vegetation structures and within them, to quantify the effects of the emergent vegetation on overbank flow structure.

Subsequently, laboratory flume work was set up to simulate the flow conditions on the Mattole estuary during the 15 year flood event. This was carried out to gain a plan view perspective of the flow conditions which could not be seen during the flood event. In particular, these include the influence of the willow baffle on flow attenuation and its effect on channel- floodplain flow interactions. Field and flume conditions are linked by means of the dimensionless Reynolds numbers computed from the field velocity profiles, and by the configuration of the flume apparatus to simulate the porous vegetative filter to overbank flow on the Mattole estuary floodplain.

5.1.1. Soil bioengineering design

The chosen design was based on the brush traverse or live siltation construction developed by Schiechtl (1980, p. 155, Figure 5.1) to utilize stream power for enhancing sediment deposition and bank stability on stream banks.
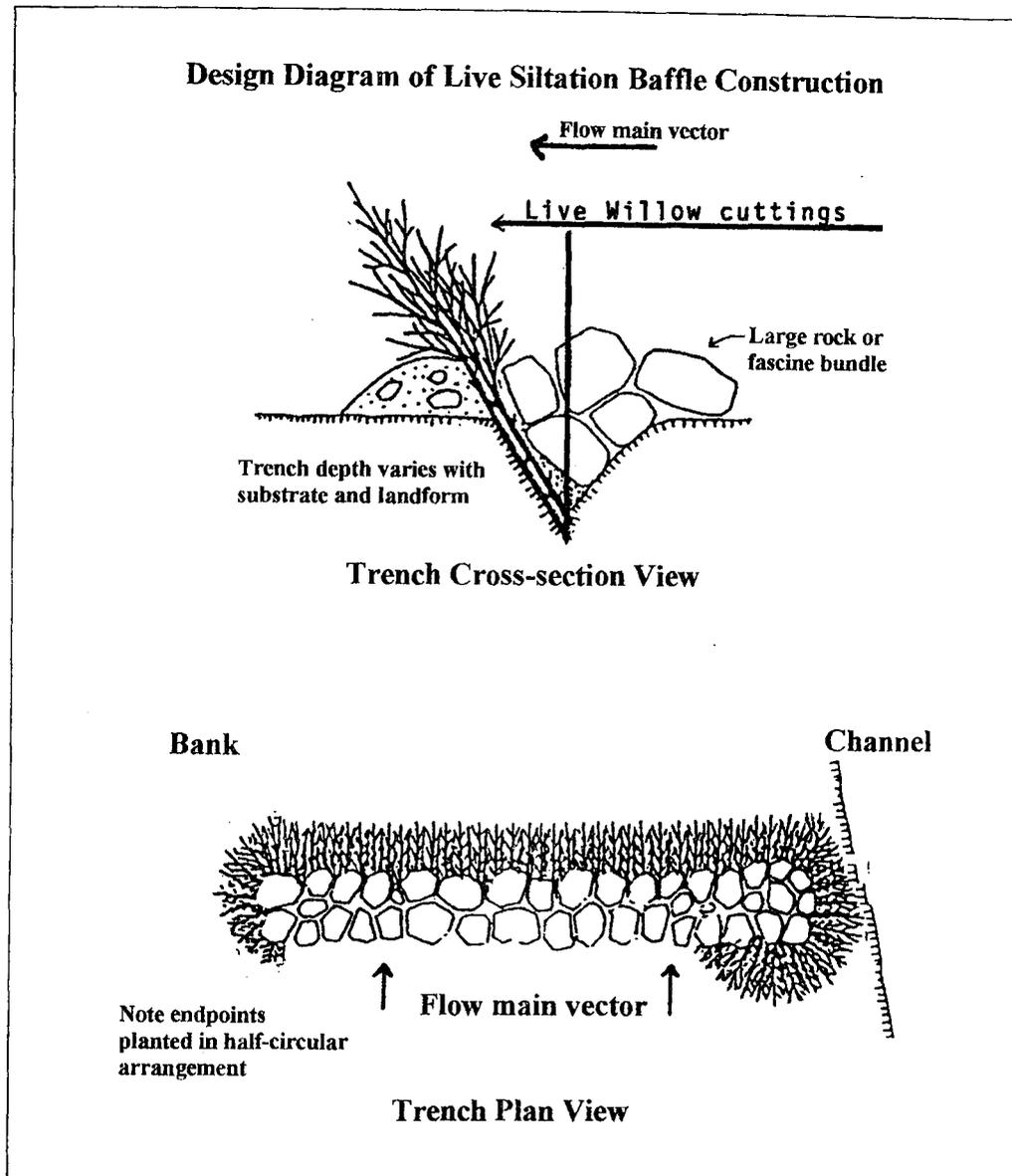
Figure 5.1. Transverse section and plan view of the soil bioengineering design, the brush traverse or siltation baffle construction, after Schiechtl (1980).

Ten live siltation baffles were constructed in 10m trenches placed perpendicular to flow. Being porous to flow, the siltation baffles were designed to provide relatively low resistance to high overbank flows, and to create zones of turbulence where fine suspended particles can settle out of suspension. These structures were designed to maximise sedimentation during floods, and to assist the natural plant

recruitment process in order to recruit fish habitat within the estuary floodplain on a shortened timescale. As the willows mature, rooting tensile strength increases, above-ground stems and branches increase in area, and the baffle series is designed to become a region of relative bank stability, through a combination of soil reinforcement and reduction of shear stress on the bank surface.

In plan view, the trenches on either end of the baffle grouping angle downstream 60 degrees to flow on the upstream end, and angle upstream 30 degrees into the flow on the downstream end. The angle of these end baffle trenches is discussed in Chapter 7, section 7.6.

Ten trenches shown in Fig.5.2 were placed on the north side of this mid-channel island, primarily limited in number by available funding. The spacing of the trenches was determined from guidance found in Schiechtl (1980), that trench spacing is in width 1.5 times the length of the trenches. After some discussion, trench length was set somewhat arbitrarily at 10m, with the ensuing width spacing between trenches set at 15m. See the discussion in Sec. 6.4.2. regarding the trench length determination, and section 6.5.3, Flume analysis of baffle spacing.

Figure 5.2. shows the layout of the site with live siltation baffles in plan view.

Mattole Estuary Live Siltation Baffles in Planview

LEGEND

- ⌒⌒⌒ Break in slope, arrows point downslope
- ✕ Native willows, Salix sitchensis or S. exigua
- Live siltation construction, showing curved ends
- Fine sediments, sands and silts
- Gravels
- Cobbles and coarse sediments

Summer low-flow channel ←

10m.

10 9 8 7 6 5 4 3 2 1

Drawn by N.C. Perala
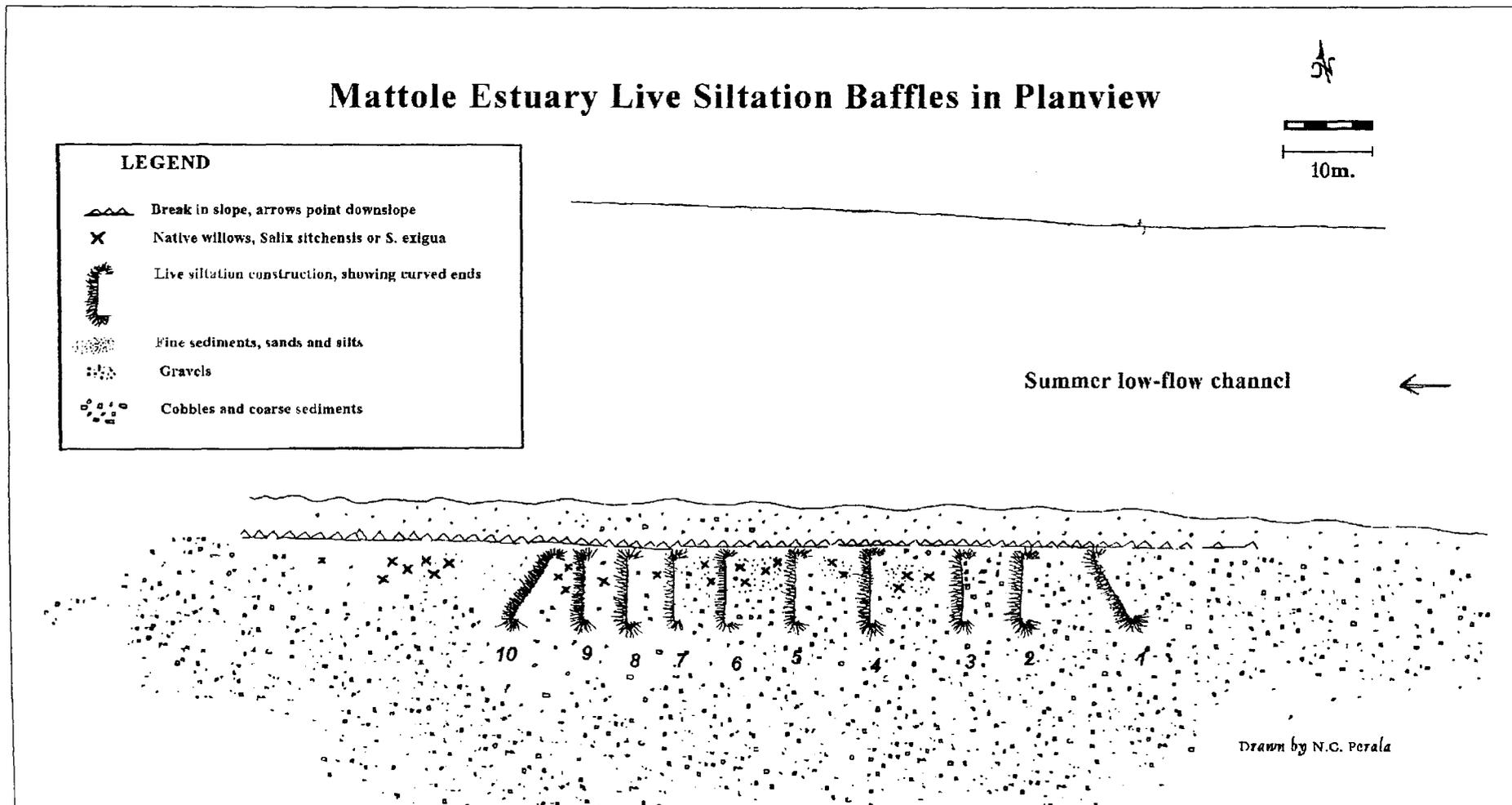
Figure 5.2. Diagram of live siltation baffles in plan view

5.1.2   Construction methods

Ten siltation baffles were constructed over 180 metres of mid-channel island bank just above the summer low flow water margin. Construction was undertaken during dry weather on 5 November 1993 by the Mattole Restoration Council , with paid labour by Petrolia High School students. Cuttings of willows *Salix sitkensis, S. lasiolepis, S. hookeriana* and cottonwood or poplar *Populus trichocarpa* were taken from the nearby estuarine riparian forest (shown in Figure 4.2) the day before construction began, and were delivered to the construction site by truck. Cuttings were stored butt-end in the river to retain maximum moisture content.

On the day of construction, trenches were dug by mechanical backhoe to a depth of approximately 1 m. The backhoe piled sediment on both sides of the trench, leaving a mound or 'backstop' on the downstream margin to increase baffle resistance during overbank flow. Photo 5.1 shows the backhoe in construction.

Photo 5.1. The backhoe during construction process.

Working with the backhoe operator, the field crew divided into teams of three, those bringing cuttings to the trench, those handing stems to the person in the trench, and those packing willow cuttings thickly into the trench, shown in Photo 5.2. The cut ends of the stems were anchored firmly into the base of the trench. The teams helped the backhoe operator to refill the trench with the sediment from the upstream mound. Photo 5.3 shows the typical size of the willow cuttings.

Photo 5.2. Placement of willow stems in a trench.

Photo 5.3. J. Morrison (MRC) showing typical size willow cutting.

The backhoe replaced the fill material from the upstream side, leaving the mound on the downstream side as a "pillow" against which the cuttings leaned downstream on an angle approximately 65 degrees from the vertical (see Figure 4.3). Completion of the design called for placement of small boulders (diameter unspecified in the design manual, Schiechtl, 1980) on the upstream side of the trench (Figure 5.1), for reinforcement against fluvial erosion of the soft fill material. This stone placement was not carried out at the time of construction or

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subsequently (see Chapter 7, section 4, Analysis of failure mechanisms). The crew placed on the baffles the largest stones found on the floodplain, (those transported by floods) as a way to save money over importing quarried boulder rocks. The option of fastening the baffles with fascine bundles of willows was not considered in the design phase or at the time of construction.

Using a submersible pump placed into the river, all trenches were watered by a high pressure firehose, to wash much of the fill material back into the trenches, to mobilise the fine sediments into near contact with the willow stems and to saturate the soil matrix for the new cuttings, shown in photo 5.4. The resulting construction is shown at ground level in photo 5.5., and from a photopoint at elevation 98m MSL, photo 5.6. A post-construction longitudinal view at ground level is shown in photo 5.7.

Photo 5.4. Irrigation of the freshly planted baffle trenches.

Photo 5.5. Post-construction of live siltation baffles, showing dense leafy cuttings.

Photo 5.6. Post project construction viewed from Taylor slide photopoint.

Photo 5.7. Longitudinal view looking upstream post-construction, note the sediment mounds on the downstream side of the baffles.

After construction, the area was surveyed to document baseline conditions.

5.1.3 Details of plant handling methods during construction

Cutting branches for soil bioengineering involves a pruning process on the host tree, so that the donor plant has a series of growth points from which to recover (Engber, pers. comm, 1993). The host willow plant will resprout with vigour under normal conditions, and "Growth follows the knife", as the old English saying goes (Newsholme, 1992). Thus the use of donor plants for soil bioengineering practices need not destroy local willow (or other genera) populations, and when pruned using horticulturally sound methods, can actually improve the health of the donor plants and extend the plants' lifespan (RSPB, 1994).

The whole cut stem, branches and leaves is used in the Schiechtl live siltation construction system, rather than removing leaves or using only pieces of stems. This approach allows the stem to retain the greatest amount of available energy, including the proteins and carbohydrates stored in the leaves and stems (Schiechtl, 1980). These nutrient reserves enable the plant to mobilise the energy needed to produce new roots faster, assuming adequate water levels available to the plant. The green leaves will die back over a few days, but will first deliver to the stem all the energy held in the leaves which the stem can absorb. Stems of most *Salix* species have a remarkable ability to produce numerous adventitious leaf and root meristem nodes along vertical, horizontal and slanted stems, given water, oxygen and light (Newsholme, 1992). The willow cuttings on the Mattole project were expected to lose the original leaves and to resprout a new set of leaves during the late winter months, which did occur, shown in Photo 5.8.

Photo 5.8. New leaf growth and flowering shoots on 3 month old cutting stems.

Although the literature generally recommends using this and other techniques involving use of live plant material in the dormant season (Schiechtl, 1980, Sotir & GSWCC, 1995), the *Salix* and *Populus* species used were not dormant during project construction. The literature is based primarily on European experience, where climatic variations are pronounced. In more moderate climates such as the maritime northern California and the Pacific Northwest, the seasonality for using live woody plants for construction materials may not be as proscribed as in central Europe. Methods exist to extend their season, such as cool storage and irrigation (Sotir & GSWCC, 1995). Further research is needed to extend the database of plant cutting, storage and handling reliability by native species, and by region.

See Section 6.1.4. for discussion of irrigation methods.

5.2.   Methods in sedimentation research

Fluvial sedimentation research is guided by the timescale of inquiry. For short-term processes (less than 5 years) where the influence of a single flood event may

be observed, a number of research tools are available. These include geomorphic mapping and field survey (Dunne & Leopold, 1978, Kondolf & Micheli, 1995), Wolman pebble counts for characterization of sediment particle size (>2mm) distribution (Wolman, 1954), and sediment sampling for particle size analysis (Thorne, 1998). To relate field data to fluvial conditions, typically more than one method is used to link site-specific responses to larger scale processes.

Field research efforts in 1992-93 on the Mattole floodplain were devoted to devising methods of measuring natural sedimentation around natural willow clumps. The problem of characterising stem density for natural plants is considerable, where the standard deviation of willow stem density in natural clumps can easily be of the same order or greater than the mean.

Distinguishing among thin layers of fine sediment deposited during different flood events is difficult, owing in large part to the dynamic fluvial conditions under which any sediment or topographic marking system must endure. During overbank flow conditions, all components of the fluvial system can be in motion; the flowing water, sediment suspended in the water column, the upper layer of the bed sediments and the plant branches, so that no fixed point, or baseline, exists against which measurements can be made. If such a fixed point were inserted into the fully mobile system, it would change the hydraulics of flow, increase scour and alter the local sediment transport and deposition dynamics. Deposition and scour at the boundary layer can occur in close sequences, and deposition rates seem to vary widely along the rising and falling of the flood hydrograph.

During the period 1992-93, field work made evident that distinguishing between sediments deposited by different flood events was not possible with available technology. When the opportunity arose in 1994 to construct vegetative structures near the margin of the summer low-flow channel on the Mattole estuary, the problem of quantifying stem density was resolved, as was the difficulty of finding a discrete boundary between the base layer and sediments deposited by a single flood event. The structural arrangement set up with the live siltation baffle construction offered a stable configuration and more quantitative control over such parameters

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as a distinguishable substrate layer, stem density per unit area, relatively uniform stem diameter, plant height, relative uniformity of stem flexural properties and absence of dead wood within the plant region as a complicating source of error.

In the period 1994-95, further field data collection focussed on sediments deposited by an annual flood. The 94-95 sediments deposited were analysed for particle size distribution (see section 6.1.3). In 1993, 1994 and 1995, channel surveys and geomorphic maps of the project area were made by T.B. Dunklin of the Mattole Restoration Council with the author. MRC published data are included in this analysis.

5.2.1   Measurement of the extent and depth of fine sediment deposition for an overbank flood flow influenced by woody vegetation

Particle size counts were made to characterise the sediment distribution after construction and before the first flood. After the first high water event on 8 Dec 1993 (RI = 1.3 years, Figure 4.2), sediment samples were analysed for depth, distribution, and particle size. Average water depth for this event was estimated from the debris line to be approximately 0.15m, ranging from approximately 0.12m on the bank side to 0.18m near the channel margin. Figure 5.3 shows the locations of sediment samples in relation to baffle locations.

Legend

Baffle number   4
Sediment sample   12
Break in slope
Cobble/gravel
Sand/ fine
Woody debris
Existing willow   ☉

Sediment deposition map of the Mattole Estuary baffles

Sediment sample locations, from flood of Dec. 1993

Direction of flow

Scale 13.7m

Full lagoon water level

Relict high water debris line

drawn by N.C.Perala
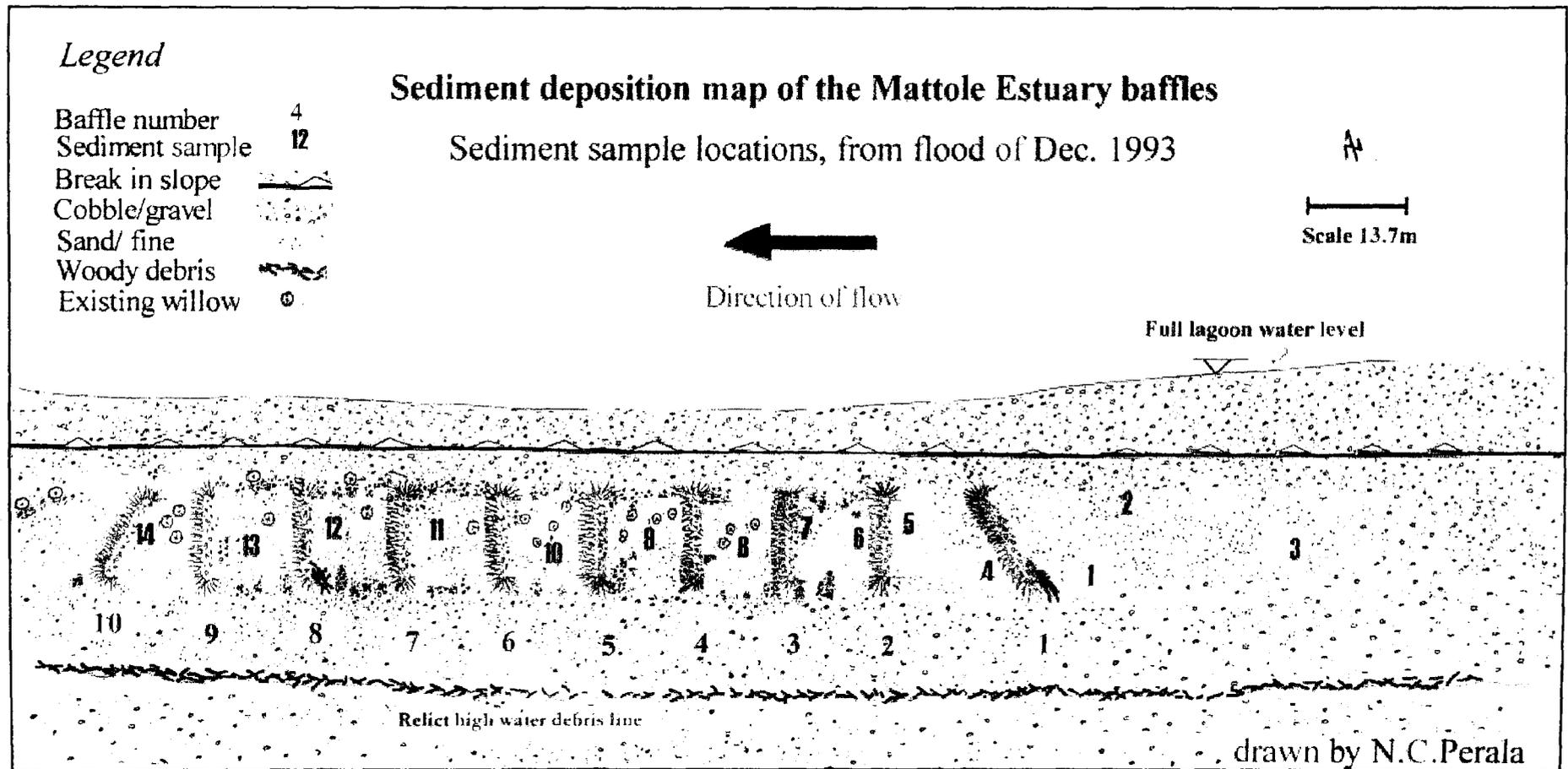
Figure 5.3. Sediment sample locations map (Numbers 1-14). The numbers below the vegetation structures (1-10) relate to the baffle number, beginning at the upstream end. Approx. Scale 1:1000.

5.2.2 Soils laboratory methods of particle size analysis

Seventeen sediment samples were gathered for analysis of particle size, by means of a 50cc cylinder pressed into the sediment surface. The sampler had a 10cm diameter, a maximum depth of 5cm, and the sediment layer was approximately less than or equal to 5cm deep. These sediment samples were collected in a stratified random sampling pattern, with 3 samples taken upstream of baffle 1, two samples taken between baffles 1 and 3, where sedimentation was heaviest, and one sample taken between baffles 4 and 10. Samples were analysed in the laboratory for soil texture, percent sand, silt and clay.

Particle size distribution of the deposited sediments was analysed for percent composition. A standard laboratory analysis of sand/silt/clay fractions was carried out in the Geology Dept. laboratory at Humboldt State University, Arcata, California. Samples were air dried, then oven dried for measuring weight and volume.

The coarse, medium, fine and very fine sand fractions were separated mechanically from the silt and clay by a rotap sieve-shaking machine, shaken for 30 minutes. Sieves were sized by millimeters (mm) and Wentworth size classes (shown here in parentheses). Sizes used were 2mm (very coarse sand), 1 (coarse sand), 0.5 (medium sand), 0.25 (fine sand), 0.125 (very fine sand), and 0.0625 (coarse silt). Percent size class of the total volume of the sample was computed from dry weights, as a fraction of the total weight of the sample.

Smaller sizes of silts and clays were separated by wet analysis. The clay fraction is all particles finer than 0.002m, or 2μ (microns). From the finest sediment remaining in the bottom pan after the sieve shaking, 25g of each remaining silt and clay sample was made into a paste using distilled water in a 600mL beaker. Three samples contained only enough material remaining to make 8g samples.

Then 30% hydrogen peroxide H_2O_2 was added in aliquots of 10ml, 5ml and 5 ml, to oxidise all organic particles. This paste was let to stand for 6 hrs, then divided into two lots. One lot of the sample was oven-dried, then weighed for the combined silt-clay fraction.

To the second lot, the flocculent calgon was added to separate the clay particles. Water was added to make about 400mL solution, and was placed into an ultrasound bath for 20 minutes further to break apart any sediment structure. A quantitative transfer was made to a 1000mL cylinder, which was stirred using a masher to distribute the particles evenly in solution. After 20 seconds, a 25mL pipette was placed to a depth of 20cm in the cylinder, then 25mL of solution was extracted. This solution was oven-dried on a pre-weighed clay tare. The weight of the clay was subtracted from the weight of the tare, then subtracted from the percent weight of the silt-clay sample, to give the silt fraction. These were then computed as fractions of the total weight of the sample. Results of the analysis are given in section 6.1.2.

5.2.3   Field sampling methods

Because the baffles were constructed on a mid-channel bar composed of mixed coarse and fine sediment, (D_{84} = 51.8mm prior to construction, D_{50} = 24mm, D_{16} = 6mm), a distinct layer between the two sediment types could be clearly detected. Using a hand-held probe (Photo 5.9) with gradations marked in tenths of feet (same scale as the field survey), depths of the fine material were measured throughout the baffle study area (n=1372).

Photo 5.9. Sediment probe and fine sediment layer, which supported seeds (fine white spots on brown silty sand) from planted willows, March 1994.

Although fine sediment was also observed outside the baffle area, it occurred at detectable levels only within the baffle area, where the depth of the fine sediment layer was measurable.

The sediment samples and the depth map of the fine sediment layer form the basis for analysis of the influence of these baffles on sediment deposition, presented in Chapter Six. The sedimentation response to the annual flood in the vicinity of the baffles was measured by mapping the extent and depth of the fine sediment.

Photo 5.10 shows the discrete sedimentation boundary between vegetated and unvegetated areas. In photo 5.9, the sediment captured among the baffles supported seeds from the willow branches, indicating that the natural processes of sediment retention and willow seedling recruitment have been enhanced.

Photo 5.10. Fine sediment deposition among willow baffles, with discrete sediment boundary at the baffle margin.

The depth sampling strategy was based on a series of north-south transects laid across the vegetated region, perpendicular to the flow pattern. Transects were laid out approximately on a 0.75m spacing, with samples taken at 0.75m intervals. Actual mapping locations are indicated by the layout of the sediment depth data in Figure 6.1.

Sediment sample depth was observed using a hand-held probe with graduated markings, pushed through the fine layer down to make contact with the armour layer beneath. A total of 1372 depth measurements were made and mapped for location and depth to armour layer (Figure 6.1, map of the sediment deposition after first flood, Dec, 1993). The total volume of sediment was estimated for the flow depth and duration, to estimate the sediment filtration capacity of the baffles. Results are given in section 6.1.1.

The contrast between sediment sizes for pre-construction conditions and that following the flood of 8 Dec 1995 is shown in photo 5.11.

Photo 5.11. Differential layers of fine sediment was deposited by the annual flood, Dec. 1993, contrasting vegetated and unvegetated surfaces.

Pebble counts taken following construction were compared with pebble counts taken after the 15 year flood of Jan 1995.

5.2.4   Analytic methods used

Comparison of sediment particle size for two overbank flow events

Particle size distribution is compared for two overbank flows, based on the parameter flow depth, rather than discharge, because only a small portion of the total discharge flowed over the vegetated island to interact with the baffles.

Contrasting the sediment particle sizes deposited in the vicinity of the baffles between the flood of Dec 1993 (RI = 1.3) and the flood of Jan 1995 (RI = 15), Wolman pebble counts were taken for the two events, the data were mapped and photographed (see photo 5.12). Analysis of the data set is presented in section 6.4.

Photo 5.12. Sediment particles transported by 15 year storm, 10 Jan 1995.

Comparison of the sediments trapped by vegetation for two flow depths gives an indication of the ability of flexible willow structures to capture sediments across a range of flood flows. No previous data on this subject have been identified.

Analysis of the baffle sediment filtration capacity

The hydraulic model used to assess the efficiency of sediment capture by the baffles is by Tollner *et al*, (1976). The Tollner model is described in section 3.2.2. Flexibility of the filtration media and its capacity to induce additional turbulence into the flow was included in the model only through a turbulence coefficient, but stem flexibility may be an important additional physical parameter of filtration media such as young willow stems.

The reach slope for the Mattole estuary is relatively constant at 0.002, and the floodplain water surface slope was surveyed during flood stage on 8 Jan 1995 near the baffles at 0.002.

Discharge was estimated from the width, depth and velocity data measured during the Jan 95 flood event, and scaled by depth to the Dec 1993 event, using real rather than synthetic flow data. The spacing between stems of a single baffle structure was computed on a range of values to reflect real variation, to give high, medium, and low values. High, medium, and low values were also assigned to

flow depth, velocity, hydraulic radius and Reynolds numbers, in order to compute reasonable ranges of sediment trapping efficiencies. Particle fall velocity data are taken from Gibbs *et al* (1971) for each of three sediment fractions; sand, fine sand and coarse silt, and fine silt and clay.

Back-calculation of suspended sediment load

Reasonable estimates of the suspended sediment load were made as a surrogate for real data on the concentration of sediment inputs to the baffle filtration system. Probable sediment inputs were run through the model for known flow depth, velocity, and stem densities. This approach enabled an analysis (or reality check) of the results of the Tollner model from field data where the basic assumptions of the flume derived model were not upheld. The results were compared with the known quantity of captured sediments, to gain another estimate of the likely filtration efficiency of the baffle structures.

5.3   Methods in field flow research

Rows of woody stems made possible the measure of velocity among the vegetation zones, which is more difficult to achieve amid the random configuration of wild shrubs found under natural growing conditions.

The velocity profile (Figure 3.1) is a fundamental tool used to characterise the structure of flow, especially to predict shear stress in the near-boundary region. The influence of dense but porous woody vegetation on overbank flow on natural streams is evaluated using comparative velocity profiles. Profiles were recorded during the 15-year flood event within the floodplain overbank flow. Profile locations were distributed in a sampling scheme upstream of any vegetative roughness and within the willow clumps (shown in Figure 5.4). Profiles 1 and 2 are paired by virtue of being sampled during comparable flow conditions, as are profiles 3 and 4.
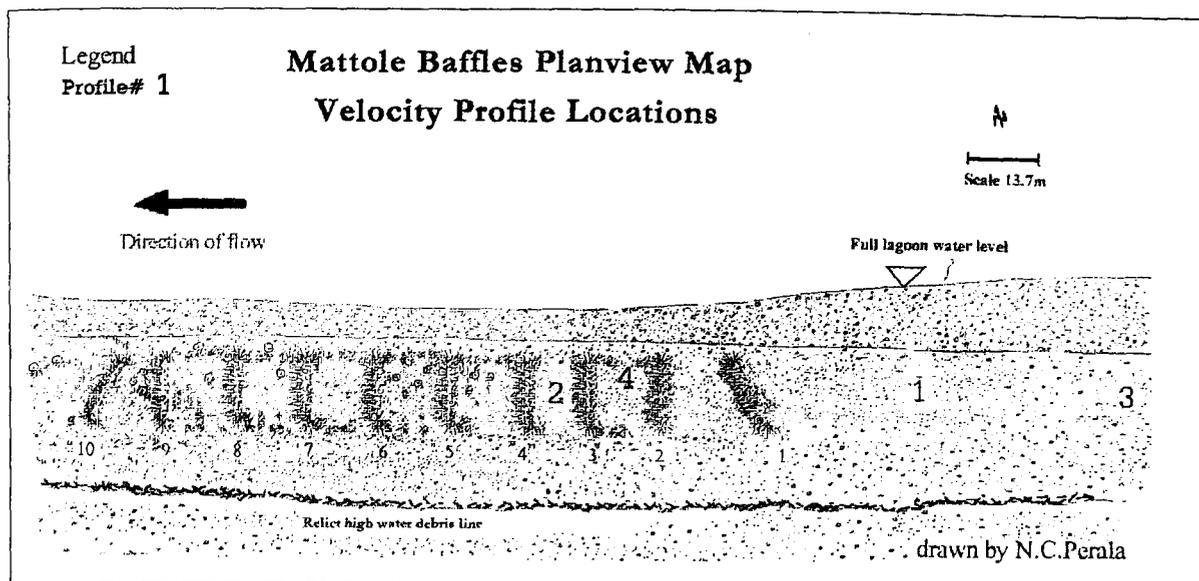
Figure 5.4. Plan map of study site showing velocity profile locations. Approximate scale 1:1500. Note profile 4 is taken near the channel boundary, because of available flow depth at that time.

5.3.1 Assessment of the change in floodplain velocity profile owing to the presence of floodplain woody vegetation

Denoting 6th Jan 1995 as Day 1 of the storm, overbank flow began in the lower Mattole River on Day 2, (7th Jan) at approximately Q=540cms. (See the storm hydrograph Figure 4.3). Flow was observed on Day 3 over the estuary midchannel island, and velocity was measured on Day 3 (profiles 1 and 2). The flood peak occurred on Day 4, (9th Jan) at 1660 m^3s^{-1}. On Day 5, there was sufficient flow over the mid-channel island to record velocity measurements upstream of and between baffles (profiles 3 and 4). On Day 9, (14th Jan), channel changes began. The profile sampling locations are shown in Figure 5.4.

During this high water event, four velocity profiles were measured on the floodplain at two different flows. On the rising limb of the storm hydrograph on Day 3 (8 Jan), at discharge Q = 650cms a detailed velocity profile was made from a position 40m upstream of the first baffle to characterise the overbank flow on a mid-channel island unaffected by the presence of the vegetation baffles. On the same day, a second detailed velocity profile was made from a position downstream of the third baffle, to characterise the flow influenced by presence of the baffles.

This approach was designed to generate detailed velocity profile measurements to allow comparison of bare floodplain surfaces with vegetated surfaces.

The primary velocity sampling instrument used was a mechanical, stainless steel "Mini" current flow meter by Scientific Instruments, model 1205. This machine is set on a top-setting wading rod, with three steel cups rotating on a pivot axis. See Figure 5.5, Diagram of the 'Mini' current meter, from Scientific Instruments. The meter rotates around a central shaft, passing a 'cat-whisker' wire across an electrical contact with each rotation. The contact sends a audio signal to a headphone set, and the recorder (person) counts the number of clicks per unit time (usually 1-2 minutes to capture the variation in flow speed). The number of clicks per minute is then calibrated to compute the average water velocity, (Scientific Instruments, 1994).
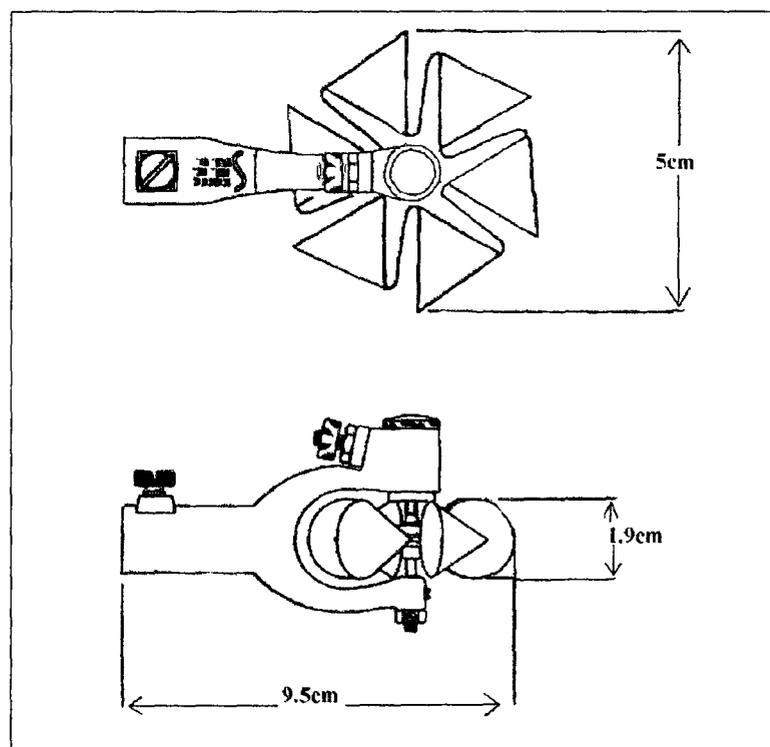
Figure 5.5. Diagram of the 'Mini' current meter, from Scientific Instruments, Inc. 1994.

Flow near the boundary was measured carefully to characterise the boundary layer (Figure 3.1) as precisely as possible. Velocity measurements were repeated until the average number of clicks came approximately within a standard deviation of

each other. Some readings required as many as six measurements for a single data point. Points nearer the surface had only two samples taken. Flow data were recorded at 15mm intervals near the boundary to characterise the boundary layer up to 90mm, then at 30mm intervals to near the water surface. Construction of a single profile took approximately two hours because of the multiple readings at each depth location.

Even with living accommodation only 3 miles from the study site, and rising before sunrise, access to the floodplain required about five hours of logistics, co-ordinating the efforts of a team of people involved in numerous sequential tasks. Field data collection began around 1300hours. Further readings on the rising limb were constrained by lack of daylight.

The position of the current meter downstream of the baffles for profiles 2 and 4, where the hydraulic influence of the vegetative filter is measured, is shown in Figure 5.6. A total of 139 readings were taken over the four profiles, for an average of 35 readings per profile.

The limit of tolerance for the Mini current meter was approximately $1m\ s^{-1}$. The meter capacity was exceeded in both upstream profiles, 1 and 3, as velocities in the upper water column exceeded 200 revolutions per minute. In Profile 3, the capacity of the meter was exceeded about 50% in flow greater than $1.5m\ s^{-1}$.

See Appendix B for metric field velocity data; data were collected in English units. Photo 5.13 shows the use of headphones for counting revolutions.

Photo 5.13. Author counting clicks for velocity measurements.

Analysis of the velocity profile data is given in section 6.2.3.

Vertical cross-section of velocity profile #2

Current meter

Willow baffle #3

Direction of flow

Water surface

Av. depth =0.55m

Bed surface

$\bar{v}$= 0.39 m/s

Distance from baffle to current meter 6.1m

Drawn by N.C. Perala
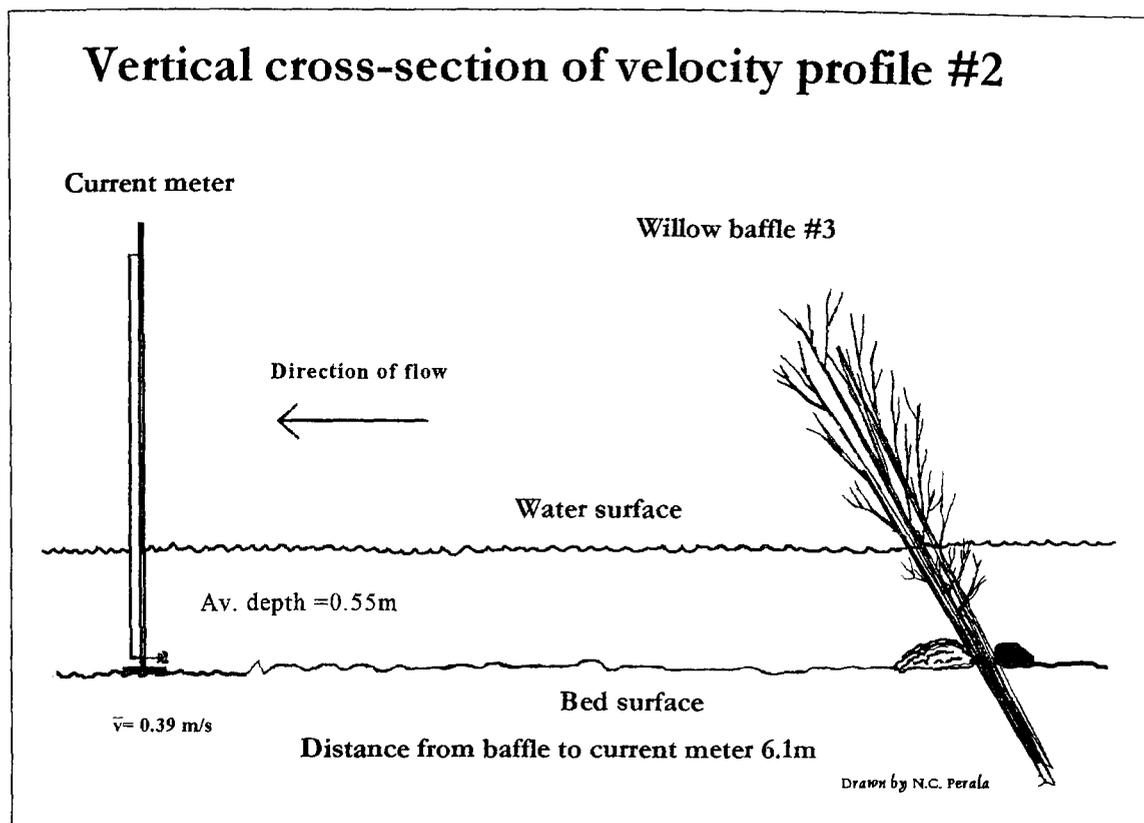
Figure 5.6. Diagram of flow through baffles and velocity measurement location downstream of baffles 2 and 3.

5.3.2   Access to the floodplain during flood stage

Owing to the physical challenges inherent in field conditions during high flood stage, no attempt was made to characterise flow conditions in the main channel during the flood peak. However, because the floodplain had been mapped and surveyed carefully prior to the storm, knowledge of conditions on the floodplain permitted careful entry onto these surfaces during the rising and falling stages of the flood.

Accessing the study site on the midchannel island required a means to enter the floodplain and cross a secondary channel, where water depth exceeded 2m. Equipment required for entry onto a flooded floodplain include an inflatable boat, secure tool boxes strapped to the boat, 13 mm neoprene wetsuits for insulation and flotation, stream boots and neoprene footgloves for wading, thick layers for warmth and rainproof cover, fingerless gloves, the current meter and stopwatch, and a waterproof notebook.

The floodplain was entered first by walking, carrying an inflatable raft holding the gear. Photo 5.14 shows the inflatable boat used to access floodplain. We waded into the flooded area pulling the boat, then swam into the secondary channel, holding onto the sides of the boat, so no oars or rope were needed. Thick, full-body neoprene has the added advantage of making it possible to keep one's head above water in all circumstances.

Photo 5.14. Inflatable boat used to access the floodplain during flood, 8 Jan 1995.

A video film, made from the viewpoint of the cliff photopoint above this area of the estuary by a member of the Mattole Restoration Council, illustrates the mode of access used to enter the floodplain during overbank flow conditions. The duration of field observations extended from the rising limb of the storm hydrograph, beginning on 8 Jan 1995 through the extent of floodwaters occupying the midchannel terrace ending on 14 Jan. The peak of the flood occurred on 9 January, (see Fig. 4.3, storm hydrograph for January 1995 and photo 5.15, view of the valley during the flood peak), during which time no flow data were collected. Field work began on the two days preceding the peak and commenced again during the falling limb, for a total of 5 days in data collection and 7 days in the field.

Photo 5.15. Flood peak over the revegetated midchannel island, photo taken from Taylor photo- point, 9 Jan 1995.

5.3.3 Analytic methods used for hydraulic data

Flow data are used in an analysis of vegetation roughness segregated from channel and bed roughness following an hydraulic model by Petryk and Bosmajian, (1975). Computation of the influence of woody vegetation on floodplain roughness is derived from survey data and velocity measurements taken on the floodplain during the storm event 7-14 Jan 1995.

Photo 5.16. Flow through stems of baffle no. 8 during rising flood taken, on 8 Jan 1995.

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This model is based on the Manning equation, and assumes non-submerged flow, a small amount of plant bending, relatively low velocity, relatively uniform vegetation distribution, and relatively small variations in flow velocity over the flow depth(Petryk & Bosmajian, 1975). This was the only model found to relate to the field conditions under study.

One challenging assumption of this model is the use of the drag coefficient C_D with a given value of 1.0. Estimates for this parameter in the literature range from 10^{-2} to 10^2 (Henderson, 1966, Gordon *et al*, 1992). Li & Shen (1975) found an average value of C_D for flow through cylindrical rods to be at 1.2.

The drag coefficient C_D is based on the frontal area of the object, and relates the pressure force to the frontal area. It is most strongly affected by the state of turbulence expressed as Reynolds number **Re**, except at very high values of **Re**. Counter-intuitively, in high turbulence situations, surface roughness or rugosity reduces rather than increases drag, which is why golf balls have dimples (Gordon *et al*, 1992). Thus the surface rugosity of natural woody stems with bark may actually decrease the surface roughness, which would have the effect of reducing local resistance (drag) to the flow around stems. This situation highlights some of the difficulty in modelling natural flexible vegetation in hydraulic flume models, which has typically represented natural trees on floodplains using smooth wooden dowels.

In the Petryk and Bosmajian model, a value for bed roughness is computed first, and then the vegetation roughness is derived mathematically from it. A small variation in the value for bed roughness may have a significant effect on vegetation roughness, which may not be logical in light of the ways vegetation can vary over any given geomorphic surface. A vegetation density expression is based on the sum of stem areas, the drag coefficient and the area times length factor, as shown in Equation 5.4.

$$Veg.density = \frac{C_d * \Sigma A_i}{(AL)} \qquad \text{Eqn. 5.4.}$$

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This condition is shown in Photo 5.17, where shallow flow during rising flood stage encountered high flow resistance.

Photo 5.17. Flow through baffle stems on rising hydrograph, note staff gauge in mid-ground.

5.4 Methods in post-construction analysis of the geomorphic and biological responses to the revegetation project

5.4.1 Historical assessment in the design phase

Geomorphic maps of the lower estuary documented historic channel changes for the period 1942-92. Overlays of the air photos for each decade revealed the lateral extent of lateral channel migration for the period of record. These data are used in the next section to analyze lateral migration potential and the use of these data in revegetation design.

5.4.2 Analysis of channel and floodplain width for baffle design

Following the flood of Jan. 1995, channel thalweg migration rates were analysed, including historic meander rates in the lower estuary. This process suggested a methodology for the use of historic air photo data in soil bioengineering design, following other workers such as Gurnell (1995). Analysis of the actual width of the Mattole baffle system is related to the channel width, valley width and meander planform to review appropriate widths for future baffle construction on an alluvial river floodplain.

5.4.3 Sources of error in construction

Construction design is related to actual construction practise to identify sources of error in the construction process, and the potential for remediation of common errors in construction.

5.4.4   Channel lateral migration during the flood recession

Field observations of lateral erosion during the flood recession Jan 1995 are based on measurements of bank retreat, and photo identification of landmarks and their rate of loss during flood recession. Scour patterns in the vicinity of the baffles identified unanticipated geomorphic processes of bank failure. These processes were analysed, in order to improve soil bioengineering design on large, alluvial floodplain rivers.

5.4.5   Willow cutting survival rates during the first year

Field observations identified the survival rates of the willow cuttings used in the baffle construction. Factors affecting survival are identified, with the probable effects of irrigation and groundwater table variation.

5.4.6   Root growth during the study period

From cuttings eroded from the baffles during the flood recession, rooting patterns were identified for *Salix sitchensis*. Although cuttings were ripped from the rooting substrate causing losses of fine root hairs, estimates were made of the number and length of roots developed during the 14 months of growth following construction.

5.5   Methods in laboratory flume research simulating field observations

"*All scale models are wrong* (in simulating the behaviour of full-scale (1:1) conditions), *but some are wronger than others.*" Dr. D. Hardwick, Imperial College Dept. of Civil Engineering, London.

5.5.1 Description of the laboratory flume and its comparison with the Mattole floodplain

Use of a flume to set up flow conditions in similitude with field conditions was made as an addition to the original field research. Only after seeing the hydraulics of flow through vegetation during the flood of 1995 was the lack of planform view apparent, although this 'bird's eye' view was clearly in mind when Li & Shen (1976) described their experiments of wake width, length and re-entrainment from flow through tall (emergent) vegetation. This perspective is one of the advantages that flume study has over typical field research conditions.

The limitations of collecting velocity data in the field under dynamic fluvial conditions are matched by the limitations from loss of natural complexity in the laboratory. Both approaches are circumscribed, yet both are needed to progress our quantitative understanding of complex natural processes. It was decided that a complementary laboratory investigation could strengthen results from the field investigation, recognising the potential problems of scale and wall effects (see section 3.1.20.), in particular adding the perspective of the longitudinal view of hydraulic influences from the baffles, something observed obliquely but was not measurable in the field.

Translating field conditions to a flume required the deletion of a large number of parameters from the field data, in order to observe flow through emergent porous 'shrubs'. These included channel/ floodplain width ratios, sediment transport and deposition, slope, fully open channel conditions (limited by the presence of the flume wall), and higher Reynolds numbers. Benefits gained by the flume conditions included controlled flow depths of long duration, lack of topographic variation and complexity, a fine-scale digital current meter and repeatability (in the sense of controlled or 'on-demand' replication of flows), in addition to the plan view described earlier.

The medium-sized flume at Imperial College London was made available for this research exercise, along with guidance from teaching staff there and laboratory technical support.

Flume dimensions are:

12m x 0.75m x ~0.5m

Objective 3 (section 4.3.2) set the task to simulate, in the laboratory, flow conditions observed in the field, to observe flow patterns in overbank flow influenced by a porous vegetative filter. The dimensional problems were overcome to a limited degree by use of comparable Froude numbers. The horizontal scale of the Imperial College flume used for this exercise was 50:1, and the vertical was 20:1, introducing substantial scale distortion, which is not uncommon practice in flume modelling. See Appendix E for flume dimensional analysis and Froude number calculations. This distortion cannot be overcome, and limits the use of flume data for prediction purposes at other scales. Photo 5.18 shows the physical laboratory and flume apparatus.

Photo 5.18. View of the flume laboratory.

According to Henderson (1966), the key to relating 'prototype' or full-scale conditions to flume model conditions is by holding Froude numbers *Fr* constant (Eqn. 3.10). The appropriate Froude number was used to scale flow velocity from field to flume conditions based on 'average' turbulence conditions. Froude numbers for the Mattole floodplain flows were computed from observed flow data. For the flume, velocity and depth were calibrated to achieve Froude numbers in the range 0.5-0.7. Calibration of the flow is an iterative process, where flow depth (5cm over the terrace) and velocity are achieved gradually, depending on pressure from the main tank.

Flow velocity was measured using a Nixon Streamflo low speed probe with a propeller and digital current meter. Digital readings are given in Hz, and these data are converted to velocity readings using a calibration curve chart to yield velocity in cm sec^{-1}. Velocity measurements are valid only above about 5 cm sec^{-1}. Below this value, the instrument fails to spin reliably.

Following the work of Pasche & Rouve (1985), only half of the channel was simulated in the flume (see Ch. 3, Figure 3.6). A floodplain terrace platform

created a separation of floodplain flows from main channel flows, to simulate the upstream slope of the midchannel island found under field conditions.

The platform had approximate dimensions L x W x D of:

~1500mm x 250mm x 50mm.

Since the flows of interest are on the floodplain, and only floodplain velocity data were collected on the study site, measurements were made only on this terrace.

For several months prior to the flume tests, various materials were tested for their ability to simulate willow baffles at this scale. Eventually, highly porous Enkamat™, welded polypropylene filament mat sections were adopted for use in the flume.

This material has the properties of being porous to flow, having an appropriate resistance to non-submerged flow and being moderately flexible without collapsing under the force of the flows. Sensitivity testing was carried out on the Enkamat design by testing its resistance to flow conditions. Design modifications were made by changing the base and top thickness, and by cutting vertical slices from the top of the baffle section downward. These slices reduced flow resistance in order to increase similarity with the vertical flexibility of willow baffles. Photo 5.19 show the flume baffle simulation.

Photo 5.19. View of the final baffle design (Mark V Meyer's hedge)

This simulated 'hedge' had approximate dimensions of L x W x D of

200mm x ~10mm x 900mm.

Only the 2 baffles furthest upstream of the 10 constructed in the field could be simulated in the laboratory. Attempts to further simulate flow obstructions would have given unreliable results (Hardwick, pers. comm. 1998).

The purpose of this exercise was to recreate some aspects of flow patterns on a 'floodplain' influenced by vegetation 'baffles'. Flow behaviour derived from soil bioengineering and hydraulic theory predicted definite flow structures, including

the effect of the upstream-most baffle angled at 60 degrees upstream and the backwater effect. Flow patterns and vectors around and among the baffles were illustrated using a potassium permanganate solution. A digital video camera stationed above the flume was used to record flow structures for qualitative analysis of these complex structures and interactions among the channel, floodplain and simulated vegetation.

Schiechtl (1980) recommended spacing the baffles at 1.5 times the baffle length, but did not mention if this was for hydraulic or geotechnical reasons, or both. This 1.5*l* spacing was used as a starting point to explore the hydraulic effect of baffle spacing on wake re-entrainment of the flow.

5.5.2 Qualitative observation of the effect of vegetative filters on flow resistance and backwater effect

To make meaningful observations, the assumption was made that the complex flow observed in the field can be recreated in a small laboratory flume. Building on other innovations in hydraulics research (for example, Hoyt & Selling, 1997), tracer dye was used in a flow visualisation study, to illustrate flow patterns which can inform understanding of the effects of the vegetative filter on flow resistance. Of special interest is the nature of the backwater effect from porous baffle structures, and whether the extent of this effect can be measured in relative terms. The upstream extent of the fine sediment deposited by the Dec 1993 storm is considered by the author to be a clear expression of this backwater effect.

Wake re-entrainment theory was developed for single cylinders, simulating large trees, and for ellipsoids, but it is unknown whether wake behaviour functions in the same way for vegetative filters such as coppiced willows. It is likely that the momentum transfer from the flow to a flexible stem could re-distribute energy to the stream in such a way as to prevent a clearly defined wake from being formed behind a 'waving' or bending stem. This could be because the turbulent, chaotic

pattern of energy distribution in the flow eludes quantitative analysis of any behaviour larger than micro-scale (Naot *et al*, 1996).

The laboratory exercise began with calibrating the flow with the Froude number. Then a single cylinder was placed into the flow, and tracer dye illustrated the flow patterns around the cylinder. Next a single baffle was placed into the flow, then tracer dye was again released. Wake patterns were examined and compared visually.

5.5.3   Variation of baffle spacing to observe flow wake re-entrainment and the relative distance at which wake re-entrainment occurs.

One of the more challenging aspects of the design of the live siltation baffle (or brush traverse construction) is the determination of trench length and spacing width. One key parameter of the spacing width may be based on whether the baffle generates a defined wake and the length of the wake relative to the length of the baffle. This exercise was designed to identify the presence of a wake width downstream of a baffle to aid in the revegetation design process for a design flood stage. Because of spatial constraints, two baffles were the maximum number which could be placed in this flume.

5.5.4   Interpretation of flow processes influenced by floodplain vegetative structures during overbank flow

In the laboratory, average velocity measurements can be used to observe relative changes in average velocity upstream and downstream of the porous filter obstruction. These observations were also recorded on digital video, for comparison with visual observations in the field recorded on still camera. Key features tested are the effect of the baffle on channel – floodplain flow interactions, the detection of baffle influence in the upstream direction, and the length of baffle effect, through drag, in the downstream direction.

5.6 Conclusions

Theories regarding vegetation influence on overbank flow, identified from literature in Chapters Two and Three, are carried forward into practical application in the research. The background for the case study and its relevance as a field site were discussed in Chapter Four. Materials and methods used in the field work and laboratory investigation have been presented in Chapter Five.

Methods are presented by the major categories of vegetation influence on sedimentation, and influence on overbank flow structure. Field conditions controlled the development of parameters used in the laboratory flume. Methods of data collection and analysis are set within a framework linking theory and field practice, and linking the natural riverine conditions with the laboratory flume conditions.

Limitations encountered in the laboratory are acknowledged, and observations from the flume will be analysed and discussed accordingly. Work in the flume underlined the value which would have accrued from using a competent three-dimensional, digitally recording flow meter in the field, instead of the inexpensive one-dimensional flow meter which was employed in this field research. The ability to characterise flows in longitudinal, lateral and vertical dimensions would greatly increase the utility of velocity data collected. Bearing in mind that multiple readings were taken at a single location and depth in order to average the data scatter, using multiple, digital meters (3-5) on a single wading rod would have increased the amount of data collected by an order of magnitude or more. This is particularly important because the window of sampling opportunity is typically brief.

In Chapter Six, analysis of the field data will follow the categories outlined in Chapter Five.

Chapter 6: Data Analysis

"There remains a pressing need for data from field observation of overbank flows against which prediction performance can be evaluated. Only when shown to predict field-scale flows reliably can (laboratory-derived) methods be rated as satisfactory design tools."
Prof. B. B. Willetts, Univ. Aberdeen Dept. of Civil Engineering (1997)

6.1 Measurement of the extent and depth of fine sediment deposition for an overbank flood flow influenced by woody vegetation

Common knowledge holds that, where trees and shrubs occur on river banks, sediment accumulates, but the mechanisms by which these processes operate are not well understood. In fact, large, widely-spaced large trees can induce scour and bank attack (Thorne, 1990), indicating that some hydraulic threshold is crossed as flexible woody stems become mature tree trunks. The properties of flexible woody stems in flowing water are under investigation here, with the understanding that the movement of these stems in overbank flow is so chaotic that no publicly-available model exists to describe this behaviour. From field visual observations, young woody stems bend in the streamwise direction, flex in proportion to the velocity and consequent shear force of the water, distribute momentum along the stems and leaves into the roots and substrate, and oscillate in three dimensions as instantaneous velocity variations pulse along the banks and floodplains (Figure 1.1). Despite this complexity, repeatable patterns occur.

6.1.1 Sediment volume and distribution analysis

The volume of sediment retained by the entire baffle construction was sampled following the flood of Dec. 1993. Results of the probe sampling are reported in Appendix A, with the locations and depths illustrated by the data layout. The volume of fine sediment retained for that flood event was 85.5m^3.

Distribution and depth of the observed fine sediment deposition pattern are illustrated in Figure 6.1.
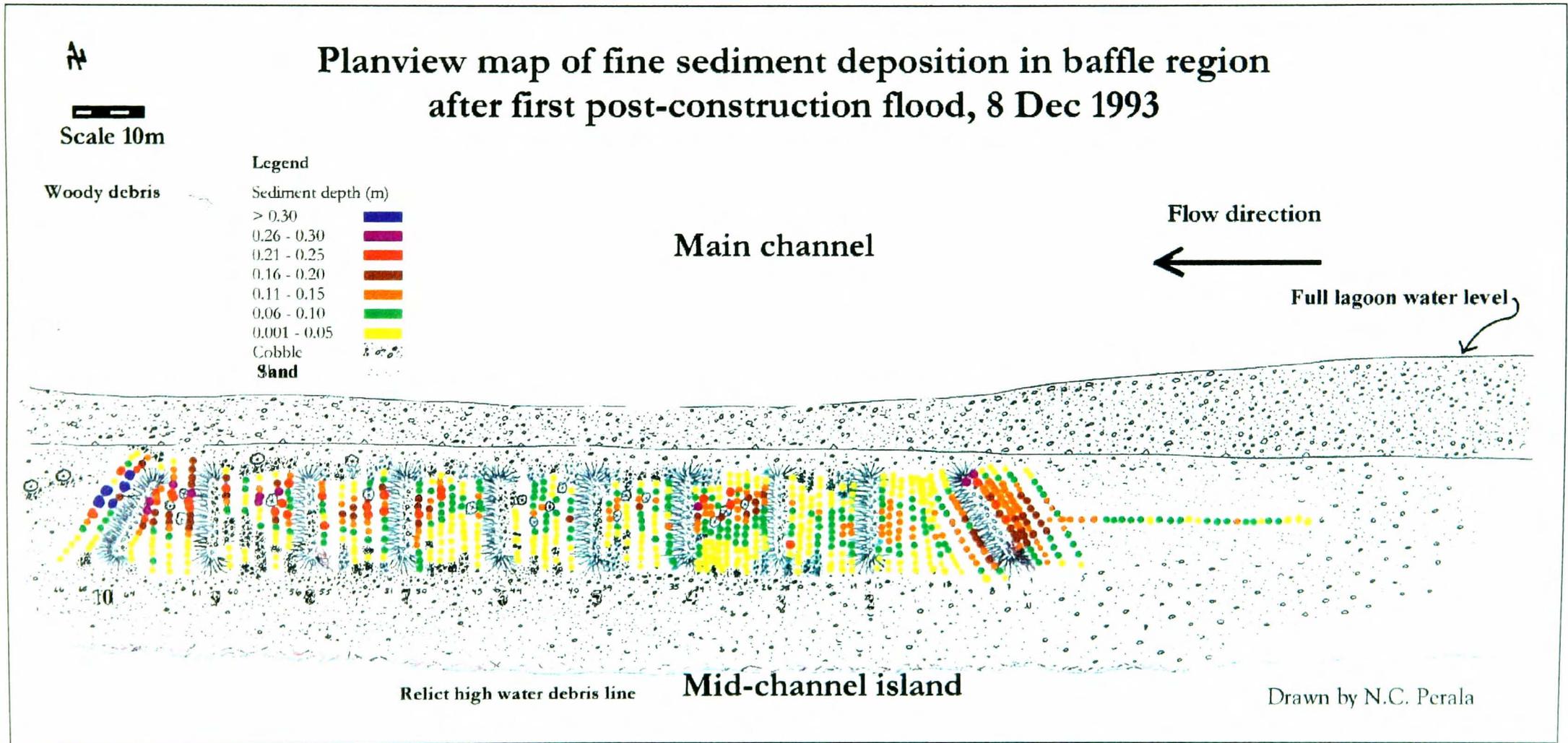
Planview map of fine sediment deposition in baffle region after first post-construction flood, 8 Dec 1993

N

Scale 10m

Woody debris

Legend

Sediment depth (m)

> 0.30
0.26 - 0.30
0.21 - 0.25
0.16 - 0.20
0.11 - 0.15
0.06 - 0.10
0.001 - 0.05
Cobble
Sand

Main channel

Flow direction

Full lagoon water level

Relict high water debris line

Mid-channel island

Drawn by N.C. Perala

Figure 6.1. Plan view map of fine sediment deposition in baffle region after first post-construction flood.

6.1.2   Sediment particle size analysis

Results of the laboratory sediment analysis revealed statistically similar fractions of sands, silts and clays throughout the area and depths sampled, however, in absolute terms, percent sand, silt and clay varied widely across the sample area. Mean and median values are shown in Table 6.1.

Results of sediment size fraction analysis for sediment deposited Dec 1993			
Sediment size	*Median %*	*Mean %*	*Stand. deviation*
Sand	28.77	34.36	23.76
Silt	37.27	36.71	10.89
Clay	23.75	28.94	19.64

Table 6.1.   Mean and median particle size class values for deposited sediments in the area of the Mattole baffles, for the flood event 8 Dec 1993.

According to the predicted flow velocities and particle fall velocities, sediment sizes were expected to be coarse sands through fine silts. The particle fall velocity for particles 2 microns or less was predicted to be too low for clays to be able to settle out of suspension during the rising and peak flood periods (Lu *et al*, 1988).

The laboratory analysis revealed a surprising percentage of clays distributed throughout the length of the baffle area. Upstream of baffle 1, the percent clays ranged from 3 to 60%, increasing in the upstream direction, reflecting the backwater effect, as sediment-laden water encountered the first baffle. Discernible layers of clay were not observable in most sediment samples; rather clays appeared to be mixed heterogeneously throughout the samples in varying fractions.

The distribution of sediment fractions is reported in Figure 6.2.
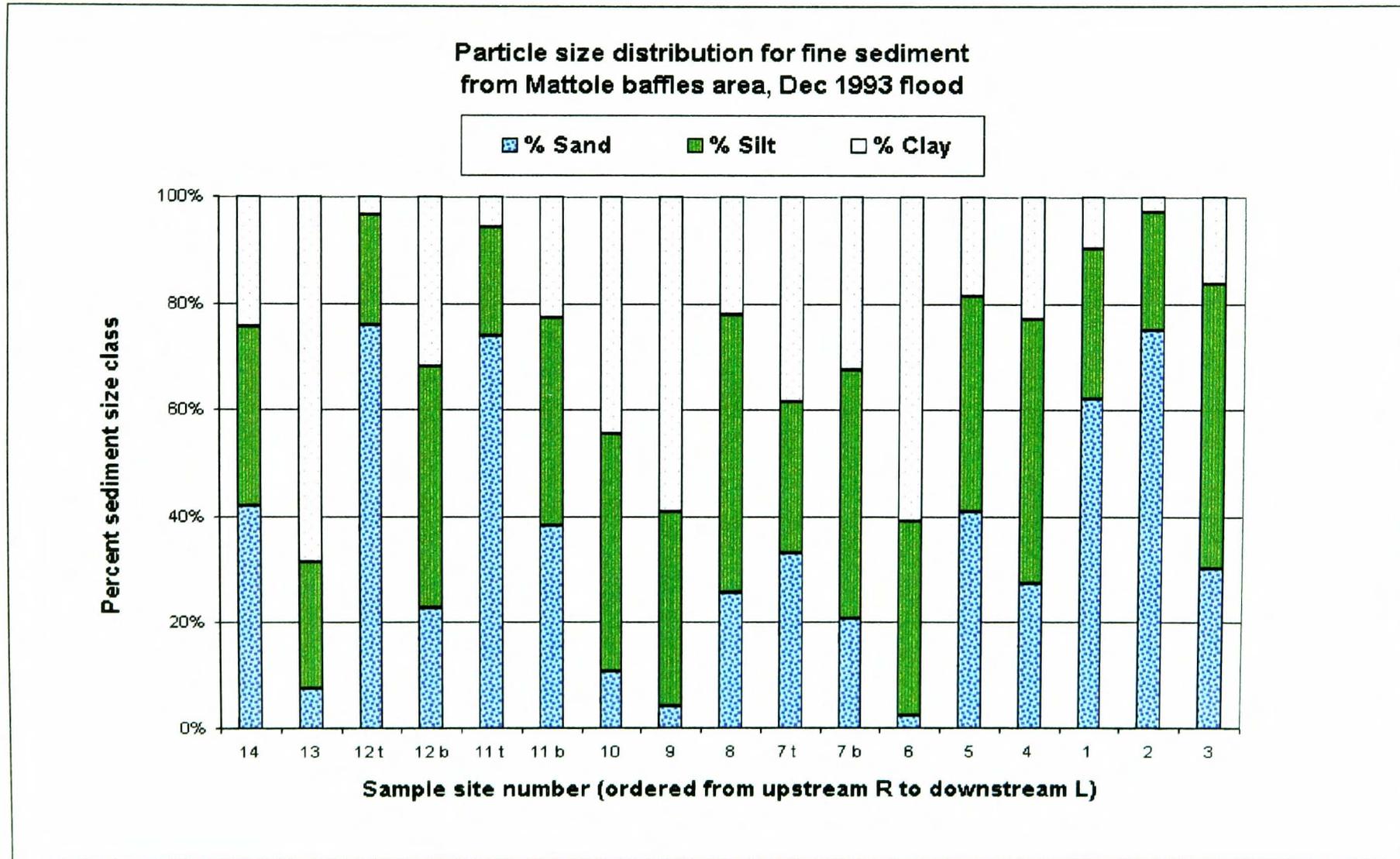
Figure 6.2. Particle size distribution for Mattole baffles sediments resulting from the Dec. 1993 flood. Samples are shown by location in order from upstream right to downstream left .Samples with t and b designations are taken from the top and bottom of the sampling container, (ht = 5cm).

This observation contradicts the widely held view that clays do not commonly settle out of overbank flows except at the very lowest velocities and in standing water (Davis *et al*, 1995). Decreasing velocity and moderate turbulence induced by flexible emergent vegetation within or near the boundary layer may provide another condition under which very fine particles can settle out of suspension.

In three samples, 7,11 and 12, distinct layers were identified upon extraction from the sampling container.

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Sample #	7 upper (t)	11 upper (t)	12 upper (t)
% sand	32.9	74.0	76.0
% silt	28.5	20.4	20.5
% clay	38.6	5.7	3.5
Sample #	7 lower (b)	11 lower (b)	12 lower (b)
% sand	20.6	38.3	22.8
% silt	47.0	39.0	45.8
% clay	32.4	22.7	31.8

Table 6.2. Comparison of particle class fractions for distinct layers of sediments in selected samples, deposited during the Dec 1993 flood.

To explore the sediment fractions for these 'top' and 'bottom' layers, the two halves were analysed separately, and are reported in Table 6.2. as 7t, 7b, 11t, 11b, 12t and 12b. This exploratory analysis was carried out to determine whether distinct processes in sedimentation could be identified from these samples. Located in the middle and downstream (lower) region of the baffles (see location map Figure 5.3), these strata of sediments may have been produced by different flow regimes, such as the rising and falling limbs of the storm hydrograph. In each case, the upper layer contained significantly more sand than the bottom layer, indicating that coarser sediments were deposited on the hydrograph declining limb or during the latter part of the storm. This may reflect erosional processes upstream, occurring at or near the peak, releasing fine sediments into the flood wave that diminish (as erosion diminishes) toward the end of the flood.

A graphic presentation of these data is given in Figure 6.3.
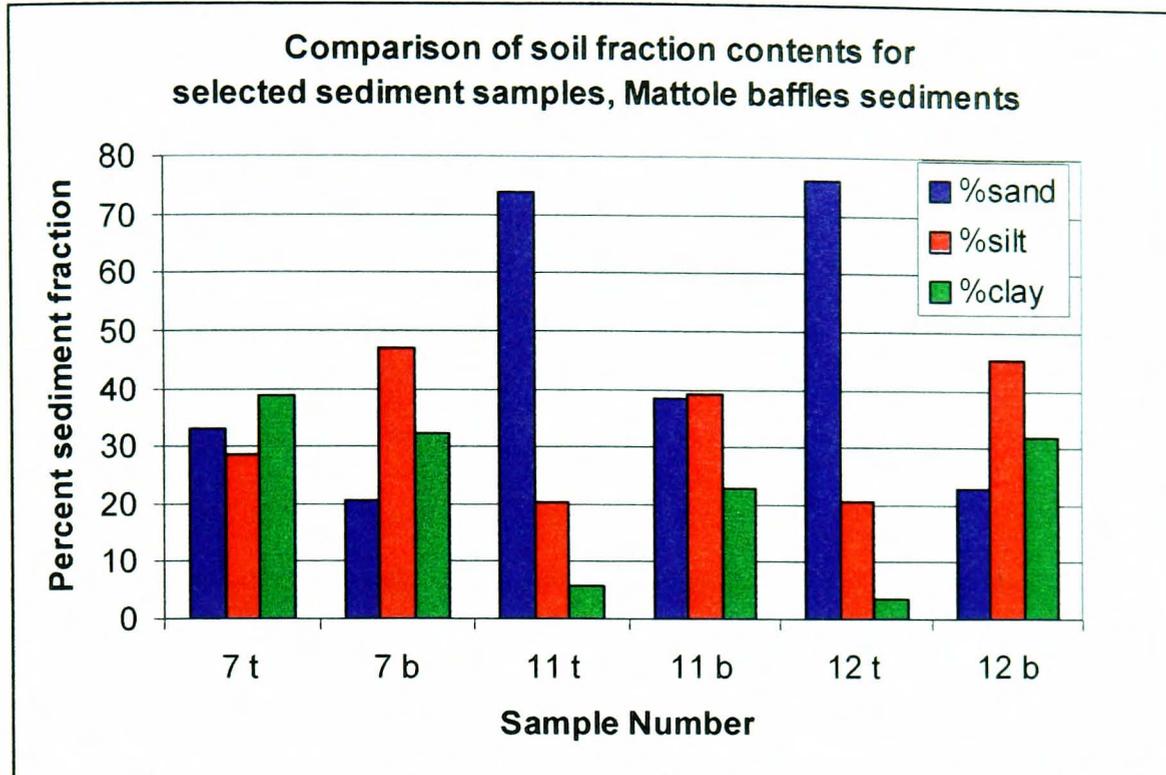
Figure 6.3. Comparison of soil fractions in selected sediment samples, showing clay fractions distributed in upper (t) and lower (b) layers of flood-deposited sediments, 8 Dec 1993.

6.1.3 Sediment distribution patterns and potential sources of error in mapping and reporting

Sediments retained by the baffles concentrated the greatest depths in the centre region. The layer of fines at the baffle margin was generally shallow compared with the interior zone. A discernible 'captured sediment' boundary occurred at the baffle margins. This appears to reflect the hydraulic forces set up by the shear friction caused by interaction among slower- and faster-moving water around the baffles, considered in plan view.

The first baffle appears to be very efficient at filtering suspended sediment from overbank flow. The backwater effect caused by the baffles is strong, and sediments deposited upstream of the first baffle accounted for about 20% of the total sediment retention. Lateral mixing caused by the hydraulic shear zone around the baffles appears to be the primary agent of fine sediment delivery to the downstream baffles.

The greatest sediment depth occurred just downstream of the last baffle, number 10. Because of the near presence and density of the naturally recruited shrubs and the slight crest in mid-channel bar landform, this depth cannot be attributed to the hydraulics of flow around the constructed baffles. Complications in the measurement of the sedimentation pattern could have been caused by the presence of the small number of naturally recruited Sitka willow shrubs (*Salix sitchensis*), around which fine sediment deposits were deeper than in other areas in the mid-baffle region (Figures 5.4, 6.1).

This lends support to the observation that micro-topographic landform variation affected the location and depth of fine sediment deposition. Occlusions of pebble clusters poking up into the flow of water have been noted for small-scale effects on thresholds of entrainment and deposition (Gordon *et al*, 1992). As the cumulative particle size frequency of the geomorphic feature (such as a mid-channel island or side bar) increases in size, so does the variability or heterogeneity of particle sizes (Gordon *et al*, 1992, pg. 205). In other words, as the armour layer becomes more coarse, it also becomes more heterogeneous, or sand beds tend to be more uniform in particle size than cobble-sized armoured features (Gordon *et al*, 1992).

In comparison, the approximately 75cm flow depth of the flood of Jan 95 deposited heterogeneous coarse and fine sediments across the entire northern portion of the mid-channel island, Photo 6.1.

Photo 6.1. Typical heterogeneous sediments deposited by the 9 Jan 95 flood on the upstream end of the estuary mid-channel island.

Downstream of the baffle region by approximately 30 m, a large and distinct set of sand dunes formed, shown in Photo 6.2. This pattern of deposition may have formed in response to the bedform roughness of the mid-channel island, which may have induced a long wake from the island tip toward the downstream end.

Photo 6.2. Sand dunes formed downstream of the baffle region, 9 Jan 1995.

Patterns of coarse and fine sediments immediately around the baffles showed a scour zone where an opening in baffle 7 occurred during the flood, shown in Photo 6.3. The increased hydraulic force created by a break in the baffle stem density

caused a complex reaction of scour and deposition, but illustrated the effect of the unbroken baffles on flow filtration.

Photo 6.3. Scour zone formed by a break in stem density, baffle 7, 9 Jan 1995.

Although the data gathered do not support an analysis of these sediment distribution patterns, the scale of the pattern (greater than 100m in scope) suggests that the pattern of hydraulic forces generated by the vegetated area had a profound influence on turbulence structures. Bedform roughness is clearly a major factor in larger-scale sedimentation phenomena, but is outside the scope of this research. In larger floods, heterogeneity increases across all scales, making quantitative observations difficult.

Lateral mixing between the faster flow in-channel and the slower water over the floodplain is a strong hydraulic feature of the of flow through a vegetation zone at the channel- floodplain margin. This supplies fresh sediment to the downstream reach, concentrating retention in the centre region as the shear force re-entrains sediments captured near the margins.

6.2   Influence of flexible woody vegetation on floodplain velocity profiles

The velocity profiles are created from flow data observed during the 15 year storm, 6-11 January 1995. The map, given in the Methods section as Figure 5.5, is repeated here for the convenience of the reader, to aid in placing the locations of the velocity profiles.

Profiles one and two were made on 8 Jan, day three, on the rising limb of the hydrograph, from 20m upstream of baffle one and between baffles three and four. Following the flood peak which occurred on 9 Jan 1995, two additional profiles were taken on day 5, 10 January. The third velocity profile was made from 40m upstream of the first baffle, and the fourth was made from between baffles two and three.

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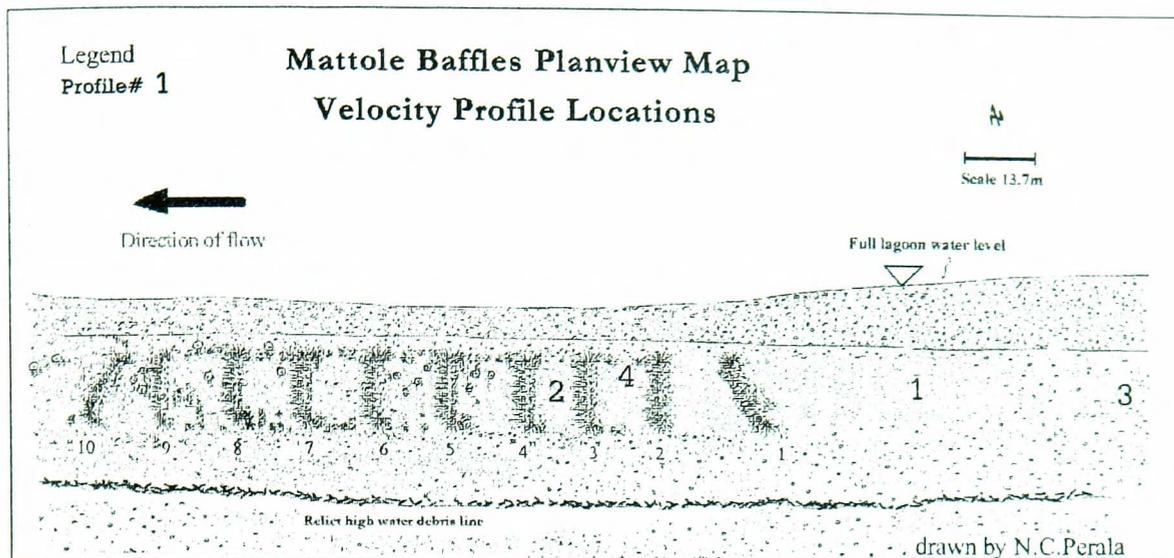
Map showing location of the velocity profiles.

6.2.1 Velocity profiles from observed flow during 15 year storm

Current meter readings were taken over 1-minute intervals at a given depth until the standard deviation among readings was minimized. Greatest variation was observed in Profile 1, when up to six readings were taken for a single depth location. Graphs of the velocity profile data are given in Figures 6.4 - 6.7.

The metric velocity data are reported in Appendix B.
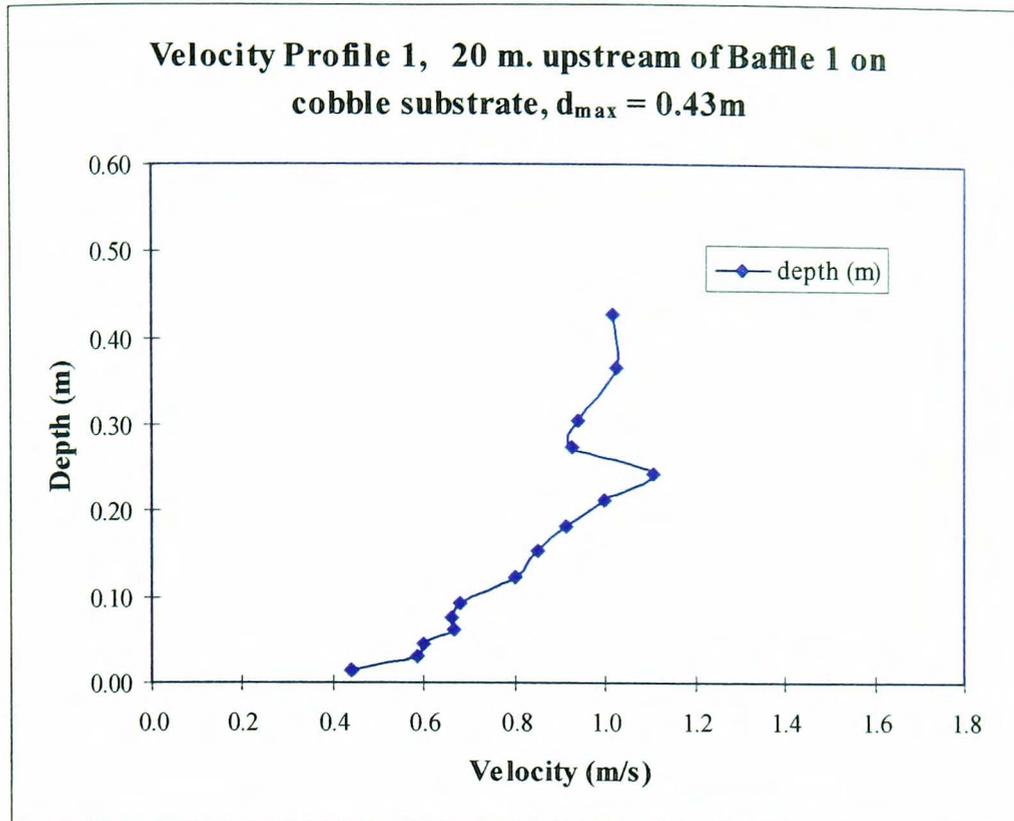
Figure 6.4. Velocity Profile One, taken 20m upstream of Baffle 1 on Day 3,
8 Jan 1995 (flood waters rising).
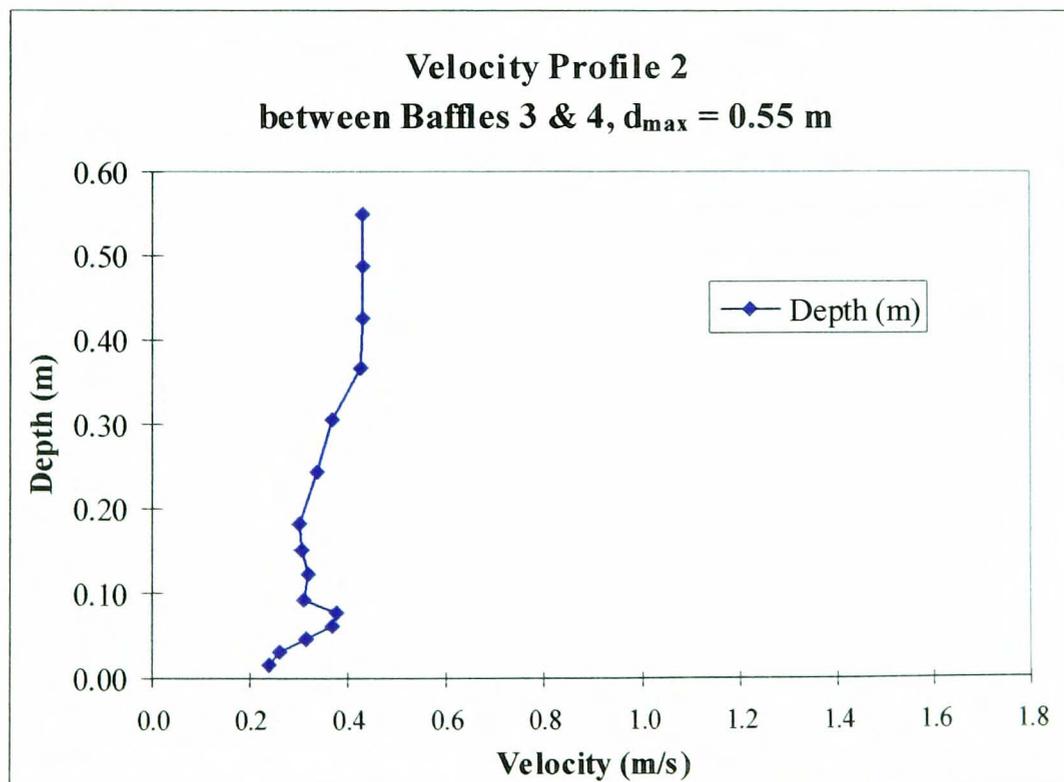
Figure 6.5. Velocity Profile Two, taken between Baffles 3 & 4 on Day 3,
8 Jan 1995, (flood waters rising).
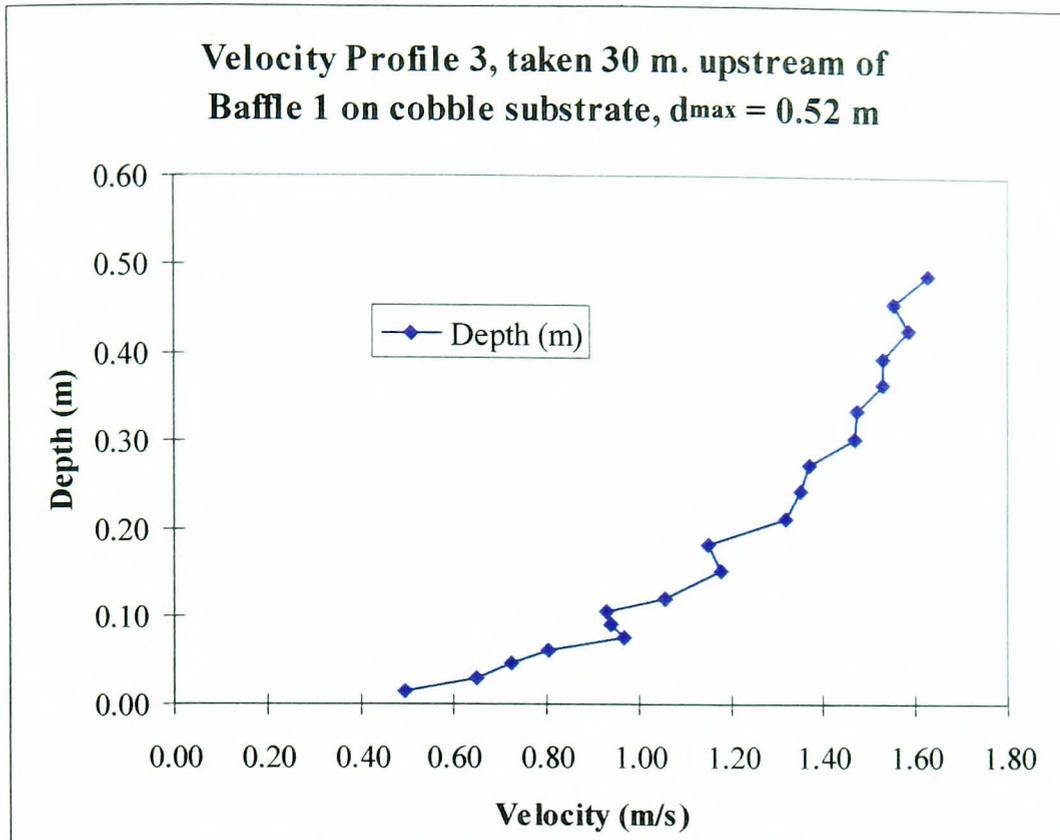
Figure 6.6. Velocity Profile Three taken on day 5, 40m upstream of baffle 1, 10 Jan 1995, during flood recession.
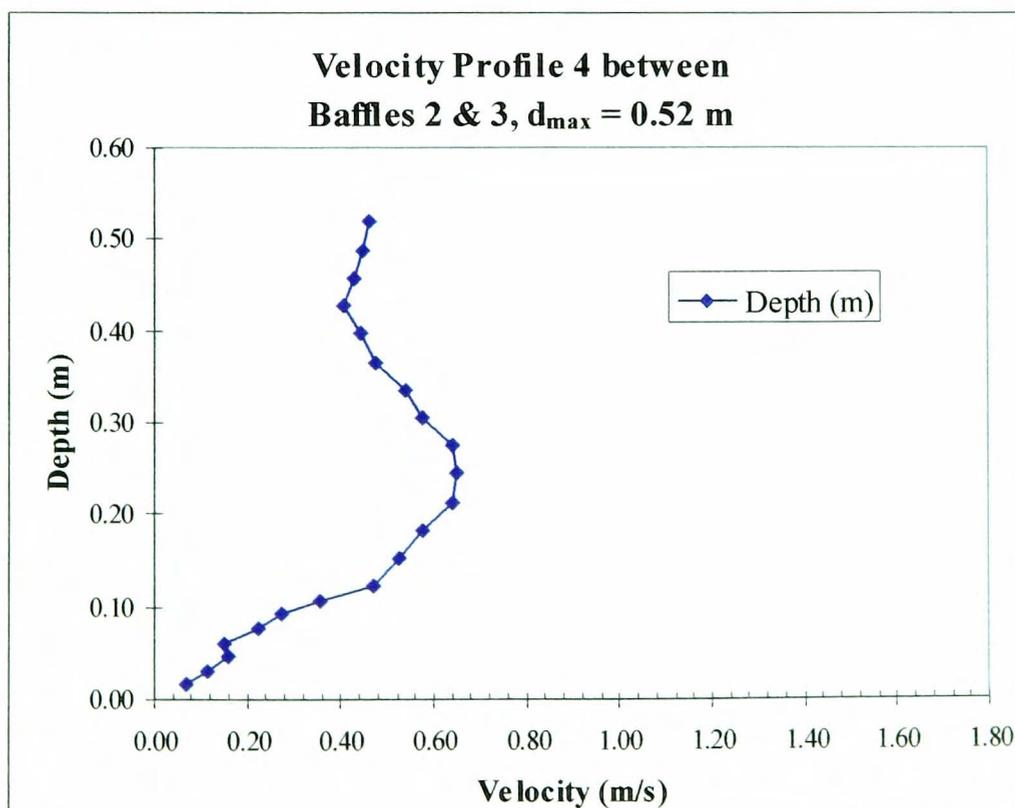
Figure 6.7. Velocity Profile Four, taken on day 5 between Baffles 3 & 4, 10 Jan 1995, during flood recession.

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A comparison is made for each of the two sets of profiles taken for comparable discharges. These graphs illustrate the change in flow velocity between profiles 1 and 2, and between profiles 3 and 4 for comparable flow conditions. Velocity data are the calibrated raw field data showing error bars for average values where multiple observations were made for the same flow depth. Unsteady flow conditions must be assumed, as both discharge and depth changed gradually but constantly, and instantaneous pulses in velocity were observed. Figures 6.8 and 6.9 present the graphs of profile comparisons.
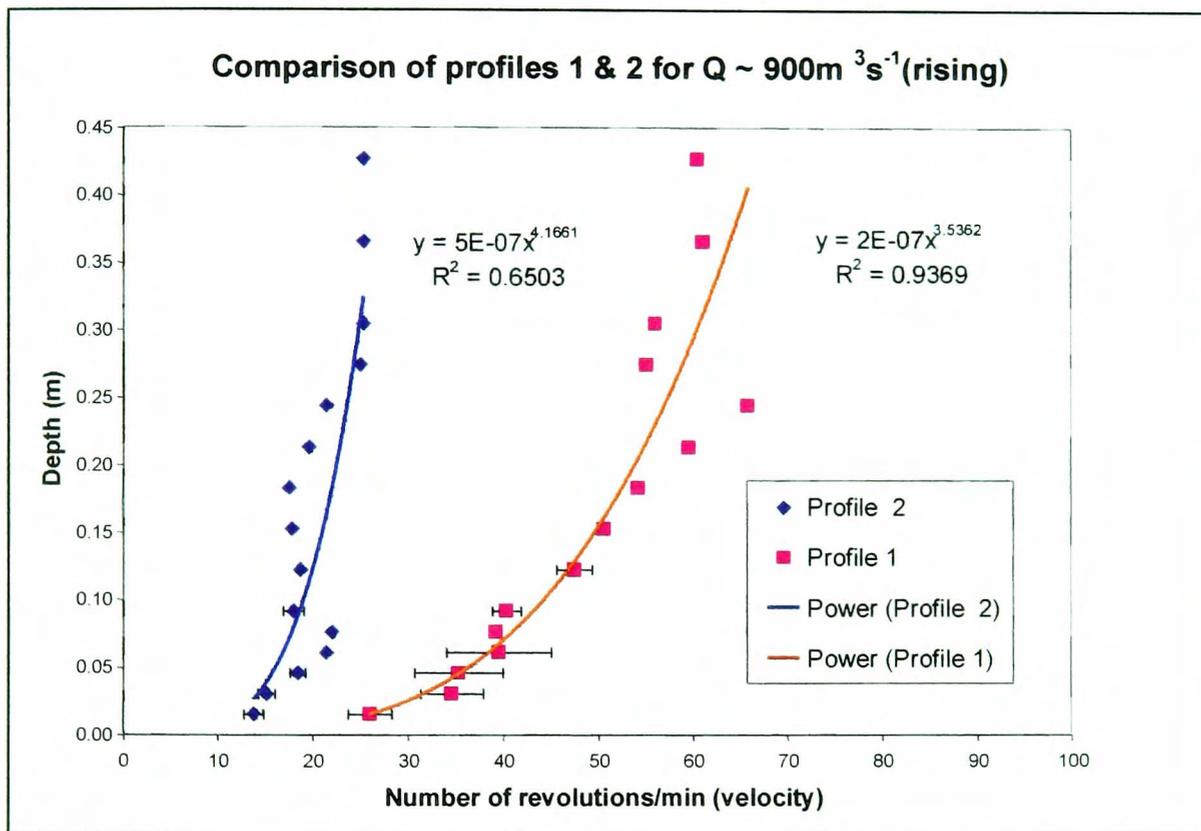
Figure 6.8. Comparison of velocity profiles 1 and 2 for Q ~ 900 m^3s^{-1}, data collected on the rising limb of the storm hydrograph, 8 Jan 1995.

Note the greater variability in velocity for the flows upstream of the vegetation zone, shown by the width of the error bars.

Comparison of profiles 3 & 4 for Q ~ 735 m³s⁻¹ (falling)
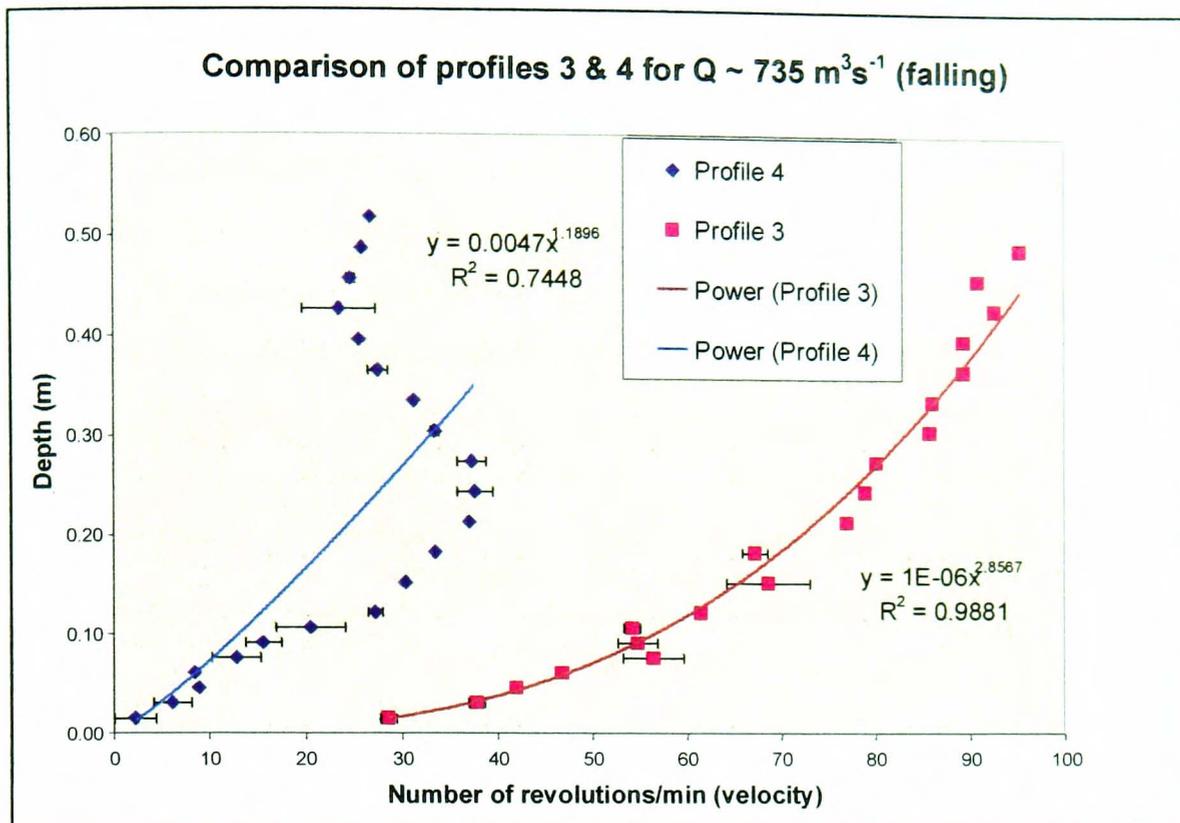
Figure 6.9. Comparison of velocity profiles 3 and 4 for Q ~ 735 m³s⁻¹, data collected on the falling limb of the storm hydrograph, 10 Jan 1995.

Field conditions on the falling limb of the hydrograph dictated the locations possible to read velocity profiles based on sufficient flow depth. Profile four was observed between baffles 3 and 4, nearer to the channel margin than was profile 2, which was located well in the middle of the vegetated region (see location map Figure 5.5). There was, in the location of profile four, a high potential for cross-flows eddying off the edge of the first baffle to enter the vegetated region downstream from the direction of the main channel, which may have increased turbulent mixing at the near channel margin. This flow behaviour was observed in the flume (see section 6.5.2).

6.2.2   Possible flow structures within and around the baffles

Consideration of some cumulative effects of a series of baffles suggests that the retardance of flow may occur in both upstream and downstream directions. In the

upstream direction, the transverse component of the flow velocity increases at the expense of the longitudinal velocity, causing the familiar 'backwater effect'. Kinetic energy is converted to static head. Downstream, the flow is retarded or 'attenuated', as the velocity profile is homogenised and becomes relatively uniform. This observation has been made in several flume experiments, using simple rigid cylinders in varying spacing densities (Hodges & Diplas, 1998). A suggested interpretation of this flow retardance is given in Figure 6.10.

Long profile view of the backwater influence owing to willow stems retarding overbank flow

Direction of flow

Length of velocity profile arrow indicates relative velocity

Water depth ~ 0.5m

Profile 2

Profile 1

Zone of flow attenuation

Zone of backwater

Profile 2 approx. 20m downstream of Baffle 1

1st Baffle

Profile 1 approx. 20m upstream of Baffle 1

Drawn by N.C. Perala

Figure 6.10. A long profile view of baffle influence on retardance of overbank flow, showing two mechanisms of velocity reduction, the backwater effect and downstream flow attenuation.

The effects of emergent, flexible, porous vegetative structures on floodplain flows are complicated by the induced lateral flows, slightly upstream of the baffles. These lateral flows cause eddy vortices around the ends of the vegetation zone, as the set up a shear zone against the faster-moving water in the main channel (also discussed in section 6.5.2). This hydraulic behaviour was observed on the Mattole

during the flood of Jan 1995. Photo 6.4 shows turbulent eddy vortices shedding from baffle branches at channel margin.

Photo 6.4. Lateral mixing of faster water in-channel and slower water flowing inside baffle 'envelope'. 10 Jan 95.

Using the sedimentation patterns as a surrogate for observed flow structures, two flow regimes are indicated. Water flowing through the baffles at lower depths encounters porous resistance, which induces high turbulence. The boundary layer height would be at a maximum in the baffle region. Water flow at the margin of the baffle construction would encounter higher velocity water moving around the baffles, and a vigorous momentum exchange between the two areas of lower and higher velocity flow is likely. This momentum exchange has been observed in interactions between the two velocity regimes of main channel and floodplain flows in flume experiments (Pasche & Rouve, 1985). Similarly, a hydraulic 'wall' and momentum exchange seems to be apparent in the flow regimes between flow within and around the baffles, from the resulting pattern of sediment distribution.

Understanding of the nature and mechanics of this flow exchange would benefit from large-scale flume modelling using a porous, flexible filter medium to simulate shrubs, early seral stage riparian trees or the coppice method of bank maintenance, complementary to the use of cylinders to represent mature trees. The addition of suspended sediments would complicate greatly the analysis of flows, as well as the turbulent exchange among vegetated, non-vegetated and channel areas, but such analysis would increase the predictive capability of the consequences of riparian and floodplain revegetation (see also Chapter 7).

6.2.3   Analysis of velocity data for influence of vegetation structures on floodplain roughness

An analysis of the velocity profile data examines the roughness values for the vegetation, using the hydraulic model developed by Petryk & Bosmajian (1975). This model developed the concept of the vegetation area factor (for relatively

uniformly distributed vegetation), to segregate bed roughness and vegetation roughness into separate components. The present analysis is based on the assumption of ranges of minimum, average and maximum values for stem diameter and area, flow depth and average velocity, and cross-sectional area of flow. This approach indicates a range of possible true values, based on field data. The resulting values are therefore not precise, but may be relatively accurate for describing actual field roughness conditions.

Two methods were used to estimate n_b, roughness of the channel in the absence of any vegetation. The Cowan method (Cowan, 1956) is given in Chapter 3, section 3.1.14., Eqn 3.16. The Cowan method yielded a roughness value for the floodplain bed of $n_b = 0.058$. One must assume a base roughness value for the floodplain bare surface which accounts for bedform and cross-section variation, as well as particle size distribution. Three different values could be computed for this base value n, from the field data.

See Appendix D for computation results from the Petryk & Bosmajian (1975) method. To compute a Manning's n value for the bare bedform, only the velocity and other data measures taken from the unvegetated floodplain were used. The model is given in Eqn. 3.26.

The Manning method yielded the following baffle roughness values based on two methods with varying assumptions for computing bed roughness, shown in Table 6.3.

Flow depth d (m)	Manning's n_b value =0.015	Manning's n_b value = 0.020	Cowan n_b value = 0.058	Average values from Petryk & Bosmajian
0.34	0.0246	0.0279	0.061	Min: 0.025
0.53	0.0367	0.0390	0.067	Avrg. 0.047
0.69	0.0497	0.0515	0.075	Max 0.075

Table 6.3. Variation with depth in Manning's roughness values for Mattole baffles, computed with varying base values for bed roughness.

These values conform well with those predicted by Tabled Values of Roughness Coefficient n, Table 5-6 Section D-2, Floodplains, Brush, given in Chow 1959, for light brush and trees in winter, ranging from 0.035- 0.050. These values also correlate with the wide range given by Cowan for low vegetation value of 0.005-0.10 (Cowan, 1956, p.474).

One may wonder, however, whether the wide variation shown in these values computed from field data might increase the difficulty for the field engineer, rather than reducing the complexity. It would seem that the determination of flood damage potential resulting from streamside vegetation could result more from the initial assumptions made in computation, than the inherent dangers or physical processes the vegetation may confer to the fluvial system. Consideration of the fluvial system could assist by providing a context for relative roughness.

On the wide, relatively bare, floodplain and open spacing between vegetated areas as well as the porous nature of the vegetative structure, the live siltation baffle construction presents a low roughness value to the overbank flow, especially when considered more at a reach scale, for which Manning's n values typically are used.

Petryk & Bosmajian provide two means of estimating velocity in vegetated areas. One is a modification of the Manning equation using a vegetation density factor, shown in equation 6.1:

$$V^2 = \frac{S}{\dfrac{Cd \sum A_i}{2gAL} + (n_b)^2 R^{4/3}} \qquad \text{Eqn 6.1.}$$

The second is taken from the inverse of vegetation density area parameter (2gAL/ Cd*Sum A_i) and slope. From theory, Petryk & Bosmajian propose that this method makes average velocity independent of depth or discharge, in the equation:

$$V = \sqrt{\frac{2gAL}{C_d \sum A_i}} S^{1/2} \qquad \text{Eqn. 6.2}$$

This approach indicates that flow through a vegetated region is a function of vegetation density. If flow through vegetation is independent of depth and discharge, then the assumption of the universal logarithmic velocity profile does not hold true for this computation method, but this fundamental change in assumption was not stated by Petryk & Bosmajian.

Using the algorithm Eqn. 6.2, measured and calculated average velocity for vegetated profiles are shown in Table 6.4.

Discharge Q in $m^3 s^{-1}$	Flow depth d(m)	Measured av. V thru baffle (m s^{-1})	Computed V Eqn. 6.1 (m s^{-1})	Computed V Eqn. 6.2 (m s^{-1})
905	0.34	0.40	0.97	V at av. stem density = 0.87
735	0.56	0.57	1.26	V at min stem density = 1.12

Table 6.4. Comparison of calculated average velocity (Petryk & Bosmajian, 1975) with measured velocity values.

Equation 6.1 over-estimated the average velocity in the region of vegetation. It assumed that, where the sum of vegetation area is lower and velocity is increased, which appears to be logical, except that shrubby vegetation may not decrease in stem density with increasing height.

In order to make sense of the relationships among velocity, bank/bed area, length of reach, and the sum of vegetation area, the higher A_i value had to be assigned to the lower discharge, as though the water were "seeing" a greater area of plant surface at the lower discharge. In practical experience with shrub-form living plants, as the number of branches increases upwards, the area of vegetation surface presented to the flow can increase with depth, although the stem diameter decreases slightly. This method of calculating average velocity independent of depth in vegetated areas could apply to the vegetation structure of young willows, coppiced trees or soil bioengineering constructions such as the siltation baffle or brush mattress, all of which exhibit a more complex, branched structure which can

act more as a coherent group than as individual plants, as branches interact with each other in the flow field.

6.2.4   Calculation of boundary shear stress from velocity profiles

The placement of the velocity profiles was designed to permit hydraulic comparison between gravel-surfaced areas and the flow space inside the vegetation zone. This allows an estimate of the contrast between the flow conditions for the two zones. A common estimator for computing boundary shear stress τ is given in Eqn 3.13, based on hydraulic radius, slope, water density and viscosity. According to Gordon *et al* (1992 p. 247), if the velocity profile is measured near a (bed or floodplain) surface and it plots approximately as a straight line on a linear-log plot, then shear stress can be calculated from the slope of the profile. In this method, the slope of the regression line (b) from the velocity- log (depth) graph is an independent parameter from which shear stress can be calculated. Boundary shear stress is represented by the parameter shear velocity V* in equation 6.3, where b is the slope of the logarithmic velocity profile:

$$V* = \frac{b}{5.75} \qquad\qquad \text{Eqn. 6.3}$$

The slope of the line from velocity profile 1 is illustrated in Figure 6.11.

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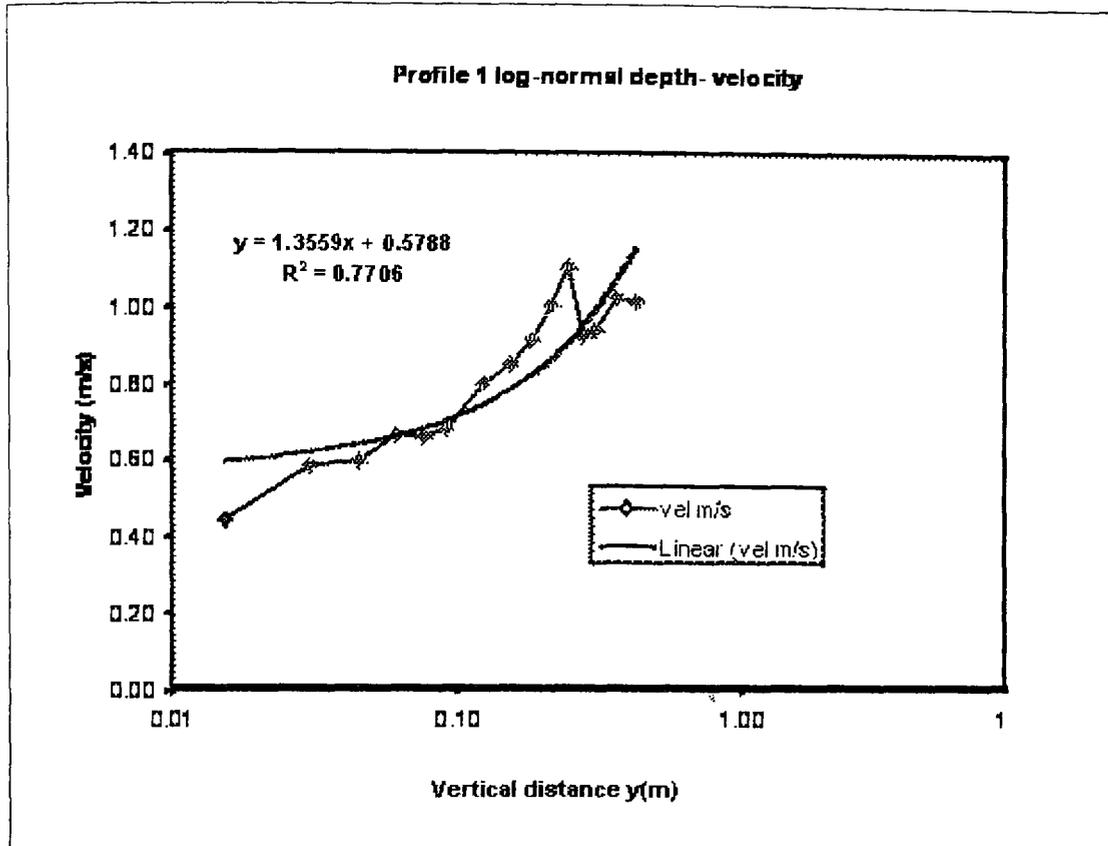
Figure 6.11. *Graph of log-normal depth velocity relationships from Profile 1, showing regression equation from which boundary shear stress is computed (after Gordon et al, 1992). Vegetation height is approximately 1.2-1.4m.*

Referring to Figures 6.2 - 6.5 for the original profile graphs, owing to the influence of the baffle vegetation on flow structure, profiles 2 and 4 are not logarithmic. In this case, the assumptions of this equation are not upheld, and the regression r^2 value reflects this (for profile 4, r^2=0.318). However, assuming that the reasoning of computing shear stress from the velocity profile is valid, a rough estimate of the reduction in boundary shear stress owing to the vegetative structures can be made from these data.

Computed from V* values, reduction of boundary shear stress is compared between the flow over the bare gravel surface and the flow through the vegetation structures (see Table 6.5).

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Computed regression slope data from velocity profiles					
Profile #	Surface (on which taken)	b values	V*	Regression equation	r^2
1	Gravel	1.356	0.236	Y= 1.356x + 0.578	0.771
2	Baffle	0.301	0.052	Y = 0.301x + 0.284	0.693
3	Gravel	2.150	0.374	Y = 2.15x + 0.713	0.905
4	Baffle	0.624	0.109	Y = 0.624x + 0.266	0.318

Table 6.5. Comparison of shear stress for vegetated and bare floodplain surfaces calculated from velocity profiles.

From Profile 1 to Profile 2, the change in boundary shear stress is

$$1-[(0.052/ 0.236) * 100] = 78\%.$$

From Profile 3 to Profile 4, the change is

$$1-[(0.109/ 0.374) * 100] = 71\%.$$

On average, the baffles may have decreased boundary shear stress from the bare gravel bars to the area within the vegetation by approximately 75%. Although the number of the velocity profiles is small, the nature of their construction is detailed (average number of observations is 38, min no. observations = 32, max # = 51).

Returning to the hypotheses set out in Chapter Four, the hypothesis was tested that groups of woody stems on streamside floodplain terraces have no effect on the logarithmic floodplain velocity profile during an overbank flow event. An analysis was conducted of the slopes of the regression lines of the logarithmic data, following Gordon *et al* (1992). The depth data were converted into logarithms, then a regression analysis was performed.

For multiple comparisons among regression slopes, the test statistic based on Eqn. 6.4 was used:

$$q = \frac{m_B - m_A}{SE} \qquad \text{Eqn. 6.4}$$

where m is the slope of the regression line, SE is the standard error of the regression equation, and q is the test statistic (Zar, 1996). Profiles 1 and 2 were compared with each other, and Profiles 3 and 4 were compared with each other, to test whether there is a significant difference between the line slopes of the logarithmic profile data for bare and vegetated surfaces. The test results are given in Table 6.6.

Parameter	Profile 1	Profile 2	Profile 3	Profile 4
m	3.578	4.855	2.883	1.377
SE	0.110	0.274	0.047	0.223
df	14	14	19	19
Sums Squares	2.345	2.100	3.394	2.752
Test q at $\alpha = 0.10$	3.648		3.607	
Calculated q	**6.65**		**11.15**	
Confidence interval	(0.577,1.977)		(1.02, 1.993)	

Table 6.6. Results of the test of regression slope differences, comparing the bare and vegetated velocity profiles taken under comparable flow conditions.

From the results of this test, the null hypothesis can be rejected with 95% confidence that groups of woody stems on streamside floodplain terraces have a measurable effect on the logarithmic floodplain velocity profile during an overbank flow event. This supports the observation made in section 6.2.2, that for overbank floodplain flow through a vegetation zone, the logarithmic velocity profile is modified by floodplain vegetation to a more uniform velocity profile.

6.2.5   Shear stress resistance in biotechnical bank protection

A standard method for reporting changes in shear stress against the banks from soil bioengineering construction methods is being developed in Switzerland by Oplatka (1996), Gerstgraser (1999), and others. The European units convention, Newtons ($N\ m^{-2}$) or kiloNewtons per square metre ($kN\ m^{-2}$), is the international scientific mode most widely reported in the literature. English usage is sometimes reported as watts per square foot ($W\ ft^{-2}$). The equation used to compute shear stress S_W on the baffle is shown as Eqn. 3.25, and is repeated here for the convenience of the reader, and values for $C_D * A$ are taken from the tables in Oplatka (1996).

$$S_W = C_D * A * \rho * v^2/2$$

Following Oplatka (1996), estimates are made from each of the velocity profiles from the Mattole flood data of Jan 1995.. Using the lowest value of

$C_D * A = 0.15$, a value for the shear resistance of the Mattole baffles is computed.

Velocity Profile	average Velocity $m\ s^{-1}$	Shear environment this baffle ($kN\ m^{-2}$)
1	1.0	74.9
2	0.3	6.8
3	1.2	107.8
4	0.45	15.2

Table 6.7. Computation of boundary shear stress for Mattole baffles using Oplatka (1996) method.

Computation of the reduction in shear stress is based on comparison from these velocity data. Between profiles 1 and 2, the reduction is

$(1 - (6.8 / 74.9)) = 0.91$ or 91%.

Between profiles 3 and 4, the reduction is

$(1 - (15.2 / 107.8)) = 0.86$ or 86%.

This model does not reflect the effects of the vegetation on the flow structure, only that the drag coefficient is dependent on velocity.

Boundary shear stress data are given in Schiechtl & Stern (1997) for numerous types of floodplain or streambank soil coverings. Gerstgraser (1998) reports resistance of six soil bioengineering methods, summarising available published data. In another approach to computing shear resistance on the siltation baffles (Oplatka, 1996), flow data were estimated for the peak of the Mattole flood (9 Jan 1995). Conservative values for flow maximum height and velocity are $d = 1m$, and $v_{max} = 2.0m\ s^{-1}$. Using Eqn 3.25, a shear stress of $399.3N\ m^{-2}$ is obtained for the flood peak, which the baffles resisted.

Worth noting was the condition of the stems, which were sanded smooth and free of bark on the upstream side, scoured by the abrasion force of the suspended sediment load, shown in Photo 5.12. Allowing that this estimate may be high, a value of $350N\ m^2$ is used to compare the siltation baffle construction with other bank treatment types in Figure 6.12. A comparison of shear resistance for soil bioengineering treatments and natural bank materials is given in Figure 6.12.

Comparison of shear resistance for bank treatment methods

Legend:
- Siltation baffles (after 14mo.s)
- Riprap w / live branches (after 3-4 seasons)
- Riprap w / live branches (after construction)
- Brush mattress (after 3-4 seasons)
- Brush Layer (after 3-4 seasons)
- Brush Layer (after construction)
- Willow cuttings
- Fascine
- Turf (after 3-4 seasons)
- Wattle fence
- Cobbles
- Coarse gravel
- Stiff clay
- Fine gravel
- Turf (after construction)
- Silt loam
- Fine sand

X-axis: Shear stress (N m^{-2})
Y-axis: Treatment types

Figure 6.12. Comparison of computed boundary shear stresses for various floodplain materials. Data are from Schiechtl & Stern (1997), Gerstgraser (1998) and the siltation baffle data are computed from field work, this thesis.

This approach is conceptually soft, because a solid theoretical foundation has not yet been developed, although European soil bioengineers are working on this subject at present (Oplatka, 1996, Gerstgraser, 1998). A great deal more field data are needed to progress use of vegetation in river engineering, so that prediction of vegetative bank prediction becomes more accurate, and design for bank protection and ecological rehabilitation can improve. This research represents a step toward this goal.

6.3 Interactions among sediments and floodplain flows influenced by woody vegetation

This section contains analyses of the interactions among overbank flows and the trapping of suspended and bedload sediments using a model for flow through a vegetated channel by Tollner *et al*, (1976). This model analyses the sediment filtration capacity of the baffles. An estimate of the probable suspended sediment load concentration is made for the Dec. 1993 event. This latter analysis was carried out as a check on the trapping efficiency predicted by the Tollner model.

6.3.1 Analysis of sediment particle size variation for two overbank flow events

Two aspects of floodplain retention of sediment particles are considered; the sediments transported and those sediments deposited or retained on the floodplain. The size of particles which can be carried onto the floodplain is controlled by stream power (Eqn. 2.1), determined from slope, velocity and depth. The particle size classes retained on the floodplain are a function of those available transported sediments (inputs) and the friction on the floodplain which either allows transport to continue to carry particles in suspension, or induces sediment deposition (losses to the sediment transport system).

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The maximum velocity estimated from the observed data (1995) was used to estimate the 1993 flow, up to 15cm in depth. This maximum was 0.80m s^{-1} for the unvegetated surface and 0.30 m s^{-1} for the vegetated surface.

For the 1995 flood (RI = 15 years), the maximum observed flow depth was 0.55m, the maximum velocity observed was 1.02m s^{-1} for the unvegetated surface, and 0.46m s^{-1} for the vegetated surface.

Using Figure 3.8, the Vanoni diagram from Yang (1996), the maximum particle sizes available to be transported by the two floods were estimated. From the observed maximum water velocities taken before and after the flood peak, the maximum particle size for the 1993 overbank flow event was circa 4mm for the unvegetated floodplain, and circa 2mm in the vegetation zone. For the 1995 flood event, the maximum particle size for the unvegetated floodplain was at least 20mm, as the maximum flood velocity was not measured. Through the vegetation zone, the estimated 1995 maximum particle size was circa 5mm.

Sediments of the midchannel bar on which the baffles were constructed (1993) were mixed, poorly graded gravels and sands with a coarse armour layer (d_{84}~ 51mm) above a sandy matrix with gravels and silts (existing conditions shown in Photo 4.4). In the vicinity of the crest of the island, several native willow clumps were surrounded by a poorly defined zone of finer sediments. The author assumed that these finer sediments deposited as a result of two major geomorphic processes, the greater of which influence is bedform roughness, and the lesser influence being from vegetation resistance during overbank flow.

Four pebble counts (n=100 in each count) for 1993 conditions are given for the baffles region prior to construction. Four pebble counts were taken after construction, after the first annual flood. Contrasting particle size distribution for the two conditions indicates the change in hydraulic resistance for varying flow depths, some of which is bedform friction. However, in the immediate vicinity of the baffles, an important component of resistance is owing to the flexible stems of the siltation baffle construction. See Figure 6.13, comparison of particle sizes

following two flood events in the region of the baffles. Photo 6.5 illustrates fine sediment deposition in the baffle region. Photo 6.6 shows the contrasting cobble layer deposited by the flood peak 9 Jan 1995.

Photo. 6.5. Fine sediment deposition in the region of the baffles, March 1994.

Photo. 6.6. Cobble layer deposited among baffles during flood peak 9 Jan 1995.

Average Particle Size Distribution Baffle Sediments 11/93-1/95
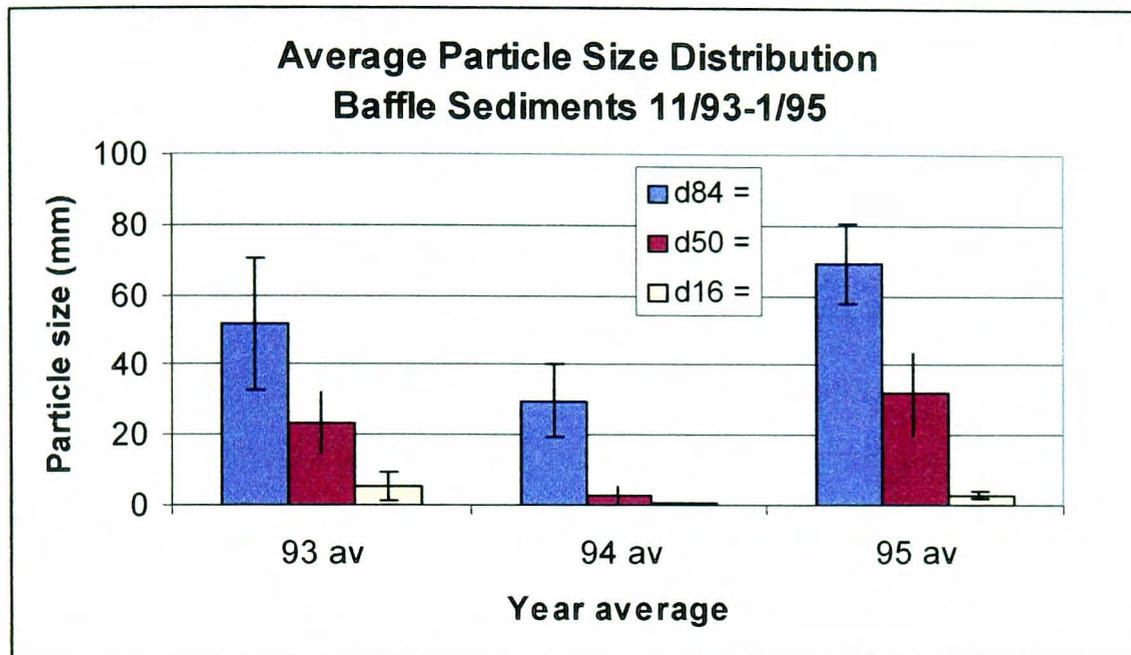
Figure 6.13. Comparison of particle sizes for the period before construction 1993, after a 150mm flow Dec 1993, and a 750mm flow Jan 1995.

6.3.2   Analysis of the baffles' sediment filtration capacity

The storm hydrograph for the first flood event following construction is shown in Figure 4.2, for the flood of 6-9 Dec 1993. This flow submerged the siltation baffles to a depth of 150mm for a maximum duration of 15 hours. A layer of fine sediment was deposited above the coarse armour sediments, shown in photo 6.7.

Photo 6.7. Fine sediment deposition in the region of baffle construction, after the first flood Dec 1993, photo taken March 1994.

Regions of greatest depths were around baffle one, the upstream end, and below or downstream of baffle ten. Figure 5.4 illustrates the plan view map of sediment deposition around the baffles.

The volume of sediment accumulated during a single flood event was estimated from the sampling scheme. Measurable sediment is assumed to be retained because of the vegetative structures, based on visual observation of the area and the absence of significant deposits outside the baffle region. Deposition data are summarised in Table 6.8.

Sediment sampling after annual flood Dec. 1993		
Area sampled	1030	m^2
Average fine sediment depth	0.08	m
Est'd volume of fine sediment	85.8	m^3
Number of observations	1372	

Table 6.8. Fine sediment measurements post- annual flood 9 Dec 1993.

Analysis of the sediment filtration capacity of the Mattole baffles was conducted using the Tollner *et al* (1976) model. The model design is given in section 3.2.2, Eqn. 3.30. Computation of the Tollner model and results are shown in spreadsheet form in Appendix C.

An abbreviated version of Tollner *et al* sediment trap efficiency model (Eqn. 3.26, shown with symbol explanation on p.111), is given in Eqn. 6.2 as:

$$\frac{S_i - S_o}{S_i} = EXP\left\{A * R_{eT}^{\ b} * N_f^{\ c}\right\} \qquad \text{Eqn. 6.2}$$

For the first run of the model, the trapping efficiency was greater than 99% for all sediment sizes and all high, medium and low classes, a result which raised suspicion for flow behaviour under natural field conditions. For this reason, a sensitivity exercise in modification of the coefficients was undertaken, to adjust the trapping function to less than perfect efficiency, a state more likely to reflect natural field conditions.

Modification of the Tollner model coefficients

	Tollner	Coeffs 1	Coeffs 2	Coeffs 3
A	-0.00105	-0.005	-0.05	-0.05
b	0.82	0.6	0.4	0.2
c	-0.91	-0.7	-0.5	-0.3
Fraction Sediment Trapped				
Coarse sand	1.001	0.962	0.840	0.925
Fine sand-coarse silt	0.882	0.848	0.601	0.855
fine silt+clay	0.580	0.585	0.288	0.749

Table 6.9. Coefficients from the Tollner et al model, coefficient adjustments and resulting trapping efficiencies for a single baffle.

Computed for a single baffle of reach length 15m, the Tollner coefficients are given in Table 6.9, along with adjusted values and their results. Coefficients were adjusted somewhat arbitrarily to investigate the effects of coefficient values. Results from the adjusted coefficients 2 and 3 indicate that these values have little effect on the prediction of sediment trapping efficiency. Results shown in Table 6.10, for application of the model to the entire length of the Mattole baffles, yield very high estimates of trapping efficiency for the lowest coefficient values.

Fraction of Sediment Trapped	when Lt =100m.			
	Tollner coeffs	**Coeffs 1**	**Coeffs 2**	**Coeffs 3**
Coarse sand	1.001	0.993	0.949	0.963
Fine sand-coarse silt	0.986	0.970	0.859	0.927
fine silt+clay	0.941	0.906	0.689	0.869

Table 6.10. Sediment trapping efficiency from adjusted coefficients for the entire length of Mattole baffle area.

This exercise suggests either that the siltation baffles are very efficient at trapping available suspended sediments, or that Tollner's flume model over-estimated the filtration efficiency of the vegetation. This is discussed further in Chapter 7.

6.3.3 Back-calculation of the suspended sediment load

A check on the accuracy of Tollner's flume-derived model was conducted using field conditions, back-calculating a range of suspended sediment concentrations which would have been needed to deposit the observed volume of sediments. Again a range of high, medium and low values were used for particle size, stem density, flow depth and flow velocity. The discharge over the baffles area was computed from the hydrograph data for the flood of Dec. 1993 (Figure 4.2). The discharge for this exercise was estimated based on the area of the Mattole baffles, rather than on the main channel discharge, over the flow duration of the observed 15 hours of overbank flow.

Calculations for this exercise are shown in Appendix C. Flow duration for various depths was estimated from the hydrograph (Figure 4.2) and depths observed from debris lines on the baffles.

Reasonable assumptions of suspended sediment concentrations were made for the first flood of the winter. Estimates of 100ppm, 500ppm, 1000ppm, 5000ppm and 10000ppm were used, and then computed by the flow volume through the baffle area for the duration of the flood discretised into ten depth classes. Using the area of a single baffle, an estimate was made for the volume of sediment trapped by a single baffle. This volume was then extended over the 1500m^2 to predict the total volume of sediment available for deposition by the volume of flow over that area.

These sediment volumes were compared with the observed volume of sediment deposited, 85.5 m^3, (over an area of 4000m^2, including the backwater deposition upstream). If the average suspended sediment concentration for the Dec 1993 flood was only 500ppm, then the baffles trapped less than 10% of the available sediment. If that average concentration was 5000ppm, then the trapping efficiency was approximately 1% . These estimates conform more closely with expected performance under natural conditions. It is likely that the actual sediment concentrations fell within this range, so that the large variance with Tollner's results may have more to do with the boundary conditions in the flume compared with field conditions.

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6.4 Post construction analysis of the responses to the revegetation project

A review of the project performance is possible in the light of the two floods that occurred 1 month and 14 months after construction. Such post-project appraisal is essential for stream rehabilitation projects if the science and technology are to progress, to increase our understanding of physical and biological processes, and to reduce uncertainty in risk for future projects.

6.4.1 Historical assessment in the design phase

The meander migration patterns identified in Section 4.1.5, Figure 4.4, "Alluvial floodplains of the lower Mattole and erosion history" were developed in 1995, after the experimental revegetation project constructed in 1993. Without this historical analysis, the potential for channel migration could not be taken fully into account during the design phase of the soil bioengineering project, and this resulted in a planting project that was vulnerable to large-scale, predictable channel changes.

In the project assessment phase, an analysis of the historical meander migration rate of the channel would have revealed that the channel had moved laterally over 150m in 38 years (MRC, 1995), during abrupt flood-pulses rather than a gradual rate of 4m/ year. From the channel surveys 1991-1994 (Figure 6.14 and 6.15 *Mattole estuary channel cross-sections*), the channel at this cross-section accreted 27m of sediments on the south bank and eroded nearly 27m in the same area from 1993-94.
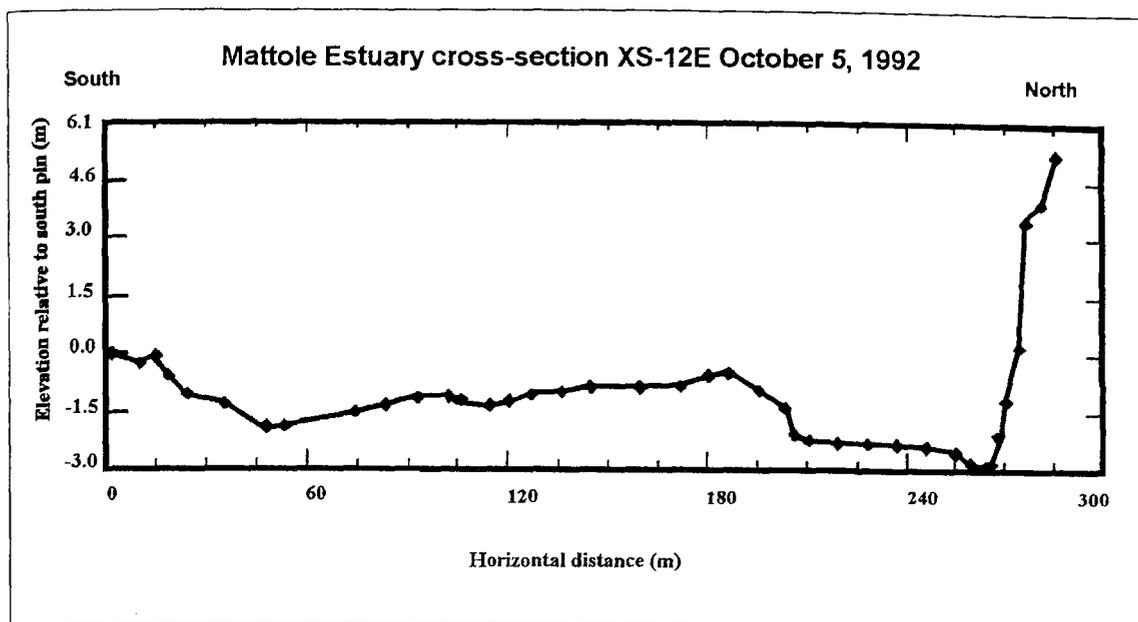
Figure 6.14. Floodplain cross-section at study site, Mattole estuary 1992 (Cross-section data from MRC, 1995).
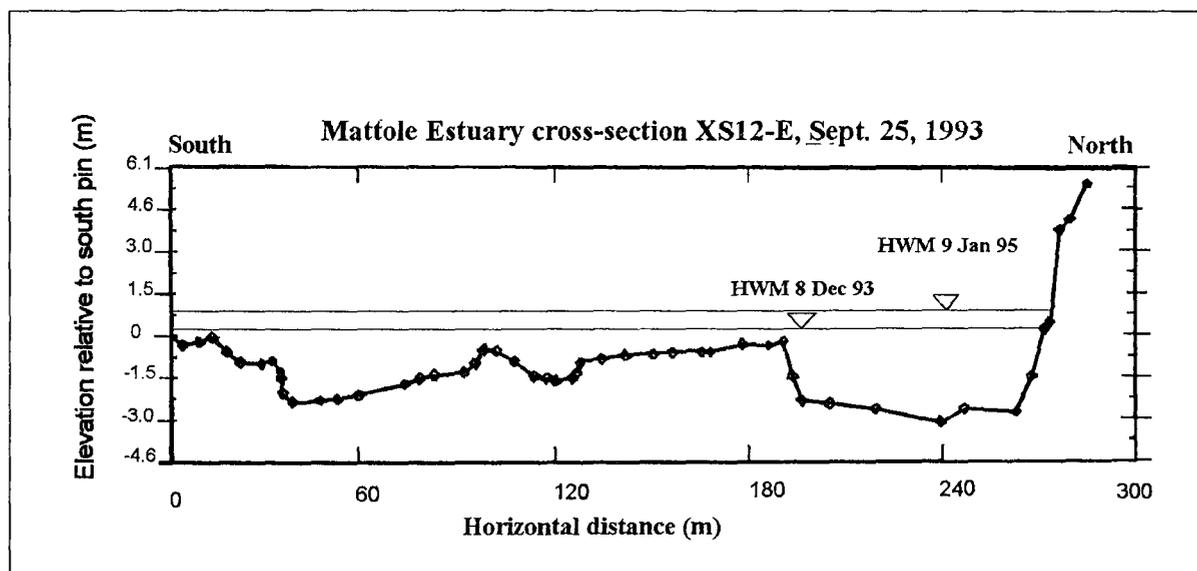
Figure 6.15. Floodplain cross-section at study site, Mattole estuary 1993, showing high water marks for the floods of Dec 1993 and Jan 1995. Cross-section data from MRC, 1995.

During the flood of 1995, a further 30m (maximum) lateral erosion occurred during a 5-day period (see discussion Sec. 7.4). This resulted in scour beneath the root zone of the baffles, an erosive force for which they were not designed, and the upstream five baffles collapsed during the flood recession 14-15 Jan 1995.

Figure 4.3. shows the storm hydrograph 6-15 Jan 1995, and Photo 6.8 illustrates

the scour beneath the root zone. This process is discussed further in Chapter Seven.

Photo 6.8. Scour beneath the root zone of baffle 1 during declining storm hydrograph, 14 Jan 1995.

6.4.2   Analysis of channel and floodplain width for baffle design

One approach to include lateral erosion potential in the design phase is to carry out an assessment of historic channel changes using the air photo record (Gurnell, 1997). Using hand drawing or computer graphing methods, the study reach can be analysed to define channel sinuosity by drawing the thalweg location for each air photo sequence. Using overlays and scale rectification, these data can be used to compute a meander migration rate. The low-flow channel widths and floodplain widths can be determined from the air photo record to compute channel width changes over time, expressed as a ratio of channel width: floodplain width. An example of this type of analysis produced Figure 4.4, relative pathways of channel migration from 1942-92, but this work was done after the revegetation design project was conducted.

The width of the soil bioengineering construction is a critical design parameter. A geomorphic design process reflects the relationships among the width of the low-flow channel, the high-flow channel and floodplain width, which together represent the potential meander migration zone.

In Table 6.12, data were taken from the 1992 WAC Air Photo. For this retrospective analysis, the width of the baffle (10m) was used as the unit of measure, to scale the widths of the landform features.

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Width ratios on the lower Mattole Estuary Channel & Floodplain		
	Average relative width	Ratio
Low-flow channel	4	
High-flow channel	20	0.20
Low-flow channel	4	
Floodplain	42	0.10
Baffle width	1	
Floodplain	42	0.02
Baffle width	1	
High-flow channel	20	0.05

Table 6.11. Comparison of widths among channel, floodplain and baffle construction.

Based on the potential for channel lateral migration computed from the historical analysis, the riparian width should, at a minimum, be the width of the low-flow channel, in order to accommodate the range of lateral shear forces from the bankfull flow. This estimate of the riparian width would give baffle widths four times greater than those constructed, or 40m. On the Mattole, the low-flow channel width is 20% of the high-flow channel width. From the historic migration analysis, an estimate of baffle width, instead of 10m, would have given 100m in width, covering the entire width of the midchannel island on which the construction was made. The 10m average baffle width was on the order of 5-10% wide enough to accommodate the potential for channel lateral erosion at this site.

6.4.3   Sources of error in construction

A shortcoming in the execution of the experimental design was the failure to complete the soil bioengineering construction, which called for placement of large rock boulders or fascine bundles on the upstream side of the planted trenches. Only stones found on the floodplain were placed on the upstream side of each trench. Since the stones were located on the floodplain, they were transported there by a recent flood, so they could not offer the increased resistance needed to protect the baffles from the surface shear forces of a flood of higher magnitude.

During construction, the spacing of the baffles departed from the proposed design spacing. Rather than being an unusual occurrence, this problem may be common in practice, in that carrying out an engineering design in the field challenges the crew and machine operators to make the design 'fit' the small-scale variations of the field site. Post-construction site inspection showed no significant variation in floodplain surface sediment size from the pre-construction site data set. The large cobbles used on the upstream side of the baffles were taken from outside the immediate study area; these large stones (D_{84} = 50mm) did not project significantly above the surface, as the design specified.

For future revegetation construction operations, whether for research or for practical 'ecosystem enhancement', this potential problem can be anticipated with a continuity of experienced staff at each level: the design team, project supervision and the machine operator(s), throughout the duration of the project.

6.4.4   Channel lateral migration during the flood recession

One month after construction, an annual flood occurred during which event the siltation baffles performed as predicted, capturing fine sediment among the baffles. Fourteen months later, during a 15-year flood (see hydrograph Figure 4.3), the structure of the baffle system remained in place during the flood peak. During an 18 hour period on hydrograph day 8, 12th Jan, the main channel migrated laterally to the south, cutting through the unconsolidated alluvium of floodplain sediments. See Photo 6.9 showing the freshly cut left bank edge.

Photo 6.9. TB Dunklin showing freshly cut left bank edge following the declining limb of the storm hydrograph 15 Jan 1995.

On Day 9, 13th Jan., flow in the main channel was observed to change direction toward the location of the mid-channel island where the baffles were built, removing the upstream end of the midchannel island. The upstream location of the survey benchmark eroded rapidly during the course of a twelve hour period, and this migration continued as the channel began to erode the upstream-most baffle.

During an 18 hour period on 13-14 Jan., the primary streampower of the flow was directed at the base of the bank. Bank undercutting from beneath the baffles' rooting zone was observed at 0.6m below the ground surface. Approximately 15m upstream of the first baffle, 9.5m of lateral, erosion was measured on the south bank at an erosion rate of approximately 0.53m /hr. Stems in the baffles capitulated slowly before this erosive force, and were lost at a rate of 0.3m/ hour. This change in bank erosion rate from the bare alluvial surface to the baffle region indicates a bank erosion rate reduction of approximately 40%. See Photo 6.10, lateral erosion being resisted during channel migration, and Photo 6.11, bank calving from below the root zone. This reduction in erosion rate could be an indication of the increased resistance of the stem (fibrous) inclusions into the alluvial matrix of the bank, although it could also be partly a function of the geomorphic dynamic of the reach.

Photo 6.10. Siltation baffle resisting lateral erosion during migration on declining hydrograph.

Photo 6.11. Calving bank and baffle eroding from below root zone during declining Day 9.

Figure 6.16 illustrates the channel and reach-scale changes to the estuary following the 15-year flood. As this flood receded, the first five baffles were lost to thalweg lateral migration and bank erosion. During a 10-year flood which occurred in February, 1995, the remaining five baffles were lost to subsequent lateral migration and bank erosion, thus ending the opportunity for further experimentation and data collection.

Post 15-year flood map Mattole Estuary 15 Jan 1995

arrows show pathways of major flow routes, erosion and sedimentation

Legend

Fiduciary mark	+
Slump/landslide	
Eroded bank	
Scour feature	
Native vegetation	
Sand accumulation	
Cobble deposit	
Survey benchmark	X

barn

XS-12E

Dunes

Siltation baffles

LWD

Erosion pin

140m.

Lighthouse Road

Drawn by Dunklin & Perala, 1995
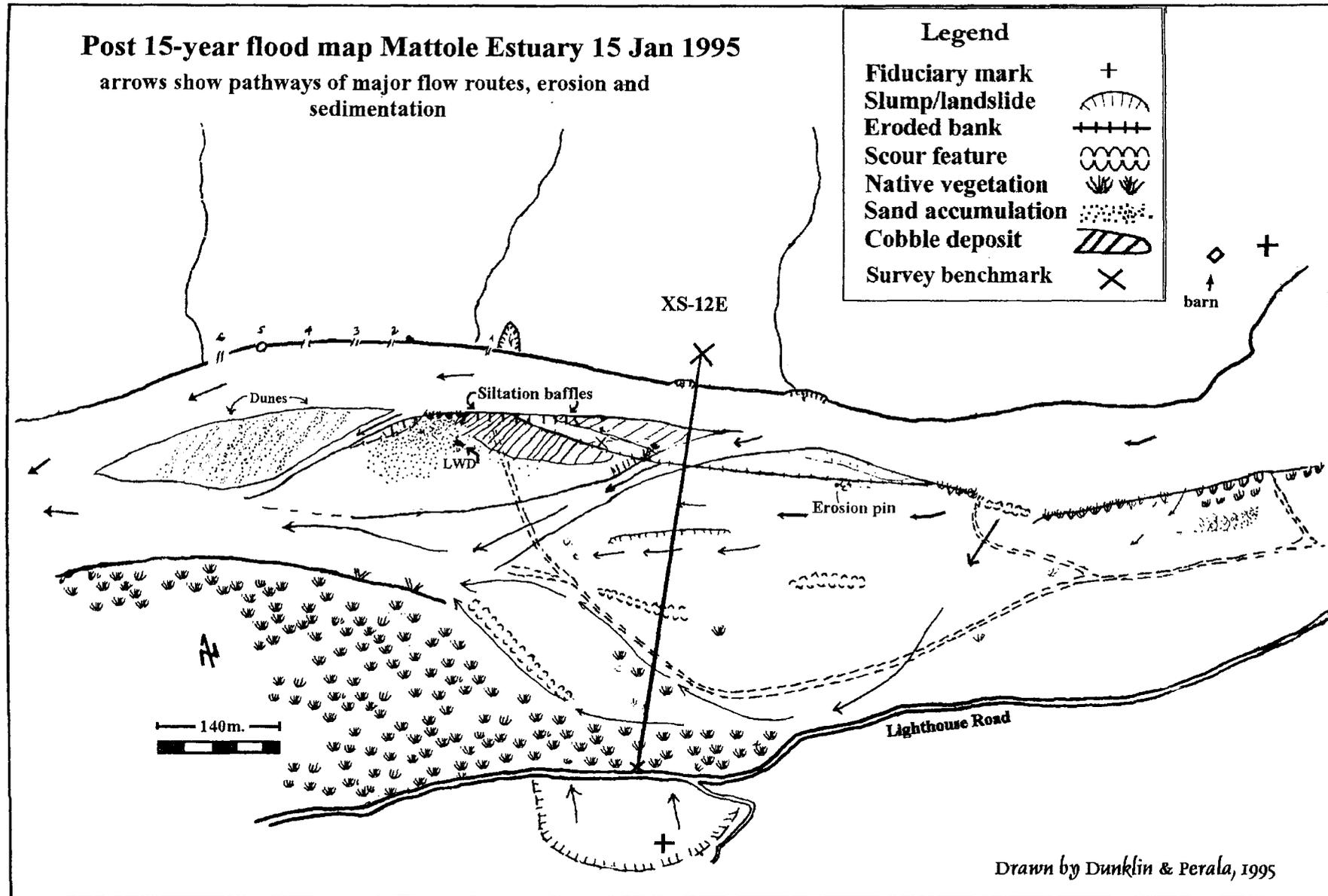
Figure 6.16. Post-15-year flood map of channel changes.

Channel lateral migration continued during the flood recession (Day 10, 15th Jan) and the first five baffles were finally lost to lateral erosion during this storm event. A re-survey of the estuary cross-section 11 (MRC, 1995) in July 1995 showed that the channel had migrated 16m to the south in this reach during the period of the two storms described during this study, 1993-1995. From direct field observation during and following the flood, most of this bank erosion occurred during the final two days of the Jan 95 flood, not at the flood peak. The channel lateral migration removed the first five baffles, but did not erode to the south much past their former location. If the baffles had been constructed to the width suggested by the historic analysis, approximately 30m of live siltation baffle structure would have remained.

The initiation of lateral erosion may have begun earlier during the flood at some point upstream, migrating downstream as flood stage declined. While relatively minor local perturbations in channel stability occur in many places along a stream channel during a flood, only some become dominant, accumulative driving processes. Such forces may be difficult to predict, such as where and when bed incision or thalweg migration will begin, but on unconsolidated alluvial channels such as the lower Mattole, it is predictable that such processes will occur.

Although the construction of this revegetation scheme failed to place anchoring boulders on the baffle trenches, it appears that the baffles failed, not by this absence of heavy stone on the upstream side, but owing to erosion below the stem/root zone, against which the rock placement could have added no resistance. Clearly, locating the depth of planting with the known thalweg depth in areas at risk from lateral thalweg movement can protect the revegetation structure against scour below the root zone. In the Mattole estuary, this would also have improved survival and growth rates for the willow stems. This approach is limited in alluvial sediments where non-cohesive particles will not allow excavation beyond a certain depth, within economic constraints.

The role of massive resistance on the upstream side of the baffles may not be as important as the design suggests. The fact that the baffles held in place for both an annual and a 15-year flood indicates that such expense may not always be justified.

Further design modifications should be based on an analysis of potential failure mechanisms.

6.4.5 Willow cutting survival rates during the first year

Summer winds in the estuary blowing east from the ocean are a significant factor on the Mattole in seedling survival and plant establishment. Stems planted in the lee (downwind) of existing native willow clumps grew more robustly than those exposed to the strong, sand-laden westerly winds elsewhere. Quantitative estimates of stem survival were made in July 1994, observing bark and stem condition as well as overall 'leafiness'. Based on ten random samples taken from each of the ten baffles, 98% survival was observed eight months after construction. Loss of some percentage of the top growth of the willow and poplar stems was expected, but the submerged stems were expected to have high survival rates and subsequent regrowth from the below-ground stocks.

This ability to resprout from submerged stems under mesic, aerobic soil conditions is one of the remarkable properties of many species of the genus *Salix* (Newsholme, 1992). Even if above-ground shoots had only 20% survival, the stand as a whole was expected to be able to continue to retard overbank flows, and to recover from flood damage by resprouting from the subaerial stems. This phenomenon has been observed by the author in other uses of the live siltation construction, where the willow branches have been buried by up to 1m of accumulated sediment, with stem tips still exposed, only to resprout vigorously from the new surface during the following growing season.

6.4.6 Root growth during the study period

Species in the genus *Salix* can be segregated by rooting patterns on cut or broken stem ends. Some species root only on the cut or broken stem end, while other species are also capable of rooting along the length of the submerged stem (Chmelar, 1974). Evidence of the root growth on willow stems 14 months after

planting was obtained by examining the baffle stems from failed structures deposited into the near channel. These roots were fibrous, with side roots poorly developed. Photo 6.12 show the root development during the study period.

Photo 6.12. Root development on willow cutting after 14 months growth.

Although the roots observed cannot be tied to the effects of the irrigation given, they do support the assertion that roots of Sitka willow *(Salix sitkensis)* are distributed along the below-ground stem, and grow best nearest the source of constant moisture, usually near the basal cut on the stem. Average root length was 0.37m in length ($n = 21$, standard deviation $= 0.127$), maximum root length measured was 0.57m, and roots were found along the entire length of the stems. Fine root hairs were also observed, but an insufficient number were available on which to collect data. During bank collapse they were probably ripped from the substrate to which they were attached. These fine roots are unlikely to offer much shear resistance as the saturated bank became mobilised, but this extent of growth observed in a relatively short period (14 months) reinforces the potential for willow roots to play a significant role in soil particle cohesion and bank reinforcement for more mature willow cuttings and established plants, as observed by Amarasinghe, (1992).

6.5   Flume flow visualisation analysis

This work addressed the limited objectives considered in section 4.3.2. In the laboratory, velocity measurements were made to characterise flow conditions, in order to achieve some similarity with field conditions. Tracer dye injections illustrated flow patterns influenced by the porous filter structure. Velocity data are presented to illustrate relative, rather than absolute, flow conditions. The limited similitude of the flume with field conditions suggests that the observations made in the following sections, while of a specific enquiry, are of a general nature.

Linking field conditions with laboratory simulation is an avenue of progress for understanding behaviour which is otherwise too complex. When modelled over-simplistically, key processes can be lost; nonetheless, simple models, when linked

to field observations, can progress our understanding of complex natural behaviour.

6.5.1 Simulation of field conditions in a laboratory flume

An important feature of the flume arrangement is the simulation of a channel and floodplain. The simulated vegetation occupies only a small portion of the flume cross-sectional area, allowing for channel - floodplain flow interactions. This permitted flows around the vegetated area, minimising the possible distortion which arises from allowing flow only through a vegetated region, which has been reported numerous times in the literature, for ex. Tollner *et al* (1976).

On a terrace occupying only a half-side of the channel, the terrace was placed next to the wall. A 'wall effect' was observed in the movement of the tracer dye, which appeared to distort the flow, so the terrace was moved away from the wall to simulate a mid-channel island. With a gap between the terrace and the wall, water flowed behind the baffle with a marked pull, as the flow sped up to go around the 'land' end of the baffle. Photo 6.13 shows the flow visualisation of the wall effect.

Photo 6.13. Flow visualisation of the wall effect in the flume.

To reduce the complication of the pull forces flowing behind the baffle, the terrace was returned to the location next to the flume wall. This made the flow structures at the channel margin of the baffle more coherent, apparent from the tracer dye movements. This wall distortion could not be overcome within the given flume arrangement; only a much wider flume (greater than 2m width) could simulate proper form relationships for a natural floodplain river.

Flume simulation of the baffle was an objective of this research (Objective 3). The selection of a material to simulate the flexibility of a linear group of 2m long willow stems partially inserted into the floodplain is not simple. Materials considered include bassine fibre (a tropical herbaceous plant used commonly in brooms), traditional broom corn, polyester filament (toothbrush fibres), and coir strands (from coconut husk fibre). However, the visually more-similar natural fibres and these synthetic fibres did not simulate young willow branch flexibility under

partially submerged conditions; typically the natural fibres were either too stiff or lost resistance when saurated, and the polyester fibre was too smooth.

The industrial geotextile Enkamat™ was chosen because of its flexural properties and complex porous structure. Made from high-strength, smooth, multi-directional polyester filament, it is a lightweight, nonwoven fabric with high porosity and tensile strength.

Scaling the field prototype to the flume dimensions, a baffle would be 6mm wide by 600mm in height by 200mm in length. The first version of the baffle (or hedge, as it appeared in the laboratory), was a slice of Enkamat 10mm wide, 60mm in height and 200mm long, glued on edge to a metal base plate. This 'hedge' was flattened by hydraulic forces when placed into the flume flow at $Fr = 0.5$. A second prototype was widened to a 30mm base to increase basal resistance and 15mm top, making the hedge 'wedge-shaped' in cross-section. This hedge was too stiff, and did not allow water carrying tracer dye to pass easily through the filament structure. Subsequent modifications to the design focused on 'thinning' by vertical slits of up to 1cm in width from the top to reduce the distal resistance of the hedge structure. Photos 5.19 and 6.14 present a view of the final baffle design.

Photo 6.14. View of the final baffle design for the flume.

Flows were calibrated until the correct relationship was measured between velocity upstream of the baffle ($Fr = 0.65$) and that downstream ($Fr = 0.12$), which Froude numbers were computed from the field velocity profiles. The final design allowed greater porosity through the upper 'branch structure', as would natural willow stems, and prevented the 'baffle' from being flattened by the design flows.

6.5.2   Qualitative observations of the effects of a porous, vegetative filter on flow resistance and backwater effect.

Reynolds developed his equation for a turbulence index in 1883 by introducing a dye into a stream of smooth-flowing water (Montes, 1998). Based on a flow visualisation where the dye remained visible as a coherent thread, Reynolds

determined that a laminar flow regime exists, and that a threshold could be identified between laminar and turbulent flows. From his experiments, the dimensionless Reynolds equation (Eqn. 3.9) was developed.

Following this well-trodden path, the flume investigation of objective 4 began by introducing a tracer dye into a calibrated flow with no obstruction on the floodplain terrace, to visualise the nature of the unobstructed flow. Photo 6.15 illustrates the unobstructed flow at Froude number of 0.65 in the flume with a terrace.

Photo 6.15. Flume flow at Fr=0.65, with no obstruction on the terrace.

This turbulent flow showed much stronger longitudinal forces than lateral or vertical vectors. Turbulent cells were observed developing as layers of flows with differing velocity interacted with each other, but the pull of the downstream force gravity, caused by head difference from upstream to downstream, caused the flow to be strongly directed in one primary vector.

Next a single cylinder was introduced into the flow. Photo 6.16 illustrates the flow around a single cylinder. Dye injected into the flow illustrated the wake produced by cylinder resistance, and the familiar wake re-entrainment process was observed. The physical processes involved in flow around a single, emergent, rigid cylinder and the resulting wake re-entrainment are well understood (Li & Shen, 1975, Montes, 1998). The hydraulic wall effect was observed at the channel margin, but did not appear to be a dominant feature of the flow with a single cylinder on the terrace. A well developed "Karman vortex street" of eddies, shed from both sides of the cylinder, was observed.

Photo 6.16. Flow visualisation around a single cylinder, showing the "vortex eddy street".

An hydraulic effect is generated by resistance from the bedform roughness of the floodplain itself, as the flow visualisation study of Pasche & Rouve (1985) showed. Photo 6.17 illustrates the pattern of eddy shedding at the channel - terrace margin. At the boundary of the simulated floodplain

terrace, an eddy field is created which 'sheds' turbulence into the main channel flow. This hydraulic wall is, in part, a function of the pressure head differential from the change in flow depth between deeper channel and shallower floodplain, and in part is caused by the bedform resistance to the high velocity water from the main channel.

Photo 6.17. Eddy shedding at the channel-terrace margin increased in vigour with the presence of the hedge.

Into the same calibrated flow, a baffle hedge was introduced onto the terrace. The porous vegetative filter affected the flow structure over the simulated floodplain in lateral, longitudinal, and vertical dimensions. The baffle structure had a pronounced effect on the eddy shedding pattern at the channel-terrace margin, which has been reported by other workers (such as Pasche & Rouve, 1985, Naot *et al*, 1995).

When the baffle was present on the floodplain, the eddy shedding 'vortex street' increased markedly in vigour, shown in Photo 6.18. This suggests that this flexible, emergent filter on the floodplain increases turbulent momentum exchange between channel and floodplain. This phenomenon was observed during the Mattole flood, and is shown in Photo 6.4.

With increased flow resistance and the backwater effect, only a moderate percentage of the flow approaching the baffle flows into and through it. The flume visualisation showed that flow entering from approximately the middle third of the baffle frontal area actually enters the baffle, and the other thirds on either side seemed to be pushed to the sides, but more markedly to the channel side. This phenomenon occurred both when the baffle was placed against the wall, and when it stood free from the wall, allowing flow to pass on the wall side. Photo 6.18 shows the midpoint where the tracer dye entered the baffle most efficiently.

Photo 6.18. Tracer dye flowing through a single perpendicular baffle; note the dye entry vector at midpoint of baffle width.

In the lateral dimension, water is pushed from in front of the baffle to either side, partly explaining the lower water velocity among the baffles. Pushing the flow to either side of the baffle also pushes water upstream in a backwater effect (Chow, 1959, p72). Photo 6.19 shows the tracer dye retention and eddy shedding enhanced by the baffle.

Photo 6.19. Flume baffle showing tracer dye retention and eddy vortex shedding at the terrace channel margin.

Compared with the hydraulic effect of a cylinder where a distinct wake is detectable, the porous filter diffused the tracer dye across most of the baffle width, by converting large eddy cells to smaller ones as the flow passed through the filter. If eddies can be said to have cells of lower and higher velocity water, the porous filter breaks up the cell size of the eddy, reducing the average cell size but increasing the heterogeneity (or variation) of average velocity (Hardwick, pers. comm, 1998). This mechanism is fundamental to the calming of turbulence caused by flow through baffles.

6.5.3   Variation of baffle spacing to observe flow wake re-entrainment and the relative distance at which it occurs

The baffle simulation using Enkamat^{TM} exhibits the properties of emergence, porosity and flexibility. From the Naot *et al* (1996) model (developed for emergent rigid cylinders), a floodplain vegetation zone should increase turbulence, attenuate velocity, increase eddy vortex shedding and increase longitudinal shear stress at the channel-floodplain margin, described also section 6.5.5.

Process observations in this flume were limited in scope by the physical dimensions of the flume. The intent of Objective 5 was to observe wake re-entrainment of the flow downstream of a single baffle, which is not possible to observe in the field, and to determine whether a second baffle could be made to influence the wake re-entrainment process from the first

baffle. A surprising observation was made about the hydraulic influence of a single baffle on the overbank flow structure. Diffusion caused by the baffle expanded the lateral dimension of turbulence to such an extent that wake re-entrainment was not discernible, even at flow with elevated Froude numbers (Fr = 0.7).

The hydraulic influence of a single baffle was so large that the physical dimensions of the flume study area were insufficient to contain the turbulent interactions of two baffles without distortion. Thus the results of Objective 5 were unable to make a determination about the combined effects of two baffles and their interactions. Downstream velocity of a single baffle was both more turbulent and more calm than expected. The flow was also more heterogeneous, as seen from the slow swirls, lateral sweeps and eddying dye movements over the floodplain. The turbulence cells of lower velocity had discernible momentum, which carried downstream a significant distance.

A series of velocity measurements were made to determine the downstream extent that the flow remained influenced by the porous filter structure. The flow was recalibrated without obstruction, then with a single baffle. Because of the low velocity region downstream of the baffle, current measurements were unreliable as readings failed to meet the minimum threshold of 5Hz (6cm s^{-1}) consistently. Flow downstream of a single baffle was so attenuated that no meaningful data could be measured to make a comparison between flow conditions upstream and downstream of a single baffle. This is again a result of flume limitations, which could be overcome only by the use of a wider flume.

To illustrate the hydraulic effects of a single baffle, the baffle width was used as the unit length in the downstream direction. Velocity sampling locations were taken as multiples of the baffle width. The dependent variable, relative velocity (Hz) is given as measurements are taken in the downstream direction, with a graph of the data shown in Figure 6.17.

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Velocity distribution influenced by porous filter
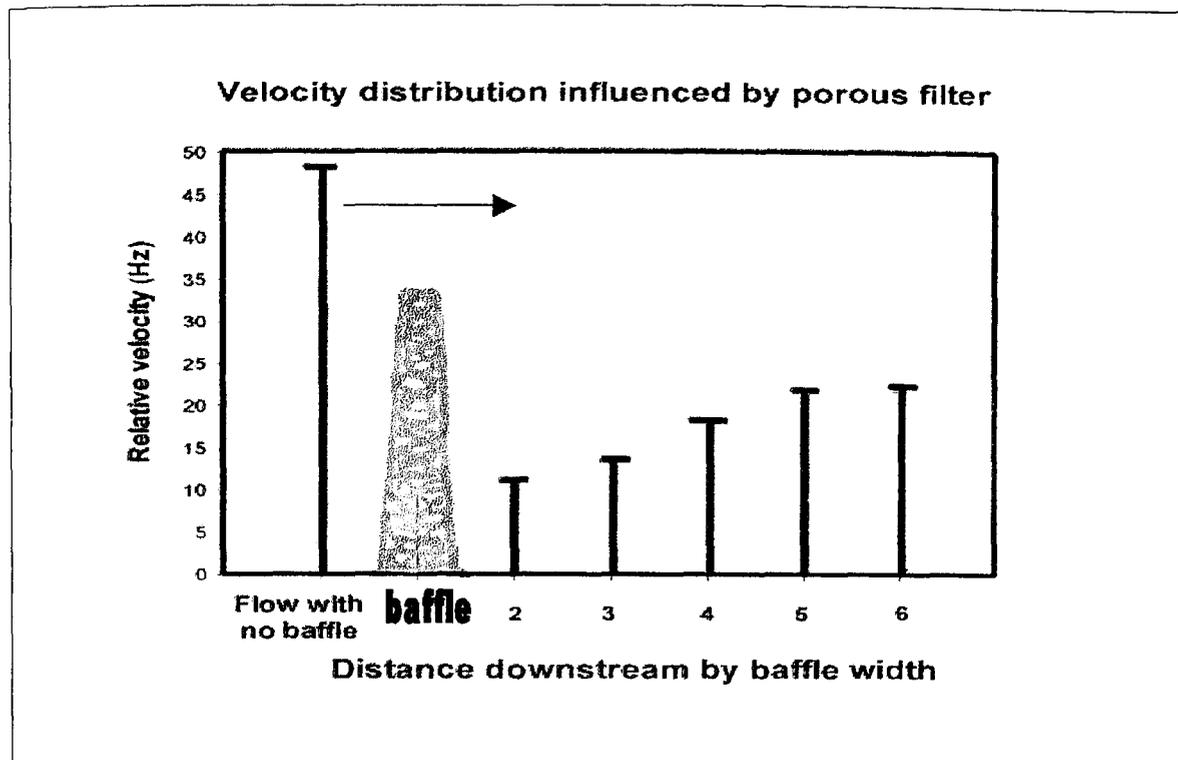
Figure 6.17. Graphic illustration of the influence of one baffle on velocity in the downstream direction, compared with flow velocity with no baffle, (n total = 90, n bar = 15.)

After six baffle widths downstream, the flow had recovered only half its original velocity of 48 Hz. Visual observations placing the dye injector at increasing distances downstream suggested that the flow may not have 'remembered' its original, pre-baffle structure until approximately ten baffle widths downstream. The porous, flexible, emergent, vegetative filter demonstrates significant properties of increasing local turbulence, retarding turbulence cell generation, retarding velocity and attenuating flow over the floodplain. The width of the porous filter is a dominant factor in the length of the turbulent eddy street propagated downstream.

Remembering the guidance from Schiechtl (1980) with regard to the spacing of live siltation baffle construction on a floodplain, the design parameter for spacing was 1.5 times the baffle width (see section 5.1.1. Soil bioengineering design). From an hydraulic view, this spacing may be unnecessarily close. From the flume experiment, a single baffle has a large effect on turbulence induction and velocity

attenuation on overbank flow. Results from this flow visualisation indicate that siltation baffles could conservatively be spaced at least five widths apart, but that design spacing should be related to floodplain geomorphic conditions.

6.5.4 Vary the placement of the upstream-most baffle from perpendicular to parallel to flow

Pursing Objective 6, the variation of the angle of baffle placement with respect to the dominant vector of main channel flow did not yield significant insights into an observable change in flow over the floodplain. In a study of drag coefficients for large wood in streams, Shields & Gippel (1995) found that drag for a model tree trunk without roots or branches decreased markedly at angles of 30° upstream and 30° downstream, but for trunks with roots and branches, orientation had little effect on drag. A trunk with roots and branches would have the effect on flow similar to a porous structure, so it is possible that the porous nature of the siltation baffle prevents a significant increase in drag for the upstream and downstream baffles. This exercise was unable to detect the significance of Schiechtl's guidance for instructing that the upstream and downstream baffles be oriented 60° from the dominant flow vector, from a purely hydraulic viewpoint (Schiechtl, 1980). Further research is needed to shed light on this topic.

6.5.5 Comparison with results from a hydrodynamic model of flow through a vegetated floodplain

The numerical hydrodynamic model by Naot *et al* (1996) modelled flow over a partly vegetated floodplain, using an approach which combines a k-ε (k-epsilon) numerical turbulence model with analysis of experimental flume data. This study created visualisations of the flow field and the shear stress at the margin of a vegetated floodplain with main channel. Figure 6.18 illustrates the variation in velocity distribution with increasing vegetation density on the floodplain, calculated from the model.

Floodplain vegetation density N = 100nHD is a non-dimensional measure, where n is the vegetation stem density/unit area (m^2), H is flow depth(m), and D is the average stem diameter (m).
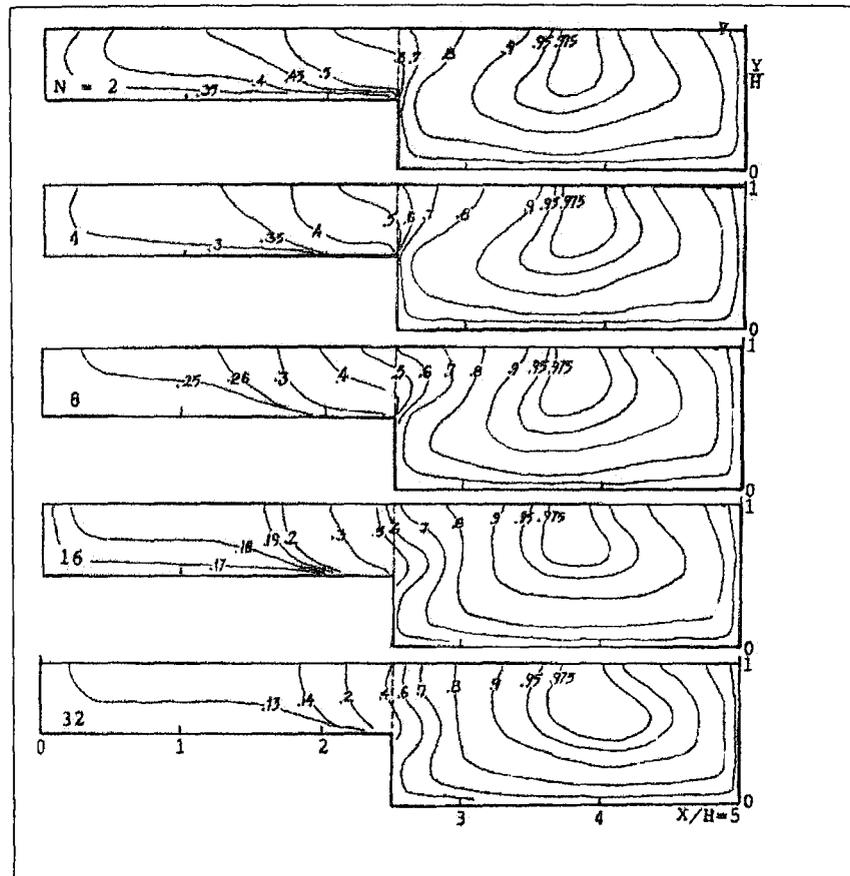
Figure 6.18. *Compound open channel with vegetated floodplain showing calculated streamwise velocity contours W/W$_{max}$. Vegetation density increases from the top diagram toward the bottom (increasing N numbers (stems per unit area) from 2 to 32, shown in left-hand corner of each diagram). Naot et al (1996).*

The model shows that, as vegetation density increases, flow velocity over the floodplain decreases. In Fig. 6.18, for low N values (N<=16), the floodplain offers low resistance and the velocity profile is non-homogeneous (more closely resembling the logarithmic profile). For N>16, floodplain resistance is high and the floodplain velocity profile becomes increasingly homogeneous, or vertically uniform (non-logarthmic).

Figure 6.19 illustrates the Naot model distribution of turbulence energy with increasing vegetation density on the floodplain.

Compound open channel with vegetated floodplain, calculated turbulence energy
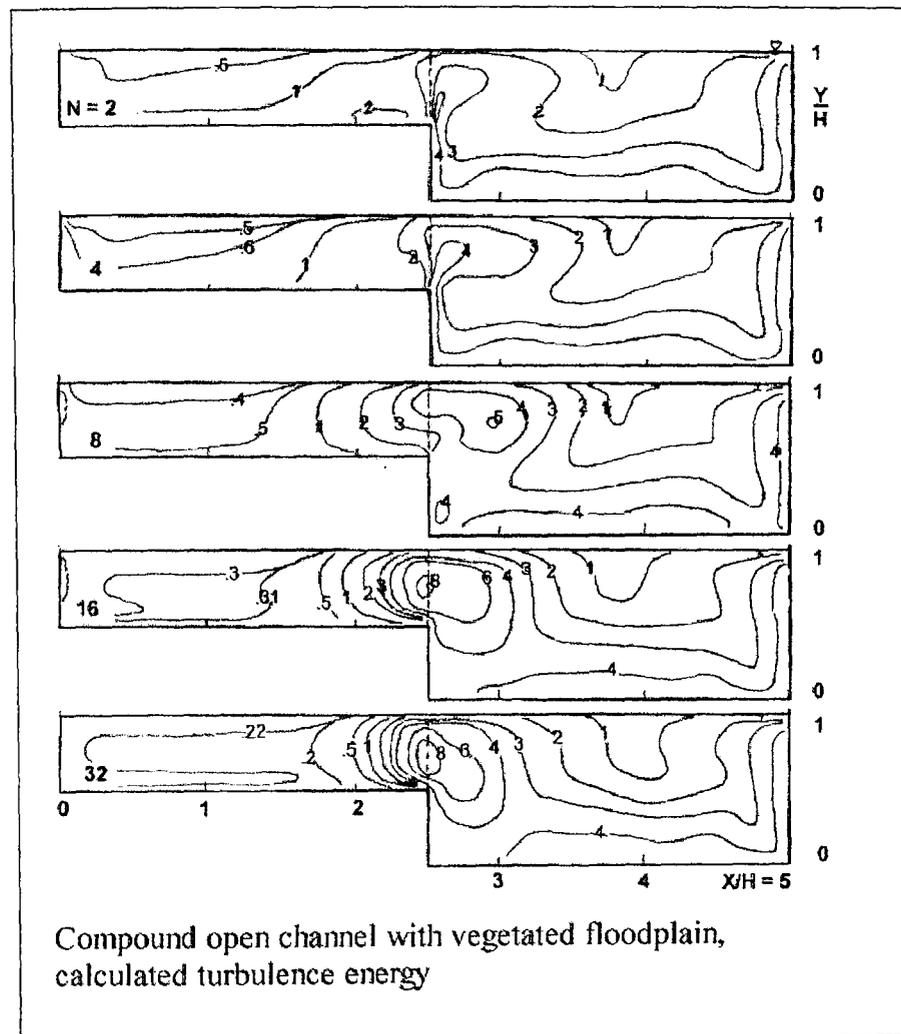
Figure 6.19. Calculated distribution of turbulence energy 10^3 k/W^2_{max} with increasing vegetation density on the floodplain (from N=2 to N=32 from top to bottom). From Naot et al (1996).

This diagram shows vegetation density as a dominant factor influencing the distribution of turbulence across the channel-floodplain unit during overbank flow. As floodplain vegetation density increases, the eddy-shedding vortex street becomes more intense at the channel-floodplain margin. Naot *et al* found that floodplain turbulence decreases with increasing vegetation density. These computed results support field observations in the present research and by others, such as Pasche & Rouve, (1985) and RIZA (1997),

that the hydraulic 'wall' at the channel-vegetation boundary creates an intense turbulent field at the channel-floodplain margin.

6.6   Conclusions

From the sediment particle size analysis, particle fall velocity theory predicted the sediment fraction to be primarily fine sands. However, clays were mixed heterogeneously throughout the samples in varying fractions. This observation contradicts the widely held view that clays do not commonly settle out of overbank flows except at the very lowest velocities and in standing water (Davis *et al*, 1995). Moderately calm turbulence near stems of moderate density within or near the boundary layer appear to provide conditions under which very fine particles can settle out of suspension. Clays may be transported as aggregate particles, which could increase their settling velocity and the trapping efficiency of vegetation zones.

The Tollner *et al* (1976) sediment trapping efficiency model was tested against field data. This model predicted nearly 100% trapping efficiency for sands, 88% efficiency for silts and 58% for clays. Lacking measurements of actual average suspended sediment concentration (inputs), a back-calculation was made from real flow data and the volume of sediment captured. This approach indicated that the baffles sediment trapping efficiency may have been closer to 1-7%. This suggests that the Tollner model may overestimate trapping efficiency by an order of magnitude. This may have resulted from the Tollner flume arrangement (like many others) which caused all the flow to pass through the vegetated field, not allowing for flow deflection around the vegetated area.

In the field flow analysis, the vegetated area was shown to reduce boundary shear stress by an approximate factor of 70-90%. From an hypothesis test for the effects of floodplain vegetation on the velocity profile, the data show that groups of woody stems on streamside floodplain terraces have a measurable effect on the logarithmic floodplain velocity profile during an overbank flow event. Comparison of the velocity profiles for comparable flow conditions suggests that for flow

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through a region with emergent flexible vegetation, assumption of the universal logarithmic velocity profile does not hold for flow through a vegetated floodplain, but may be more uniform in vertical structure.

In the flume flow analysis, intense momentum exchange was observed in interactions between the two velocity regimes of main channel and floodplain flows. The formation of a hydraulic 'wall' and the channel - floodplain momentum exchange was more energetic in the flow regime influenced by a baffle than for a single cylinder. A porous vegetative filter had a profound effect on flow structure in the downstream direction and for lateral mixing on the floodplain.

No clearly defined wake could be detected downstream of a single baffle, leading to the conclusion that no wake may be generated by a porous vegetative filter. In the presence of a baffle, eddy-shedding is intensified at the channel - floodplain margin. This phenomenon is not well understood, but it is predicted in the numerical model by Naot *et al*, (1996).

The field data are in conceptual agreement with a numerical model (Naot *et al*, 1996) which suggest that flow through a vegetated floodplain follows more closely a relatively uniform vertical velocity distribution.

Conflicting findings between flume work and numerical modelling do not clarify whether floodplain vegetation increases or decreases turbulence for overbank flows. More refined methods of measuring turbulence may be needed to resolve this question. The flume findings suggest that turbulent cells are reduced in size as a consequence of flowing through a vegetative filter, but heterogeneity is increased, producing a calming effect. Floodplain flow through vegetation may be both turbulent and calm.

The flexible emergent vegetative filter (or region of riparian shrubs) is well adapted to induce sedimentation across the floodplain, both upstream and downstream of the vegetation. This function is in part because of the increase in the boundary layer height, and in part by the breaking up of flow cells into smaller turbulent eddy cells.

The decrease in floodplain velocity appears to have a role in increased channel velocity and turbulence, which may increase sediment transport potential outside the vegetation zone, or in the main channel.

Finally, the design of revegetation structures for bank protection needs to take into account the potential for lateral migration of the thalweg in the reach , to prevent destabilisation during a high-magnitude flood event.

In Chapter 7, results of the data analysis are presented in light of the literature reviewed in Chapters 2 and 3. Chapter 7 concludes with a framework for floodplain revegetation within the disciplines of fluvial geomorphology, floodplain hydraulics and riparian ecological horticulture.

Chapter 7: **Discussion of the results, synthesising the field and laboratory work, towards a hydraulically based 'riparian ecological horticulture'**

The goal of this chapter is to synthesise the data and observations from the fields of fluvial geomorphology, floodplain hydraulics and plant ecology with respect to the question of overbank flow and sedimentation through streambank and floodplain shrubby vegetation. The purpose is to develop a framework for the revegetation of temperate alluvial floodplains and streambanks, which utilises the dynamics of the stream system to aid the recovery of native floodplain plant communities.

7.1   Sediment deposition during overbank flood flow influenced by woody vegetation

The 1500m^2 area influenced by siltation baffles on a midchannel island in the Mattole estuary retained approximately 85.5m^3 of fine sediment during a single storm event of 15 hours duration. Those sediments, which would otherwise have remained in suspension and been transported into the estuary or ocean, were retained on the banks, keeping the downstream channel slightly more free of fine sediments. Applied to a reach or larger scale of a fish-bearing stream, this process could potentially be significant for the maintenance of fish spawning gravels and downstream channel morphological diversity. If the area of vegetated floodplain had been 150,000 m^2 distributed along the middle reaches of the Mattole river, could that vegetated floodplain have retained 8550 m^3 of fine sediments from the spawning gravels of the lower Mattole?

The data from this research suggest that retention of such volume of fine sediments from an alluvial stream is possible. It is also possible that the trapping efficiency may increase over a larger area, owing to the fact that the larger area in woody vegetative cover would also trap increasing amounts of large woody debris, and the ratio of centre area would increase over the area of the margins. However, heterogeneous distribution of stems under natural conditions would likely result in the formation of secondary flow channels across the floodplain, in which velocity

and scour distribution would be greater in patches than the more uniformly vegetated area.

Composition of size classes

Sedimentation in the baffle region did not follow predicted patterns. The retention of approximately 25m^3 of clays dispersed through the sediment profile contradicts the widely held view that clays do not commonly settle out of overbank flows, except at the very lowest velocities and in standing water (Davis *et al*, 1996). Fluctuations of velocity and moderate turbulence within or near the boundary layer may be another condition under which very fine particles can settle out of suspension.

These data suggest that the Tollner *et al* (1975) model for prediction of suspended sediment trapping does not accurately characterise the field conditions in which mixed fine sediments, including clays, deposit from suspension around emergent stems. This is a matter of some consequence, as clay colloids easily adsorb many types of pollutants, so that increased retention of suspended clays could be beneficial to river management for fish habitat and water quality concerns. This finding will be of great interest to fisheries managers, because fine sediments are a major pollutant of spawning gravels, and controlling it is extremely difficult where dramatic land use changes have occurred, releasing fine sediments to overland and fluvial flows.

7.1.1   Critique of the use of the Tollner *et al* (1976) model

For this research effort, the Tollner *et al* (1976) model was the best available for testing the sediment trapping efficiency of the siltation baffles. The two major parameters influencing sediment retention are the turbulent Reynolds index R_{eT} and the particle fall number N_f. The basic Tollner model is repeated for the convenience of the reader.

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$$\boxed{\dfrac{Si - So}{Si} = EXP\ \{\ A * R_{eT}^{\ b} * N_f^{\ c}\ \}}$$

$$A\ Term\quad B\ \ Term\quad C$$

This model relates the percent sediment deposited as an exponential function of the Reynolds turbulence index R_{eT} and the particle fall number N_f (a velocity based on particle size).

Back-calculation of the likely suspended sediment concentration showed that a concentration of only 100ppm would have provided enough sediment to deposit the observed volume. This indicates that the sediment trapping efficiency is more likely to be less than 8%, contrasted with the Tollner results of between 89-99% efficient. This discrepancy begins with the problem of relating flume-derived empirical models using closed systems to simulate natural, open systems. In this flume model, and in others, the vegetated area spans the width of the channel, so that all flow is forced through the vegetated region. This excludes any backwater effects which could occur when the vegetation occupies only one side of the flume floodplain and not the entire channel. The use of coefficients developed from flume study applied to natural field conditions is therefore questionable, as the boundary conditions are not comparable. From this research, the author observed that the backwater effect is a far more significant feature of the hydraulic and sedimentation consequences of establishing flexible woody vegetation on a streambank or floodplain than has been previously understood.

Another finding of this research is that, under natural conditions, such thick vegetation directs flow in the lateral direction, that allowing flow around the vegetation zone is an important feature to include in any flume model of sedimentation influenced by a vegetation zone.

A research review of the Tollner model, using a larger flume which allows for channel – floodplain interactions, could provide an opportunity to revise the model's simulation of flow and sediment behaviour under conditions that simulate the faster main channel flow and the slower flow on the vegetated floodplain.

The particle fall velocity is related to the physics of settling based on particle size, but it assumes that particles are spheres. Use of other settling models which permit non-spherical shapes may be important for characterising the physics of clay plates or non-spherical aggregates settling out of suspension. The coefficients for the particle fall number should vary only by particle size. Further applications of the model to field conditions could extend the data set for analysis of the empirical model coefficients, including application to flow through flexible emergent stems, and to further variations in stem densities, to test the importance of the Reynolds turbulence index in the overall trapping efficiency.

The potential range of variables which could influence the resulting prediction of trapping efficiency is large. Building on the work of Naot *et al* (1996) where R_e $\leq 10^2$, use of the dimensionless Reynolds values in the range of 10^3-10^5 could be employed to increase the dimensional analogy to natural river conditions, to progress understanding of sediment-laden flow behaviour on natural vegetated stream channels and floodplains.

7.1.2 Backwater effects of the siltation baffle construction

A backwater effect can be inferred by the extent of the fine sediment layer observed following the Dec 1993 storm, where detectable fines were measured in a relatively homogenous pattern approximately 40m upstream of the first baffle (Figure 6.1). Some of this deposition may have been enhanced by bedform effects, which may be sufficient to trap small amounts of sediment, but the data do not permit a separation of the two processes.

The 'vegetative filter' effect of the siltation baffle construction appears to interact with low overbank flows in a manner hydraulically similar to the model proposed by Tollner *et al* (1976). However, the backwater effect causes the flow to be pushed around the obstruction, losing some of its transport capacity and thereby inducing sedimentation in the distinct pattern seen in the deposit of fine sediment upstream of baffle 1. In fact, the greatest average sedimentation depth occurred in this region and the downstream-most baffle (shown in Figure 6.1).

An explanation is suggested here. When the flow encounters the siltation baffles, resistance from the stems induces lower velocity within the region of the baffles, and this slower water also pushes faster-moving water to either side of the vegetated area. A meso-scale effect of the baffles appears at the margins of the construction; a 'wall' effect occurs at the boundary of the baffles, where slower-moving water mixes with the faster flow around the baffles. The distinct pattern of sediment deposition at the perimeter of the baffles indicated the presence of two distinct flow regimes within and around the baffles. Figure 6.10 shows a long profile view of baffle influence on overbank flow retardation showing two mechanisms of velocity reduction (in one dimension only).

The strength of this hydraulic behaviour and the shear resistance of the siltation baffle suggest that this construction method merits wider consideration for revegetation applications. The question of baffle spacing will remain a design challenge, but the results of this investigation indicate that the structures can be placed at least five widths apart for hydraulic reasons. In field applications, geomorphic and geotechnical considerations must also be taken into account.

7.2 Influence of flexible woody vegetation on floodplain velocity profiles

Critique of the Petryk & Bosmajian (1975) model
This simple model reduces much complexity to aid the practicing field engineer, providing a rough approximation of flow through emergent vegetation under field conditions. Use of the Manning equation is acknowledged both for significant limitations and wide utilisation. A fundamental problem with the model is the mathematical dependence of the computed vegetation roughness on the initial selection of the bed roughness value. A bedform such as a side-channel bar may support no vegetation, small weedy plants, dense grass, young shrubs or tall saplings, depending on recent flood history.

Assuming the correct selection of a base n value for the bedform roughness, this model can not distinguish among the range of potential vegetation types. Thus, tall grasses and short shrubs of the same total height with the same area of stem density would have no difference in either flow resistance or roughness value, although the ability to resist shear forces varies dramatically between grasses and woody stems. For flows nearly submerging the plants, grasses will flatten before the rising hydrostatic and hydrodynamic forces, while shrubs will continue to resist the flow even at near-submergence, with a waving, bending motion inducing calm turbulence into the flow profile. The combination of greater stiffness and interweaving of branches tends to make the baffle one resistant body rather than a collection of individual stems, which might individually flatten to a greater extent.

This approach indicates that flow through a vegetated region is a function of vegetation density and spacing. If flow through vegetation is independent of depth and discharge, then the assumption of the universal logarithmic velocity profile does not hold true for this computation method, but this fundamental change in assumption was not stated by Petryk & Bosmajian (1975).

7.3 Interactions among sediments and floodplain flows influenced by emergent, flexible woody vegetation

A significant observation to be derived from this study is the clear indication that flow through vegetated floodplains does not follow the widely assumed logarithmic velocity profile, but follows a vertically more uniform profile. This incorrect assumption underlies much of the early work on floodplain vegetation effects on roughness, such as Barnes (1967), Petryk & Bosmajian (1975) and Arcement & Schneider (1989).

An important conclusion gathered from this thesis is that a border of perpendicular shrubby vegetation at the floodplain margin is more effective at retaining fine sediments than has previously been reported. The shrub border is more effective at retaining sediment than a narrow strip of vegetation (such as willow spiling fence

or a single row of trees) placed parallel to the main channel flow. A shrub border at the channel - floodplain margin sets up a strong free shear layer created by the hydraulic interaction of slow and faster moving water mixing near the channel margin. This feature is difficult to measure in the field and problematic to model, overcoming scale effects in the flume, yet its effects can be seen clearly under the right field conditions. This research programme provided the conditions under which this behaviour could be observed and measured.

In the laboratory, tracer dye established visually the phenomenon of the hydraulic separation point (photo 7.1), which was observed but not measured in the field. At the hydraulic separation point, eddy shedding begins to develop at the differential between slower and faster flows near the channel margin.

Photo 7.1. Flume visualisation of the hydraulic separation point upstream of a single porous vegetative filter.

This separation is related to the increase in channel capacity with vegetated floodplains, where main channel velocity increases when vegetation retards the floodplain flows. This observation was also made by Pasche & Rouve (1985).

Hydrodynamic numerical models capable of simulating unsteady flow have been developed more recently to predict behaviour of overbank flow on vegetated floodplains. These more sophisticated models are able to cope with 1-dimensional or quasi 2-dimensional computation, and the assumption of relatively uniform flow through the vegetation zone can be managed. To avoid the problems associated with using roughness factors such as Manning's n, computation methods are often based on energy expressions of friction, drag and turbulence. The numeric and practical solution to the problem of the non-logarithmic velocity profile is still emerging.

Steady-state hydraulic models typically take into account only overbank flow processes, without the inclusion of larger-scale phenomena such as geomorphic processes. Geotechnical considerations such as particle entrainment (raising thresholds of entrainment into flow), bank failure mechanisms and erosional processes, (typically the domain of geomorphic research), can yield benefits such

as floodplain scour reduction. To understand the real influences of floodplain woody vegetation during floods, the combined effects of hydraulic and geotechnical processes need to be considered simultaneously. Even with the introduction of sediment transport modules on the unsteady ISIS and MIKE series of hydrodynamic models, this complex process is beyond the scope of available models and remains at the forefront of research (Thorne *et al*, 1998).

A prototype flume study by Kutija & Hong (1996) developed a numerical model to assess the resistance of submerged flexible vegetation in steady uniform flow, simulating flow through a vegetated wetland. This model is based on a differential-difference equation which can compute velocity and drag in three dimensions. Using cantilever beam theory, the pressure load distributed along a single, flexible stem such as a reed can account for the bending of the stem, reducing its height and thus its potential load. Key parameters identified by the model are reed height, density, diameter, and stiffness, which is not constant along its length. The case of rigid vegetation also meets the model criteria. It is not able to compute the effects of interactions between groups of reeds and the change in flow induced by the reeds.

The model awaits verification by field measurements taken in the presence of flexible vegetation. The authors suggested that synthetic data derived from dimensional analysis, neural networks or genetic algorithms can more cost-effectively provide the missing data for model verification. The model can be used as a module in a 2-dimensional flow model to characterise flow resistance for flexible wetland vegetation, but specific data for species and age will be needed form large flume and field experiments at the prototype scale of 1:1.

7.4 Field geomorphic context and responses

This research programme began as a quantitative inquiry into the performance of a soil bioengineering structure and its consequences for fluvial processes. During the course of the programme, discovery of the paucity of literature and theory in hydraulics available to predict overbank flow and sedimentation through woody

vegetation changed the research orientation, to a broader investigation of the hydraulics of overbank flow through flexible, emergent woody vegetation. It became clearer that this difficult area had been neglected in some aspects, in no small part because of the difficulty of field data collection.

Geomorphic research on natural rivers is limited by the unpredictable occurrence of natural flood events during which to observe overbank flows. Selecting a suitable location to set up studies of floodplain geomorphology and vegetation interactions is a considerable challenge. A high degree of risk is involved, either that during the study period, a flood of sufficient magnitude may not occur, or that a flood too high in magnitude may occur, leading in either case to a failure to collect adequate data on fluvial processes and geomorphic responses. The risk of a flood of too high a magnitude is greater on larger floodplain rivers, downstream of several tributary confluences; the risk of not having enough flow is more likely on smaller order streams.

One approach to reduce these risks is to work on streams below glaciers or on snowmelt streams, following a winter of adequate snowfall. Under these conditions, a longer period of relatively constant overbank flow is likely to occur at a predictable seasonal period, reducing the uncertainty of when to prepare for the data collection process. On such an experimental site, research methods could employ a number of laser-doppler anemometers (or other electronic current meters) simultaneously, to increase the sample size in longitudinal, vertical and transverse (x, y and z) directions, as well as over time. This approach would be more expensive, on the order of $30,000+, as compared with the $1,400 required for the 'Mini' current meter employed for this thesis, but it would make best use of the duration of natural overbank flows. The present study was hampered by the relatively short and unpredictable duration of the flood events, limiting the number of velocity readings which could be taken in the time available.

Many montane snowmelt streams in the western USA have experienced channel degradation and over-widening from overgrazing, logging, road construction and aggravated runoff. Extensive areas and potentially thousands of miles of streams

may be suitable candidate sites for revegetation using soil bioengineering methods. Such field conditions could allow the researcher to quantify stem density, spacing, substrate texture and elevation above mean high water, and project elevation with respect to expected flood stage. With quantified field conditions and predictable flow duration, many of the uncertainties associated with the present research programme could be minimised.

For safety considerations of access onto the floodplain during a flood, it is crucial that the researchers have personally surveyed the topography of the area in careful detail. Not only are field maps essential sources of data for analysis, but the surveying process itself informs the researchers of topographic details of the site, which may become key safety features during flood stage. Only an intimate knowledge of local topography can inform rapid decisions about appropriate responses, should emergency conditions arise.

Evaluation of bank failure mechanisms

In the Mattole estuary during the declining limb of the January 1995 flood, 8.8m of lateral erosion was measured at the study site during a 17 hour period. Bank scour below the root zone of the baffles was not anticipated in the structure's design, but highlighted the need to consider the possible mechanisms of failure under field conditions. Understanding of the basic modes of bank failure mechanisms is fundamental to the planning and design of any bank stabilisation measure. These mechanisms are so important to the functionality of riparian revegetation designs that a discussion is needed of the dominant processes of bank failure. In retrospect, these comments on the consideration of processes and mechanisms are offered here as an aid to adaptive management for future field research and design.

The primary modes of potential failure of vegetative structures on the Mattole estuary were:

- Channel thalweg migration causing bank failure by scour beneath the root zone.

- Rapid change of hydrostatic pressure in the hysteresis loop during the flood event, leading to bank 'blow-out' by excessive pore water pressure in alluvial river bank sediments.

- Incomplete design installation, such as rocks not placed on the baffle trenches.

- Plant death by drought, animal browse or vandalism.

Bank erosion during thalweg lateral migration

At the macro-scale, bank instability can be driven by factors such as increasing or decreasing sediment load, rapid variation in stream power (or water stage height), and low relative water depth leading to sensitive feedback from local aggradation or degradation to flow and sediment transport (Hooke, 1997). The factors involved in initiation of change in the thalweg location are outside the scope of this paper, but channel thalweg migration occurs over decadal time scales and over reach and greater landscape scales. The effects of these large-scale processes are very difficult to segregate, but cumulatively drive major channel change.

Mass failure of non-cohesive banks occurred on the Mattole during the declining limb of the storm (shown in Figure 6.14, Post-15-year flood map of channel changes). The excess capacity of the Mattole River to remove bank sediments delivered to the base of the bank by this shallow slumping permitted very rapid rates of bank failure and lateral migration of the channel, exceeding 0.5m/hr in some places (shown in Photo 6.9, left bank freshly cut during flood recession). It is unlikely that any vegetation configuration, natural or engineered, could withstand such erosive forces from below the root zone for longer than a few hours. The duration period of such erosive force directed at the bank was approximately 48 hours during the 15- year storm.

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Many observers have noted that bank erosion losses are most common as flood waters recede (for example, MRC, 1995). For non-cohesive, unconsolidated alluvial banks such as those found in the Mattole estuary, bank stability at the micro-scale is driven by a balance of processes of grain detachment and entrainment into flow, dependent on the geotechnical properties of the bank material (Thorne, 1990). Motivating forces on an individual particle are the downslope component of submerged weight and the applied fluid forces of lift and drag (Dingman, 1984, shown in Figure 3.2). Resisting forces are the slope-normal component of submerged weight and inter-granular forces due to friction and interlocking. Interlocking of grains can be a major source of erosion resistance in imbricated alluvial deposits (Yang, 1996). Lift and drag forces are often represented by the boundary shear stress (Eqn 3.11).

Other factors which may influence erosion resistance in natural riverbank soils include the presence of silt and clay fractions, the apparent cohesion due to capillary suction in the unsaturated zone, and the binding effect of vegetation roots and rhizomes (Schumm, 1960).

According to Thorne (1990), mass failure of non-cohesive banks at the meso-scale occurs by shearing along shallow, planar or slightly curved (sub)surfaces. The downslope component of weight causing shear stress is resisted by the shear strength along the potential failure plane. Deep-seated failures are rare in non-cohesive banks, because in these materials, shear strength increases more quickly with depth than does the shear stress (Terzaghi & Peck, 1948). In well-drained banks, failure occurs when the bank slope angle exceeds the friction angle. Processes of basal scour, or fluvial removal of toe material, further destabilises the slope (Thorne, 1990). Mass failure can be triggered by heavy precipitation or by rapid draw-down of the water level, as seen in receding flood stages.

Thorne (1990) articulated the concept of basal endpoint control, the linkage between sedimentary processes operating on the banks and those operating in the channel. The reader is referred to this work if the concepts are not well understood.

Rapid change of hydrostatic pressure in the hysteresis loop during the flood event

The term 'hysteresis loop' is defined as the lag between a cause and its effect. In hydrology, the hysteresis loop on the graph of flood stage (water height) vs. discharge can induce a lag between the falling channel water level and drainage of pore water from the bank, creating a hydrostatic hysteresis (Dingman, 1984). The rapid loss of pore water pressure in the pores or interstices of bank materials during flood recession can trigger rapid loss of bank stability (Selby, 1993). Bank protection measures should be designed with consideration of this process when deciding on methods to reduce erosion losses.

Incomplete installation of the design and its remediation

The design by Schiechtl (1980) for the live siltation baffle construction was not intended for the size of channel and floodplain found in the Mattole estuary. Rather, the design was intended for banks of lower order (1st -3rd) streams, and was intentionally extended to this 5th order application for experimental purposes, speculating that fundamental processes would be similar. As noted in section 6.4.2, ratios of channel width, floodplain width and baffle construction width should have been considered in the design process, as well as potential for channel thalweg migration. For any revegetation design, the physical principles underlying the design need to be thoroughly understood, and followed through to completion. Where basal scour is a possibility, consideration should be given to increasing resistance or the diffusion of scour at the toe region.

In the case of the Mattole estuary baffles, a design modification could include a set of large willow branches placed along the bottom on the trench in which the willow stems were set on end (see Photo 5.2), set with the fine branches pointing toward the channel. Assuming these large willows placed transversely at the trench bottom died, the finer branches would remain for several years before decomposing. This approach would increase the inclusion of woody fibres in the soil matrix, which would increase resistance to fluvial erosion at the toe of the

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baffle. Figure 7.1 suggests a modification to the live siltation baffle design where the possibility of root zone undercutting could occur.
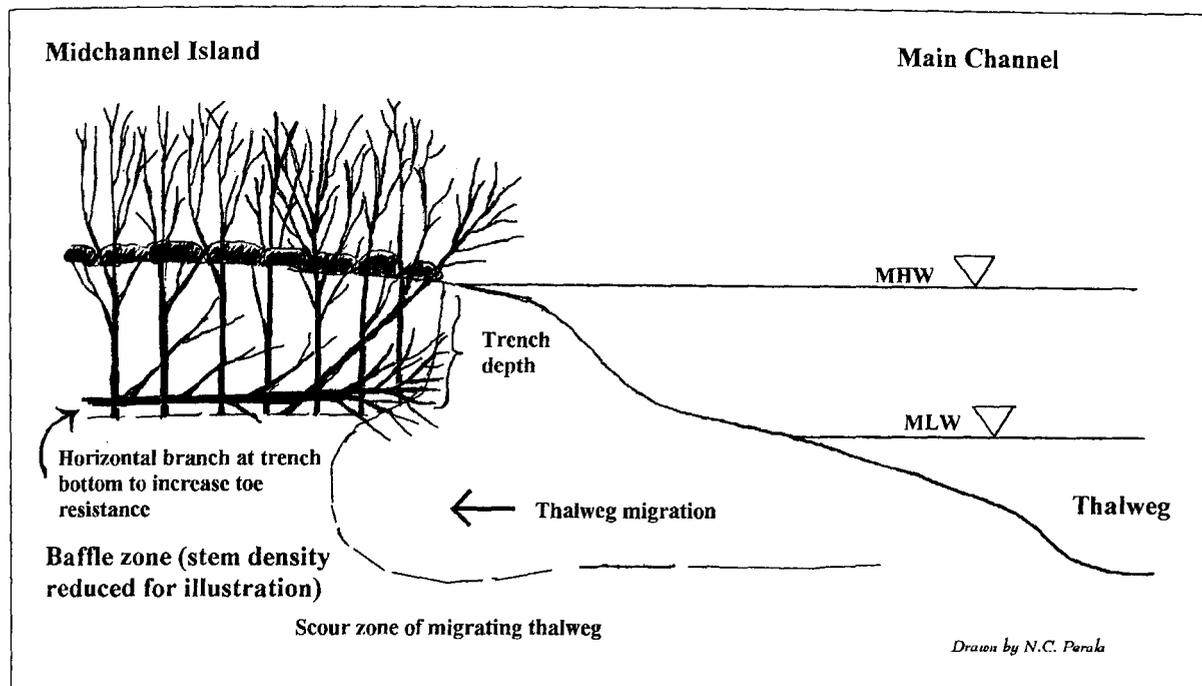
Figure 7.1. Design modification for live siltation baffles using a horizontal branch in trench bottom to strengthen resistance against erosion at or below the toe region.

This approach, combined with a wider, longer floodplain region of cover by vegetative structures, would increase the likelihood of survival of the structures, and subsequent floodplain vegetation recruitment processes, following a major flood event.

For an estuary mid-channel island where thalweg migration is a significant possibility, increasing vegetative resistance using soil bioengineering structures at the upstream end of the island could strengthen resistance against the erosive force of thalweg migration. Once lateral erosion reaches the vegetative structures in the middle island region, there is relatively less resistance available than if erosive energy can be deflected or partially absorbed at the upstream end.

If the baffles were longer (40m instead of 10m), and spaced at least 130m. apart and were more numerous, these structures would have been more effective at hydraulic retardance, at trapping fine sediments on the floodplain, at retaining fines

captured, and at decreasing wind scour and seedling losses in the process of natural recruitment of the native plant community.

A bank with a wide band of mature riparian vegetation, perpendicular (or at the least, not parallel) to the channel could significantly increase bank cohesion and resistance, and retard the delivery of sediments to the channel. A wider zone of mature riparian trees would have greater potential to resist erosive forces both above and below ground for the duration of moderate storm events. For high-energy, alluvial channels widened in recent decades owing in part to the loss of the riparian corridor, recovery of such vegetated banks may well be a vital link in the recovery of historic channel widths, depths, and channel morphological diversity.

The annual migration of active channels in unmodified rivers was well documented for the Willamette River from historic records by Sedell & Frogatt (1984), who emphasised the importance of the floodplain forest for overall channel and floodplain stability, not least because of the energy dissipation through the braided systems of channels and varied floodplain topography. The presence of large amounts of woody debris plays a significant role for alluvial rivers like the Mattole in their ability to maintain deep pools and stable river banks (Sedell & Froggatt, 1984). Large woody debris has been lost from the Mattole system over recent decades, but recognition of its importance has spurred local residents to prevent the loss of newly deposited LWD by digging such pieces into floodplain sediments and marking them to discourage cutting for firewood (MRC, 1995).

7.5   Synthesis of Field and Flume Investigation Results

Given that flume research results are applied to natural rivers with great frequency, the use of natural river flume conditions on a scale of 1:1 has been applied comparatively infrequently. On the Stillwater Oklahoma facility, grassed swale hydraulic research in the 1950-60s did much to promote the application of grass swales for erosion control, based on extensive hydraulic analysis of grass deformation for several flow regimes (Ree & Crow, 1977). In the 1990s, when plant community succession to trees had replaced the Stillwater flume grass cover,

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hydraulic research addressed the influence of woody debris on roughness and discharge (Abt *et al*, 1998).

In a flume study with a floodplain and open channel, Pasche & Rouve (1985) observed rather constant velocities over the floodplain, varying with the density of vegetation. They concluded that for high vegetation densities, the friction factor λ can be actually increased by reducing the width of the wooded floodplain, such as the narrow-ribbon type of vegetation recruitment which would increase eddy shedding on both sides of the vegetation strip. This suggests a review is needed of 'narrow ribbon' type revegetation patterns, such as the willow spiling (live woven woody fence bank protection) or even the common, narrow row of riparian trees along a stream channel. These narrow vegetation patterns appear to have higher friction values than wider vegetation buffers which include the width of the bank and a significant part of the floodplain, with hydraulic consequences for bank stability during flood events. This parallel vegetation placement offers little in the way of flow resistance or attenuation which could retard velocity and encourage settling of suspended sediments. The work by Pasche & Rouve (1985) represents some of the earliest work on the hydraulics of vegetation (buffer) zone width, and could be extended to more specific channel, flow regime, sediment and vegetation types.

The flume behaviour of flexible emergent porous filter has some similarities to the effects of permeable river groynes (Bettes, 1990), where lines of dikes or groynes can create an eddy-shedding field, either submerged or emergent. Bettes notes that permeable groynes cause less disturbance to the flow field than impermeable ones, that permeable ones reduce shear velocities compared with impermeable ones, and the scour depth at the ends of the groynes decreased as the groynes were inclined more downstream (Bettes, 1990). The reasons for these similarities are based on energy absorption, where the permeable structure is capable of absorbing energy from the fluvial system rather than reflecting that energy back to the

stream channel or its banks, as would a rigid structure. Groyne structures can be valuable design tools for field conditions where channel lateral migration has the potential to compromise bank integrity, with high economic consequences.

The shrub form at the floodplain-channel margin is a persistent feature of many floodplain ecosystems before and after anthropogenic alteration of the ecosystem. The riparian and floodplain shrub-form, 'coppiced willow' or streamside shrub willow such as *Salix exigua*-type of flow obstruction has not yet been modelled hydraulically, with the measured properties of emergence, flexibility and porosity. An approach to characterise roughness using large scale effects (1:40 or 1:150) such as the method described by Klumpp & Falvey (1988), seems less likely to yield helpful insights on its influence on patterns of flow than would be measures to characterise drag, turbulence energy and shear stress. Research opportunities could exploit the many phenomena riparian plants exhibit with respect to flood hydraulics, drag over natural, rough bark and sediment transport dynamics.

Increasing the capacity of floodplains to retain sediments may affect channel morphology in two ways. First, through the increased turbulence zone at the channel margin of a vegetated floodplain, main channel flows increase in velocity while floodplain flow velocities decrease, as illustrated by the modelling work of Naot *et al* (1996). Higher main channel velocities alongside vegetated floodplains would increase channel sediment transport capacity and the resulting particle size of channel sediments. Second, by reducing floodplain velocities, the capacity for floodplain sediment retention is increased, reducing sediment inputs to the main channel in return flows. If the findings of this research are confirmed by fieldwork elsewhere with regard to deposition of clay particles (which is contrary to accepted thinking), this could provide a powerful new incentive in support of such riparian revegetation, especially where clean river gravels are needed for fish spawning habitat.

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Turbulence, expressed by the Reynolds number, is a major factor in settling rates for suspended sediment (as in Tollner *et al*, 1976). For example, suspended sediment particles concentrate centrally under the centrifugal forces in an eddy cell, and settle out when the cell dissipates. The generation of turbulence by flexible, emergent porous vegetative structures appears to be extremely effective, observed in the laboratory and seen in the field by the settling of silts and clays between the Mattole baffles.

For the plants to remain in the shrub form, instead of converting over time into large, single-stemmed trees, either the plants must be in fine balance with the fluvial regime (pruned by infrequent floods), or they may require some form of maintenance, whether by appropriate animal browse, by careful pruning or stem harvest. See section 7.6 for further discussion on the role of riparian vegetation maintenance.

Objective 6 of this research set out to investigate the effect of the angled placement of the upstream most baffle in a multiple configuration. Schiechtl, the author of the most highly regarded manual on soil bioengineering, specified that the first baffle be angled at 60° from perpendicular, but did not say why. A laboratory experiment was carried out to test this effect. Although not conclusive, both field and flume observations suggest an explanation.

The suggested reasoning is twofold. First, rather than take the full brunt of the flow force head-on, the first baffle deflects some flow back into the main channel. Second, angling the baffle increases its length with respect to the primary flow vector. The greater length allows more flow through into the area of the baffles, similar to the way the angled weirs on the River Thames increase the potential inbank discharge by about 10% (J. Gardiner, pers. comm.). It was not possible to verify the second effect in either field or flume, but the flume showed this effect qualitatively.

7.6 Revegetation strategies with hydraulic considerations

A new group of disciplines known in the USA under the general title of 'environmental engineering' have made significant strides in identifying that engineering with living plants is, in many cases, appropriate technology. Research in the USA, Europe and elsewhere has demonstrated that the interactions among living plants with flowing water and transported sediment can be more resilient to catastrophic events than rigid structures (Schiechtl, 1980, Bache & MacAskill, 1984, Coppin & Richards, 1990, Gray & Sotir, 1996, Schiechtl & Stern, 1997).

Much of the contemporary focus on river 'restoration' has been devoted to recovery of channel morphology (Holmes & Nielsen, 1998), and to reducing impacts to or recovery of the hydrological flow regime (Petts, 1996, Molles *et al*, 1998). While there is much popular interest in America and the UK in planting trees to 'restore' rivers, this level of effort is typically site-based in its focus, with little assessment or monitoring of catchment or channel conditions. The many good efforts at the level of individual or community-based tree planting programmes typically have little geomorphic context and poor connectivity to the river in hydraulic terms.

A key feature of the structural approach to revegetation for bank stability is the connectivity of the structure to the bank at the endpoints and at the channel margin. These are the regions most vulnerable to scouring flows, perhaps the most challenging part of any project design. Theoretical relationships among the river banks, floodplain area and revegetated area are not yet well articulated, and more work is needed to guide practitioners in stabilising the endpoints of a design where existing banks are unstable. In broad floodplains like the Mattole estuary, where securing bioengineering structures to a stable bank is not an option, the vegetation structure should be significantly wide enough in relation to floodplain width and the channel lateral migration width to withstand some losses at a meandering channel margin.

This research programme addresses the intersection between the restoration ecological approach to streamside revegetation and the river engineers' strategy for river management. It grew from several years' experience in revegetation practice. From this perspective, the 'bridge between disciplines' is key to progressing the work of ecosystem enhancement. A prioritisation to the riparian revegetation process is offered, based on a synthesis of personal experience and the extensive and growing literature on this subject.

A framework is suggested for prioritising the approach and resources needed to recover a healthy streamside plant community without compromising public safety. Economic costs and benefits are difficult to analyse when multiple benefits are likely to be realised over a long period of time, so the decision over which approach to take is often governed by excluding many potential benefits and including only short-term costs.

The Fundamental Riparian Revegetation Strategies

1.   *Setting the geomorphic context for vegetation-fluvial interactions*

2.   *Natural recolonization or natural recruitment.*

3.   *Vegetation maintenance for riparian recovery*

4.   *Geotextile treatments*

5.   *Parkland tree-planting for aesthetics or wildlife habitat considerations.*

6.   *Structural uses of woody plants*

7.6.1   Setting the geomorphic context for vegetation-fluvial interactions

As was experienced on the Mattole, a basic understanding of where the site or reach of concern is located at the catchment scale is of primary importance (Gregory & Gurnell, 1988). Much more has been articulated in the literature in terms of location within the river planform, but a "real-world" major constraint is often that the revegetation process is governed by the allowable width of the river

corridor, constrained by development. On floodplains unconstrained by development, many options may be possible for allowing natural recovery of the damaged fluvial ecosystem. The more this width is constrained by development pressures, the fewer options exist for a 'natural recruitment' strategy, allowing plant ecological interactions with fluvial geomorphic process to lead the process of floodplain vegetation recovery.

Physical parameters of riparian and floodplain revegetation are initially determined by the width of the allowable river corridor. At an absolute minimum, the recommended riparian corridor width should be at least as wide on each bank as the width of the stream channel itself. Historic, pre-industrial riparian floodplain corridor widths may have been as much as or more than six times the width of the stream channel on each bank (W.Trush, pers comm, 1993). Between these two themes are determinations based on stream order, flood hydrology, sediment transport regime, fish and wildlife habitat requirements and human desires for resource manipulation and extraction. Connectivity between channel and floodplain, and between floodplains and upland areas, increases the geomorphic and ecological functionality of the revegetated area.

7.6.2. *Natural recolonization, also called natural recruitment*

Where possible, allowing nature to recover the optimal relations among channel geometry, discharge, sediment transport regime, and vegetation species and distribution is the preferred option. Natural recruitment assumes that adequate floodplain widths exist, and that minimal claims are made which could restrict channel evolution. On western American streams degraded by excessive grazing, exclusion fencing for rotation grazing, or rest from grazing, has been shown to deliver significant water quality and habitat benefits to the stream ecosystem, by allowing regrowth of the native riparian plant community (Platts, 1984). The time-scales involved in channel and floodplain recovery from disturbance are generally poorly understood or unknown, as are the existing trends in landscape evolution, especially in disturbed catchments (Kaufmann *et al*, 1997).

In Mendocino County, California along tributaries of the South Fork Eel River, where planted willows had suffered two seasons of heavy browse from wild deer, the beneficial effects of exclusion fencing around areas of bioengineered willow treatments astonished landowner and contractor alike in terms of the volume of plant growth in a single, unbrowsed season (E. Engber, pers. comm, 1997). In the UK on the Thames near Oxford, cows were removed from one of the famed hay-meadows for a prospective new floodplain development. The resulting growth of wildflowers was so profuse and diverse that English Nature's predecessor authority, the Nature Conservancy Council, hastily renotified it an SSSI, a site of special scientific interest, alongside the remaining protected hay meadows. Control of ungulate browse and grazing is often key to success in rural stream restoration (Platts, 1984).

Potential complicating problems for floodplain plant communities include the modification of historic hydrographs by dams and land use change, the recent introduction of invasive exotic plant and animal species, loss of native plant and animal reserves available for recolonization, water abstraction, road construction, mineral extraction, and human resource claims on set-aside areas. Where any of these factors dominate, natural recruitment is not likely to succeed toward a self-sustaining, biologically diverse ecosystem. Factors such as climate change pose unknown challenges to all ecosystem rehabilitation efforts everywhere.

Natural recruitment is being tested on a river restoration project in the UK, the River Restoration Project on the River Cole funded by the European Union LIFE programme (Holmes & Nielsen, 1998). In the EU-LIFE river restoration programmes for the UK and Denmark, emphasis was placed on careful site assessment and monitoring, with the primary activities being re-meandering straightened stream channels (Holmes & Nielsen, 1998). For the River Cole, remeandering an historic channel was accompanied by a strategy of natural recruitment of riparian vegetation, with grazing as a primary vegetation management strategy for the floodplain. In this strategy, seedling recruitment of willows and other phreatophytes is most likely to survive at or near the margin of the summer low-flow channel. In dry years, seedlings may not survive at higher

bank elevations, so that the primary 'natural' vegetation could take the form of a thicket of willows near the bankfull channel. This scenario would greatly increase maintenance requirements where floodplain constraints exist, and could discredit the reputation for the 'working with Nature' paradigm. To avoid this, careful monitoring of recruitment patterns can assist where appropriate. Planting in phases could establish shade trees at the high flow channel margin prior to channel reconfiguration. After several seasons' growth, shading trees higher on the banks could reduce tree seedling survival at the winter channel margin.

At the Oregon Nature Conservancy Preserve, Middle Fork John Day River Preserve, Oregon USA, an approach is being tried removing all cattle grazing to allow wet meadow grasslands and riparian forests to recover from decades of overgrazing (personal experience of the author). A 650 ha reserve is fenced at the perimeter to allow native ungulates passage and access to floodplain pastures at much lower stocking rates. Only native ungulates can leap the fences, so cattle grazing pressure has converted to lighter browse pressure. Natural succession recruitment of willows and sedges is in the process of providing shade to the channel for wild salmonids.

The extensive problem of invasive exotic weeds complicates plant community evolution wherever human disturbance has altered the historic plant community structure. Where natural recruitment can be expected be more likely to succeed is where riparian lands are returned to wet meadow or wet forest, where the invasive plant species are less likely to tolerate the restored hydrological conditions.

7.6.3. Vegetation maintenance for riparian recovery

Local and regional jurisdictions typically allocate funds each year for channel, levee and floodplain maintenance programmes. These actions typically involve planning and operations to carry out modifications to channel and floodplain vegetation. Multi-objective planning has been recognised for the many benefits accruing from integrated planning and operations, and it is to be hoped that the organisation of capital funding programmes will change accordingly.

As vegetation hydraulics become more widely understood, it is possible that rather simple changes in operations could result in significant improvements to either flood capacity, water quality or both, without harm to the stream corridor plant communities. In urban flood defence planning in Portland, Oregon on Johnson Creek, a major theme to emerge recently for future catchment management solutions to address notorious, chronic flooding problems in the urban floodplain was "Eco-geomorphology". Another major theme was "Policy", meaning the backdrop of legislation and economic incentives including insurance against flooding, which largely determines the riparian and floodplain land use, the riparian corridor width and the state of the river.

The multi-objective approach is especially attractive where floodplain management integrates flood defence criteria with channel and bank stability goals, water quality, fish and wildlife habitat, and recreation objectives. An economic demand for locally-produced construction and fibre materials is potentially compatible with sustainable land use. In this regard, the primary obstacles to implementation are not technical but are institutional and socio-economic.

Several methods of streamside vegetation management are available from historic, traditional European practices. The ancient method of 'Coppicing', used primarily on willow and hazel, involves cutting the shrub at the base of the stems, removing all or part of the above-ground mass. This removes senescing and decaying wood, and rejuvenates the plant to produce a new set of shoots, while retaining and increasing root mass, which increases below-ground stability factors.

Extensive research on coppicing is being conducted within the Kew Gardens system and at Long Ashton Research Centre, Bristol, but the practice is almost unknown in the USA.

Figure 7.2 illustrates the basic concept of willow coppicing.

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Streamside willow

Stems removed at base

Shoots regrow, while root mass increases

Basic coppice technique and regrowth

Drawn by N. C. Perala
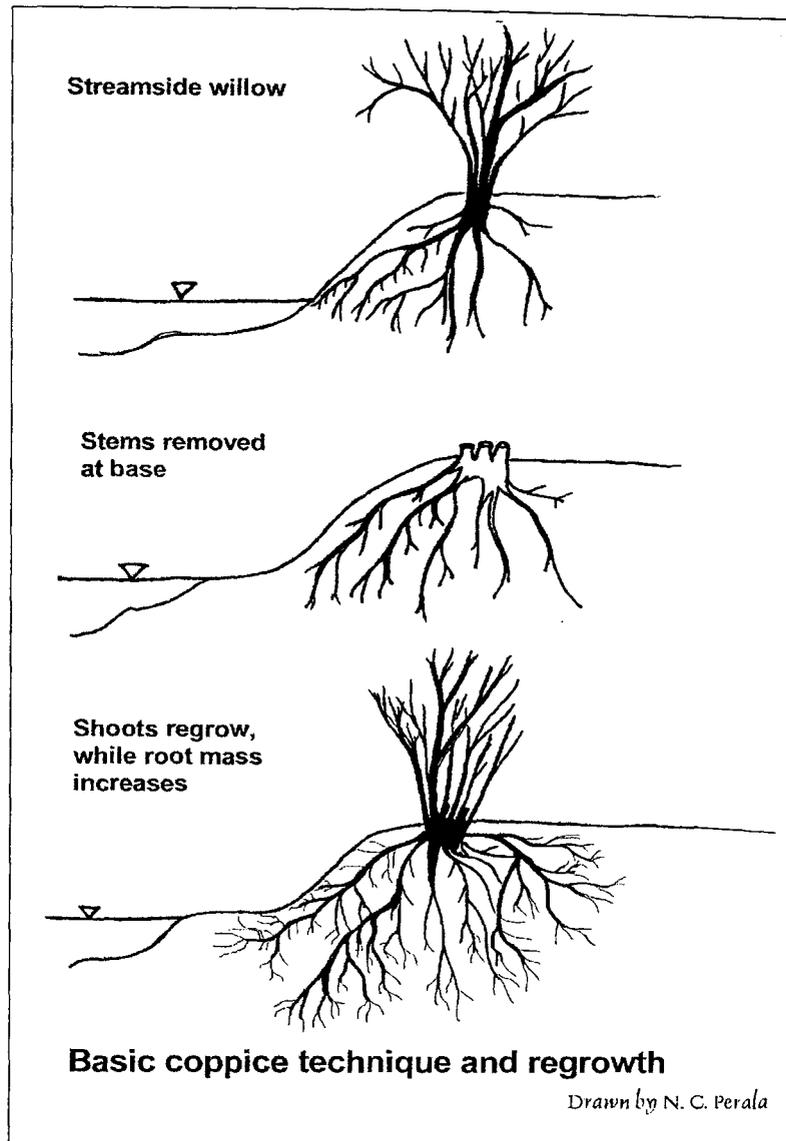
Figure 7.2. Diagram of the basic coppice method.

Coppicing floodplain trees and shrubs may be one of the oldest forms of riparian management, being of great utility to non-industrial societies for reducing flood hazards locally while producing potentially large amounts of useful construction materials and fuels. Coppicing was used extensively for many centuries and into the present day, by Europeans and many groups of native Americans, as a source of materials for construction of woven containers and furniture (Newsholme, 1992).

As soil bioengineering construction projects mature, smaller diameter stems increase in diameter and height. At some threshold around 10 -15cm diameter or about 4-8 years in age, larger stems gain enough mass to become rigid. These pose problems for bank integrity during floods, where the force of high water

pushing against the trunk can drive the turning moment of failure. In order to reduce the probability of tree toppling, Schiechtl (1980) recommended the removal of large diameter woody stems on mature soil bioengineering projects on a scheme of roughly 5 year maintenance intervals. Such a practice rewards the hand maintenance labour required with an abundance of woody materials useful either in subsequent soil bioengineering projects, or as fuel or fibre. Linking such maintenance practices with local economic needs could provide a strong economic incentive to revegetate floodplains and to manage the plant community resource on a sustained yield harvest cycle.

Other methods of timber harvest in floodplain forest with potential application for modern river management include pollarding, the practice of removing large tree limbs while retaining the bole or trunk of the tree. This method is still in use in Europe today as a logical response to the brittle nature of stems of the crack willow, *Salix fragilis*. Pollarding has been demonstrated to increase the lifespan of a senescing tree by promoting new shoot growth. The high young shoots are valuable for wildlife habitat, while their roots increase bank stability. If done in combination with shrubs or low, flexible branches, pollarded trees can reduce potential damage from local scour (Corporation of London, 1996). Another new development is the use of small willow plantations for water quality improvements, where willows have been shown to have high uptake of nitrogen, other nutrients, pesticides and some heavy metals (Mortensen *et al*, 1998).

In the UK, Sweden and elsewhere, willow plantations are being used for biomass fuel production (Willow Bank, 1997). Other forestry applications now being pursued in the USA, France, the UK and elsewhere include the now-familiar hybrid poplar plantation for pulp and paper production. These methods of 'riparian stem' harvest for a variety of objectives demonstrate the huge potential for resource applications of floodplains in potentially sustainable ways; provided the ecological, geomorphic and hydraulic context for such management schemes is kept in place. However, from a plant ecology standpoint, any monoculture always has the potential for ecological disaster (Botkin, 1990), particularly for hybrid clones.

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Research in each of these fields is needed to link the primary application, such as forestry, water quality, etc., within the hydraulic and geomorphic context, especially as such schemes are proposed within the context of floodplains uses set aside for flood defence objectives. It is often possible that recovery of natural vegetation functions can be achieved through changing the maintenance regime, and local and regional land use practices such as storm water management. Greater land area devoted to native plant cover in a catchment will provide more source areas and propagules to support the sustainable natural recruitment of the locally native, riparian plant communities. The control of invasive exotics will typically become a dominant, long-term management challenge.

7.6.4   Geotextile treatments

Geotextiles are a major tool of the global erosion control industry. They are sturdy fabrics made either of woven or felted fibres or of various synthetic construction. For surficial erosion, geotextiles are often laid directly on the earth surface to reduce particle entrainment by rainsplash or gravity flow. These are often combined with seeding treatments.

For bank stability, some biotechnical designs use geotextiles incorporated into the bank architecture. An example of a bank stability treatment is the 'vegetated geo-wrap', a series of 'lifts' or layers of soil wrapped in a fabric which provides tensile strength for bank horizontal stability. The vegetated geo-grid lift places layers of willow cuttings at intervals between the geotextile layers of encapsulated soil (Hoitsma, 1999). A relatively expensive treatment, this method has had numerous applications in the USA on constrained and urban river reaches, such as steep river banks below utility corridors on outside bends.

This technology has unfortunately sometimes been applied without adequate analysis of the underlying geotechnical or fluvial forces causing slope instability (Gray & Sotir, 1996). Appropriate application of the method depends, as with any other method, on sufficient site and reach analysis to identify driving erosive or mass-wasting forces. Geotextiles can pose problems over time when exposed to

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sunlight, which degrades the fabric, or when exposed by construction procedures, as the method is relatively inflexible to disturbance. Synthetic materials can leave toxic residues upon decay, and for this reason, natural fibres such as coir, sisal or hemp, are preferred for ecological reasons.

7.6.5. Parkland tree-planting for aesthetics or wildlife habitat considerations.

The single row of trees along the river, or a few lines of trees, perhaps with shrubs in a linear park, are a common response of the landscape architect for urban parks , and even for rural improvement schemes. Such proposals have been recommended for a substantial number of urban stream enhancement programs, and continue to be implemented on banks and in reaches in need of structural measures, such as Johnson Creek in the City of Portland, Oregon, and for linear urban parks such as the proposed Los Angeles River Parkway.

The 'single-tree planting' approach has value to offer, especially where volunteer labour forces are the manpower behind a neighbourhood improvement scheme. However, caution should be exercised in the site assessment and design phases that the strategy is appropriate to meet overall land management goals within the fluvial geomorphic context. Where plants may encounter significant hydraulic forces and shear stresses, such as on outside bends, or near the channel - floodplain margin, the single tree with a low root: shoot ratio has little chance to withstand high shear stresses during flooding. In these conditions, structural revegetation may assist the initial stabilisation period. Dry-season irrigation is almost always required to achieve satisfactory survival rates. Obtaining a widened river corridor land use designation enables a higher margin of safety with lower risks.

In this wider zone, greater habitat values, biodiversity and potential geomorphic stability are best achieved by including shrub species in the planting mix. Since riparian plant communities exhibit distinct patterns of community succession, a sequenced pattern of planting could utilise the early successional species in the first round of planting, avoiding initially those plants which require more shade or soil

moisture to prosper. As always, the job of the project manager is to ensure that appropriate native species are used in the appropriate places.

7.6.6. Structural uses of woody plants

Where channel dynamics are high and constraints exist on banks and on the riparian width, the soil bioengineering or biotechnical option for bank stabilisation is likely to be appropriate. Biotechnical options may be relevant where the natural recruitment process may be too slow to stem the loss of valued endangered species, or where the channel dynamics are too high to permit seedling recruitment when floodplain topsoils have been lost.

Soil bioengineering projects depend for their success on good planning, design, communication among the stakeholders, highly competent implementation and informed maintenance practises. Interactions among many disciplines are needed in each phase of the process. This approach appears initially to be the most expensive option, because the approach depends on detailed site analysis, integrated design and hand labour in construction, as well as long-term follow-up maintenance. When multiple criteria are demanded of a project, the soil bioengineering approach may become the most cost-effective option for rivers under constrained conditions, especially where several sources of funding can be applied to meet multiple objectives, such as fish habitat combined with bank stabilisation, water quality improvement and recreation.

Although the project construction phase may not take long to implement once the implementation stage is reached, soil bioengineering is a longer-term strategy than traditional engineering. This is because the use of live plants in a geomorphic context sets up conditions to which the eco-geomorphic system will respond positively. This approach requires sufficient width of the river corridor to allow for backwater effects for vegetation interactions with fluvial processes. Allowance may be needed for circumstances when maintenance may not be kept to design standards, and in any case, various, quite different methods have been invented for specific applications.

Specific applications

In the USA, the willow post method (Roseboom *et al*, 1995) is a special category of soil bioengineering developed for degraded streams in the glacial till landscapes of the Midwestern USA. The method is applicable for steep banks on outside bends as well as straight reaches. It uses a toe stabilisation feature to reduce bank erosion on outside bends, and applies willow poles in series along and across the river bank. This approach uses few pieces of heavy equipment, primarily a post-hole driver which runs off any farm tractor, so the approach has wide appeal to farmers who can implement the method using local labour. Many successful applications of the Roseboom willow post method have been reported (Roseboom *et al*, 1995).

Willow stake planting is a common technique in America, favoured recently by engineers for planting after placement of a riprap blanket. One example used in Oregon in 1999 called for use of 50mm diameter steel pipes to direct the willow stake through the riprap, hopefully to make direct contact with the soil mantle below. This method is not a good example of soil bioengineering, and 'successes' have been reported in terms of the surprisingly low survival rates of only 10%.

A technique recommended by the Bureau of Land Management (McCluskey *et al* 1983) is the use of short willow cuttings, recommended at that time for enhanced wildlife habitat and increased bank stability. These small cuttings are hand placed, presumably in fine-textured soils, at the beginning of the rainy season. With little energy reserves held in the stem, this method is liable to high losses during the first year, and the stems have no resilience to shear stresses in the first few years. However, many projects in the Western USA have grown lots of streamside willows using this method.

Fully-developed soil bioengineering methods artfully combine natural materials such as wood, stone, fibres such as coir (coconut husk) or hemp, and other plant materials with the structural uses of woody stems, herbaceous stems and roots. This approach requires co-ordinated design skills from a multi-disciplinary team including hydrology, hydraulics, geomorphology, engineering, soils, botany and

ecology, as well as social and economic evaluation. It comprises a set of labour-intensive methods which use natural, indigenous materials in environmentally compatible ways (Gray & Sotir, 1996).

Soil bioengineering methods can be combined with 'biotechnical slope stabilisation' methods which may use concrete, steel or other hard engineering structures, where more intensive treatments are called for to stabilise the toe of the slope. Soil bioengineering methods are not recommended where toxic conditions exist, or where less intensive methods will accomplish project goals (Gray & Sotir, 1996).

7.6.7 Site assessment and monitoring for soil bioengineering construction

The field experiment provided opportunities to observe the performance of a soil bioengineering construction under fluvial conditions, a subject on which few hydraulic or geotechnical data exist. Some of the lessons learned in this process have to do with the cycle of purposeful revegetation; site assessment, design, construction and monitoring. Together these elements form an interdependent process which has been termed 'adaptive management'.

Numerous incidents have occurred in which project failure has followed lack of assessment or poor design practices. Lack of monitoring plagues the river and wetland restoration industry, as funders consider expenditure on follow-up data collection and analysis either as secondary to further 'first-time' restoration or as superfluous to requirements.

In order to learn from design flaws, all aspects of implementation construction practise and the eco-geomorphic consequences of works, the resulting physical construction and the fluvial geomorphic responses must be monitored. Data analysis is integral to this learning process, so quantitative measures can inform future design improvements. Good data are relevant data, obtained from a diligent site assessment programme, based on the initial question or problem statement.

Figure 7.3 illustrates the cycle of assessment and monitoring for stream revegetation projects.

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**Evaluate with
Stakeholders against
Success Criteria**

**Identify / Communicate
with Stakeholders
(Data Sources!)**

Problem
Identification;
Symptoms &
Causes

Analyse monitoring data to
learn from responses to
project, review design for
future improvements

Review Problem

**Identify resources
needed to address
problem**

Site Assessment; scope,
collect and analyse data at
catchment, reach and site
scales

**Identify Success/
Evaluation Criteria**

Figure 7.3. The
Stream Revegetation
'Adaptive
Management' Cycle

Monitor geomorphic and
biological responses based
on site assessment data

Initial Problem Statement &
Assessment Data
inform the option generation
& comparison process

**Document Field
Conditions**

**Address liability
and risk issues**

**Communicate with
Stakeholders**

**Communicate with
Stakeholders**

Implementation / construction
Good communication between
design and construction
participants before during and after
implementation process

Final design:
Identify resources and
people needed to carry out
design to construction

Communicate with Stakeholders

N.C. Perala

The site assessment process includes potentially all of the data collection and analysis methods described in Chapters Four, Five and Six. Other methods may be relevant, depending on the initial problem posed. The fundamental areas in which information is needed for analysis are:

1. A geomorphic assessment of the contributory catchment area, geology, soils, drainage network and landscape-scale processes, including interpretation of historic patterns of channel change and land use from maps and air photos.

2. Hydrological assessment of flood records, channel capacity and hydraulic geometry (reach-scale flood stage levels and recurrence intervals), as well as climate, rainfall and groundwater data.

3. A biological assessment of historic plant communities, fish, birds and wildlife communities and their habitat requirements

4. Site surveys and geomorphic mapping, to inform the design process and also provide the baseline against which future changes can be measured (Kondolf & Micheli, 1995).

5. Historic and contemporary human land uses and site access.

In particular, the data collection process relates physical feature changes over time, measured along the same transects to the greatest extent possible. Post-project monitoring should continue for at least a decade, with surveys conducted after major flood events (Kondolf & Micheli, 1995). Decadal timescales are short for measuring geomorphic processes, especially for larger-scale phenomena such as channel change.

7.6.8 Context for using soil bioengineering technology for stream bank stabilisation

These valuable tools for 'gentle' or 'working with nature' river engineering naturally need to be grounded within the fluvial geomorphic context of the river system. Using the goals of biodiversity conservation and enhancement to guide decision-making priorities, enhancing ecosystem processes is preferred over driving

the river toward an anthropocentric distortion of fluvial processes. Using soil bioengineering works to stabilise or fix a river bank in place may be an engineering challenge, where in nature the bank in question may be at risk from forces of erosion by virtue of its place in the river planform, such as on an outside bend. Prevention of bank erosion is not always a desirable goal.

When human land management criteria become involved in pre-determining a fixed outcome, the potential exists for natural erosive processes to be considered 'bank failure', with the implication that the land manager has failed to protect the bank. This places considerable constraints on the bank revegetation process, and requires the river manager to raise the threshold of acceptable standards for bank treatment. This trend can only make river management more expensive at greater levels of risk. An alternative strategy could include a review of the economics of site protection by extensive engineering. In some cases relocation of the structure(s) needing protection may be less expensive than "high-technology" bank and channel treatments, which may have attendant losses to the stream ecosystem and wildlife productivity, or short term successes at best.

Soil bioengineering is potentially more vulnerable in the early years following implementation to high erosion events (see Figure 6.15, the map of channel changes following the Mattole flood peak of 9 Jan. 1995). Until soil bioengineering becomes an acceptable method of river engineering and floodplain revegetation, projects will likely continue to be 'overbuilt' in defence against the perception of failure on the part of the methodology, even if it would be 'value neutral' or geomorphically beneficial for a given bank to erode under the current river regime. Quantitative evaluation of projects based on funded monitoring programmes will continue to be the only long-term strategy to inform research and adaptive management, so that lessons from mistakes can be learned and the discipline of river restoration as a whole can progress (Haltiner *et al*, 1996, Kondolf & Micheli, 1996). Soil bioengineering, like other forms of river engineering, are most reliable and cost-effective when practitioners are honest about working with natural processes.

One of the great challenges to the incorporation of soil bioengineering methods into river engineering practice lies in the differential between a bioengineering construction immediately after planting and after 3-4 seasons. These structures, when constructed and properly maintained, become stronger over time. To meet stringent engineering requirements in liability and to perform comparably with hard engineering methods such as riprap, biotechnical or bioengineering applications are often 'over-built', because of the window of vulnerability following construction (R. Sotir, pers comm., 1997).

7.7 Conclusions

Substantial opportunities exist to incorporate floodplain vegetation into river engineering and management for a multitude of benefits. "Fixed bank" revegetation is not a substitute for allowing a river the freedom to adjust to changing catchment conditions, which may involve migration through its planform. Structural revegetation methods can provide an environmentally more beneficial means of stabilising a bank vulnerable to erosion than placing riprap or constructing wood, steel or concrete retaining walls. The geomorphic context should inform the decision whether or not to stabilise a particular bank.

Stabilising banks with soil bioengineering techniques utilises the capacity of plants to grow in strength over time, unlike inert structures, which can only deteriorate once built (Sotir & GWSCC, 1995). A key to the design philosophy lies in absorbing, rather than reflecting, hydraulic and other environmental energies. In the longer-term, this approach meets physical system adjustments with diversity and growth rather than decay.

The challenge for engineers is to understand and utilise non-homogenous living construction materials, whose properties can at best be described only in terms of a range of values. Key to this strategy is to investigate not only single plants, but also groups or aggregates of plants, in a geomorphic context, and to build up the body of knowledge not so much through scientific reductionism but through science-based consideration of the complex whole.

Chapter 8   Conclusions and topics for further research

8.1   Summary of Goals, Objectives and Conclusions

The goals of this thesis were:

- To review the major literature in fluvial geomorphology and river hydraulics on the subject of vegetative influences on overbank flow, floodplain sedimentation processes and channel morphology;

- To measure the effects of a revegetation structure on floodplain sediment deposition;

- To test the assumption of the logarithmic velocity profile where flexible, emergent woody vegetation is present;

- To relate field observation and data analysis with laboratory experimentation, to test current assumptions about the hydraulic effects of floodplain vegetation on overbank flow.

Field Objective 1. Measure the extent and depth of fine sediment deposition for an overbank flood flow influenced by woody vegetation.

Conclusion: For an annual flow maximum depth of 15cm, over a duration of 15 hours, a vegetated floodplain zone retained 85.5m^3 volume of fine sediment over an area of approximately 4000m^2. This is equivalent to a mean depth of 0.021m for a single flood event. The retained sediment revealed mean values of sand = 34.4%, silt = 36.7%, and clay = 28.9%. (Section 6.1, p.172).

Significance: This thesis reports a quantitative sedimentation response to a quantified flow depth, duration and plant spacing architecture. These data can be of utility to increase accuracy in the prediction of floodplain sedimentation in numerical modelling, or for predicting the sediment transport consequences of this or other revegetation strategies involving groups of shrubs.

As existing sedimentation models do not predict the retention of clay particles during overbank flow, the finding that 29% clay and 37% silt were captured on a

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vegetated floodplain is of great significance to catchment, river and floodplain managers (section 6.1.2). This finding shows that floodplain revegetation can reduce even very fine suspended sediment loads during flood events, effectively to reduce the range of damages caused by these sediments, such as clogging of salmonid spawning gravels and downstream loss of channel capacity.

Field Objective 2. Assess the change in the floodplain velocity profile owing to the presence of woody vegetation on the floodplain.

Conclusion: From an hypothesis test for the effects of floodplain vegetation on the velocity profile, the data show that groups of flexible, emergent, woody stems on streamside floodplain terraces have a measurable effect on the logarithmic floodplain velocity profile during an overbank flow event (Section 6.2.1). Comparison of the velocity profiles for vegetated and bare surfaces during comparable flow conditions (Figures 6.8 and 6.9) suggests that the flow through a region with emergent, flexible vegetation, does not follow the universal logarithmic velocity profile. The field data are in conceptual agreement with a numerical model (Naot *et al*, 1996) which suggest that flow through a vegetated floodplain follows more closely a relatively uniform vertical velocity distribution.

In the field flow analysis, the vegetation structures were shown to reduce boundary shear stress by an approximate factor of 70-90% (Section 6.2.5).

Significance: Existing tools to predict floodplain roughness do not generally account for the change in velocity profile caused by emergent vegetation during overbank flow. Because the higher velocites predicted by the logarithmic profile numerical methods are not achieved on the floodplain vegetated in shrubs, such flows could be routinely overestimated. Field verification of the findings from numerical modelling strengthen the validity of this approach for predicting the complex interactions among channels and vegetated floodplains, but such models should be extended to a higher range of Reynolds numbers.

Few data exist on the actual effects of biotechnical methods for shear stress reduction. The data reported here should be used as part of a larger data set including other methods and subsequent applications of the siltation baffle method, to increase predictive engineering capability for biotechnical (soil bioengineering) design methodology. A 70-90% reduction in shear stress owing to the presence of flexible, emergent woody plants is of great significance both for hydraulic theory and for river management.

Laboratory Objective 3. Simulate field conditions in a laboratory flume, holding the Froude number constant, to observe flow patterns in overbank flow influenced by a porous vegetative filter.

Conclusion: This approach, relating field conditions to the laboratory flume, holds great potential to progress specific topics in fluvial hydraulics (Section 6.5). Intense momentum exchange was observed among interactions between the two velocity regimes of faster main channel and slower floodplain flows. The formation of an hydraulic 'wall' and the channel - floodplain momentum exchange was more energetic in the flow regime influenced by a baffle than for a single cylinder. A porous 'vegetative' filter had a profound effect on flow structure in the downstream direction and for increased lateral mixing on the floodplain. The effects of a single baffle, expressed in terms of the baffle width as a unit, were observed at between six and as much as ten units downstream (Section 6.5.2, Figure 6.17).

Significance: Hydraulic engineering analytic methods currently have little theory to guide the prediction of flow through the category of 'groups of emergent, flexible woody stems' (shrubs) especially at the reach scale. Overbank flow is chaotic and turbulent, but becomes calmer where vegetation is present in groups. The flow through groups of shrubs placed near the channel- floodplain margin has a strong effect on the free shear zone at the margin, increasing the vigour of exchange between slower- and faster-moving water. This is one of the

mechanisms by which shrubs increase bank stability at the channel- floodplain margin.

Biotechnical design methods can be improved using these data, as groups of shrubs or biotechnical baffles should be spaced in relation to the widths of the channel and floodplain (Section 6.4.2.) For hydraulic reasons, baffles can be spaced more widely apart than current design guidelines suggest (1.5 times the baffle width) to at least five times and up to ten times the baffle width, depending on the geomorphic conditions encountered during flood stage.

Laboratory Objective 4. Develop qualitative observation of the effects of a vegetative filter on flow resistance and the backwater effect.

Conclusion: The flexible, emergent vegetative filter (or region of riparian shrubs) is well adapted to induce sedimentation across the floodplain, both upstream and downstream of the vegetation, even though vegetation at the channel margin increases the intensity of momentum at the shear zone (Section 6.5.2). This functions in part because of the increase in the boundary layer height, and in part by the breaking up of large turbulent eddy cells into smaller cells.

The backwater effect may be a primary mechanism for inducing fine sediment deposition, but further research is needed to clarify the hydraulic and geomorphic conditions under which this behaviour occurs.

The decrease in floodplain velocity appears to have a role in increasing channel velocity and turbulence, which may increase the sediment transport potential outside the vegetation zone, or in the main channel.

Significance: If floodplain vegetation increases retention of fine sediments and deflects higher-velocity flows into the main channel, then this is a primary mechanism by which vegetated floodplains provide for clean gravels in-channel for aquatic organisms which are harmed by excessive fine sediments in-channel. For water quality, bank and channel stability, and fish habitat criteria, wider floodplain

zones (rather than narrow strips) of riparian vegetation are needed to provide these physical functions during critical flood (sediment transport) events.

Laboratory Objective 5. Vary the spacing between baffles to observe flow wake re-entrainment and the distance at which wake re-entrainment occurs.

Conclusion: No wake could be detected from a porous filter structure (Section 6.5.3). In the flume, the hydraulic effects of a single baffle strongly affected the simulated floodplain flow structure. Because of scale effects, no interaction among two baffles could be detected, as the tracer dye could not be made to flow past a second baffle. This behaviour may be highly sensitive to scale effects.

Significance: If an emergent, wide, porous filter to flow does not set up a wake, then existing hydraulic theory does not currently provide adequately for prediction of flow through groups of flexible, emergent woody stems. This obstruction to flow is fundamentally different from grasses because the vegetation is emergent at higher flows, and is more resistant to the shear stresses of higher flows. It differs from flow through a zone of trees because resistance is flexible, which absorbs more momentum from flowing water in multiple dimensions (Figure 1.1). Because of the increased shear at the shrub zone margin, the component of lateral mixing around the shrub zone may be more significant in vegetated floodplain hydraulics than the components of wake dimensions and resulting scour.
In the presence of a baffle, eddy-shedding is intensified at the channel - floodplain margin. This phenomenon is not well understood, but an early prediction of this behaviour is given in the numerical model by Naot *et al*, (1996).

Laboratory Objective 6. Vary the placement of the upstream-most baffle from perpendicular to parallel to flow, to observe whether a perpendicular angle or a 60° angle increases the volume of flow onto the floodplain.

Conclusion:

No measurable difference in the flow field was detected, but this may have been owing to the limitations of the flume scale dimensions. Because this feature is embedded in the design of siltation baffle construction, further research is warrented to increase engineering predictive capabilty and factors of safety.

Summary of Conclusions

1. Substantial retention of silts and clays is possible during floodplain overbank flows by filtering flow through a flexible, emergent, porous, vegetative filter or groups of shrubs. On alluvial floodplains where floodplain soils and plant communities have been lost to large-scale geomorphological change, such a biotechnical approach can re-initiate topsoil development and succession within the native plant community.

2. Among interactions between channel and floodplain during flood flows, groups of flexible emergent shrubs hold great potential for calming overbank flows by breaking up turbulent flow structure into smaller eddy cells.

3. The Manning equation is not an effective analytic tool for predicting roughness on vegetated floodplains. This is in part because the model is based upon the logarthimic velocity profile, and in part because floodplain flow is not 1-dimensional.

4. This field research effort has confirmed theory developed in numerical modelling, that flow through a vegetated floodplain departs from the logarithmic velocity profile, and tends toward a more uniform vertical velocity distribution.

5. Linking field research with laboratory work holds great potential to progress geomorphic and hydraulic theory and practice when the laboratory work simulates specific field conditions. More specifically, fieldwork should precede laboratory work, in order to define more closely the conditions which are to be modelled in the flume.

6. Numerical models derived from flume studies without field data, such as the Tollner *et al* (1976) model, are not likely to provide useful tools for predicting floodplain sedimentation response to flood events.

8.2 Recommendations for further research

The research recommendations are summarised here by categories.

Relating the flume floodplain to field conditions

1. *Flume work scaled at 1:1 is needed to progress understanding of geomorphic processes.*

Field experimentation is needed with woody vegetation on the banks and floodplains for a range of stream conditions, constructed on the stream at the prototype scale of 1:1, where full-sized plants can be grown on banks and floodplains. This was the approach taken at the Stillwater Research Center in Kansas in the 1950s, where field-based laboratory research pioneered the use of grassed channels for sedimentation control. 1:1 scales flumes have been used in other efforts, in Kanazawa Japan for floodplain herbaceous annuals and in Vienna for testing soil bioengineering construction thresholds of failure.

A field-based laboratory programme using instrumented streams with controlled discharge is needed to quantify the effects of woody plants under varying life stage, stem growth characteristics, spacing between plant clumps, differing spatial arrangements and varying stem density.

Extending this research into the interactions between flows of channel and vegetated floodplain to non-straight reaches, meander bends and for morphologically diverse channels is also needed for design guidance. Many potential research sites have been recently created in the UK, for example in the Environment Agency Thames Region, where one of the key areas of conservation effort has been in revegetation of headlands on a river's inside meander bend (A. Driver, pers. comm, 1997). Several opportunities are arising from new directions

in UK forestry policy aimed at reforestation of floodplains (UK Forestry
Commission, verbal comm., 1997).

2.   *Progress an alternative to the Manning equation for flexible, woody
vegetation energy resistance.*

Research is needed to progress an alternative theoretical model to the Manning
equation, to predict floodplain vegetation friction or roughness. Because
hydrodynamic modelling is being used increasingly to progress river capital works
design, there will be greater application for expressing the effects of floodplain
vegetation in terms of energy friction rather than roughness (as is becoming more
common in European practice).

Based on the work of Smith *et al* (1990), a research programme is needed to
model flow through woody emergent floodplain vegetation, in order to develop the
coefficients *a, b* and *c* for the Darcy-Weisbach friction equation for a relevant
range of floodplain vegetation conditions. These would include extending the
range of values for non-submerged plants, for stems over a range of flexible
resistance, and for fully turbulent flow with Reynolds numbers in the range of 10^5-
10^6.

The number of potential parameter combinations is large, thus the research
programme should begin with a strategic plan to test for submerged versus
emergent, flexible versus rigid, grouped patterns versus random, for a range of
flows over a few different floodplain configurations. The work of Darby & Thorne
(1995) could be extended to guide prediction of various vegetation regimes on
stage-discharge relationships. This work could be progressed simultaneously with
investigation of the flexural resistivity of shrubby stems over a range of stage
heights, allowing for flow interactions between main channel and floodplain.

3.   *Model combinations of flexible and rigid emergent vegetation simulating
natural floodplain vegetation, allowing for channel-floodplain interactions.*

An exercise which combines the porous, flexible, vegetative structure with rigid
cylinders simulating floodplain trees would be very helpful in identifying the

hydraulic and geomorphic effects of various vegetation maintenance regimes, where both trees and shrubs are normally found, as in many natural floodplain river systems. Some agricultural models of buffer zones (Schultz *et al*, 1994, Figure 2.7) for pollution attenuation currently suggest the use of large trees at the channel margin, with shrubs at further distance from the channel, but the geomorphic consequences of this vegetation arrangement, for example in hydraulic resistance, sediment retention or flood stage downstream are unknown.

Understanding the nature and mechanics of the flow exchange between channel and vegetated floodplain would benefit from large-scale flume modelling using a porous, flexible filter medium to simulate shrubs, early seral stage riparian trees or the coppice method of bank maintenance, in addition to cylinders representing mature trees. The addition of suspended sediments would complicate greatly the analysis of flows, as well as the turbulent exchange among vegetated, non-vegetated and channel areas, but such analysis would increase predictive capability of the consequences of riparian and floodplain revegetation.

The potential variations among vegetation location, spacing and porosity are numerous. It would clearly be impractical to attempt quantitative measurement associated with each possible configuration. However, this research shows that patterns readily observable in the flume can be related to full-scale fluvial processes, to inform decisions over which configurations should be subject to flow measurement to meet specific project goals. Such configurations could attract the attention of flood defence engineers wanting to achieve attenuation of flood flows on the floodplain without having to construct levees, especially as multi-objective planning for ecosystem protection becomes grounded in institutional policies. Developing this work in the laboratory will accelerate the time and minimise the resources needed to identify useful hydraulic effects of various vegetation patterns. However, the geomorphic context for 'real-world' conditions must be kept closely in mind while developing hydraulic simulations in the laboratory.

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4.   *Progress the problem of flow through a porous filter with eddy shedding,*
linking the flume architecture with field conditions.

The study of flow wake re-entrainment around single and multiple stems could greatly progress the technical design specifications needed to bring soil bioengineering to the civil engineer, and revegetation to streambanks and floodplains with public safety in view. By testing the hydraulic effects of various 'vegetative structure' spacing configurations and by using flow visualisation to observe resulting flow structures, better quantitative methods of prediction could be developed for the consequences of soil bioengineering and other revegetation approaches. Soil bioengineering methods are labour-intensive, therefore any technical progress to reduce the number of structures needed to achieve design goals, improves the cost-effectiveness and implementability of these methods. Earlier efforts to model flow through flexible vegetation were hampered by neglecting the dimension of channel – floodplain open flows in the flume architecture (Thompson & Roberson, 1976). Because of the hydraulics of backwater effects around the vegetated zone, the flume must allow for flow through non-vegetated areas (Naot *et al*, 1996).

Investigations will be needed to progress the findings from flume research, relating a variety of fluvial conditions to theoretical models to test the limits of geomorphic thresholds influenced by vegetation. Recalling the findings in Section 6.4.2, channel and baffle construction widths analysis, the vegetative buffer should be no less wide than the low-flow channel width, and be wide enough to accommodate the potential width for channel lateral erosion on a floodplain. Because of the intense eddy shedding from the baffle at the channel-floodplain margin, the flume wide enough to permit this momentum exchange without interference from wall effects is needed to simulate field conditions.

The flume visualisation and flow metering was not able to detect a wake re-entrainment downstream of even a single baffle, perhaps because the flume was too narrow relative to the channel, floodplain and baffle widths. While baffle width

may be a critical parameter in the design of siltation baffles, the hydraulic 'calming' response of a baffle extends much further than has heretofore been suspected or determined. Indications from the flume study suggest that the hydraulic distance for wake re-entrainment downstream of a flexible, emergent, porous vegetative filter may be an order of magnitude greater than the width of the obstruction. In the field, experimental construction of shrub forms of woody vegetation are needed to investigate longer baffle structures normal to flow spaced at greater intervals, with and without a riparian fringe of woody vegetation.

Topics in floodplain and streambank sediment deposition influenced by woody vegetation

5.   Develop a geomorphic approach to prediction of the effects of a shrub buffer on floodplain sedimentation.

Better models are needed to predict the sediment trapping efficiency of shrubby, emergent plants in various configurations, some of which should mimic natural plant recruitment patterns to the greatest extent possible. To progress research in this field, flume flow are needed which support Reynolds numbers in the range of 10^4 -10^5. A regional basis for these criteria is logical, to reflect the climate, geomorphology and thresholds for plant community ecology on floodplains.

The use of a framework or classification scheme could assist in identifying the channel floodplain dimensions, following a floodplain classification scheme such as that by Nanson & Croke (1992). At a regional or national scale, a geomorphic river and floodplain classification system could provide a logical assessment framework of physical conditions, as an aid to prioritise streambank and floodplain revegetation efforts. Within that context, linking the assessment criteria with project design and monitoring will enable a cost-effective research programme to progress criteria for success or failure. Such a research programme could greatly inform a regional river vegetation management strategy for river managers working in national institutions such as the UK Environment Agency and the US Army Corps of Engineers. A regional agency is best situated to inform management

guidelines for local riparian owners in large countries, whose needs may not be met by research which is national in scope.

A wide range of shrub genera such as *Salix, Rosa, Sambucus, Prunus* tend to maintain a branched network of stems up to and above 1m in height. These plants have very high wildlife habitat and biodiversity values, and can be brought into modern river management for criteria such as flood defence, by more detailed hydraulic consideration of patterns of placement which allow for shrub growth on the floodplain. Research can progress by working with operations and maintenance agencies to reduce management costs while increasing ecological and hydraulic benefits. Although the coppice method is simple in concept, its potential applications are extensive, and considered by this author worthy of inclusion in geomorphic and ecological field research. Research investigation into the operations of farms practising floodplain vegetation management is now possible, beginning with Long Ashton IACR research station, Bristol, who have links to private farms in the UK and Europe.

6.   Refine models of vegetation influence on sedimentation, to account for the retention of very fine particles.

Based on the findings of this objective of the present research programme, available models for predicting sedimentation resulting from flow through flexible, emergent woody vegetation do not predict accurately the capability of shrubby vegetative structures to induce deposition of very fine suspended sediments during overbank flow. The fact that approximately 30% of the sediments measured in the Mattole floodplain sediments after an annual flood were clay was not predicted by any available models.

One of the features observed during the flood which is not accounted for in the sedimentation model is the role of the emergent flexible stem to absorb momentum energy and induce turbulence in a flowing water column carrying sediments smaller than 0.1mm. This feature of riparian plants is so fundamental to the nature of

streamside vegetation, and the implications for anadromous fish spawning habitat so profound, that there is a pressing need for this feature to be addressed in sedimentation modelling. An approach to modelling floodplain vegetation effects on overbank flow and resulting sedimentation could use geomorphic responses to floodplain retention of sediments as a function of floodplain topography, local slope, flow depth, vegetation density, areal cover and degree of vegetation flexibility.

7. *Develop a theoretical framework for evaluation of revegetation projects against hydraulic and geomorphic criteria.*

In current practice, no theoretical framework exists against which performance of streambank and floodplain revegetation projects can be evaluated in a systematic fashion. Institutionally, the need for routinely funding adequate assessment and monitoring has not yet been widely recognised.

Quantifying the effects of flexible emergent woody vegetation on boundary shear stress is challenged by a lack of theoretical models to predict flow behaviour through a porous vegetative filter. Leopold *et al* (1964, p.160) relate bed friction resistance $(1/\sqrt{f})$ to a ratio of flow depth to bed particle size (D/d_{84}) to express resistance as a function of the relation between flow depth and roughness height. For gravel bed rivers instream, this relation holds well. For floodplains vegetated with shrubs taller than the water column, the 'roughness height' parameter is insufficient to characterise the increased resistance exerted on flow velocity by dense flexible stems.

Better understanding is needed of the theoretical relationships among flow depth, velocity, flexible emergent woody vegetation and shear stress based on co-ordinated field and laboratory research. A large number of data sets will also be needed to segregate the large number of variables involved across widely varying conditions. A standardised methodology, as yet lacking, is needed to calculate boundary shear stress for vegetated banks and floodplains, so that findings are

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comparable. As a research objective for hydraulic engineering, this is an achievable goal once the research question has been framed. This 'vegetative boundary shear stress' methodology should be widely applied in field practice, much as the range of Manning's n values have been developed for a wide range of field conditions. Once a solid theoretical foundation has been laid, structural uses of vegetation in river and hillslope engineering practices may progress technically with much greater speed.

This methodology could then be applied within the regional research strategy suggested in Section 8.2, for the substantial number of streambank, floodplain and hillslope revegetation methods developed within the soil bioengineering discipline. Only by being able to identify the thresholds of resistance (shear stress) and potential failure in this way will give civil engineers sufficient confidence to rely on these 'soft engineering' methods, to the extent that questions of project liability can be more fairly assessed.

8.   Eco-geomorphic research is needed to progress the potential benefits from mycorrhizal associations of floodplain revegetation projects.
The use of mycorrhizae in other fields of restoration ecological practice is gaining wide acceptance. Collaborative research with engineers and mycologists could progress understanding of the role of soils and mycorrhizal fungal association for floodplain revegetation projects. Much scope exists to advance revegetation technology through this synthesis, improving plant survival rates and biodiversity values for restored floodplains. These relationships may be critical to the successful recruitment of riparian plants on more challenged sites, such as streams flowing out of old mining operations.

8.3   Conclusions

From a comparison of current theoretical modelling, flume research and the field data from this thesis, much more remains to be learned about the complex physical nature of the relationships among woody vegetation, flooding and sedimentation. This research demonstrates that the interactions of the living, physical dimensions of habitat resources with the floodplain overbank flow and sediment processes, call for detailed understanding of the dynamics of physical and biological processes from catchment- to local -scales.

Accurate understanding of floodplain processes and resources will progress through an iterative dialogue among fluvial geomorphologists, hydraulic engineers, botanists, ecologists, horticulturists and others to improve theoretical models and practice. Far more field data are needed to inform this dialogue and calibrate working models to improve their predictive capability. Applying such models improves our ability to rehabilitate and manage river ecosystems in support of those complex, multiple functions on which ecosystem functions and ecosystem health depend. However, we should continue to develop adaptive management strategies (of flexible solutions to river restoration, for example), because this strategy allows us to progress toward landscape sustainability.

Rehabilitated floodplain and streamside plant communities have much to contribute to modern river management, not least by adding beauty where development has dominated our most natural landscapes. If this work is successful, our children and their children may have a few reasons to be thankful that we found the courage to change our relationship to Nature, by being faithful to natural processes.

N.C. Perala-Gardiner

7 December 1999

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Appendix A:

Field data on sediment depths deposited from

the flood of 8 Dec 1993

Appendix A

Bafl1	TR1	TR2	TR3	TR4	TR5	Transect perpendicular TR6	to baffle 1
	0.09	0.07	0.13	0.07	0.03	0.12	upstream
	0.09	0.09	0.10	0.06	0.09	0.12	
	0.09	0.09	0.12	0.07	0.08	0.11	
	0.14	0.09	0.12	0.09	0.10	0.10	
	0.17	0.15	0.16	0.16	0.13	0.10	
	0.14	0.16	0.13	0.16	0.13	0.06	
	0.20	0.19	0.15	0.18	0.06	0.05	
	0.25	0.12	0.17	0.16	0.12	0.05	
	0.17	0.14	0.14	0.18	0.13	0.07	
	0.23	0.17	0.13	0.16	0.08	0.03	
	0.21	0.14	0.13	0.13	0.07	0.05	
	0.16	0.13	0.12	0.14	0.06	0.05	
	0.12	0.10	0.14	0.06	0.02	0.06	
	0.18	0.12	0.11	0.03		0.04	
	0.12	0.12	0.16	0.06		0.03	
	0.11	0.13	0.13	0.05		0.05	
	0.16	0.14	0.06			0.05	
	0.16	0.09	0.05			0.08	
	0.11	0.03	0.02			0.11	
	0.15					0.09	
	0.12					0.09	
	0.16					0.10	0.11
	0.10					0.05	0.09
	0.09					0.07	0.05
	0.10					0.06	0.11
	0.16					0.07	0.08
	0.21					0.05	0.06
	0.20					0.09	0.03
	0.23					0.08	0.01
	0.41	0.35					

Prepared by N.C. Perala,

Appendix A

TR22	TR21	TR20	TR19	bafl 2	TR13	TR14	TR15	TR16	TR17	TR18	TR9	TR8	TR7
0.02	0.00	0.04	0.00		0.02	0.02	0.02	0.03	0.06	0.03	0.02	0.07	0.02
0.06	0.03	0.03	0.04		0.11	0.03	0.09	0.02	0.06	0.07	0.02	0.09	0.12
0.07	0.05	0.02	0.07		0.15	0.10	0.09	0.06	0.03	0.15	0.08	0.13	0.16
0.09	0.03	0.06	0.08		0.11	0.12	0.08	0.12	0.11	0.15	0.10	0.10	0.14
0.10	0.06	0.12	0.12		0.11	0.09	0.07	0.10	0.12	0.12	0.10	0.12	0.16
0.07	0.05	0.12	0.15		0.11	0.13	0.09	0.09	0.08	0.11	0.10	0.14	0.17
0.09	0.09	0.09	0.09		0.15	0.11	0.11	0.13	0.15	0.12	0.10	0.12	0.15
0.12	0.04	0.06	0.12		0.27	0.12	0.13	0.15	0.07	0.14	0.10	0.12	0.09
0.04	0.04	0.05	0.05		0.30	0.08	0.10	0.15	0.10	0.03	0.12	0.09	0.17
0.00	0.02	0.02	0.03		0.55	0.15	0.08	0.03	0.07	0.03	0.02	0.09	0.12
0.04	0.00	0.02	0.02		0.49	0.16	0.03	0.03	0.03	0.03	0.03	0.07	0.13
0.00	0.02	0.00	0.00		0.26	0.00	0.00	0.03	0.03	0.00	0.01	0.03	0.11
					0.26						0.04	0.05	0.11
											0.01	0.01	0.07
													0.03
													0.05
													0.01

Prepared by N.C. Perala,

Appendix A

Bafl 4	TR34	TR33	TR32	TR31	TR30	TR29	TR28	TR27	TR26	Bafl 3	TR25	TR24	TR23
	0.03	0.02	c	0.02	0.00	c	0.02	c	c		0.02	0.02	0.00
	0.09	0.01	c	0.02	0.01	0.03	0.02	c	c		0.04	0.05	0.02
	0.06	0.01	0.03	0.01	0.01	0.02	0.01	0.04	c		0.15	0.03	0.02
	0.01	0.02	0.03	0.02	0.05	0.04	0.04	0.05	0.05		0.21	0.02	0.02
	c	0.01	0.02	0.02	0.06	0.05	0.06	0.05	0.06		0.10	0.03	0.05
	c	c	0.03	0.08	0.08	0.04	0.06	0.04	0.05		0.08	0.05	0.05
	0.11	0.06	0.02	0.09	0.08	0.05	0.09	0.07	0.06		0.03	0.03	0.02
	0.11	0.05	0.06	0.06	0.13	0.15	0.11	0.07	0.08		0.07	0.05	0.02
	0.15	0.11	0.13	0.17	0.21	0.15	0.18	0.17	0.09		0.12	0.02	0.04
	0.30	0.09	0.09	0.06	0.14	0.14	0.15	0.17	0.10		0.04	0.00	0.00
	0.09	0.21	0.13	0.03	0.23	0.09	0.10	0.12	0.11		0.02	0.02	0.00
	0.00	c	c	c	0.21	0.15	0.01	0.02	0.15		0.02	0.00	0.00
	0.00	c	c	c	0.05	0.03	0.04	0.03	0.12				
		c	c	c	0.02	0.00	0.02	c	0.05				
							0.02		0.02				

Prepared by N.C. Perala,

Bafl 6	TR44	TR43	TR42	TR41	TR40	BAfl 5	TR39	TR38	TR37	TR36	TR35
	0.00	c	0.02	c	0.02		c	0.00	0.02	0.02	0.02
	0.04	c	0.01	0.01	0.01		c	0.01	0.03	0.02	0.06
	0.02	0.03	0.01	c	0.04		c	0.00	0.01	0.03	0.07
	c	0.01	0.03	0.02	0.07		c	c	0.01	0.08	0.09
	0.01	0.02	0.07	0.03	0.10		0.02	0.01	0.05	0.02	0.10
	c	0.06	0.05	0.02	0.17		c	c	0.09	0.04	0.13
	0.03	0.05	0.07	0.05	0.08		c	c	0.05	0.05	0.03
	0.04	0.14	0.09	0.08	0.07		0.03	0.02	0.07	0.06	0.08
	0.03	0.05	0.15	0.07	c		0.10	0.05	0.18	0.12	0.10
	c	0.05	0.09	0.03	c		0.13	0.00	0.02	0.10	0.03
	c	0.05	0.06	0.05	c		0.05	0.01	0.03	0.03	0.10
	c	0.08	0.06	0.02	c		0.05	c	c	c	c
	0.00	c	c	c	c		c	c	c	c	c
			c				c	c			

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Appendix A

Bafl 8	TR55	TR54	TR53	TR52	TR51	BAfl 7	TR50	TR49	TR48	TR47	TR46	TR45
	d	c	c	c	c		0.06	c	c	c	c	0.02
	d	c	0.02	0.02	0.02		0.08	0.05	0.05	0.01	c	0.01
	d	c	0.03	c	0.06		0.09	0.02	0.04	0.04	0.02	0.02
0.02	c	0.03	0.06	0.09			0.15	c	0.03	0.04	0.01	0.03
0.02	0.01	0.02	0.12	0.06			0.15	0.02	0.06	0.01	0.04	0.03
0.21	0.05	0.08	0.13	0.08			0.13	0.02	0.06	0.04	0.03	0.05
0.04	0.12	0.15	0.21	0.23			0.19	0.03	0.08	0.06	0.04	0.14
0.02	0.15	0.20	0.23	0.14			0.23	0.09	0.09	0.05	0.09	0.01
0.09	0.04	0.16	0.14	0.21			0.18	0.12	0.09	0.05	0.06	0.11
0.09	0.03	0.11	0.08	0.19			0.18	0.15	0.23	0.09	0.03	0.10
0.22	0.02	0.03	0.02	0.10			0.09	0.11	0.20	0.06	0.01	0.07
0.11	c	0.01	c	0.03			0.09	0.06	0.12	0.01	c	c
0.12	c	c	c	c			c	0.02	0.03	c	c	c
c			c	c			c	c	c			

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Appendix A

Mattole baffle sediment depths for flood Dec 1994 by transect in m.							Laid out for mapping					
TR66	TR65	Bafl 10	TR64	TR63	TR62	TR61	Bafl 9	TR60	TR59	TR58	TR57	TR56
0.05	c		0.00	0.05	0.03	0.02		0.01	c	c	0.01	c
0.03	0.03		0.01	0.06	0.03	0.02		0.02	0.02	c	0.01	c
0.03	0.03		0.08	0.04	0.05	0.02		0.02	0.01	c	c	0.01
0.03	0.03		0.05	0.02	0.03	0.05		c	c	c	0.01	0.03
0.09	0.06		0.02	0.02	0.06	0.03		c	c	c	0.02	0.14
0.12	0.09		0.11	0.10	0.11	0.11		c	c	0.07	0.08	0.10
0.22	0.07		0.20	0.16	0.17	0.16		0.06	c	0.05	0.19	0.22
0.43	0.35		0.24	0.20	0.19	0.15		0.04	0.08	0.04	0.24	0.22
0.55	0.20		0.27	0.21	0.21	0.20		0.13	0.04	0.29	0.24	0.29
0.05	0.34		0.27	0.14	0.23	0.23		0.20	0.05	0.29	0.27	0.22
0.23	0.55		0.03	0.11	0.26	0.26		0.24	0.10	0.12	0.16	0.07
0.09	0.21		0.21	0.05	0.12	0.17		0.11	0.09	0.03	0.03	0.02
0.03	0.15		0.11	c	0.03	0.19		0.19	c	c	c	c
0.01	0.11				river	river		0.03				
c		down						c				
		stream										
		west end										
		study										
		site										
c = cobble												
d = debris												

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Appendix B:

Raw metric velocity data from flood of Jan 1995

Appendix B:
Velocity Profile Raw Data

Profile # 3		Near channel on cobble substrate 100 ft. upstream of baffle #1								
Depth							average	av velocity		
m	# revs/min	# revs/min	# revs/min				no.revs	m/s		
0.02	98	94					96.0	0.49	n = 32	
0.03	129	125					127.0	0.65		
0.05	141	141					141.0	0.72		
0.06	158	156					157.0	0.80		
0.08	197	182					189.5	0.96		
0.09	189	179					184.0	0.93		
0.11	180	184					182.0	0.92		
0.12	206	207					206.5	1.05	meter	
0.15	241	220					230.5	1.17	capacity	
0.18	230	221	226				225.7	1.15	exceeded	
0.21	258	259					258.5	1.31		
0.24	265						265	1.35		
0.27	269						269	1.37		
0.30	288						288	1.46		
0.34	289						289	1.47		
0.37	300						300	1.52		
0.40	300						300	1.52		
0.43	311						311	1.58		
0.46	305						305	1.55		
0.49	320						320	1.63		
0.52		choppy waves breaking surface								
6/10 depth average =								1.46		

Profile # 4		Near channel on vegetated substrate between baffle #2 & #3								
Depth							average	av velocity		
m	# revs/min	# revs/min	# revs/min	# revs/m	# revs/min		no.revs	m/s		
0.02	10	16	12				12.7	0.07	n = 51	
0.03	13	19	22	29			20.8	0.11		
0.05	30	30					30.0	0.16		
0.06	28	29					28.5	0.16		
0.08	38	34	48	52			43.0	0.23		
0.09	48	46	54	62	52		52.4	0.29		
0.11	66	53	79	78			69.0	0.38		
0.12	89	92	94				91.7	0.50		
0.15	102	102					102.0	0.56		
0.18	112	113					112.5	0.61		
0.21	125	124					124.5	0.68		
0.24	131	122					126.5	0.69		
0.27	130	120	126				125.3	0.68		
0.30	114	112	111				112.3	0.61		
0.34	105						105.0	0.57		
0.37	90	95					92.5	0.51		
0.40	86						86.0	0.47		
0.43	70	88					79.0	0.43		
0.46	84	82					83.0	0.45		
0.49	87						87.0	0.48		
0.52	90						90.0	0.49		
6/10 depth average =								0.61		

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Profile #1			Cobble substrate upstream of baffle #1							
Depth							average	av velocity		
m	# revs/m	# revs/m	# revs/m	# revs/m	# revs/m	# revs/m	no.revs	m/s		
0.02	95	93	94	78	84	80	87.33	0.44	n = 38	
0.03	130	113	107	110	107	130	116.17	0.59		
0.05	140	98	120	124	111		118.60	0.60		
0.06	150	132	100	150	136	128	132.67	0.67		
0.08	132	133	130				131.67	0.67		
0.09	139	132					135.50	0.69		
0.12	164	155					159.50	0.81		
0.15	170						170.00	0.86		
0.18	182						182.00	0.92		
0.21	200						200.00	1.02		
0.24	221						221.00	1.12		
0.27	185						185.00	0.94	meter	
0.30	188						188.00	0.96	capacity	
0.37	205						205.00	1.04	exceeded	
0.43	203						203.00	1.03		
6/10 depth average =								1.10		

Profile # 2			Vegetated substrate between baffle #3 & #4							
Depth	# revs/min	# revs/min					average	av velocity		
m.							no.revs	m/s		
0.02	44	49					46.5	0.24	n=18	
0.03	53	49					51	0.26		
0.05	60	64					62	0.31		
0.06	72						72	0.37		
0.08	74						74	0.38		
0.09	58	63					60.5	0.31		
0.12	63						63	0.32		
0.15	60						60	0.30		
0.18	59						59	0.30		
0.24	66						66	0.34		
0.30	72						72	0.37		
0.37	84						84	0.43		
0.43	85						85	0.43		
0.49	85						85	0.43		
6/10 depth average =								0.36		

Appendix C:.

Computation results of the

Tollner *et al* (1976) model

Model of Sediment Filtration Capacity:

where coefficients A, b, c are from the Tollner model shown, contrasted with three sets of coefficient variables

	Tollner	Coefs 1	Coefs 2	Coefs 3
A=	-1.05E-03	-5.00E-03	-5.00E-02	-5.00E-02
b=	0.82	0.6	0.4	0.2
c=	-0.91	-0.7	-0.5	-0.3

$$\frac{Si - So}{Si} = EXP \{ A * R_{eT}{}^{b} * N_{f}{}^{c} \}$$

$$A \ldots\ldots Term \ B \ldots\ldots Term \ C$$

Calculation of Sediment Filtration Capacity of Baffles using Tollner et al model:

Term B	Tollner	Cf 1 = 0.6	Cf 2 = 0.4	Cf 3 = 0.2
high	474.808	90.872	20.212	4.496
med	154.890	40.037	11.703	3.421
low	35.941	13.748	5.739	2.396

Term C	Tollner	Cf 1 = -0.7	Cf 2 = -0.5	Cf 3 = -0.3
high	0.0046	0.0159	0.0518	0.1693
med	0.0865	0.1522	0.2606	0.4463
low	1.6122	1.4439	1.3001	1.1705

Fraction of Sediment Trapped when total length = 100m.

	Tollner coeffs	Coeffs 1	Coeffs 2	Coeffs 3
sand	1.001	0.993	0.949	0.963
fsand, csilt	0.986	0.970	0.859	0.927
fine silt+clay	0.941	0.906	0.689	0.869

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Appendix C: Analysis of sediment filtration capacity of Mattole Baffles

N_f = particle fall number		sand	max =	372.22						
(dimensionless)		fine sand	med 1=	14.72		$N_f = \dfrac{L_T\,V_m}{d_f\,V_s}$				
		silt	med 2=	0.59						
		clay	min =	0.42						
Calculation of Rs spacing hydraulic radius :										
Spacing between stems in the Mattole baffles Ss:						flow depth				
	Ss max=	1.5	cm	0.015	m	df =	max	0.18	m
	Ss med=	0.5	cm	0.005	m		med	0.12	m
	Ss min =	0.125	cm	0.00125	m		min	0.06	m
		Rs max =		0.0072	m				
		Rs med=		0.0024	m	$R_s = \dfrac{S_s * d_f}{S_s + 2d_f}$			
		Rs min =		0.0006	m				
		df =	max	0.18	m				
			med	0.12	m				
			min	0.06	m				
Calculation of Turbulent Reynolds Number ReT :									
max flow velocity	0.40	m/s		ReT max	1836.73				
mean flow velocity	0.30	m/s		ReT med	468.55	$R_{eT} = \dfrac{V_s\,R_s}{\upsilon}$			
min flow velocity	0.20	m/s		ReT min	78.90				
Dynamic viscosity mu =	at 8C	0.001402	kinvisc nu=	1.57E-06					
datum from Gordon et al, 1992 p.7-9	density rho	999.8							

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Sediment Filtration Capacity of Live Siltation Baffles						Mattole Estuary conditions from flood of 9 Dec. 93			
based on	model by Tollner, Barfield, Haan & Kao, 1976								
This model estimates the percentage of sediment trapped as a function						$\dfrac{S_i - S_o}{S_i}$			
of the ratio between sediment inflow and outflow.									
The probability of trapping is a function of particle fall number						$P(trapping) = \theta_1 (N_f)$			
influenced by the potential number of times a particle could fall to the bottom									
as it travels through the test section,									
				and some turbulence index.		$P(trapping) = \theta_2 \left(\dfrac{1}{T}\right)$			
Therefore, the trapping efficiency is a function of particle fall number and turbulence.									
						$\dfrac{Si - So}{Si} = \theta_3 \left(N_f, \dfrac{1}{T}\right)$			
Parameters used in equations:					units				
S=slope				S=	0.002				
Q= flow rate (cumecs)				Q =	625	m3/s			
L_T = distance between baffles				L_T =	100.00	m	changed from 9m		
d_f = depth of flow	df =	0.06		0.12	0.18	m			
R_s = spacing hydraulic radius									
Vs = mean flow velocity		computed		0.12	0.30	observed	m/sec	$R_s = \dfrac{S_s * d_f}{S_s + 2d_f}$	
S_s = section spacing of media				0.5	2	cm			
V_m = particle settling velocity in cm/sec at 5 deg. C									
				high	low	Ptx fall velocity data are from Gibbs, et al, 1971.			
sand	2 > x > 0.1 mm		V_m =	0.2680	0.0150	m/s			
silt	0.099 > x > 0.01 mm			0.0053	0.0001	m/s		df =	0.183	m
clay	0.009 mm > x			0.0001		m/s			

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Appendix C: Back-calculation of the suspended sediment concentration and filtration efficiency

Estimate of sediment trap efficiency based on back-calculation of flow and suspended sediment									
based on a model by Tollner, et al, 1976 for non-submerged flow									
	$Q=V*A*time$	Time		**Suspended sediment concentrations**					
Entire baffle	Q (vol)	duration		100ppm	500ppm	1000ppm	5000ppm	10,000ppm	
area A(m2)/m	m3	sec		$Q_{sed100ppm}$	$Q_{sed500ppm}$	$Q_{sed1000ppm}$	$Q_{sed5,000ppm}$	$Q_{sed10,000ppm}$	
0.16	81.75	7200		0.01	0.04	0.08	0.41	0.82	
0.33	267.85	7200		0.03	0.13	0.27	1.34	2.68	
0.49	580.87	7200		0.06	0.29	0.58	2.90	5.81	
0.66	735.77	7200		0.07	0.37	0.74	3.68	7.36	
0.82	1387.63	7200		0.14	0.69	1.39	6.94	13.88	
0.98	1014.59	3600		0.10	0.51	1.01	5.07	10.15	
1.15	1558.67	3600		0.16	0.78	1.56	7.79	15.59	
1.31	2366.51	3600		0.24	1.18	2.37	11.83	23.67	
1.64	3291.60	3600		0.33	1.65	3.29	16.46	32.92	
1.97	4356.53	3600		0.44	2.18	4.36	21.78	43.57	
total for 1 baffle=	15641.75	54000		1.56	7.82	15.64	78.21	156.42	m3/m run of baffle
Number of baffles		10		**Total volume of sediment available for deposition**					
Length of baffle area		150	m.	234.63	1173.13	2346.26	11731.32	23462.63	
Volume of sediment measured over entire area				85.5	m3				
Est'd min. sediment concentration in overbank flow for 15 hours needed to deposit 85.5m3 volume of sediment								<100ppm	
Est'd filtration efficiency				100ppm	500ppm	1000ppm	5000ppm		
				0.36	**0.07**	**0.04**	**0.01**		
									*

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Appendix D:

Computation results of the

Petryk & Bosmajian (1975) model

Appendix D: Analysis of baffle roughness after Petryk and Bosmajian (1975)

Analysis of Roughness separating vegetation and channel boundary						Q =	22,000	cfs	622.6	cms
after Petryk and Bosmajian, 1975							32,000	cfs	905.6	cms
							62,000	cfs	1754.6	cms
Change width/ area to compute change in roughness										
Formula element	**Abbrev.**	**Value**	**Unit**	**Value**	**Unit**					
specific wt. water (gamma)	gamma	9804.06	N/m3	62.4	lb/ft3					
average width of baffle	w	10.38	m	32	ft.					
water depth	d_{min}	0.33	m	1.02	ft.	at Q=622cms				
	d_{avg}	0.56	m	1.7	ft.	at Q=905cms				
	d_{max}	0.75	m	2.3	ft.	at Q=1754cms				
cross-sectional area of flow (=w*d)	A_{min}	3.47	m^2	32.64	ft^2	at Q=622cms				
	A_{avg}	5.79	m^2	54.4	ft^2	at Q=905cms				
	A_{max}	7.83	m^2	73.6	ft^2	at Q=1754cms				
length of channel reach	L	178.34	m	550	ft.	length of 1baffle+spac	13.72	m		
wetted perimeter	P_{min}	10.10	m	30.8	ft.	at Q=622cms				
	P_{avg}	10.89	m	33.2	ft.	at Q=905cms				
	P_{max}	11.29	m	34.4	ft.	at Q=1754cms				
hydraulic radius (R=A/P)	R_{min}	0.34	m	1.06	ft.	at Q=622cms				
	R_{avg}	0.53	m	1.64	ft.	at Q=905cms				
	R_{max}	0.69	m	2.14	ft.	at Q=1754cms	Avrg V			
approach velocity for ith plant	$V_{i\,min}$	0.31	m/s	0.95	ft/s	at Q=622cms		1.10	m/s	
	$V_{i\,avg}$	0.35	m/s	1.33	ft/s	at Q=905cms		1.45	m/s	
no estimate for Vi at Q=1754cms						at Q=1754cms				

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Appendix D: Analysis of baffle roughness after Petryk and Bosmajian (1975)

projected area of ith plant in x direction	$A_{i\ min}$	0.005	m^2	0.085	ft^2	min stem width m	0.015	
average projected area of ith plant	$A_{i\ avg}$	0.014	m^2	0.136	ft^2	avrg stem width m	0.025	
maximum	$A_{i\ max}$	0.026	m^2	0.213	ft^2	max stem width m	0.035	
drag coefficient on ith plant	C_{dmin}	0.0073	average	at Q=622cms				
calculated on dragcoefficient spreadsheet	C_{davg}	0.0075	average	at Q=905cms				
drag coefficient for veg (Petryk et al)	C_d	~ 1.0						
gravitational constant	g	9.807	m/s^2					
gamma again	gamma =	9804.057	kg/m/s2	gamma=rho*g		gamma= 999.7kg/m3 * 9.807m/s2		
Shear force/unit area on channel bdry						P/A	P/A^1/3	
for unvegetated channel boundary	Tao low =	3.903	N/m^2	hand-calc'd est.s		3.806	2.910	1.428
	Tao high =	10.060	N/m^2	same numbers		10.286	1.882	1.235

$$\ldots\ldots \tau_\omega = \gamma * V^2 * (\frac{nb}{1.0})^2 * (\frac{P}{A})^{\frac{1}{3}}$$

stem density		9.4	stems/m	300	# stems/ baffle			
energy gradient (surveyed water slope)	S_e	0.002	(0.93ft./390ft.)					
Manning's roughness due to bdry	n_b	0.058						
estimated using Cowan (Chow 1959, p 109)	**0.058**	n_{b_Cowan}	n0=0.028	n1=0.01	n2=0.003	n3=0.012	n4=0.005	m5=1.0
n=(n0+n1+n2+n3+n4)m5								

				Non-veg				
Eq.1 Conventional Manning's n Formula	Channel			Depth (m)	Avrg	velocity		hand calc'd
$..V = (\frac{1}{n}) * R^{2/3} * S_e^{1/2}$	n =	n_{max_Manni}	**0.020**	0.244	V@Q622	1.105	m/s	**0.026**
		n_{avg_Mannir}	**0.016**	0.305	V@Q904	1.351	m/s	**0.016**

These estimates of bed roughness are calculated from velocity profiles with no vegetation influence.

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Appendix D: Analysis of baffle roughness after Petryk and Bosmajian (1975)

Eq.2 Vegetation area factor Vaf	Ai * 300 stems/bafl * 10 baffles			Length =	178	m.	$R^{2/3}$	
$$\dfrac{Cd\Sigma Ai}{2gAL}=$$	Sum A_i min	1.506	Vaf =	0.00161	g=	9.807 m/s^2	0.0394	
	Sum A_i avg	4.183		0.00269	Area A=	2.25 m^2	0.0941	
	Sum A_i max	7.923		0.00376			0.1604	

Eq.3: Separation of veg roughness from bedform roughness		based on Cowan's n for bed		based on calc'd Manning n for bed		R = depth	
$$n = n_b\sqrt{1+\dfrac{C_d\Sigma A_i}{2gAL}(\dfrac{1}{n_b})^2 R^{\frac{4}{3}}}$$	n =	**0.061** min	**0.025** min	**0.028** min	$R^{4/3}$	0.2373
		0.067 avrg	**0.037** avrg	**0.039** avrg	avrg $R^{4/3}$	0.4181
		0.075 max	**0.050** max	**0.052** max	max $R^{4/3}$	0.5979
	nb =	0.058	nb= 0.015	nb= 0.020		

Total n for baffles from Manning's eqn =	**0.025** min	at flow depth = 0.33m, average velocity = 1.10m/s
Roughness calc'd from velocity profiles	**0.047** avrg	at flow depth = 0.56m, average velocity = 1.35m/s
with vegetation influence	**0.075** max	at flow depth = 0.75m. no measurement for flow at this depth

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Appendix E:

Computation of flume dimensional analysis

and target Froude numbers

Appendix E: Computation of flume dimensions from Mattole field data

Comparison of Mattole baffles (prototype) with Imperial College Civil Engineering flume model scales						
Flume LxWxD = 12150mm x 7600mm x 4500mm					all data in mm	
Scale ratios	Horizontal	50:1	Vertical	10:1		
Parameter	Prototype	max	Model		Vary Model	
Length	75000		1500			
Total channel + FP width	40000		800			
Baffle width (length)	10000		200		250	300
Baffle thickness	300		6			
Spacing betwn baffles	15000		300			
Baffle height	1500		150		100	
Flow depth	500	1000	50		100	
average Froude number						
upstream of baffles	0.650	0.472	0.650			
within baffles	0.117	0.163	0.117			
Av. Velocity u.s.baffles mm/s	1000	2150	18		d=100	
Av. Velocity in baffles mm/s	400	400	8			
Av. Velocity u.s.baffles m/s		2.15				
Av. Velocity in baffles m/s		0.40				
$Fr = \dfrac{v^2}{gL}$						
Slope	0.002		0.00			

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Appendix F:

Photographs

Photo 4.1. Flood waters approach bankfull stage near the Petrolia gauging station at river km 10.4, looking upriver, 7 Jan 1995. Stage is approximately Q = 540m^{3}s.
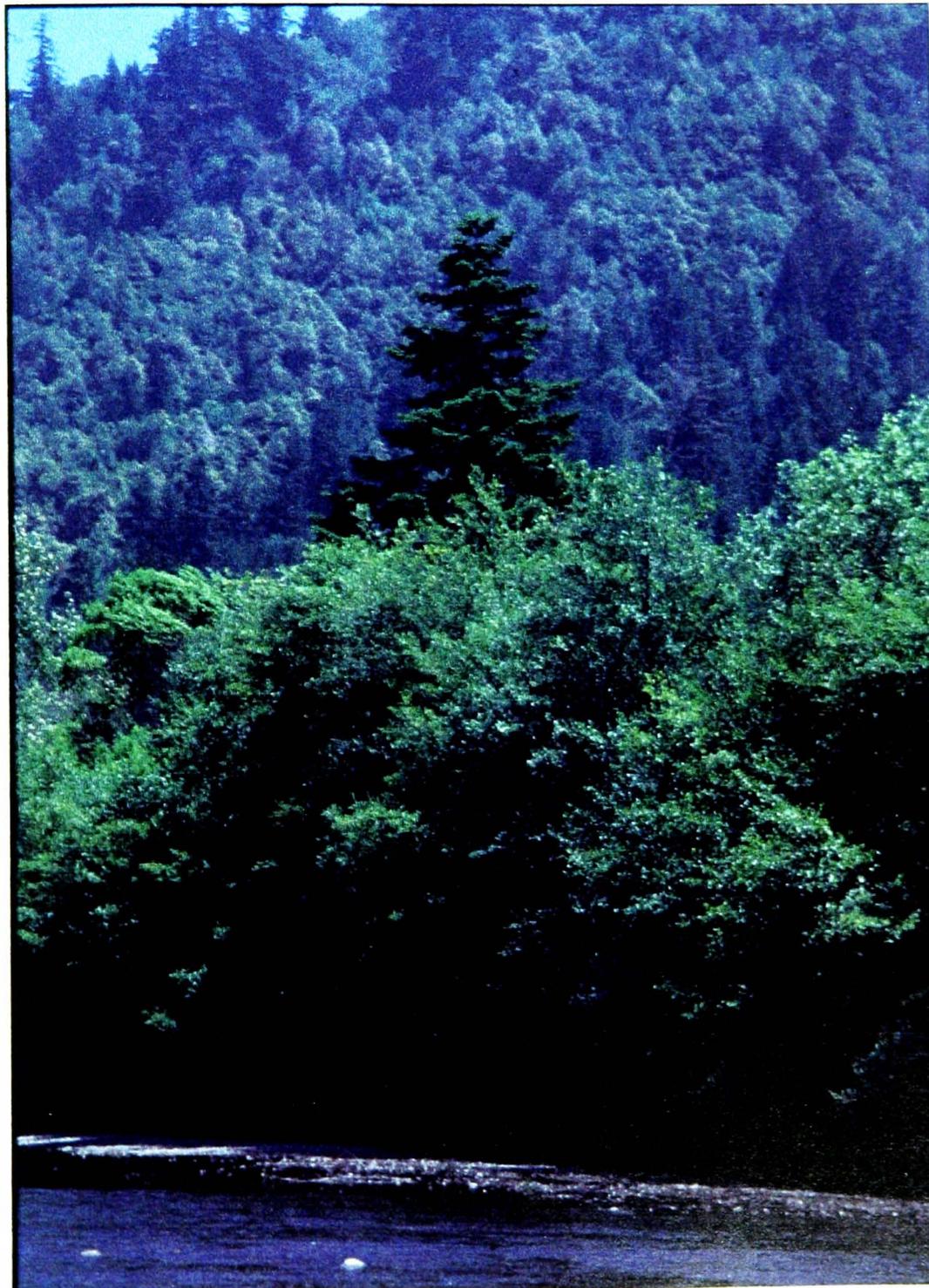

Photo 4.2. Example of native floodplain (dominated here by *Alnus, Populus*)and hillslope forest of the lower Mattole valley, July, 1994.
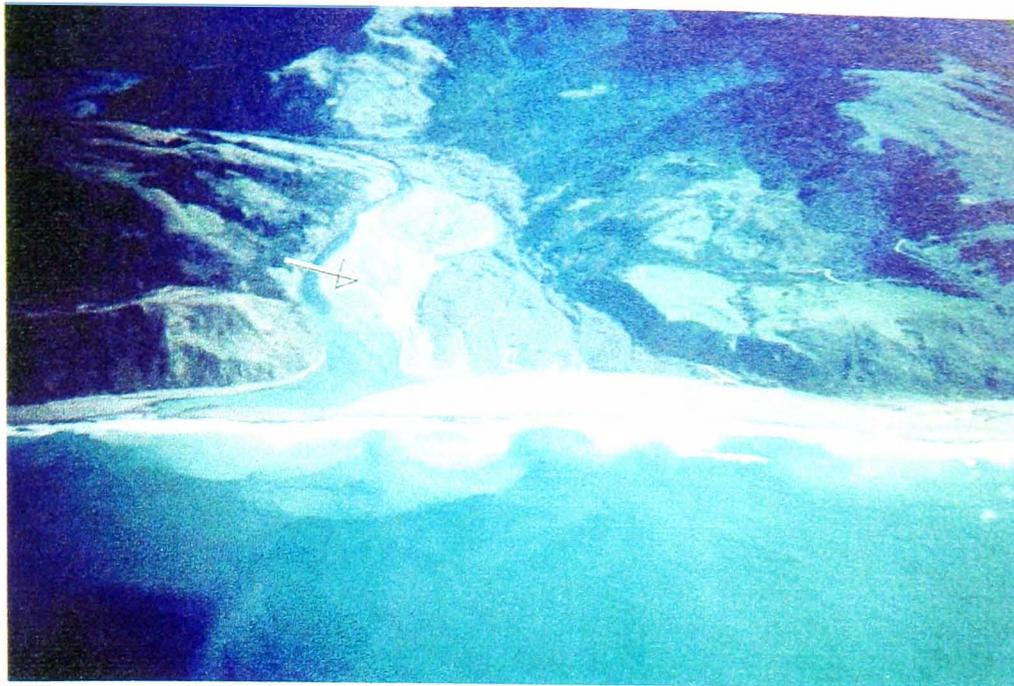
Photo 4.3. Oblique air view of Mattole estuary from the ocean looking east with arrow showing project location. Courtesy T.B. Dunklin, Nov 1992.

Photo 4.4. Study site before construction, 3 Nov 1993, showing existing native willows on coarse gravel terrace.
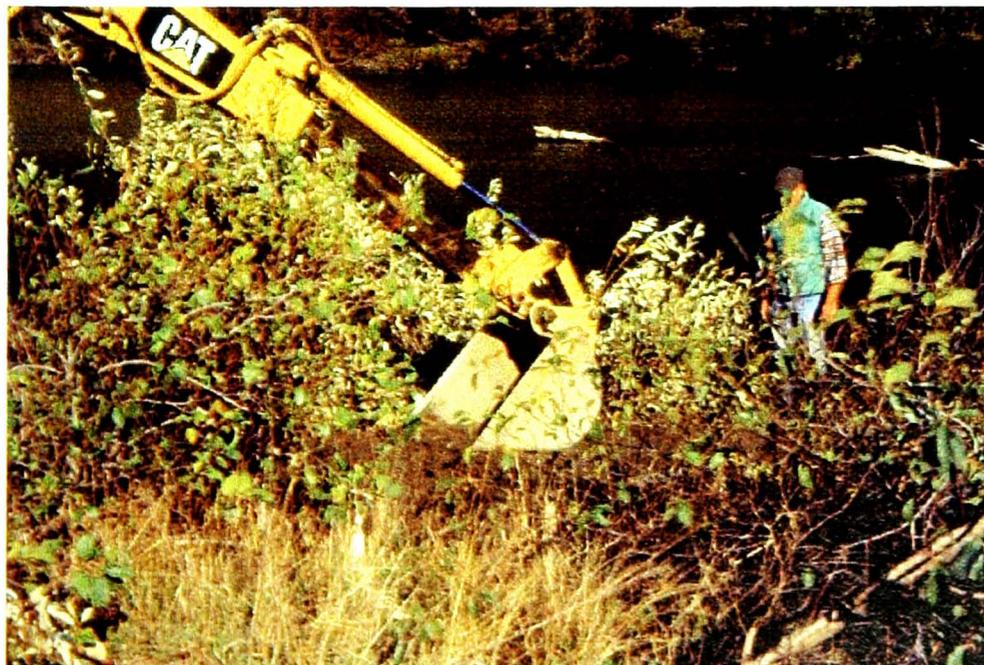
Photo 5.1. Backhoe digging trench during baffles construction, 3 Nov 1993.

Photo 5.2. Placement of willow stems in a trench, S. Hawks, BLM, 3 Nov 1993.
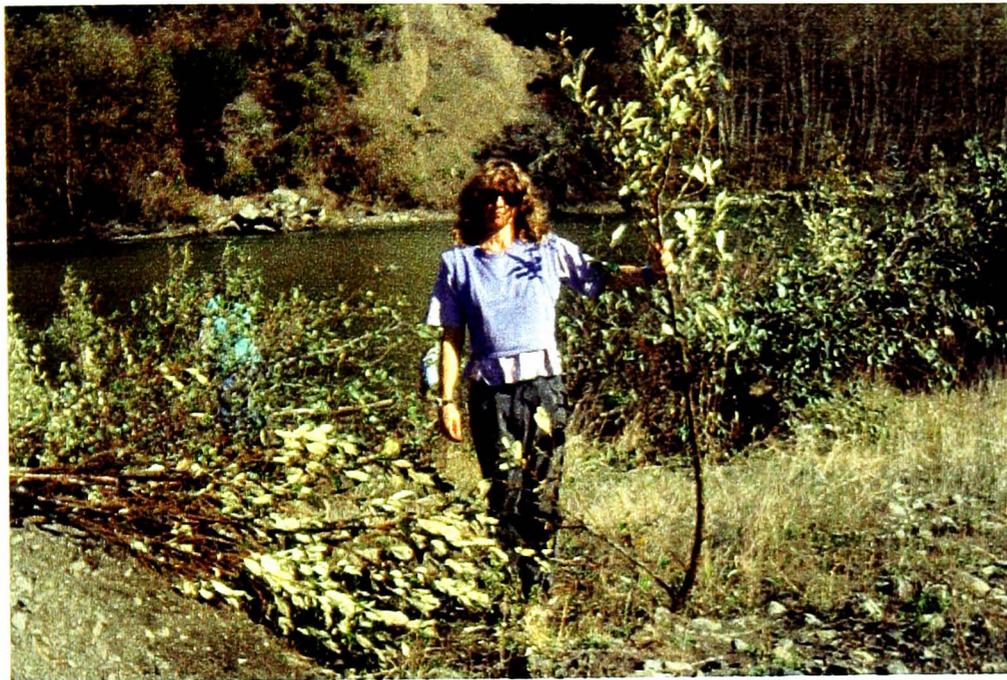
Photo 5.3. J. Morrison (MRC) holding typical-sized willow cutting, 3 Nov 1993.

Photo 5.4. Irrigation of freshly planted baffle, E. Engber, 3 Nov 1993.

Photo 5.5. Post-construction view of live siltation baffles looking downstream, showing density of leafy cuttings. 3 Nov 1993.
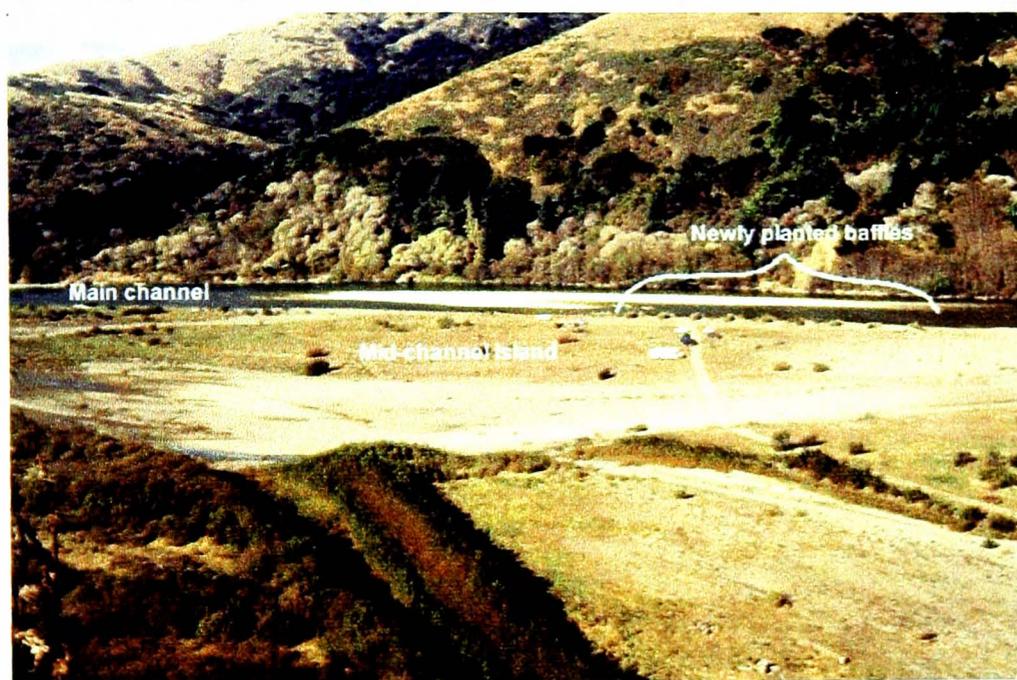
Photo 5.6 Post-construction oblique view, looking north from Taylor slide photopoint, 3 Nov 1993.

Photo 5.7. Longitudinal view upstream post-construction; note the sediment mounds on the downstream side of the baffles, 3 Nov 1993.

Photo 5.8. New leaf growth and flowering shoots, three months after construction, March 1994.

Photo 5.9. Sediment probe and fine sediment layer, supporting seeds from the planted willows, March 1994.

Photo 5.10. Fine sediment deposition among baffles following annual flood 8 Dec 1993, showing discrete sediment boundary at baffle margin, March 1994.

Photo 5.11. Contrasting sediment sizes for vegetated and unvegetated floodplain surfaces following 8 Dec 1993 flood, photographed 15 Dec 1993.

Photo 5.12. Sediment particles captured by baffles during 15 year flood, peak flow depth ~ 1m, photo taken 10 Jan 1995.

Photo 5.13. The author holding current meter, counting clicks for velocity measurements, velocity profile 4, 10 Jan 1995.

Photo 5.14. The inflatable boat used to access the floodplain during flood, photo taken on 8 Jan 1995.

Photo 5.15. Flood peak 9 Jan 1995, over the revegetated mid-channel island, photo taken from the Taylor photo-point.

Photo 5.16. Flow through stems of baffle number 8 during rising flood taken on 8 Jan 1995.

Photo. 5.17. Shallow flow through baffle stems on rising hydrograph, 8 Jan 1995.
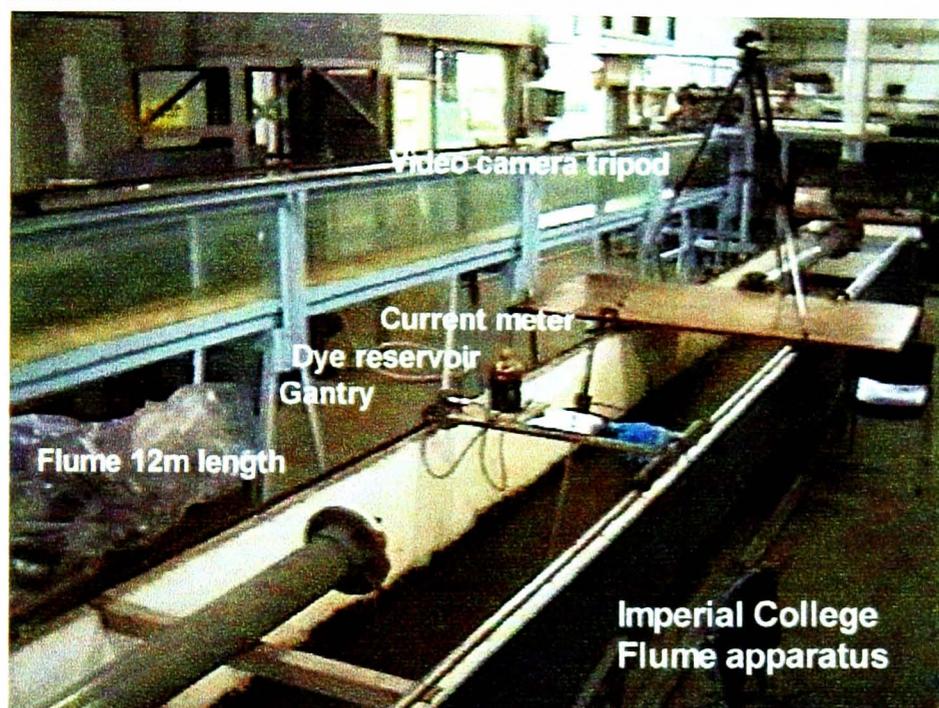
Photo. 5.18. View of the flume laboratory, 9 June 1998.

Photo. 5.19. View of the final design for simulated baffle (Mark V Meyer's hedge). 10 June 1998.

Photo 6.1. Heterogeneous sediments deposited by the flood peak on the upstream end of the estuary mid-channel island.
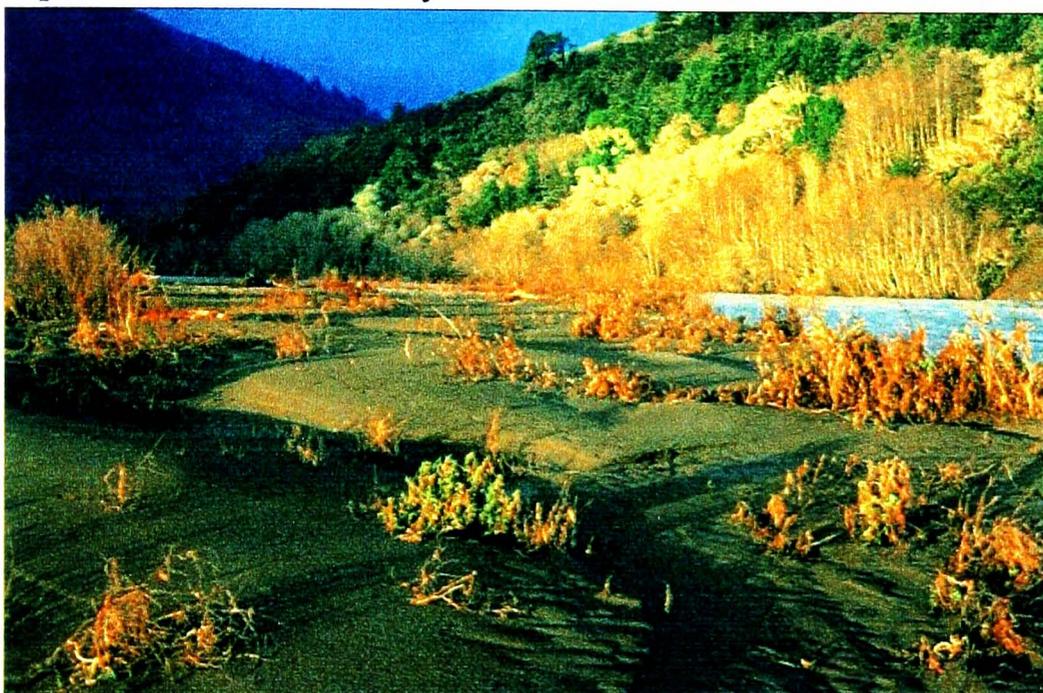

Photo. 6.2. Sand dunes formed downstream of the baffle region of the mid-channel island. Photo taken 9 Jan 1995 after flood peak.

Photo 6.3. Scour zone formed downstream of a break in stem density, baffle 7, 10 Jan 1995.

Photo. 6.4. Lateral mixing of faster water in-channel and slower water flowing inside baffle 'envelope'. 10 Jan 95.

Photo. 6.5. Fine sediment deposition in the region of the baffles, March 1994.

Photo. 6.6. Cobble layer deposited among baffles during flood peak 9 Jan 1995.

Photo. 6.7. Fine sediment deposition among baffles after first flood Dec 93. Photo taken March 1994.

Photo 6.8. Scour beneath root zone of baffle 1 during declining storm hydrograph, 14 Jan 1995.

Photo 6.9. TB Dunklin showing freshly cut left bank edge following flood recession, 15 Jan 1995.
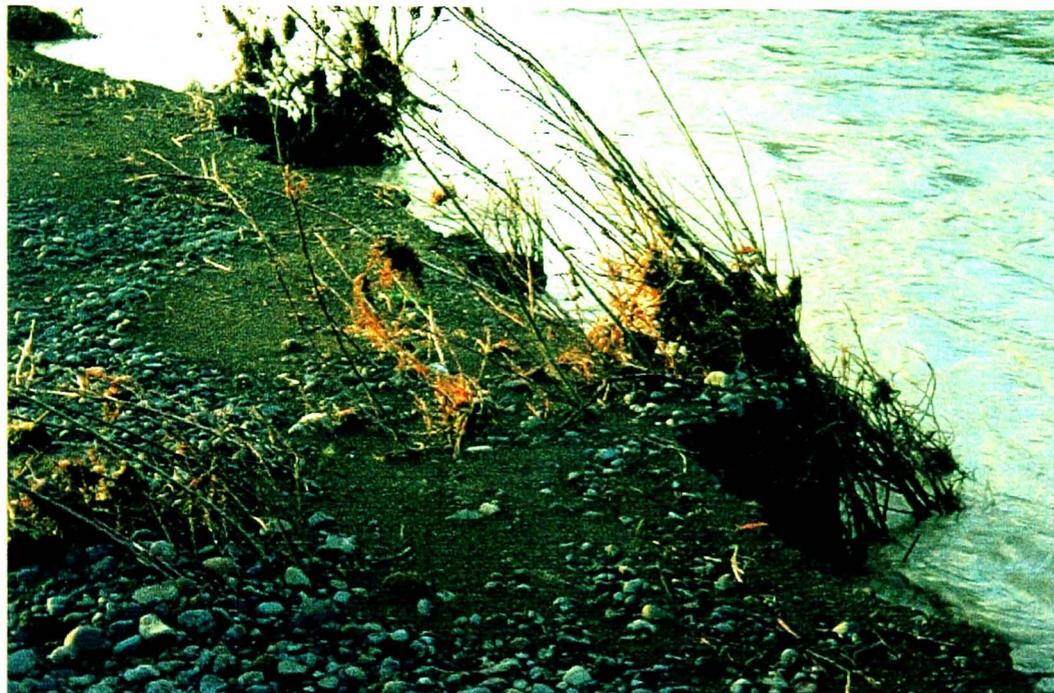
Photo 6.10. Siltation baffle resisting lateral erosion caused by thalweg migrationduring flood recession, 14 Jan 1995.

Photo 6.11. Calving bank and baffle eroding. Note wave scour below root zone occurring during flood recession 14 Jan 1995.
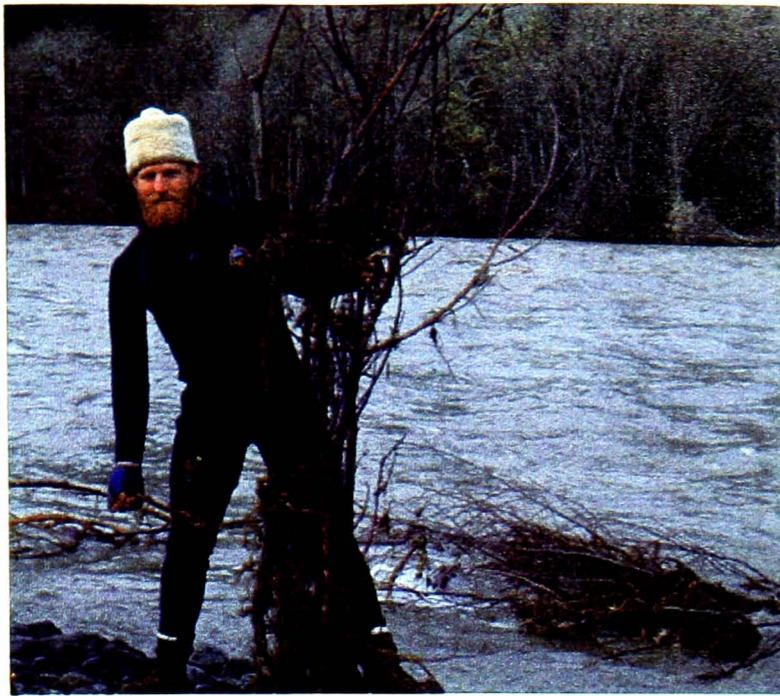
Photo 6.12. P. Sheldon holding root to show root development after 14 months growth. Cutting was scoured from baffle during flood recession, 15 Jan 1995.
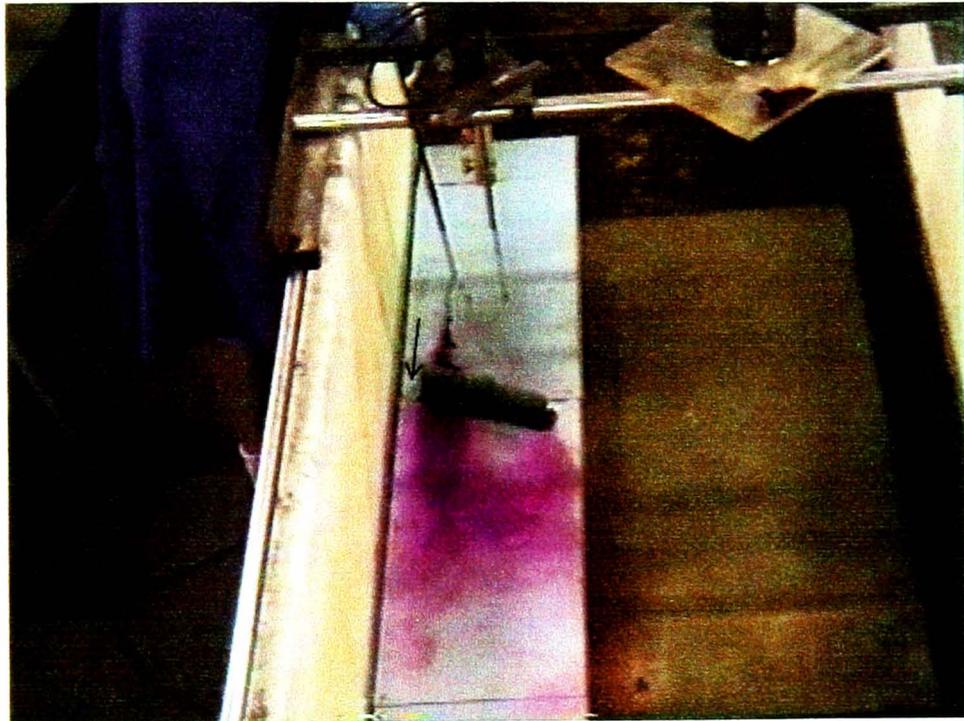
Photo 6.13. Flow visualisation of the wall effect in the flume.

Photo 6.14. View of the final baffle design and simulated terrace in the flume.
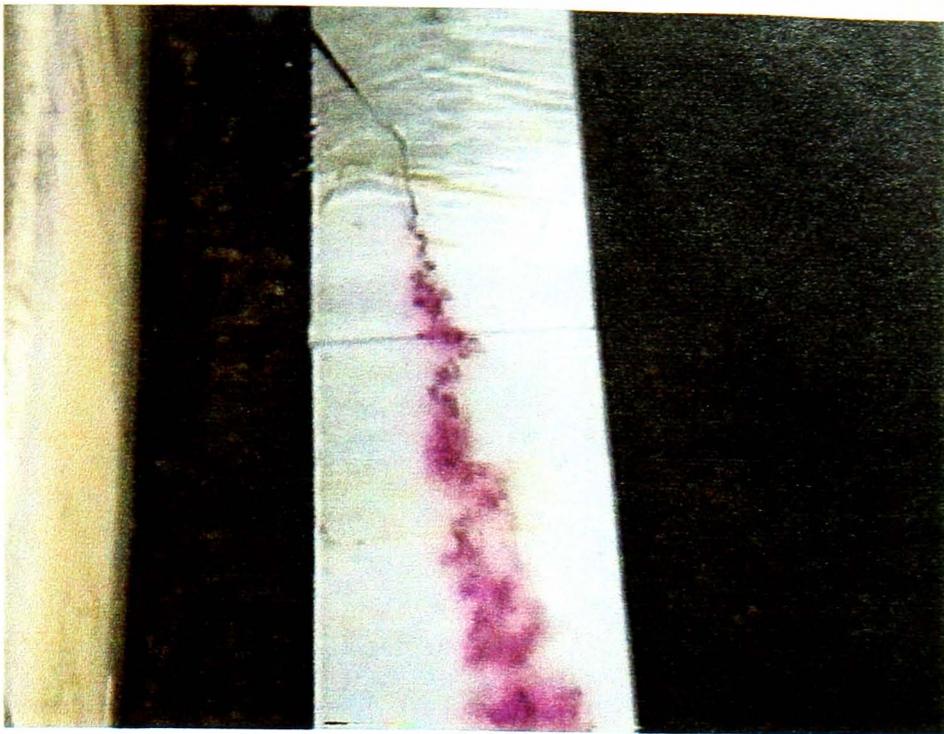
Photo. 6.15. Flume flow at Fr = 0.65, with no obstruction.

Photo. 6.16. Flow visualisation around a single cylinder, Fr~0.65, showing vortex eddy street.
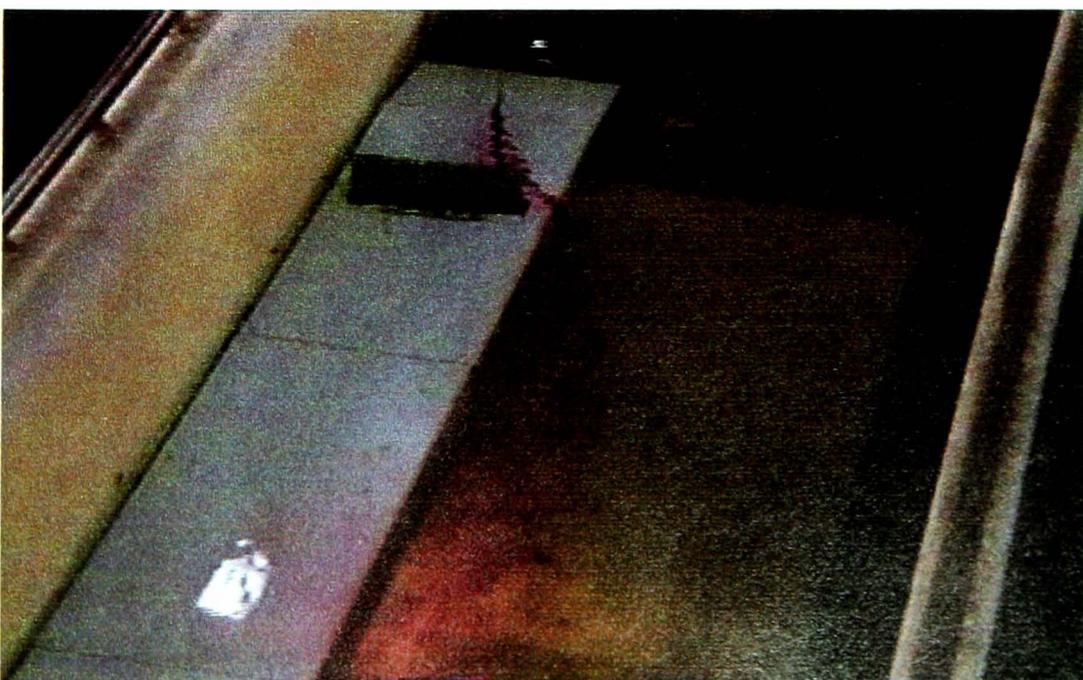
Photo 6.17. Eddy shedding at the channel-terrace margin increased in vigour with the presence of the hedge.
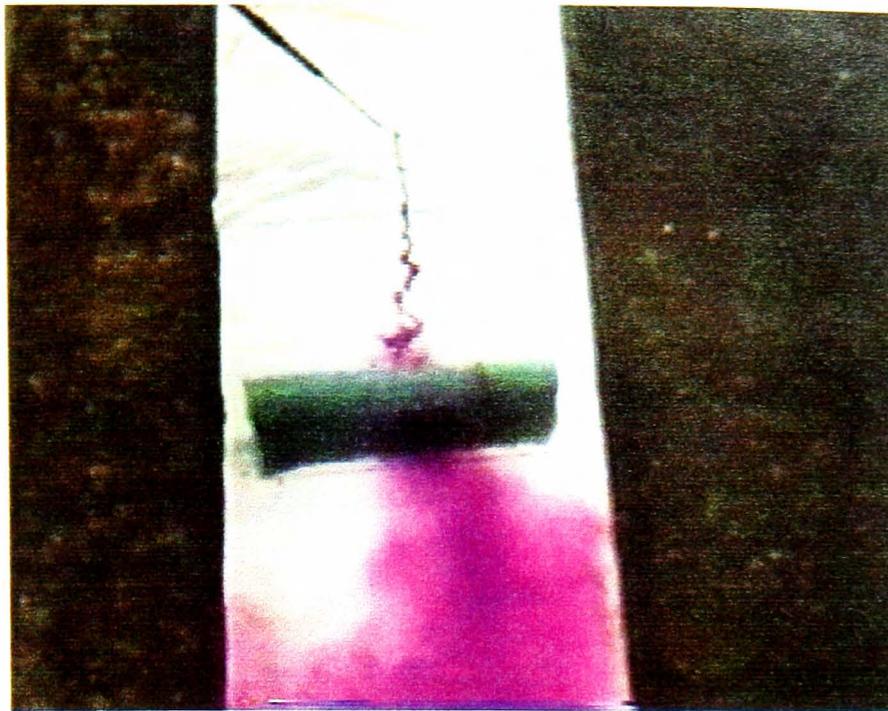
Photo. 6.18. Tracer dye flowing through a single perpendicular baffle; note the dye entry vector at midpoint of baffle width.
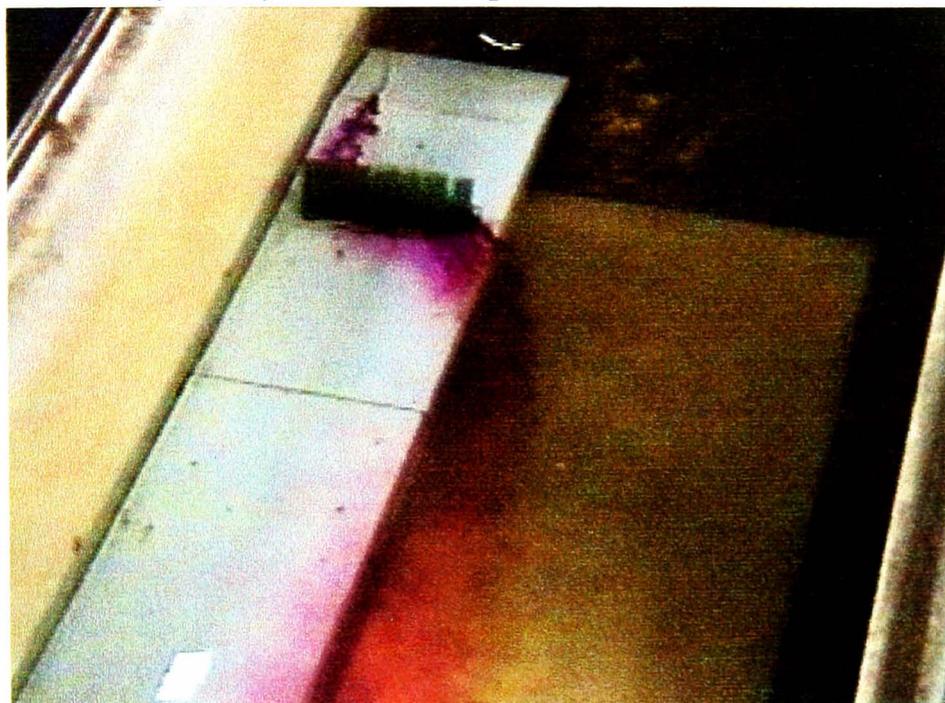
Photo. 6.19. Flume baffle showing tracer dye retention and eddy vortex shedding at the terrace channel margin.
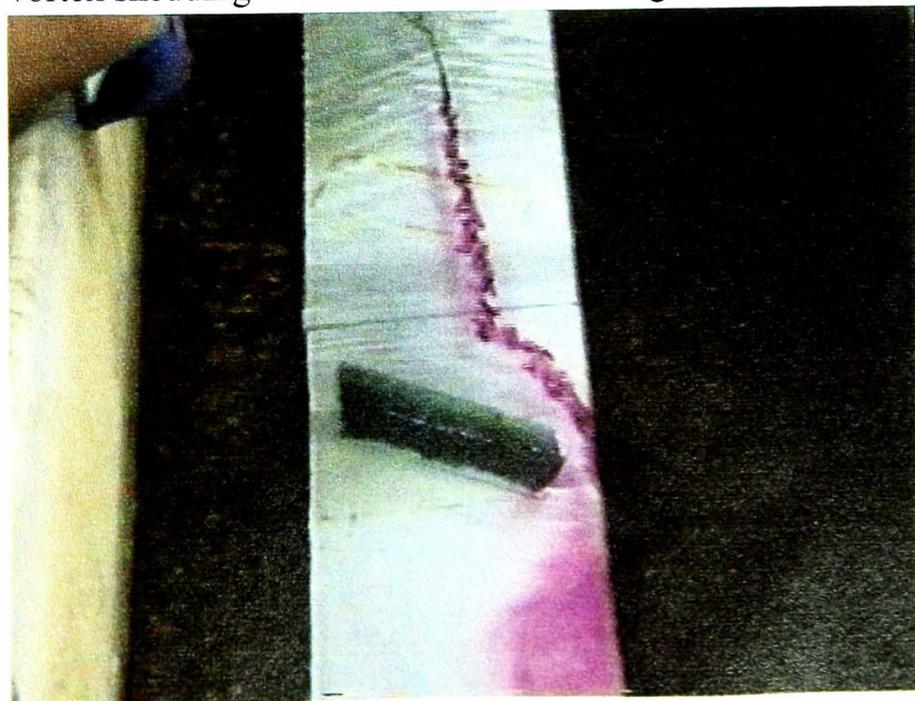
Photo. 7.1. Flume visualisation of the hydraulic separation point upstream of a single emergent, porous, vegetative filter.