THE EFFECTS OF SEDIMENT LOADING ON MORPHOLOGY AND FLOOD RISK IN A LOWLAND RIVER SYSTEM

Stephen F. Dangerfield, BSc. MSc.

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ABSTRACT

Diffuse sources of sediment may have important implications for flood risk management (FRM), especially as catchment sediment yields are predicted to increase in future. UK legislation requires FRM to work with natural processes wherever possible, including accounting for sediments. However, the importance of wash-material load to FRM has been under researched and both a robust evidence-base and practical sediment models are needed to identify, prioritise and justify sediment-related catchment management.

Research addressing these issues was centred on the River Tone, a sub-catchment of the Parrett, in which features excessive inputs of sediment in its upper catchment combined with high potential for deposition in its lower reaches. Links between sediment sources, water and sediment runoff, and downstream sediment sinks were established and the research examined the role played by sediment, especially wash-material load, within the fluvial system. The greatest sediment-related threats to the functioning of this lowland river stem from either: a protracted, major reduction in wash-material load; or a significant increase in bed-material load.

Imbalance in the Tone fluvial-sediment system may not significantly affect flood risk directly, but has implications for FRM operations, maintenance and monitoring. Impacts on land quality result from soil loss. For example, ~2.5 million tonnes of soil has been eroded from the Parrett catchment since WWII. Water quality issues include delivery of phosphate and other pollutants into the river, and potentially more frequent dredging that remobilises contaminants. The thesis defines the key sediment-related components of sustainable, integrated catchment management and provides an improved evidence-base upon which to engage stakeholders. It tests and benchmarks sediment assessment tools including the Sediment Impact Assessment Model (SIAM). An approach to catchment-scale sediment assessment for lowland rivers is recommended, which involves a nested-approach using routinely collected and project-specific field data, stream power screening and SIAM.

Keywords: River Tone; wash-material load; lowland river; flood risk management; morphology; sediment assessment; SIAM; integrated catchment management

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ACRONYMS AND INITIALISMS

AED	Annual Expected Damages
CAESAR	Cellular Automaton Evolutionary Slope and River Model
CAP	Common Agricultural Policy
CBA	Catchment Based Approach
CFMP	Catchment Flood Management Plan
CSF	Catchment Sensitive Farming
CSS	Countryside Stewardship Scheme
DEFRA	Department of Environment, Food and Rural Affairs
DO	Dissolved Oxygen
EA	Environment Agency
ELS	Entry Level Scheme
EPSRC	Engineering and Physical Science Research Council
ERDC	US Army Engineers Research and Development Centre
ES	Environmental Stewardship
ESA	Environmentally Sensitive Area
FA	Fluvial Audit
FCERM	Flood and Coastal Erosion Risk Management
FEPA	Food and Environment Protection Act 1985
FRM	Flood Risk Management
FRMRC	Flood Risk Management Research Consortium
FWAG	Farming and Wildlife Advisory Group
FWM Act	Flood and Water Management Act 2010
GAEC	Good Agricultural Environmental Conditions
GEP	Good Ecological Potential
GES	Good Ecological Status
GS	Gauging Station

HEC-RAS	Hydraulic Engineering Centre-River Analysis System
HLS	Higher Level Scheme
HMC	Habitat Modification Class
HMS	Habitat Modification Score
HMWB	Heavily Modified Waterbody
HQA	Habitat Quality Assessment
MAOD	Metres above ordnance datum
MS4W	Making Space for Water
NE	Natural England
NGR	National Grid Reference
OLS	Organic Entry Level Scheme
PAH	Polycyclic Aromatic Hydrocarbons
PCP	Parrett Catchment Project
PDP	Potentially Destabilising Phenomena
PoM	Programme of Measures
PPS	Planning Policy Statement
PSA	Particle Size Analysis
R&D	Research and Development
REAS	River Energy Audit Scheme
RBMP	River Basin Management Plan
RHS	River Habitat Survey
S4P	Soils for Profit
SFD	Soil Framework Directive
SIAM	Sediment Impact Assessment Model
SPS	Stream Power Screening
SWARM	South West Agricultural Resources Management
SWRBD	South West River Basin District
WFD	Water Framework Directive

1 INTRODUCTION

1.1 Research rationale

In June 2011 the UK Government published a White Paper on the Natural Environment (HM Government, 2011), which set out proposals for safeguarding and restoring the natural environment (see Section 3.2.2). The natural environment was given a wide definition that encompasses: all living things and their habitats; the fundamentals of human survival (food, fuel, air and water); the natural systems and cycles that maintain the health of our environment, protect us and regulate our climate; and our landscape and natural heritage. The White Paper has built upon previous work including: the action plan for securing a healthy natural environment (Defra, 2007); Making Space for Nature (Lawton *et al.*, 2010); and The UK National Ecosystem Assessment (2011).

The White Paper and research documents that underpin it acknowledge that the natural environment has become increasingly fragmented and fragile. Society therefore needs to take better account of the value of nature, particularly the services/benefits it provides, while making the correct future choices to ensure that it is conserved, protected and, where necessary restored. The White Paper sets out key messages for the future management of the UK's natural environment, which include the following that are of relevance to the water environment and catchment management:

❖ England's collection of wildlife areas is fragmented and does not represent a coherent and resilient ecological network capable of responding to the challenges of climate change and other pressures.

- Ecosystems and the way people benefit from them have changed markedly during the last 60 years. Assessing the range of ecosystem services associated with eight broad habitat types, including ‘urban’, ‘farmland’ and ‘freshwater’, reveals that over 30% are declining, often as a consequence of long-term declines in habitat extent or condition.

- Expansion of the urban environment; increased production and intensity of farmland; and fragmentation/deterioration of river and wetland habitats have all adversely affected flood risk management.

- Over 70% of England is farmed, and over a fifth of land in England is at high risk of soil erosion with resulting loss of soil quality. Soil is essential for a range of services and functions including, *inter alia*, food production, carbon storage and climate regulation, and flood management. Soil degradation costs the UK economy £150 million - £250 million per year (HM Government, 2011), while the UK economic losses from soil erosion are estimated to between £90 million (EA, 2002) to £700 million per year (Evans, 1996). By 2030 the UK Government want all of England’s soils to be managed sustainably with degradation threats tackled successfully (HM Government, 2011).

- Most rivers and lakes in England are currently failing to meet the requirements of the Water Framework Directive. Environment Agency data for 2008 showed that only 19% of waterbodies in England and Wales were achieving good ecological status (GES) or good ecological potential (GEP) (www.environment-agency.gov.uk [accessed 19th December 2008]). The target for 2015 is 32%, while the longer-term target is to have as many waterbodies as possible obtaining good ecological status or potential by 2027 (HM Government, 2011).

- The impact of land management on water will be reduced by ensuring that pollution and flood risk are addressed at source through targeted, risk-based enforcement and by identifying where land can be managed to deliver multiple benefits, including improving water quality, flood alleviation and biodiversity.

- It is important to manage ecosystems in a more integrated fashion to achieve a wider range of services and benefits. For example, linking goals on wildlife, water, soil, and landscape, and working at a scale that respects natural systems and the natural features supporting such systems.

It is well documented that many water-centric environmental problems are caused by soil degradation, soil erosion and increased sediment supply to rivers and other waterbodies. It is also accepted that climate change will exacerbate and magnify soil degradation threats in the future (Defra, 2007b; HM Government, 2011). Much of the policy and research focus recently has been on environmental and ecological effects and management driven by the Water Framework Directive (WFD). For example, Collins and Anthony (2008) assessed the likelihood of catchments across England and Wales meeting good ecological status under the WFD due to excessive sediment inputs, and concluded that 17% of catchments were non-compliant and typically required a reduction of 20% of sediment inputs (up to 80% in certain cases). Current research (Collins *et al.*, 2011) is compiling and extending the empirical evidence base on the ecological impacts of fine sediment, and developing a toolkit for informing catchment management based on ecologically-informed targets.

The Foresight Flooding project (Evans *et al*, 2004a; Evans *et al*, 2004b; Evans *et al*, 2008) identified an increasing future flood risk arising from climate change and socio-economic developments. This study defined one of the drivers of flooding as 'river morphology and sediment supply', which is defined as changes in the shape and routes of river channels and the changes in the flow of sediment that alter the river channel and floodplain and influence the channel's water-carrying capacity and its role in flood defence. Indeed, this work predicted that under a 'Global Sustainability' future, lower climate change and economic growth combined with greater environmental consciousness (and more stringent legislation) result in 'river vegetation and conveyance', environmental regulation' and 'river morphology and sediment supply' forming the primary flood risk drivers in the 2050s.

A key conclusion of the Foresight Flooding project is that sediment delivery to UK rivers has been sensitised to climatic variability, and that future sediment delivery to watercourses will increase due to increased rainfall intensity and flood frequency (Reid *et al.*, 2006; Lane and Thorne, 2007), with knock-on effects for flood risk. The study suggested that the most immediate impacts of sedimentation are likely to become apparent in the headwaters and middle reaches of rivers, although adverse impacts further downstream may follow as elevated sediment loads move through the system. There is currently uncertainty concerning how finer 'wash load' sediment (see Section 1.3.1 for a definition of wash-material load sediment) delivery drives longer-term river morphological change in the lower courses of river systems, and this topic needs significant further research.

A general lack of understanding concerning the role sediments play in flood risk management was identified by Thorne (2011) who stated that 'while substantial progress has been made in relation to broad-scale modelling and management of water-related risks, research on sediment-related risks is less advanced'. A primary reason for this lack of research progress is attributed to the belief that the flood risk management community do not perceive that sediments contribute significantly to Annual Expected Damages in the UK resulting in limited resources being made available for sediment-related research.

It can be difficult to accurately identify causal links between specific management actions to alter sediment dynamics, river morphology and flood risk. This lack of understanding and quantification of the role of sediments in flood risk management, it is suggested here, also manifests as a widely held view that any action or intervention that either reduces or increases sediment delivery to, or mobilisation within, a river must also have an measurable impact on flood risk, be it positive or negative. Sayers *et al.* (2011) supported the need for appropriate data, experience and the use of decision-support tools to understand how management intervention actually influences flood risk or land drainage functions. They note that 'all too often cause and effect have been inferred and practice has been carried out with poor supporting evidence'. It is suggested in this thesis that this inferred 'cause and effect' between sediments and flood risk is used to help justify certain catchment management actions and/or justify who should pay without being based on robust scientific evidence.

Based on a review of literature (see Section 2.3) in the UK there are very few studies which have sought to establish and quantify the link between sediments, morphology and flooding, and none that have established the link between sedimentation, morphology and flood risk (i.e. the combination of ‘probability of flooding occurrence’ with its ‘potential consequences’), which is a major research gap.

In addition to a general lack of understanding on the role of sediments in flood risk management, Newson (2002) stated that research in fluvial geomorphology in the UK has been largely limited to investigating processes and forms at small, unmodified sites, with academic geomorphological researchers neglecting lowland modified channels. He defined a heavily modified river as one which ‘through human modification or repeated actions, is constrained in its direction/rate of adjustment and diversity of features, frequently to the extent that it creates a geomorphological hiatus in the flow-sediment system, causing upstream or downstream impacts or both’.

This message was reiterated almost a decade later by Bates (2011) who agreed that geomorphologists have traditionally studied natural or quasi-natural river systems within predominantly rural landscapes, but stated that this focus is misplaced when considering the impact of altered morphodynamics on flooding due to the low density of people and assets at risk in such areas. Instead, there needs to be a fundamental shift in geomorphic research focus to urban rivers to better understand how (1) geomorphic change occurs in urban rivers and (2) how sediment transport through the wider catchment impacts on channel form and capacity in urban areas.

Within the UK soil erosion and sediment yield to rivers is already identified as a critical issue for river health and quality, and sustainable management of the land (HM Government, 2011) via the WFD and the draft Soil Framework Directive. However, the potential for linkages between diffuse sources of sediment and flood risk is less well acknowledged, as is demonstrated by a 2008 SedNet publication (Owens, 2008), which provides an overview of regulatory frameworks for sediment management but makes no mention of flood risk legislation or policy.

Flooding can have severe social and economic consequences, and traditional engineered responses, which take little account of fluvial processes and ecosystem functioning, often exacerbate these problems and lead to severe adverse consequences on the environment (Mance *et al.*, 2002). The Foresight Flooding project therefore recognised that the type of flood management response, and subsequent morphological response of the river, is inextricably linked to current and future environmental legislation, which may prohibit some interventions (i.e. sediment removal/dredging) while promoting others (i.e. source control). The study concluded that ‘a clash between flood risk management and environmental objectives could lead to a 3-fold increase in flood risk in the 2050s, rising to a 4-fold increase in the 2080s’ (Evans *et al.*, 2008).

Subsequently, the UK Government strategy Making Space for Water (Defra, 2005a) and the recent Flood and Water Management Act 2010 make a link between flood risk, land management and maintaining natural processes. Indeed River Basin Management Plans required under the WFD, and Flood Risk Management Plans (known as Catchment Flood Management Plans in England and Wales) required under the Floods Directive will sit alongside each other, and management targets and activities of each plan must not conflict, and preferably should actively support each other.

The Environment Agency has recognised that the management of sediment in watercourses in England and Wales is likely to become more contentious in the future (Thorne *et al.* 2010a), and has set out three premises for sediment management (Environment Agency, 2010):

1. A general presumption against removing sediment from rivers.

2. The justification to move or remove sediment must be evidence-based.

3. When sediment actions are found to be justified best practice must be employed… with the aim of maximising benefits to habitats and ecosystems while avoiding, or at least minimising, damage to the environment.

Where the structure and function of a river system is extensively destroyed or interrupted due to unsustainable development or flood risk management, the fluvial system is unlikely to recover in the way that rivers recover from a pollution incident (Newson, 2002). Society must then incur the cost of finding an alternative to the natural function, for example through water purification or structural flood defence measures, or increasingly through restoration of the lost/interrupted functions.

Mainstone *et al.* (2008) stated that tackling diffuse sources of sediment requires the integration of practical action with a quantitative understanding of those management changes needed to meet environmental objectives. While Owens and Collins (2006) identified that the application of mitigation technology alone is seldom satisfactory for sediment management, particularly over a long time-frame, and the solution lies in seeking collaborative approaches to find ways to use soils and sediments in a sustainable manner. The Environment Agency (2010) has established six guiding principles for river sediment management as follows:

1. Sediment management actions must be reasonable and justified.

2. Understand the sediment related problem and identify its cause.

3. Identify and prioritise the functions of the watercourse.

4. Identify and appraise sediment management options based on risk analysis.

5. Balance multiple goals of channel management.

6. Appraise maintenance outcomes by inspecting channel conditions with respect to targets set for all relevant functions.

Apitz *et al.* (2005) identified the criteria needed for successful environmental management, which are also relevant for catchment or river sediment management, as follows: actions should be environmentally sustainable, economically viable, technologically feasible, legislatively permissible, administratively achievable, socially desirable/tolerable, and politically expedient. Similarly, Skinner (2011) and Thorne *et al.* (2011) identified the need to develop tools that can be readily used in practical river management, and to be effective the tools need to be: scientifically robust; cost effective; and widely available.

1.2 Research hypothesis and key questions

Within the UK soil erosion and diffuse sources of sediment are already identified as a critical issue for river quality, but there is now a growing belief that there may also be important implications for flood risk management. This is particularly true where future climate predictions suggest that the amount of sediment mobilised and delivered to rivers is likely to increase unless management intervention occurs (Lane and Thorne, 2007; Henshaw, 2009).

The UK legislative and policy framework now recognises this issue, particularly in relation flood risk management 'working with natural process' (see Section 1.3.2), which is widely accepted should include sediment management, as enshrined within the Flood and Water Management Act 2010 and the White Paper on the Natural Environment (HM Government, 2011). Legislation, however, also places constraints on the type of river and flood risk management intervention that are deemed acceptable, and has resulted in sediment management in rivers becoming more contentious.

The best way to mitigate fine sediment problems, it is argued, is to prevent excessive sediment influx into the watercourse through sediment source-control, and greater concern regarding off-site (downstream) impacts has led to an increased emphasis on catchment-scale management. However, the role of sediment, particularly the finer wash-material load sediment, within fluvial flood risk management is poorly understood. This is coupled with a lack of research linking sediments, morphology and flood risk within the context of lowland, urban and modified river systems. Research investigating and better understanding the linkages between sediment sources, control of water and sediment runoff, and sediment sinks in the downstream channel network are key to managing the catchment sediment dynamics in an integrated approach (O'Connell *et al.*, 2004; Morgan, 2006; Wilkinson *et al.*, 2010, Newson, 2010; Thorne *et al.*, 2010b and c; Wainwright *et al.*, 2011).

Consequently, there is a need to develop a scientifically robust evidence-base to try to understand 'cause and effect' linkages between catchment (water and sediment) management and flood risk. Practical and widely available river sediment modelling tools are also required to identify, prioritise and justify sustainable catchment and river management intervention. Ideally, these tools should also identify 'win-win' FRM solutions that also enhance a range of ecosystem services.

The research presented in this thesis aims to address some of the current knowledge gaps in relation to the role sediment, and in particular wash-material load sediment, plays in driving morphological and flood risk change in a lowland river context. Hence, the over-arching research hypotheses to be tested are defined as:

1. *Excessive amounts of supply-limited, wash-material load sediment derived from erosion of the upper catchment can transition to capacity-limited, bed-material load that is deposited further downstream in the river system. Such deposition can alter channel morphology and conveyance capacity to produce significant, adverse effects on flood risk, the performance of flood defence assets, and in-stream, riparian and wetland habitats.*

2. *Management of the wash-material load sediment at source can reduce downstream deposition, reducing the need for in-channel sediment removal or management, and providing flood risk, operational maintenance, ecology and other catchment management benefits.*

This research therefore concentrates on the dynamics, fate and consequences of sediment after it has entered the river system, rather than investigating the mechanisms of sediment delivery to rivers. The research hypotheses have been tested by employing and evaluating a range of sediment assessment tools/models (see Section 5.2) to investigate and answer the following **core** research questions:

1. What is the role of wash-material and bed-material loads in the flow-sediment system, and how do they drive morphological response in a lowland modified river system?

2. How does sediment source-control and/or climate change affect the river flow-sediment system in terms of sediment continuity (sources, transfers and sinks) and subsequent channel morphology?

3. Do predicted changes in sediment dynamics, and subsequent changes in channel morphology, significantly affect inundation, flood risk or flood risk management actions?

4. How does sediment management link to and impact upon river habitats, land quality and river water quality?

5. What are the key policies, legislation and schemes to drive and deliver catchment sediment management?

In addition to answering the core research questions to test the research hypotheses, there are some **supplementary** issues that have been addressed during this research:

a. Benchmarking the selected sediment assessment tools (see Section 5.2) to compare model performance against the varying data and resource input requirements;

b. Continued testing of SIAM (see Section 5.2.4 for a description of the model) to establish whether it is appropriate for sediment assessment in lowland rivers;

c. Establishing the key components and appropriate level of investigation (including use of tools/models) needed to: understand the flow-sediment system; quantify risks associated with different management intervention; and define robust sediment management in a lowland river system; and

d. Identifying the new research needed to support enhanced future sediment assessment in lowland rivers.

This research was undertaken under the auspices of the Flood Risk Management Research Consortium (FRMRC), an interdisciplinary partnership of academic and industrial researchers (http://www.floodrisk.org.uk). The FRMRC was a major research study into the prediction and management of flood risk, which was primarily funded by the Engineering and Physical Science Research Council (EPSRC) and the Environment Agency. The over-arching aim of the FRMRC was to develop tools and techniques to support more accurate flood forecasting and warning, and reduce flood risk to people, property and the environment (FRMRC, 2011). The research presented in this thesis was embedded within FRMRC2 Super Work Package 5: Land Use Management. All raw and synthesised data collated as part of this research is held centrally within the FRMRC and can be freely downloaded on request (http:/www.floodrisk.org.uk).

1.3 Key concepts and definitions

1.3.1 Sediment load

Regolith that is eroded from a catchment and enters a river system is either dissolved (the solute load) or transported in particulate form (the sediment load). The sediment load has the most significance for river geomorphology (Sear *et al.*, 2003), and is routinely defined on the basis of either: the mechanism by which it is transported; or the source from which it is derived (Figure 1.1).

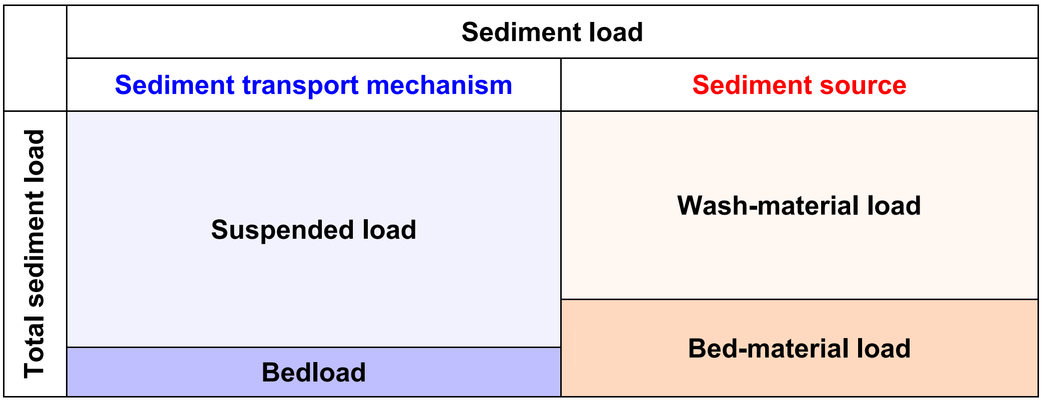


Figure 1.1 Relationship between constituents of the sediment load

Sediment defined by its transport mechanism is divided into: bedload, which is the relatively coarse fraction of the load, in frequent contact with the bed and moving by sliding, rolling or bouncing. Such material is apt to travel only a short distance in each transport event; and suspended load, which is the relatively fine fraction of the total sediment load, seldom in contact with the bed and carried within the body of the flow by anisotropic turbulence. Sediment moving in suspension may travel long distances during a single transport event before being deposited (Sear *et al.*, 2003; Church, 2006).

When considering fluvial sedimentation and river channel morphology, sediments are more appropriately defined by their source, customarily being divided into bed material and wash material (Church, 2006) with the amount of each transported through a river system defined as the bed-material load and the wash-material load (which is often referred to as wash load). More detailed definitions of bed-material load and wash-material load are given below.

Sub-dividing the total sediment load by its source is the more relevant here, as the transfer and interaction of wash-material and bed-material loads underpins the investigation of the research hypotheses. Also, the primary sediment model used and evaluated within the research, SIAM (see Section 5.2.4), works by tracking wash-material and bed-material load separately through the sediment transfer system (Thorne *et al.*, 2011).

However, although there is general agreement on the constituents of the sediment source load there is no universally accepted definition of wash-material load and bed-material load. For example, wash-material load has been defined as the finest grained fraction of the total sediment load (<0.062mm), consisting of particles whose settling velocities are so low that they are transported in suspension at approximately the same speed as the flow and only settle out when flow velocities are much reduced (Knighton, 1998). Richards (2002) defined wash-material load as the sediment derived solely from catchment slope processes, whereas (Biedenharn *et al.*, 2006b and c) defined it as sediment from catchment slope processes as well as erosion of the channel perimeter (not including the bed).

The definitions of bed-material load and wash-material load used within this research are based upon those used by Biedenharn *et al.* (2006b and c) and Church (2006), and are:

Bed-material load: Material that is found in appreciable quantities of the bed and lower banks of a river, and in alluvial channels it corresponds with the coarser part of the total sediment load transported by a river. Bed-material load is of major importance for channel morphology as it is derived from erosion of the river bed and lower banks. Bed-material load particles are constantly being exchanged with the river bed, and they return to the river bed at the end of a transport event.

Wash-material load: Material is finer than bed-material load and is not found in appreciable quantities in the river bed and lower banks, but may form a significant fraction of upper bank and floodplain deposits as the result of deposition in slack water overbank during floods. Once entrained the material is transported for a long distance, usually in suspension.

The key distinction is that wash-material load is not found in appreciable quantities in the bed or lower banks of a river channel. Within this research the threshold between bed-material load and wash-material load follows the convention of Einstein (1950) who defined wash-material load as the grain size of which 10 percent of the bed mixture is finer (D_{10}). There is no theoretical justification for selecting D_{10} rather than some other percentile (e.g. D_5 or D_{16}), but the principle adopted here is that wash-material load is defined on the basis of its absence and that its upper bound size criterion must be expressed in relative, not absolute, terms. It follows, for example, that sand constitutes wash-material load in a gravel-bed river.

As D_{10} changes downstream, sediment that is classified as wash-material load in one reach of a river may become bed-material load in another reach with finer bed material and if the capacity of the flow is insufficient it may become bed material. The converse is also true, as bed-material load may transition to wash-material load as it moves downstream through the fluvial system (Figure 1.2).

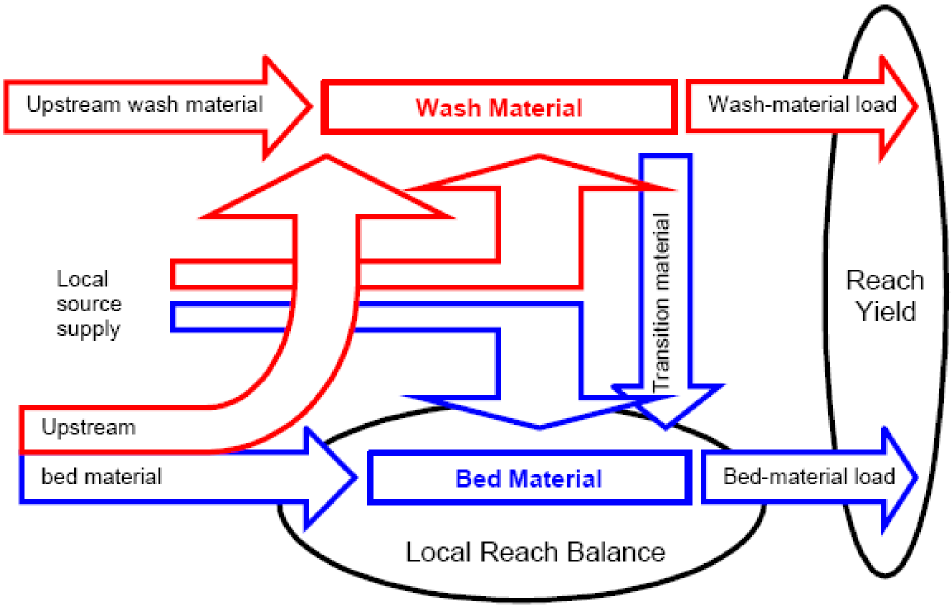


Figure 1.2 Interaction of wash-material and bed-material in a sediment transfer system (Adapted from Thorne et al., 2011)

There can be no definitive value for the percentage contribution of wash-material load to the total sediment load, however, there is a widely held view that total sediment load comprises approximately 90% wash-material load and 10% bed-material load. For example, Walling and Collins (2005) reviewed the findings from 48 sediment sourcing studies across the UK and identified that catchment agricultural soils typically account for 85-95% of the total suspended sediment load.

Lastly, as defined by Bettess (1994) and Knighton (1998), wash-material load transport is determined by the rate of sediment supply rather than the transporting capacity of the flow.

1.3.2 Working with natural processes

Recent UK Government policy and legislation has enshrined the principle of 'working with natural processes' when managing the natural environment and flood risks. The 2011 White Paper on the Natural Environment states 'it is important to manage ecosystems… at a scale that *respects natural systems*'. With respect to flood risk management the Pitt Review 'Learning lessons from the 2007 floods' made a specific recommendation for '*greater working with natural processes*', which the Flood and Water Management Act 2010 included as '*maintaining or restoring natural processes*' as a valid flood risk management action. However, the 2010 Act does not define what maintaining or restoring natural processes actually means or how it is to be achieved.

Chapter 3 of this thesis (Mechanisms available to implement sediment management in the UK) provides an overview of relevant UK legislation, policy and strategy developed and available to manage and control water runoff, soil erosion, sediment runoff and sedimentation of rivers. These documents all hint at what 'working with natural processes' may mean, and generally divide into two groups: what natural processes may include; and what natural processes may provide as a desirable outcome.

Process-based definition

The UK Government's flood and coastal erosion risk strategy, Making Space for Water (Defra, 2004a; Defra, 2005a), which was underpinned by the work of the Foresight Flooding research, establishes the need to address flood risk on a catchment-wide scale and in an integrated manner, and these principles are also included within the EU Floods Directive. The recent White Paper on the Natural Environment (HM Government, 2011) states the UK Government will support natural systems to function more effectively. Effectiveness is not defined, but in this thesis it is suggested it could mean maximising or optimising the range of ecosystem services a natural system provides or supports, which in turn could include, *inter alia*, controlling flood risk as an environmental hazard.

The Foresight Flooding project identified a future shift in focus for flood risk management moving it away from water conveyance in defended channels and towards re-connecting channels to floodplains in flood-suitable areas. This view of flood risk management is enshrined within the Floods Directive, which identifies the need to give rivers more space, to maintain and/or restore floodplains, to improve water retention, and to promote sustainable land use practices. This approach is also embedded within the UK Water Strategy, which states that risk from flooding should be sustainably managed with greater understanding and more effective management of surface water. The Environment Agency when reviewing the state of soils in England and Wales identified that many flooding problems are made worse by ignoring the water retention function of soils and that sustainable rural drainage practices that work with the natural soil hydrology are needed.

This approach to flood risk management which moves towards understanding and, where appropriate, restoring linkages between a watercourse, its floodplain and the surrounding catchment could, therefore, be seen as being analogous to ‘maintaining or restoring natural processes’. This is the view in Scotland where the Flood Risk Management (Scotland) Act 2009 has placed a requirement on the regulatory bodies to consider the function of, and consider restoring/enhancing, natural features so as to slow down, store or otherwise reduce flooding. Richards (2011) termed this ‘natural flood management’, which is founded on understanding the sources and pathways of floodwater and working with natural processes in managing them to reduce downstream flood risks.

Outcome-based definition

UK Government legislation and policy establishes the need for flood risk management to deliver the greatest environmental, social and economic benefits, consistent with the Government's sustainable development principles, which include the need to improve our environment and to ensure that the natural resources needed for life are unimpaired and remain so for future generations. In 2007 Defra published an action plan, which formed the basis for a more strategic approach to policy-making and included: maintaining healthy ecosystems and ecosystem services; and ensuring environmental limits are respected taking into account ecosystem functioning.

The Floods Directive specifically establishes the need for flood risk management to prevent and reduce damage to human health, the environment, cultural heritage and economic activity. Thorne *et al.* (2010a) identified that dysfunctional sediment dynamics can pose significant threats to people, property, infrastructure and the ecology/environment of a river, and the Environment Agency have established the need for fluvial sediment management to maximise benefits to habitats and ecosystems while avoiding, or at least minimising, damage to the environment. Furthermore, under the WFD all water bodies must reach good ecological status (GES) or good ecological potential (GEP), and the UK Government aims to achieve this for as many waterbodies as possible by 2027.

Therefore, it could be assumed that a river system which optimises, or works with, natural processes is one that has appropriately functioning flow and sediment dynamics (hydromorphology), and as such minimises threats, maximises benefits and attains a GES or GEP status. In terms of defining the hydromorphology quality component of GES or GEP, Newson and Large (2006) provide a definition of a 'natural' river (i.e. one attaining reference conditions appropriate for GES) as: *channels whose geometry and features represent the full interplay of unmanaged water and sediment fluxes with local boundary conditions. Such channels are free to adjust, by aggradation, degradation, or by lateral interaction with the floodplain or valley floor in response to unmanaged flows and sediment supplies (short term) or in response to longer-term changes in system or local drivers. They are not wilderness channels but may inspire a holistic perception of being 'intact', a popular human perception of reference conditions deriving mainly from landscape aesthetics. 'Natural' channels require minimum management intervention to offer resilience and a diversity of physical habitat, though neither of these 'natural services' is universal or perpetual. The value of these services increases with the proportion of the channel network 'fluvial hydrosystem' exhibiting the above conditions*.

1.4 Thesis structure

This thesis is structured as follows:

Chapters 2 and 3 document and establish the current understanding of sediment issues in a UK lowland river system context, and review the legislative/policy frameworks and mechanisms available to implement sediment management in the UK. Based on a literature review information is presented on: sediment sources within a lowland catchment; problems and issues for lowland river channels associated with presence of excessive amounts of sediment; and management options available to reduce sediment supply to rivers. This information sets the context for the research, whilst steering the research towards potentially critical sediment sources within a catchment. The knowledge generated also provides the basis for identifying potential solutions to sediment-related problems identified during the research.

Chapter 4 provides an overview of the study area including the river catchment and channel characteristics, and regional catchment management that may be affecting sediment delivery to the river system. This information is used to justify the selection of the study reaches and delineate the boundaries for the river hydraulic and sediment modelling.

Chapter 5 provides information on the adopted research approach, tools/models used, and data integrated into or underpinning the research methodology and tools/models. Where appropriate, this chapter sets out the evidence-base to justify the final methodological choice(s).

Chapters 6 and 7 detail the research undertaken to assess and quantify the transfer of sediment through the river system, concentrating on the interaction between wash-material load and bed-material load, and comparing the performance of different sediment assessment tools and models (i.e. bench-marking). Changes in sediment dynamics are assessed in terms of catchment management by establishing implications for: river morphology; flood risk management; sediment continuity and habitats; and land and river quality. River sediment implications are assessed and discussed, in view of current knowledge and best practice (as described in Chapters 2, 3 and 4), to identify a suite of catchment management actions and solutions capable of meeting multidisciplinary targets and delivering win-win outcomes.

Chapter 8 summarises the key findings, messages and recommendations resulting from this research, which are aimed at informing the scientific community, river managers and other relevant stakeholders and interested parties.

2 SEDIMENT ISSUES IN A LOWLAND RIVER SYSTEM

2.1 Introduction

This chapter presents the findings from relevant research exploring current knowledge on sediment issues within a lowland river context, specifically gaining an understanding on the key sources of sediment within a lowland river catchment, the problems associated with an imbalance in sediment loads in lowland rivers, and the possible management actions/solutions that can potentially be implemented to resolve any problems. This information sets the context for the research presented herein, and is used specifically to:

- ❖ Establish those critical sediment sources/issues, the knowledge of which will underpin the research methodological framework, especially in relation to field survey and sampling strategies, needed to test the hypotheses;

- ❖ Establish potential solutions and management activities that can be implemented to resolve any sediment issues identified through this research; and

- ❖ Establish the current gaps in knowledge and research in relation to sediment issues in lowland rivers.

The movement of soil, sediment and water are intrinsically linked (Collins and Owens, 2006). The geomorphic activity of a river is governed by the relationship between flow and the sediment system, which is a continuum of sediment supply, transport and storage operating at a range of scales in space and time and incorporating the terrestrial and aquatic components of a river catchment (Schumm, 1977; Sear *et al.*, 2003; Alekseevskiy *et al.*, 2008).

Rivers respond morphologically to changes in water and sediment supply (Schumm, 1969), and erosion, deposition and re-distribution of sediment are naturally-occurring components of any river system. However, dysfunctional sediment dynamics can pose significant threats to people, property, infrastructure and the ecology/environment of a river (Thorne *et al.*, 2010a).

Diffuse agricultural/urban runoff and hydro-modification are considered to be the leading sources of sediment stress in a river system, and rainfall-runoff is the primary mechanism for sediment transfer to rivers (Nietch *et al.*, 2005). The links between anthropogenic activities, sediment-related processes and stressors, ecosystem function, health and provision of services are illustrated conceptually in Figure 2.1.

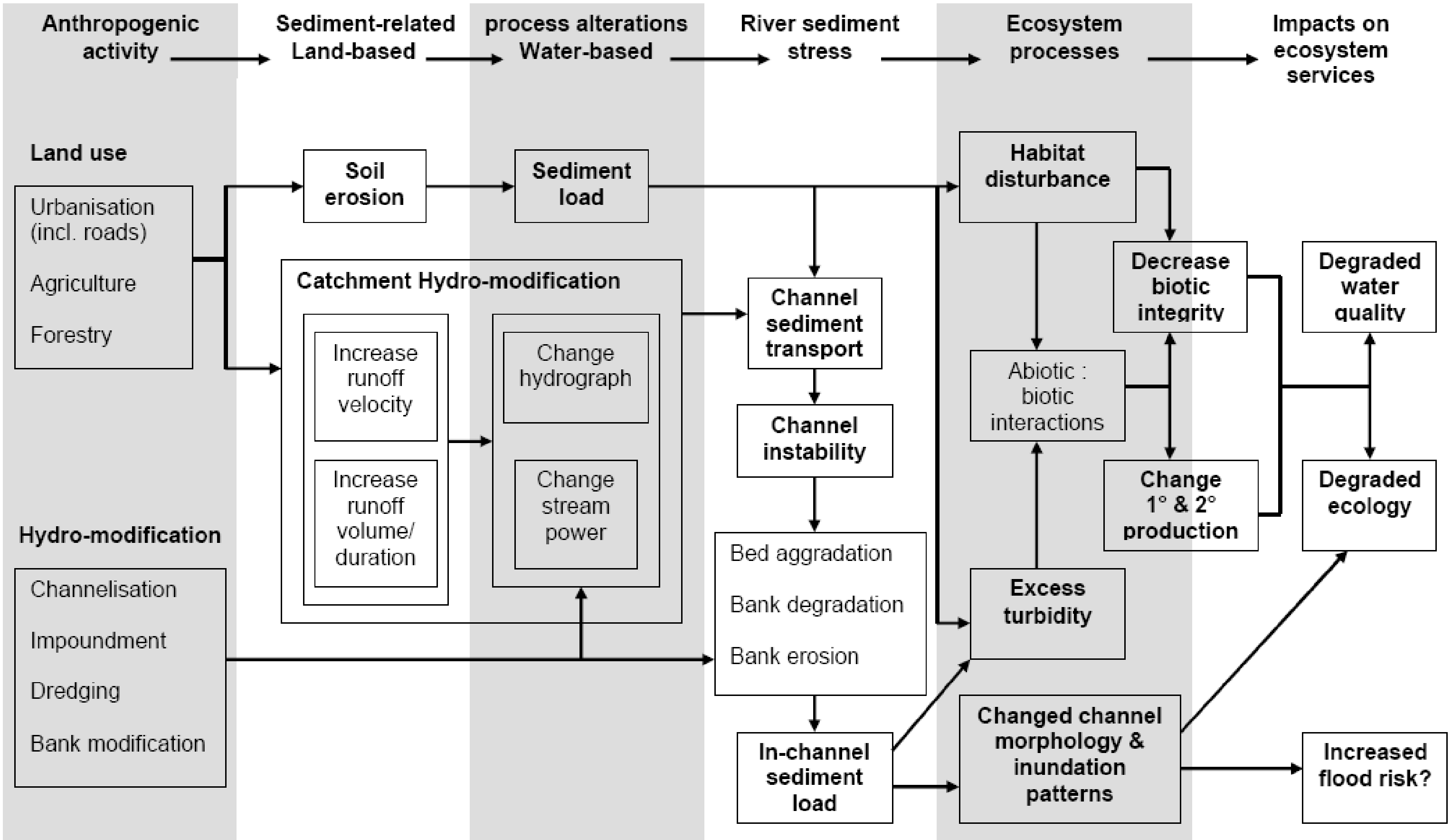


Figure 2.1 Conceptual linkages between sources of sediment stress and ecosystem functions (Adapted from Nietch et al., 2005)

2.2 Sediment sources

Even if lowland catchments were ‘pristine’ there would be a ‘background’ level of sedimentation, and it is important to recognise that there is a ‘natural’ sediment load that is not only normal but beneficial to catchment ecosystems. It is also important to understand that in the lowlands, sediment is not derived solely from eroding pasture and cultivated fields. While sediment is transported by overland flow eminating from pasture/cultivated fields, it also comes from roads and tracks, and from bed and bank erosion in ditches, streams and river channels (Evans, 2006; Collins and Walling, 2007). That said, intensification of grazing in pastoral land may be a major source of sediment (Heathwaite *et al.*, 1990; Evans, 2006a; Henshaw, 2009). The implication is that land use and intensivity of use are the most important drivers of sedimentation (Evans, 2006a; Henshaw, 2009).

Newson (1997) identifies sites which are particularly sensitive to the delivery of eroded soil into the channel network, which include: floodplain/slope contacts where overbank flow may access eroded slope material; floodplains with bare soil surfaces; and steep slopes with extensive surface drainage into the main river network. Henshaw (2009) identifies that altered catchment hydrology has the potential to de-stabilise the channel network leading to an increase in both fine- and coarse-sediment delivery to the channel network.

Collins (2008) provides an overview of literature identifying potential sediment sources in river catchments. He supports Evans (2006a) in identifying three key sediment sources: agricultural land, roads and river channel banks/subsurface sources.

It is estimated that erosion affects 40% of arable land (Evans, 1996) and investigations into the erosion of cultivated fields have been ongoing for many years. The Soil Survey of England & Wales investigated eroded fields in the lowlands between 1982 and 1986 (Evans, 2005), ADAS undertook national soil erosion monitoring between 1989 and 1994 (Chambers and Garwood, 2000), the Soil Survey and Land Research Centre investigated eroded fields between 1996 and 1998 (Harrod, 1998), and Boardman investigated sites between 1982 and 2002 (Boardman, 2002). Erosion rates varied between 0.01 tonnes/ha and 263 tonnes/ha, and these studies highlighted important drivers of erosion such as crop type (i.e. winter cereals exhibit more erosion; and crops such as maize, potatoes and sugar beet are higher risk). This finding is supported elsewhere, for example in the Wallonia Region of Belgium (Bielders *et al.*, 2003). It appears rare, high intensity rainstorms can result in exceptional soil loss and off-site damage. This is particularly true in landscapes supporting winter crops (Boardman *et al.*, 1996; Boardman *et al.*, 2003). Other factors influencing soil erosion include: removal of overland flow barriers such as hedgerows, leading to increased slope length and runoff velocities; reduction of soil organic matter; and excessive poaching through livestock intensification (Heathwaite *et al.*, 1990).

Walling and Collins (2005) reviewed the findings from 48 sediment sourcing studies across the UK and identified overall that agricultural soils (supporting pasture, arable, moorland and woodland) typically account for 85-95% of the total suspended sediment load in rivers. Arable land contribution ranged from 1-78%, with higher contributions being recorded for mixed agriculture catchments in southern England. A separate study found that 60-96% of suspended sediment measured in rivers during storm events was derived from surface sources (Withers *et al.*, 2007).

Soil erosion in agricultural landscapes can be influenced by the impact of livestock and farm vehicles on the soil surface through processes of trampling, poaching and compaction/disturbance that increase surface runoff and physically detach or mobilise soil particles, making them available for erosion. Livestock also contribute to sediment availability by direct excretion of faeces and application of manures, which can be compounded by farm vehicle movements further spreading the material. This can contribute significantly to sediment concentrations in watercourses (Brazier *et al.*, 2007).

Numerous studies have identified un-metalled roads as an important primary source of sediment (Wemple *et al.*, 2001; Zeigler *et al.*, 2006), while other researchers have identified the role of roads as an important secondary source of sediment, being sites of temporary sediment deposition (Gruszowski *et al.*, 2003; Morschel *et al.*, 2004) and important sediment pathways linking sources of erosion in a catchment to the river (Collins and Walling, 2004). A UK study assessing sedimentation in urban catchments (Ellis, 1999) suggested that roads may contribute up to 50% of the total suspended sediment in rivers, while Gruszowski *et al.* (2003) estimated that 30% of suspended sediment in the River Leadon in Herefordshire was derived from or transported via roads. Based on a range of studies, ADAS estimates that roads typically contribute ~20% of the total suspended sediment load (Prof, Adrian Collins, ADAS, pers. comm.).

There is a considerable body of evidence to support the contention that channel bank erosion is an important sediment source (Clarke, 1995; Wilkinson *et al.*, 2005; De Rose *et al.*, 2005; Collins and Walling, 2007; Lefrancois *et al.*, 2007; Henshaw, 2009). However, bank erosion contribution to suspended sediment loads varies widely both spatially and temporally. Bank erosion has been recorded as contributing from <5% to >80% (Stott, 1997; Imeson *et al.*, 1984). In the UK, Ashbridge (1995) demonstrated that eroding channel banks on the River Culm in Devon were contributing 13-30% of the silt/clay fraction of the sediment load, whilst Bull (1997) demonstrated how the silt/clay contribution from the River Severn changed depending on the period of study (i.e. 17% annually, 38% monthly, and 64% during an event).

Lefrancois *et al.*, 2007 demonstrated that availability of sediment particles from eroding banks on small agricultural catchments in northwestern France were subject to seasonal variation with maximum availability at the beginning of autumn (when discharge was low) reaching a minimum in winter (when discharge is high) and increasing again in spring. Bank degradation by cattle poaching is a key determining factor in suspended sediment dynamics, as this mechanism supplies a deposited sediment stock within the river channel even outside of flood events.

Gruszowski *et al.* (2003) assessed sediment sources in the River Leadon, Herefordshire in the UK and estimated that river banks and subsurface sources accounted for 43% of the total suspended sediment load. Walling and Collins (2005) review of sediment sourcing studies concluded that channel banks typically contribute 5-15% of the total suspended sediment load in UK rivers, with strong controls including catchment size (larger the catchment the greater the contribution) and geographical location (greater importance in north and western areas of the UK).

There is growing evidence that particles in the colloidal range (0.1-1 μm) may be readily transported through field, mole or tile drains (Brazier *et al.*, 2007; Henshaw, 2009), which are often present in lowland agricultural grassland in the UK. Subsurface drains may be responsible for delivery of up to 55% of suspended sediment loads in lowland catchments (Russell *et al.*, 2001).

2.3 Sediment problems

Historically sediment has been viewed as a river management problem primarily in relation to diffuse pollution. In this context sediment has been regarded both as a contaminant (i.e. smothering habitats, reducing light penetration) and, critically, as a pollutant vector (nutrients, organic contaminants, and trace/heavy metals) (Collins, 2008; Verstraeten *et al.*, 2003a and b). For example, sediment-associated phosphorus has been shown to account for 20-90% of the total phosphorus loss from agricultural land in the UK (Morgan, 2006). Nutrient enrichment in waterbodies can lead to algal blooms, reduced water clarity, loss of submerged plants, production of algal toxins, deoxygenation, fish kills and increased water treatment costs (Withers *et al.*, 2007; Withers and Sharpley, 2008). Indeed, eutrophication and siltation are two key challenges facing water management in the early part of this century (Mainstone *et al.*, 2008).

Sediment loading can directly or indirectly impact river habitat and ecological status affecting the feeding and health of aquatic organisms, and alterations to community structure and function in lowland streams (Wood and Armitage, 1999). Sediment supply is important in defining the amount and quality of instream habitat (diversity of sediment textures and geomorphic features), particularly in situations where there was a lack of less-mobile in-channel structures (Yarnell *et al.*, 2006; Bartley and Rutherford, 2005).

Smothering of fish spawning gravels is recognised as a critical issue associated with excessive sedimentation, which detrimentally affects the permeability (controlling the rate of oxygen supply and waste removal) and porosity (controlling the intra-gravel movement and emergence of fish fry) of gravels. Excessive sedimentation can also detrimentally affect aquatic macrophyte communities (Clarke and Wharton, 2001) and aquatic invertebrate communities (Ward *et al.*, 1998; Wood and Armitage, 1999).

A key finding from a review of rural land use and management on flood generation (O'Connell *et al.*, 2004) is that the greatest impacts of sediment delivery occur off-site, but generally within a radius of a few kilometres from the sediment source. Impacts associated with soil erosion and sedimentation tend to be cumulative and long-term. Human impacts on catchment sediment systems can induce a cascade of effects that propagate downstream, affecting other services and assets such as fisheries and fish habitat, stability of structures such as bridges, and modifying the frequency & intensity of flooding (Piegay and Hicks, 2005) as well as silting reservoirs, canals and harbours (Morgan, 2006). However, it is also important to understand and distinguish between natural fluctuations in sediment supply which can lead to a temporary build-up of sediment in the absence of competent 'flushing' flows and anthropogenically-triggered, long-term sediment deposition which can permanently modify fluvial systems (McIntyre *et al.*, 2013 in press).

Soil erosion on cultivated land, particularly winter cereals, can lead to muddy floods (Verstraeten *et al.*, 2003a and b; Boardman, 1990: Boardman *et al.*, 1996; Boardman *et al.*, 2003) which can cause significant financial and psychological damage. Furthermore, it is now recognised that the breakdown of soil by erosion releases carbon to the atmosphere, and that control of erosion could therefore make an important contribution to carbon sequestration (Morgan, 2006). Erosion is estimated to cost the UK economy £90 million/year of which 95% is associated with agriculture (Environment Agency, 2002a). This is likely to be an underestimation of the true cost as it does not include costs associated with flooding or water treatment (Morgan, 2006).

The link between altered/increased sediment delivery/deposition and increased flood risk was noted by Plate (2002) when assessing floodplain development along the Yellow River, China. The construction of embankments along the river prevented sediment from being deposited on the floodplain and increased deposition in the main channel. The channel cross section decreased, and the water conveying capacity of the river channel was also greatly reduced. Verstraeten *et al.* (2003a and b) also acknowledged that soil erosion leads to high suspended sediment loads which in turn deposit and reduce the channel capacity which hinders navigation, particularly in the vicinity of locks, and increases flood risk, resulting in the need for routine dredging of channels to maintain capacity.

The sediment loading and sedimentation of watercourses can interfere with the geomorphic functioning of river systems (Owens *et al.*, 2005), and research in the USA and New Zealand identified that changes in river bed levels through enhanced sediment delivery and channel aggradation can have major impacts on flood risk (Korup *et al.*, 2004; and Pinter and Heine, 2005). Very high concentrations (i.e. >20%) of wash-material load sediment can damp down turbulence, increasing the apparent viscosity of the flow and reducing settling velocities, enabling the transport of coarser grains and a larger bed-material load than would otherwise be expected (Knighton, 1998).

Very little research in the UK to investigate the interactions between sediment, morphology and flooding has been undertaken. One of the only studies is an investigation undertaken by Lane *et al.* (2007 and 2008). This research targeted an upland river environment, and assessed coarse sediment delivery and observed sedimentation over a 16 month period on the River Wharfe. The results were compared to changes in flood probability due to climate change, with the findings demonstrating that 16 months of sedimentation resulted in an increase in the 2-year inundation area which was equivalent with an increase predicted for the 2050s due to climate change. However, no comment on the effects of flood risk, in terms of damages to assets, was made. Research linking sediments, morphology and flood risk is evidently lacking in the UK.

The corollary of too much sediment is too little sediment, which can also have impacts on sediment dynamics, channel geomorphology and ultimately flood risk. For example, a significant reduction in sediment supply can lead to the deterioration or failure of flood defence structures and assets by facilitating increased levels of basal scour (HR Wallingford, 2008).

2.4 Sediment management options

2.4.1 Introduction

Diffuse sources of pollution, such as sediment, are often difficult to control due to their widespread occurrence and intermittent nature. Nevertheless, the importance of sediment control as part of overall water quality management was emphasised during the Third World Water Forum in Tokyo (Yamashiki *et al.*, 2006), and not only for severely degraded catchments but also where sedimentation impacts are considered small in a global context.

It has been argued that the best way to mitigate the fine sediment problems within lowland rivers and streams is to prevent excessive sediment influx into the watercourse through controlling the sources of sediment (Wood and Armitage, 1999). Greater concern regarding off-site effects of soil erosion has increased the emphasis placed on management at a catchment-scale, leading to identification of the need to address not only source areas but also hydrological linkages between different landscape units, i.e. the pathways along which the sediment is moved over the landscape (Morgan, 2006; Wainwright *et al.*, 2011).

Identification of the sources of sediment and linkages between control of water runoff and control of sediment are key to both understanding and managing the catchment sediment dynamics in an integrated approach (O'Connell *et al.*, 2004; Wilkinson *et al.*, 2010). To facilitate integrated catchment management it is vital to identify sediment 'hot-spots' within the landscape, where sensitivity to change is greatest (Newson, 2010). This could include sediment sources within the catchment as well as sediment sinks in the downstream channel network.

Evans (1996) provides an early overview of actions to curtail accelerated soil erosion and subsequent delivery to watercourses. These actions include: reducing field size; maintaining ground cover; mixed farming; appropriate livestock density; use of stream buffer zones; careful ditch clearance; and maintenance of footpaths and tracks. These issues are discussed further in the following sections under two main management options: ‘end-of-pipe’ solutions that aim to intercept and reduce runoff of water and sediment; and ‘at-source’ solutions that aim to use or manage the land to reduce soil erosion.

2.4.2 Run-off interceptors

Watercourse buffer features have often been used to intercept runoff and associated sediment, nutrients and pesticides in attempts to protect and improve water quality (Parkyn *et al.*, 2005; Lowrance and Sheridan, 2005; Muenz *et al.*, 2006; Owens *et al.*, 2005; Owens *et al.*, 2006; Owens *et al.*, 2007). Riparian buffers are areas of permanent vegetation located usually between agricultural fields or commercially-managed forests and watercourses. The buffers slow water runoff, which promotes the deposition of sediment and sediment-bound pollutants (particularly phosphorus) and the infiltration, immobilisation and transformation of dissolved pollutants (Dosskey *et al.*, 2005; Geyer *et al.*, 2001) as well as protecting the soil surface, increasing channel stability (Laubel *et al.*, 2003), and providing and enhancing terrestrial/aquatic habitat capable of supporting diverse ecological communities (Barling and Moore, 1994; Lyons *et al.*, 2000; Vondracek *et al.*, 2005; Yates *et al.*, 2007).

Literature reviews covering the role, structure and function of riparian buffers in different environments have been undertaken by, for example, Barling and

Moore (1994), Broadmeadow and Nisbet (2004) and Corell (2005). Key findings included:

- First and second order streams are key sites for buffers, as most catchment drainage moves through these streams and they provide enhanced opportunities for sediment deposition (Burkart *et al.*, 2004; Parkyn *et al.*, 2003).

- It is important to have continuous buffers on both sides of the stream;

- Buffer strips are most effective when water and sediment runoff flow is shallow (buffer is not submerged), slow, and enters the buffer strip uniformly;

- Sediment trapping performance decreases as the sediment particle size decreases, suggesting that buffer strips are better filters of coarser sediment (>silt/sand) rather than the clay fraction and associated nutrients. Most studies found that most sediment was deposited in the first few metres of the buffer; and

- Benefits are greatest where buffers support diverse habitat and replicate native riparian vegetation.

Nerbonne and Vondracek (2001) found that the percentage of fine sediment and embeddedness of channel substrate were both negatively correlated with buffer width, and that grass buffers had significantly lower percentage fines, embeddedness and exposed streambank soil compared to grazed or wooded buffers. This makes them a viable management technique, particularly if sedimentation and stream bank stability are serious concerns. Streams where banks were fenced (to prevent livestock access) and vegetated showed lower and more stable concentrations of nitrate N, suspended solids and faecal coliforms, with higher percentages of sensitive invertebrate groups (Muenz *et al.*, 2006). Research in Denmark (Laubel *et al.*, 2003) supports this finding, establishing that livestock fencing and buffer zones lowered bank erosion rates and subsequent levels of suspended sediment and phosphorus. Jansen and Robertson (2001) identify that lowered stocking rates could be used to improve riparian habitats where total exclusion of livestock is not practical.

Many field-scale investigations and modelling have assessed the trapping efficiency of different buffers in a variety of locations (Patty *et al.*, 1997; Abu-Zreig, 2001; Abu-Zreig *et al.*, 2004; Hook, 2003; Syversen, 2005; Zeigler *et al.*, 2006; Mankin *et al.*, 2007). Findings include that the key factors affecting sediment trapping are buffer width and sediment class. Trapping efficiencies ranged between 47% and 100%, depending on buffer width and substrate type. Most research has reported a trapping efficiency for silt/sand grain size >80% with the majority of sediment being trapped in the first 5-10 m of the buffer strip.

White *et al.* (2007) reported particle sizes >20 µm were largely retained through settling in the first 2 m. The 2-20 µm size fraction was largely removed within 16 m of filter. Conversely, particles of <2 µm were unaffected. Key mechanisms for sediment trapping included settling and infiltration of water and sediment into the substrate.

Owens *et al.* (2007) investigated 9 contrasting buffer strips in the Parrett catchment in Somerset, including 3 sites located in the headwaters of the River Tone catchment that were associated with sandy clay loam soils. Buffers in the Tone included 6-9 m grass strips at the bottom of fields and featuring trees, hedgerow, or a grassed riparian area. In the Tone, average sedimentation rates ranged from 0.102 (± 0.32) to 1.15 (± 1.88) g/cm^2 [mean average = 0.75g/cm^2]. The average sediment deposition for all 9 sites over the 18-month sampling programme was 0.41 (± 1.08) g/cm^2 (equivalent to an annual rate of 0.27 g/cm^2/year). Most of the sediment collected was sand-sized (>0.63µm), and about half of all collected sediment was from the first 50% of the width of the buffer strip. These findings suggest that the finer soil fraction (which tends to be enriched in total-P) may be passing through these types of buffer.

Dosskey *et al.* (2005) advocate the use of variable-width buffers that can match spatially-variable runoff loads at the field scale, thereby maximising trapping efficiency. Helmers *et al.* (2005) however investigated the effects of flow convergence and reported an average sediment trapping efficiency of 80% regardless of flow convergence/divergence.

Verstraeten *et al.* (2006) identify the need for caution when up-scaling after investigating scale-effects of riparian vegetated filter strips. They concluded that at the field scale buffers had a >70% trapping efficiency, however, at the catchment scale sediment reduction is much less (~20%) due to overland flow convergence and sediment bypassing buffers via ditches, sewers and roads.

Other runoff and sediment interceptors have also been assessed. For example, Leguedois *et al.* (2008) investigated 12m wide tree belts positioned downstream of pasture. They found a minimum of 94% of the total mass of sediment was trapped, with 'settling' being the main mechanism, although infiltration of water and sediment was also recorded. The finest grain sizes were probably trapped through absorption by leaf litter. This is supported by Williams *et al.* (1995) who found establishment of large woodland blocks can reduce water runoff.

Grassed swales have been found to reduce sediment delivery to watercourses by 77-97% with the majority of sediment retention occurring in the first few metres of the swale (Fiener and Auerswald, 2003; Deletic, 2005). Grain sizes >50 μm settled due to gravity and smaller grain sizes settled due to infiltration. This finding was supported by Ward and Jackson (2004) who recorded a trapping efficiency of 71 to 99%. Dewald *et al.* (1996) supports the use of grass hedges (narrow strips of stiff erect grasses, planted in parallel lines perpendicular to the dominant field slope) to reduce soil erosion. Fullen and Booth (2006) investigated grassland set-a-side and found that it was an effective soil conservation measure on erodible sandy soils because it increased the content of soil organic matter. On lowland clay soils set-a-side was found to increase water runoff due to soil compaction and deterioration of secondary drainage (Williams *et al*., 1995), however, this research also found levels of nitrate leaching was also reduced suggesting soil erosion was reduced by set-a-side.

When reviewing in-channel deposition of sediment within the middle reaches of the River Severn, Steiger *et al.* (2001) found that the highest levels of sediment deposition occurred in a narrow ribbon of the riparian zone (<3 m in width and <1.5 m in vertical elevation). They report that although vegetation type may affect local rates of sedimentation, it was insufficient to over-ride the reach-scale importance of geomorphic and hydrologic factors.

2.4.3 Altered land use management

Numerous studies (Barling and Moore, 1994; Verstraeten *et al.*, 2003a and b; Verstraeten *et al.*, 2006; Corell, 2005; and Bielders *et al.*, 2003) advocate that buffer strips should only be considered as a secondary conservation practice after control of the generation of sediment at source through alternative farming practices that promote greater soil structural stability, higher infiltration rates and therefore less erosion with subsequent off-site effects.

Clarke (1995) and Martin *et al.* (2004) identified that both land use and agricultural practices are important in the control of sources of sediment, although Martin *et al.* (2004) and Gilvear *et al*. (2010) did recognise the need for farmer co-operation to maximise benefits. Clarke (1995) concluded a change in land use from woodland to pasture/arable land would have a dramatic effect on erosion processes and sediment production, a finding supported by Van Rompaey *et al.* (2002) who assessed the effects of land use change from forest to arable, and *vice versa*, on sediment delivery and concluded that a relatively small increase in the area of arable land results in a relatively large change in sediment delivery.

Martin (1999) investigated the effects of different upslope agricultural practices on down-slope muddy flooding in terms of both soil erosion and water runoff. His findings identify the relationship between crop, land management and antecedent catchment moisture, with a ‘no tillage’ baseline resulting in low soil erosion and high water runoff. Compared to this baseline an ‘intercrop’ significantly reduced water runoff and maintained soil erosion rates, cultivating in humid conditions led to an increase in both water runoff and soil erosion, mouldboard ploughing increased soil erosion but reduced water runoff, and cultivation in dry conditions increased soil erosion and maintained water runoff rates. Therefore, implementing an intercrop (in this case mustard) resulted in low soil erosion with a significantly reduced water runoff rate.

Nisbet *et al.* (2004) produced a guide to using woodland to control the supply of sediment to a lake in which they advocated woodland planting to protect soils at risk from erosion in the catchment; tree planting along watercourses at risk from bank erosion; and planting trees at the locations where streams inflow into the lake to act as a wet woodland sediment sink. This is an approach advocated in recent research by Lane *et al.* (2007) who identified upland river management problems as a diffuse sediment delivery problem and recommended reducing coarse sediment delivery through woodland planting.

Godwin and Dresser (2000) undertook a review of soil management techniques for increasing water retention and minimising diffuse water pollution in the Parrett Catchment in Somerset (see Section 4.7.1). They concluded that improving soil management could reduce runoff and the subsequent mobilisation of soil with associated sediment and pollutant delivery to watercourses. Morgan (2006) supports these findings by identifying the key soil erosion control measures as minimising soil disturbance; keeping soil covered with a ground cover crop (>70% cover); maintaining or improving soil quality; creating buffer strips to control sediment movement and/or discharge of sediment into watercourses.

Investigations in relation to muddy floods in Southern England identified the need to implement land use change, for example minimising winter cereals and maize production in vulnerable areas, combined with implementation of structural solutions including the construction of small earth dams to interrupt flow (Boardman *et al.*, 1995; Boardman *et al.*, 2003). Evidence from Norfolk established that increasing field sizes and switching to winter cereals lead to extensive soil erosion, while a return to smaller fields and re-planting hedgerows/tree belts reduced the extent of soil erosion and interrupted the connectivity of flow. It also led to biodiversity gains (Evans, 2006b).

The effect of different soil cultivation techniques on sediment and phosphorus mobilisation in surface runoff has been investigated in the Hampshire Avon catchment (Withers *et al.*, 2007). Late cultivation increased surface runoff up to 5-fold and mobilisation of sediment up to an order of magnitude, and concentrations of sediment from greensand and chalk were consistently lower when the soil was minimally tilled rather than ploughed.

2.4.4 Factors influencing implementation of sediment management

In 2006 Defra undertook a Farm Practices Survey to quantify the uptake of practices to alleviate diffuse pollution. This survey found that actions such as hedgerow conservation, buffer strips, improved field drainage, reduced arable cultivation and woodland conservation appear to have the largest uptake. Implemented livestock-related management included: not spreading manure/slurry during wet periods, keeping manure away from watercourses, taking stock off land or delaying putting stock out to avoid poaching, using mobile feeders, fencing watercourses and reducing stock numbers were most commonly used.

There are barriers to implementation of best management practices (e.g. use of buffer strips, removal of arable production from sites adjacent to watercourses). These include such measures not always being economically feasible (Wood and Armitage, 1999) and the limited capacity of proponents to persuade people to change their customs and practices (Evans, 1996). The results from monitoring soil erosion in the early 1980s help explain why farmers think soil erosion is of little importance as, in the majority of cases, soil erosion did not affect how the farmer managed the land nor does it lead to a large enough removal of soil or burial of crops to affect profitability (Evans, 2002).

These barriers must be overcome if erosion is to be tackled successfully and the land used in a more sustainable manner, with Morgan (2006) recognising that sustainable soil conservation must rely on methods which are inherently economic for the land owner or user. Yamashiki *et al.* (2006) recognised the importance of effective economic evaluation of the impacts induced by sedimentation which is applicable to local farmers.

The economic viability of land management changes invoked to reduce runoff has been demonstrated in an Environment Agency study into flooding of the village of Crowlas in Cornwall (Halcrow, 2007a), which showed that land management can be an economically and technically feasible option for reducing flood risk.

This need to recognise the intrinsic value of nature and properly value the economic and social benefits of a healthy natural environment is a fundamental concept upon which the UK Government White Paper for the Natural Environment (HM Government, 2011) is based.

2.5 Key messages

Within the lowland river context there are three main sources of sediment: agricultural land (including arable and pasture); roads, which also act as key sediment pathways; and channel banks.

Excessive quantities of sediment have historically been viewed as diffuse pollution, which can adversely affect river/riparian habitat and ecology, and as such a water quality management issue. However, excessive sediment has the potential to increase fluvial flood risk through loss of discharge carrying capacity in channels. Conversely, too little sediment can also cause problems through undermining of structures via basal scour. However, the link between sediment and flood risk is a major research gap in the UK.

The control of sediment at source is advocated to prevent excessive sediment influx into rivers. Two main options are available: (1) at-source through changes land use (i.e. arable to pasture) and/or altered land management (i.e. reduced stocking density) to reduce soil erosion, or (2) runoff interceptors to reduce water and sediment entering rivers.

Barriers to implementing sediment source control include: (1) solutions not being, or not perceived to be, economically viable, and (2) inability to persuade land managers to change their ways of operating.

Given the above, the research presented within this thesis is needed to:

- Fill gaps in current knowledge relating to the link between excessive sediment delivery to rivers, particularly finer wash-material sediment derived from the catchment, and flood risk;

- Provide improved evidence, upon which appropriate policy governing sediment management, particularly at the catchment scale, can be set;

- Provide improved evidence, upon which appropriate sediment management actions, which are based on clear cause-effect links, can be determined; and

- Provide improved evidence, upon which engagement with local stakeholders and land managers can be based to facilitate a management response.

3 MECHANISMS AVAILABLE TO IMPLEMENT SEDIMENT MANAGEMENT IN THE UK

3.1 Introduction

At a catchment scale land use and land management (catchment activities), and subsequent effects and impacts related to sediment, will be influenced by local conditions, but also national trends, relevant policy and market forces. However, catchment activities will ultimately be determined by individuals (UKWIR, 2012). It is the combination of national, local and individual actions that determine the nature of land use and management change, and the options available to tackle sediment-related problems at the catchment- and/or reach/field-scale.

This chapter presents the findings from a review of the potentially relevant legislative and policy frameworks, and policy implementation mechanisms, available to drive sediment management at the catchment scale in the UK. This information sets the context for the research presented herein, and is used specifically to:

- Establish the appropriateness of existing catchment management policies and mechanisms to resolve any sediment issues, which may be identified through this research; and

- Establish whether new/refined policies or mechanisms are required, or whether there are opportunities to better promote the existing policy framework, to allow sediment management to be fully integrated into river catchment management.

Management of sediments in UK river catchments is embedded within a hierarchy of governance (Figure 3.1) – a key to acronyms and initialisms used in this figure is provided at the front of this thesis. The sustainable management of soil, reduction in sediment runoff, reduction in sedimentation of rivers or management of sediment in rivers are covered by three key legislative and policy arenas: Land & Soil Management; River Quality Management; and Flood Risk Management.

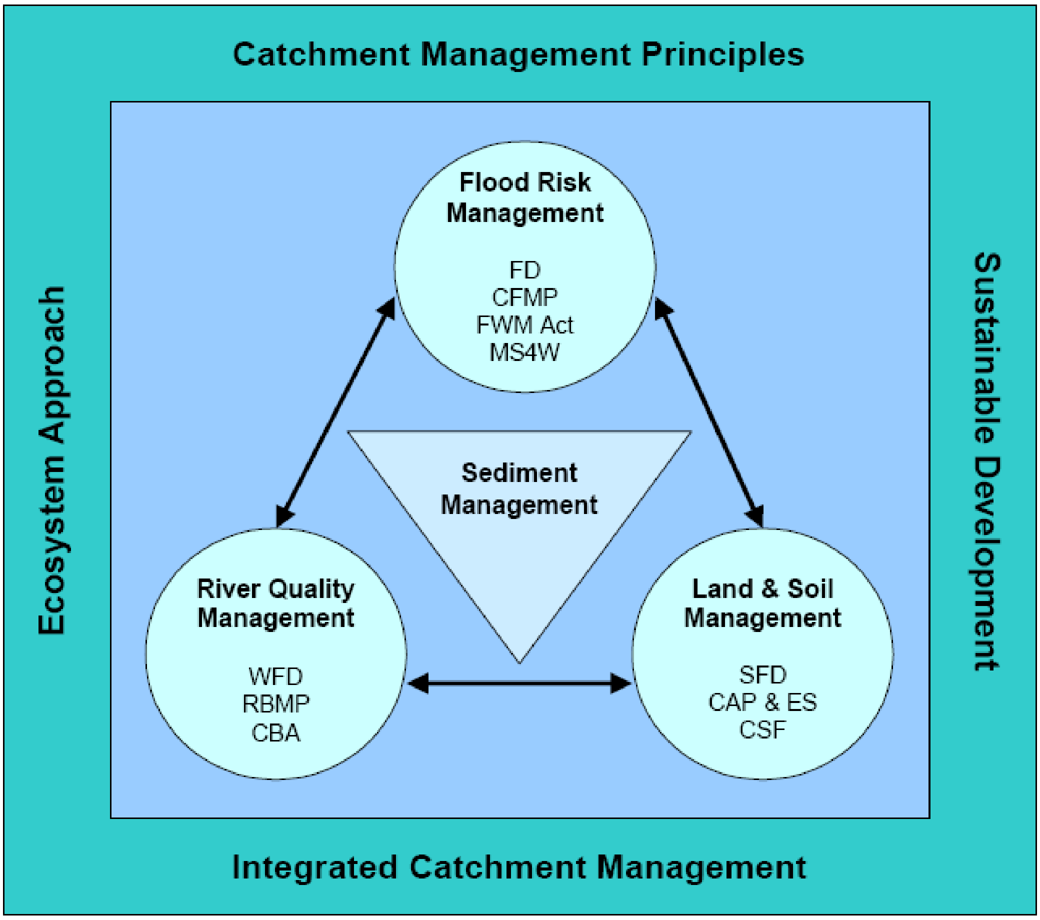


Figure 3.1 Legislation and policy governing sediment management

Legislation and policies associated with Soil & Land Management and River Quality Management are widely acknowledged as driving changes in future catchment management, but it is suggested in this thesis that Flood Risk

Management may also have a role to play in shaping the future management of soils and sediments in catchments. These three policy arenas are themselves embedded within over-arching national policies for catchment management (see Section 3.2), which encapsulates sustainable development; management of the natural environment using an ecosystem approach; and integrated catchment and water management.

3.2 Over-arching catchment management principles

3.2.1 Sustainable development

At the 1992 Rio Summit governments committed to the concept of sustainable development. There are many definitions of sustainable development, but the widely used international definition is '*development which meets the needs of the present without compromising the ability of future generations to meet their own needs*', which is taken from 'Our Common Future (the Brundtland Report) – Report of the 1987 World Commission on Environment and Development (HM Government, 2005).

In 2005 the Government published its sustainable development strategy 'Securing the future – delivering UK sustainable development strategy' (HM Government, 2005). This document defines five guiding principles for achieving sustainable development within the UK, and which now underpin the all policies in the UK:

- *Living within environmental limits*: respecting the limits of the planet's environment, resources and biodiversity to improve our environment and ensure that the natural resources needed for life are unimpaired and remain so for future generations; and

- *Ensuring a strong, healthy and just society*: meeting the diverse needs of all people in existing and future communities.

This will be achieved by:

- *Achieving a sustainable economy*: including environmental and social costs falling on those who impose them (polluter pays), and efficient resource use is incentivised;

- *Promoting good governance*: actively promoting effective, participative systems of governance; and

- *Using sound science responsibly*: ensuring policy is developed and implemented on the basis of strong scientific evidence.

Defra, as the lead Government department responsible for developing flood risk policy in England and Wales, has also published a sustainable development action plan which sets out how sustainable development is embedded within their policies (Defra, 2005b). As expected, this aligns with the UK Strategy guiding principles as set out above.

3.2.2 Managing the natural environment

Defra (2007) published 'Securing a healthy natural environment: an action plan for embedding an ecosystem approach', which formed the basis for a more strategic approach to policy-making and delivery. The ecosystem approach is intended to help deliver natural environment policy outcomes whilst balancing the core pillars of sustainability: economics, environment and society. There are various definitions of 'ecosystem approach' (i.e. Convention on Biological Diversity, available at: www.cbd.int/ecosystem; Nakamura, 2003) but Defra (2007) promote the ecosystem approach through five core principles:

- ❖ Taking a more holistic approach to policy-making and delivery, with the focus on maintaining healthy ecosystems and ecosystem services;
- ❖ Ensuring that the value of ecosystem services is fully reflected in decision-making;
- ❖ Ensuring environmental limits are respected in the context of sustainable development, taking into account ecosystem functioning;
- ❖ Taking decisions at the appropriate spatial scale while recognising the cumulative impacts of decisions; and
- ❖ Promoting adaptive management of the natural environment to respond to changing pressures, including climate change.

Defra is committed to embedding the principles of the ecosystems approach in its new policy appraisal guidance for flood and coastal erosion risk management (see Section 3.5.3) and the UK Water Strategy (see Section 3.2.3).

In June 2011 the UK Government published a White Paper on the Natural Environment (HM Government, 2011), which sets out proposals for safeguarding and restoring the natural environment. This white paper integrates and builds upon the Ecosystem Approach and other recent research (i.e. Lawton *et al.*, 2010; The UK National Ecosystem Assessment, 2011). The Government long-term vision is to:

- Improve the quality of our environment across England, moving to a net gain in the value of nature. We aim to arrest the decline in habitats and species and the degradation of landscapes. We will protect priority habitats and safeguard vulnerable non-renewable resources for future generations. We will support natural systems to function more effectively in town, in the country and at sea.

The vision will be achieved through action at local and national level to create an ecological network which is resilient to changing pressure. Government commitments, which are particularly relevant for this research, include:

- *Getting the best value from agricultural land*: including a review of how advice and incentives for farmers and land managers are used, to create a more integrated, streamlined and efficient approach to yield better environmental results;

- *Safeguarding our soils*: including a research programme to explore how soil degradation can affect the soil's ability to support vital ecosystem services such as flood mitigation, carbon storage and nutrient cycling; and

- *Restoring nature in our rivers and water bodies*: including regulatory bodies working with farmers to increase the number and appropriate location of Environmental Stewardship schemes where there are diffuse pollution problems.

A key tenet of the Natural Environment White Paper establishes the need to implement integrated management of the natural environment at a 'landscape scale', which is acknowledged as the best way to achieve multiple benefits. In this context landscape scale is used to refer to action that covers a large spatial scale, usually addressing a range of ecosystem processes, conservation objectives and land uses. As such there is a strong link between the landscape scale approach and an ecosystems approach.

Implementation of the landscape scale approach is seen in the Government commitment to establish river catchment-level partnerships to develop and implement plans for creating and maintaining healthy water bodies under the Water Framework Directive (see Section 3.4 for further detail).

3.2.3 Integrated catchment management

In 2008 the UK Government published 'Future Water – The Government's water strategy for England' (Defra, 2008), which sets out the how the Government wants the water sector to look by 2030. The vision for water policy and management encompasses the following components relevant for this research:

- Improved quality of the water environment and the ecology which it supports;

- Sustainably managed risks from flooding and coastal erosion, with greater understanding and more effective management of surface water; and

- Continuous adaptation to climate change.

Defra has published or implemented specific strategies, which contribute to the overall vision for water in the UK. The First Soil Action Plan for England: 2004-2006 Soil Strategy (Defra, 2004c) is discussed in Section 3.3; The River Basin Management Planning process developed under the auspices of the Water Framework Directive will play a key role in delivering the overall water strategy vision, and this element is discussed in Section 3.4. Making Space for Water (Defra, 2005a), which deals with flood and coastal erosion risk management, is discussed in Section 3.5.3.

3.3 Land and soil management

Agricultural land accounts for over 70% of the total land use in England (HM Government, 2011) and is the dominant land use in rural areas including this research study area (see Section 4). Posthumus and Morris (2007), as part of the FRMRC, and Halcrow Group Ltd (2007), as part of an Environment Agency review of implementing Making Space for Water, have undertaken reviews of rural land management policies and drivers, which are relevant for water and sediment management. A summary of the main drivers for land management taken from these two reviews is provided below.

The key drivers for agricultural land management (and therefore soil erosion and sediment transfer management) are policy and subsidy. After the Second

World War the Government committed to agriculture intensification and modernisation and the pre-war landscape of small fields with hedgerows and meandering rivers was replaced with one of large fields, land drains, realigned rivers and compacted soils (O'Connell *et al.*, 2004; O'Connell *et al.*, 2007). From the 1960s to the 1980s European agricultural policy continued to promote self-sufficiency, with subsidies incentivising farmers to further intensify production.

In the mid-1980s modifications to the Common Agricultural Policy (CAP) allowed the creation of agri-environment schemes, which provided financial incentives for farmers to adopt practices that protected and enhanced the farmland environment and wildlife. Two of the main components were the Environmentally Sensitive Area (ESA) scheme, which related to specific areas of England, and the Countryside Stewardship Scheme (CSS), which established voluntary agreements with landowners to meet CSS objectives.

In 2005 a new CAP-reform decoupled financial support from agricultural production, with income support payments being linked to compliance with standards to protect, *inter alia*, the environment. The Single Payment Scheme (SPS) pays producers if they are able to demonstrate that they meet the requirements of Good Agricultural and Environmental Conditions (GAEC) and Statutory Management Requirements.

GAEC requirements include (a) soil management and protection, and (b) maintenance of habitats and landscape features. Key actions potentially related to water and sediment runoff include: winter crop cover; not undertaking mechanical operations on waterlogged soil; not overgrazing land;

leaving a 2m uncultivated strip next to watercourses; and not removing hedgerows.

In the mid-2000s, the CSS and ESA were replaced with a new agri-environment scheme; the Environmental Stewardship (ES) scheme, which comprises the Entry Level Scheme (ELS), the Organic Entry Level Scheme (OELS) and the Higher Level Scheme (HLS). This scheme has, *inter alia*, the primary aim of protecting natural resources, while flood management is a secondary objective. Key ELS/HLS actions related to, or potentially influencing, water runoff and sediment erosion/runoff in river catchments include:

- ELS: management of high erosion risk cultivated land (i.e. avoiding high impact use such as outdoor pigs, potatoes, maize etc); establishment of buffer strips; maintaining over-winter stubble; cutting ditch vegetation; prevent overgrazing in woodlands; and not increasing drainage in uplands.

- HLS: creation of in-field grass areas (analogous to grass hedges); arable reversion to grassland; appropriate management of intensively grazed grassland; creation of wet grassland; inundation grassland supplements; and creation of reedbed/fen.

Financial grants for the creation and management of woodland are available through the Forestry Commission's Woodland Grant scheme. Annual Farm Woodland Payments are also available through the England and Wales Rural Development Programme. The Woodland Grant Scheme prioritises schemes that: promote woodland to help protect other natural resources; creation of floodplain woodland; and use of woodland to improve soil quality and water quality/quantity.

In 2004 Defra launched the First Soil Action Plan for England: 2004-2006 (Defra, 2004c). Of relevance to the research presented in this thesis are policies/actions related to 'interactions between soils, air and water', with key messages stressing:

- The importance of soil management which protects both surface water and groundwater; and

- The need for poor soil management that could increase flood risks or lead to decreased air and water quality to be defined, discouraged and, where appropriate, penalised. Conversely, soil managers should be rewarded for delivering public goods through good soil management.

In 2004 the Environment Agency published The State of Soils in England and Wales (Environment Agency, 2004). This report concluded that soil, water and air are strongly inter-dependent and must be managed as part of one whole. Key messages of relevance to the research presented in this thesis include:

- Meeting environmental objectives for water and air also depends on good soil management;

- Sustainable land management practices are required that are environmentally responsible; and

- ❖ Many flooding problems are made worse by ignoring the water retention function of soils such that sustainable rural drainage practices are needed that work with the natural soil hydrology.

In 2005, Defra launched the Catchment Sensitive Farming (CSF) scheme, which seeks primarily to reduce diffuse water pollution from agriculture through educating farmers and implementing best practices such as promoting good soil structure, reducing stocking density and protecting watercourses with buffer strips. Where soil erosion is a critical concern Soil Management Plans are developed, with key mitigation measures being implemented including: avoiding soil compaction; cropping across the slope where safe; harvesting high risk fields first to allow a winter crop to be established; avoiding high risk crops; and using buffer strips.

In Southwest England the CSF initiative is supported by the Soils for Profit Project (S4P), which aims to help farmers become more efficient whilst providing environmental benefits, including reducing water and soil runoff, by providing advice and training. S4P is part of the South West Agricultural Resources Management (SWARM) project, which is funded by Defra, delivered by Natural England working in partnership with the Environment Agency. The S4P is also supported by think***soils***, which is an Environment Agency initiative to help farmers assess soil condition.

The Third World Water Forum called for the establishment of international standards and regulations for controlling fine sediment delivery to watercourses (Yamashiki *et al.*, 2006). In Europe the draft Soil Framework Directive (SFD) was introduced by the European Commission in 2006, but is still under consultation. It aims to establish a common strategy for the protection and sustainable use of soil, based on the principles of preservation of soil functions within the context of sustainable use, prevention of threats to soil and mitigation of their effects, as well as restoration of degraded soils to a level of functionality consistent with the current and approved future use (Posthumus and Morris, 2007). In other words the SFD will not only recognise the need to prevent impacts arising from soil erosion and sediment transfer on receptors, but will also recognise the intrinsic value of soil as a resource (Collins and Owens, 2006).

The UK Government strongly supports the overall objective of protecting Europe's soils and agrees that there is need for action to deal with serious soil degradation. However, the UK Government's position is that the UK already has robust domestic policies to protect soils (www.defra.gov.uk/food-farm/land-manage/soil/soil-framework-directive/).

3.4 River water quality management

Improved control of point source pollution has exposed the effects of diffuse pollution exacerbated by soil erosion in river catchments. Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy, otherwise known as the Water Framework Directive (WFD), came into force in 2000 with the aim of improving the ecological and chemical statuses of the water environment, and to encourage sustainable water resource management. The WFD requires that all surface waters and groundwaters within defined river basin districts must reach at least 'good' status. The UK Government aims to achieve this for as many waterbodies as possible by 2027.

The WFD provides the means to achieve the UK water quality vision (Defra, 2008) in a way that integrates financial, social and environmental considerations. River Basin Management Plans (RBMPs) at a River Basin District scale are developed by the EA and set out the Programmes of Measures (PoM) for each waterbody to ensure they meet good ecological status (GES), or good ecological potential (GEP) in the case of heavily modified waterbodies (HMWB) or artificial waterbodies. Diffuse pollution is a key issue with solutions needed to tackle it at source.

The primary interest in runoff from farmland is associated with the potential effects of soil erosion and sedimentation on water quality and changes in hydro-morphology. Reducing the risk of floods is not one of the principal objectives of the WFD, however, it should establish a framework that contributes to mitigating the effects of floods and droughts (Wharton and Gilvear, 2006). Addressing water quality and hydro-morphology will contribute to mitigating the effects of floods as measures to reduce soil erosion and transport into rivers will result in a reduced sediment load, leading to greater river capacity and therefore a reduced risk of flooding (Defra, 2004b). The Floods Directive (see Section 3.5.2) makes explicit this link by stating 'river basin management plans and flood risk management plans [Catchment Flood Management Plans in England and Wales] are elements of integrated river basin management' and 'should use the mutual potential for common synergies and benefits'.

Furthermore, the linkages between historic flood management and water quality management are incorporated within the WFD. Existing flood risk management measures on a waterbody, which prevent that waterbody from achieving GES, will lead to the classification of the waterbody as a HMWB. As such the waterbody will need to reach GEP, which is defined as the ecological quality expected for a river of the same type at GES but allowing for the specific impact associated with the modification. Mitigation measures will be required if the primary function of flood management and associated standards of defence can be achieved in some other way that is more environmentally beneficial and without incurring disproportionate costs (Defra, 2004a).

The WFD therefore requires existing flood risk management structures, operation and maintenance works to be assessed and possibly altered to meet the WFD standards. The organisation responsible for implementing any required mitigation will be the lead organisation providing the primary service for which the waterbody was designated as a HMWB; in the case of a river designated as a HMWB due to flood risk management activities this is the Environment Agency (Ben Bunting, Environment Agency South West River Basin Planning Manager, pers. comm.).

There has been criticism that the first cycle of river basin management planning (2006-2009) at the river basin district scale does not take account of local issues and locally planned action (Crilly, 2011). As such many stakeholders have pressed for a more locally focused approach to planning, at the catchment scale. The Environment Agency is now taking forward the Government's commitment to a catchment based approach within 100 river catchments in England. Twenty-five 'pilot' catchments are being evaluated up to December 2012 to assess approaches for facilitating engagement at catchment and sub-catchment scales to, *inter alia*, deliver multiple benefits from an ecosystem approach.

3.5 Flood risk management

3.5.1 Introduction

Flood risk management is defined as 'the continuous and holistic societal analysis, assessment and reduction of flood risk' (Samuels *et al.*, 2006). In the UK during the 20th Century, there was a shift away from control of flood probability towards managing flood risks through influencing flood vulnerability of communities that recognised that people and their activities can increase or decrease the risk associated with flooding (Samuels *et al.*, 2006). Research has identified that the most effective flood risk management strategy is damage prevention by spatial planning (Samuels *et al.*, 2006), while the Foresight Flooding Project notes that it seems likely that the emphasis for flood risk management will move away from water conveyance in defended channels and towards re-connecting channel to floodplains in flood-suitable areas (Evans *et al.*, 2006). However, the Committee for Climate Change in a study assessing how planners balance the risk of flooding with new development found that development in the floodplain had increased over the last ten years, and that in England approximately 15,000 new homes each year are built in the floodplain (Cork, 2011). The study concluded that this is increasing the UK's vulnerability to climate change.

Plate (2002) argued that flood risk management is a dynamic process. As societal values change or as natural boundary conditions are modified, for example through human intervention or global climate change, then existing flood risk management solutions may no longer meet the demands of society.

What appears to be clear is that the historic river management regimes have outstripped the natural capacity of river catchments to maintain a healthy and sustainably functioning system. For example, 85% of lowland rivers in England and Wales have been physically altered, with channelisation for flood defence purposes being a significant contributor (Mance *et al.*, 2002).

3.5.2 European legislation

The European Directive on the Assessment and Management of Flood Risks (2007/60/EC of 23 October 2007) (the Floods Directive) came into force on 26 November 2007. Key messages from the Directive include:

- Member states should produce flood risk management plans, which… promote the achievement of environmental objectives laid down in community legislation;

- Plans should have a view to giving rivers more space, they should consider where possible maintenance and/or restoration of floodplains, as well as measures to prevent and reduce damage to human health, the environment, cultural heritage and economic activity;

- Flood risk management plans shall address all aspects of flood risk management… may also include the promotion of sustainable land use practices, improvement of water retention…; and

- River basin management plans (under WFD) and flood risk management plans are elements of integrated river basin management… should use the mutual potential for common synergies and benefits

Long-term flood risk management policies are developed and reported within a Catchment Flood Management Plan (CFMP). The CFMP allows delivery of a response that reduces flood risk whilst maximising opportunities to deliver multiple benefits for society and the environment. The CFMP will contribute to the implementation of the Water Framework Directive by identifying flood management policies that will contribute to the implementation of the WFD programme of measures, and flood management activities will be undertaken in ways that are consistent with the WFD (Defra, 2005a).

3.5.3 National policy and legislation

Defra is the lead Government department responsible for developing flood risk policy in England and Wales. However, up until 2010 responsibility for flood risk management was devolved to the Environment Agency, an associated public body of Defra (House of Commons Environment, Food and Rural Affairs Committee, 2008) with Defra's role to define policy, provide funding and to set targets.

In 2010 the Flood and Water Management Act 2010 changed the role of the Environment Agency to that of developing, maintaining, applying and monitoring a strategy for flood and coastal erosion risk management in England (the Welsh Ministers were tasked with this role in Wales). The 2010 Act further established that a lead local flood authority for an area in England and Wales must develop, maintain, apply and monitor a strategy for local flood risk management. The lead local flood authority is defined as the unitary authority in England, or the County Council / County Borough Council in Wales.

Making Space for Water

Making Space for Water (Defra, 2004a; Defra, 2005a) is the Government's strategy for managing flood and coastal erosion risks in England over the next twenty years. The aim of the strategy is to manage the risks of flooding and coastal erosion by employing an integrated portfolio of approaches which reflect both national and local priorities, so as to reduce the threat to people and their property as well as to deliver the greatest environmental, social and economic benefit, consistent with the Government's sustainable development principles.

Making Space for Water is explicit in confirming the move towards a more strategic approach which employs a wider portfolio of responses including greater use of rural land use and land management solutions. The strategy makes it clear that maximum advantage should be taken of the status of flood management as a secondary objective in the Environmental Stewardship scheme, and the control of water runoff from soils under the new Single Payment arrangements of the reformed Common Agricultural Policy (see Section 3.3 for further details). This more holistic approach to flood risk management involves a move away from merely local analysis to a catchment-wide view and from solely financial cost-benefit analysis to a full ecosystems approach.

Foresight Future Flooding

Much of the evidence base for Making Space for Water was provided by the Foresight Future Flooding project (Evans *et al.*, 2004a; Evans *et al.*, 2004b; Evans *et al.*, 2008). The project analysed future flood risk scenarios for the whole of the UK over the next 30-100 years to inform strategic choices, with flood risks assessed against three metrics of sustainable development. Consideration was also given to the robustness of responses (ability to cope with socio-economic and climate change uncertainty) and the precautionary principle (guarding against making decisions today that are deeply regretted in the future and the ability to cope with extreme events).

Four scenarios were developed for future policy analysis taking into account potential future climate and socio-economic change, which combined differing future changes in greenhouse gas emissions, economic growth, energy consumption and technological innovation. The key conclusions of the foresight project (2004 and 2008) are:

- There are potentially large rises in future flood risk under the baseline flood management assumption (continue 'as we are'), and updated climate change scenarios indicate we may have to cater for bigger increases in river flows than previously envisaged;

- Integrated flood risk management must lie at the core of any response employing a portfolio of engineering and non-structural responses; and

- ❖ Sustainability of flood risk management responses would improve if the design and implementation of response were applied in a socially-equitable manner taking a precautionary approach to future uncertainty

Review of Flooding in 2007

The Pitt Review ‘Learning lessons from the 2007 floods’ (Pitt, 2008) compiled and reviewed evidence pertaining to the floods that struck the country during June and July 2007. The review provided 92 recommendations for better management of flood risk, with two recommendations being relevant in the context of this research:

- ❖ Recommendation 23: Government should commit to a *strategic long-term* approach to its investment in flood risk management, planning up to 25 years ahead; and

- ❖ Recommendation 27: Defra, the Environment Agency and Natural England should work with partners to establish a programme through Catchment Flood Management Plans to achieve greater working with natural processes.

The Pitt Review was assisted by a Government Inquiry into the 2007 floods, and the Government’s response which was reported in early 2008 (House of Commons Environment, Food and Rural Affairs Committee, 2008). The Inquiry stated that the Environment Agency and Natural England need to agree on how to resolve any conflicts between drainage for flood defence and the preservation of watercourses for wildlife, whilst also investigating the role and duties of riparian owners in managing and protecting watercourses.

Flood and Water Management Act 2010

The Flood and Water Management Act 2010 makes provision for the management of risks in connection with flooding and coastal erosion. The Act consolidates recommendations developed by the Foresight Flooding project (2004 and 2008) and the Pitt Review (2008), see above.

The 2010 Act defines a flood as any case where land not normally covered by water becomes covered by water, and its causes encompass: heavy rainfall; a river overflowing or its banks being breached; a dam overflowing or being breached; tidal waters; groundwater; or anything else (not including flooding from sewerage systems or a burst water main). Flood risk is defined as a combination of the probability of occurrence with its potential consequences. Consequences include those for human health; social and economic welfare; infrastructure; and environment.

The Act also identifies examples of things that might be done in the course of flood or coastal erosion risk management, such as:

- Planning, erecting, maintaining, altering or removing buildings or other structures (including flood defence structures);

- Maintaining or restoring natural processes;

- Reducing or increasing the level of water in a place;

- Carrying out work in respect of a river or other watercourse;

- Making arrangements for financial or other support for action taken by persons in respect of a risk or preparing to manage the consequences of flooding; and

- Providing education and giving guidance (e.g. changes to land management).

3.6 Key messages

The sustainable management of soil, reduction in sediment runoff and reduction in sedimentation in rivers is governed by a hierarchy of policy and legislation. However, there are two primary policy and subsidy areas: (1) land and soil management (i.e. CAP, ES, CSF, S4P); and (2) river quality management (i.e. WFD). These are acknowledged as critical policy/legislative/subsidy frameworks, which will drive future catchment management.

Flood risk management policy/legislation (i.e. FD, MS4W, FWM Act 2010), however, is not explicit in the role of sediment source control may play in reducing flood risk, which may be either due to a perception that sediments do not contribute significantly to increased flood risk or Annual Expected Damages, or, more likely, due to a general lack of understanding in the role sediments can play in flood risk management (Thorne, 2011).

Flood risk management policy/legislation does, however, make a specific link to sustainable land management and, importantly, working with (maintaining or restoring) natural process that could, or should, include a natural or balanced sediment regime. Unfortunately, within the legislation there is no definition as to what 'maintaining or restoring natural processes' actually means or how is should be achieved.

Given the importance that 'working with natural processes' is given within relevant policies and legislation, a definition of 'working with natural processes' is provided in Section 1.3.2 of this thesis.

Through exploration and testing of the hypotheses and key study objectives, set out in Section 1.2, this research aims to identify whether the current policy, legislation and subsidy mechanisms are appropriate and robust enough to enable sediment source control to be fully integrated into catchment management given the likely implications and impacts associated with an excessive supply of sediment to rivers, with a particular focus on flood risk.

If they are not considered appropriate, then the research outcomes will allow a view to be taken on how to improve, or better promote, existing policies to facilitate catchment management which addresses both water and sediment runoff in an integrated way.

4 OVERVIEW OF STUDY AREA AND RIVER CATCHMENT

4.1 Overview of River Tone study area

The river catchment is a convenient and meaningful unit for the management of soil erosion and sediment redistribution, since the shape and characteristics of the river catchment control the pathways and fluxes of soil, water and sediment (Owens *et al.*, 2004; Collins and Owens, 2006). The river catchment is now widely adopted as the most appropriate spatial unit for characterising and managing diffuse sediment source problems (Walling and Collins, 2008).

This research is centred on the River Tone catchment, which is a sub-catchment of the River Parrett in Somerset, England (Figure 4.1). The research focuses on the lower River Tone, which flows through Taunton and across the Somerset Levels, and the Halse Water catchment which is a northern tributary of the upper River Tone (Figure 4.2).

The River Tone and its northern tributaries, which include the Hillfarrance Brook, the Halse Water and its tributary the Back Stream, have their sources in the Brendon and Quantock Hills to the west of Taunton. The upper Tone flows from north to south, and then from west to east through Taunton. It then flows northeast across the Somerset Levels and Moors to its confluence with the River Parrett upstream of Bridgwater (Figure 4.2). The three tributaries all flow north to south joining the Tone above Taunton.

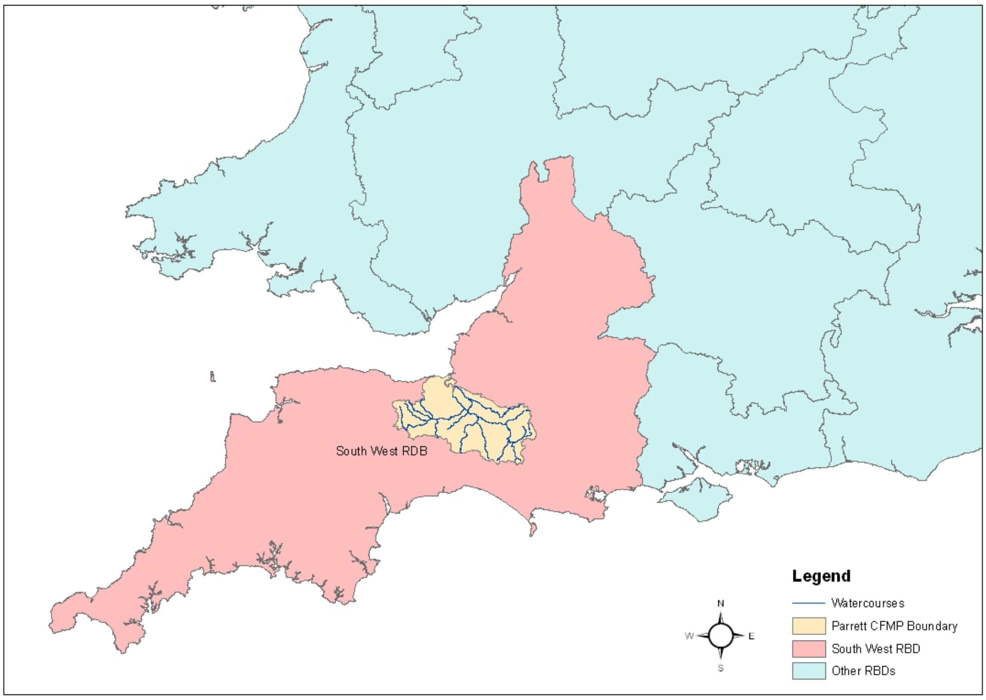


Figure 4.1 Parrett Catchment, which includes the River Tone and Halse Water sub-catchments

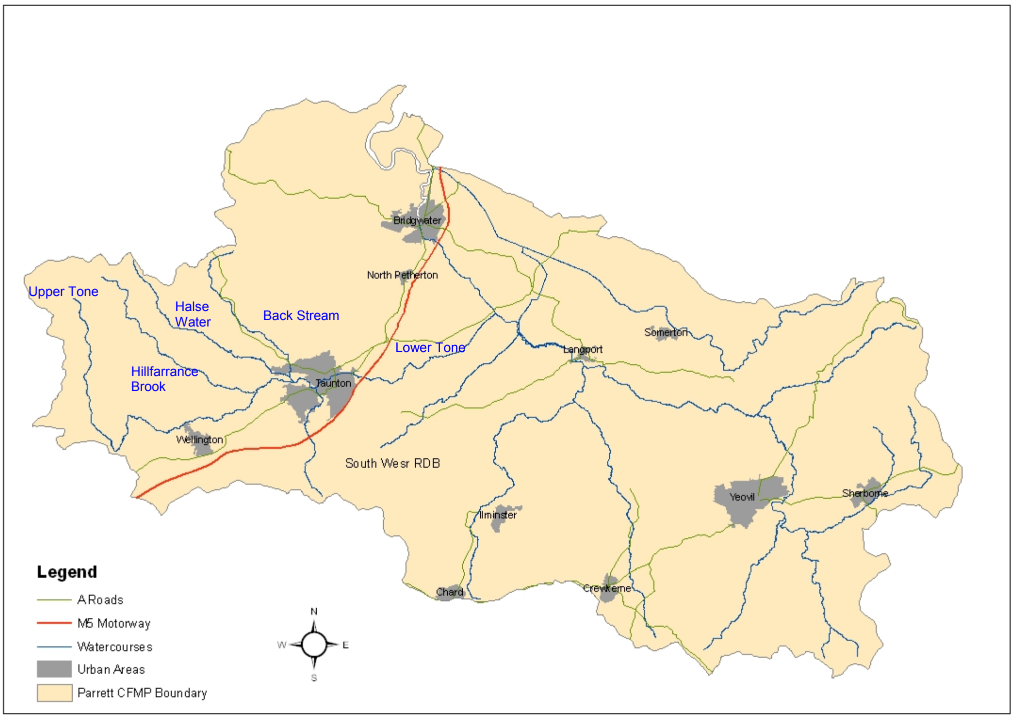


Figure 4.2 River Tone sub-catchment showing main tributaries

A full description of the River Tone and Halse Water sub-catchments are provided in the Parrett Catchment Flood Management Plan, Consultation Draft, April 2008 (Environment Agency, 2008b). It is not the intention to provide a complete, detailed description of the study catchment here, rather to identify and highlight those aspects which are of relevance to the research presented in this thesis.

This is especially true to allow the reasons for selecting the catchment (see Section 4.1.2) to be expanded upon; to contextualise the catchment in relation to the stated hypotheses and study objectives of this research; and to help define an appropriate field-based survey/sampling strategy and modelling framework which can be used to test the study hypotheses and provide appropriate information to fulfil the study objectives.

The study catchment characteristics were identified either through textual analysis of the CFMP and other relevant documents, or by fieldwork performed during the research performed to support this thesis.

The River Tone drains an area of 414 km^2, with the catchment upstream of the Bishops Hull gauging station (immediately upstream of Taunton but not including the Halse Water catchment) being 202 km^2. The area of the Halse Water sub-catchment (upstream of the Halse Water gauging station at the confluence with the River Tone) is 88 km^2.

The length of the River Tone (from Clatworthy Reservoir to the tidal limit) is approximately 52 km and it falls approximately 200m. The average gradient of the upper Tone is ~0.008, while through Taunton it is ~0.006, and downstream of Taunton across the Somerset Levels the river has a gradient of ~0.0002 decreasing to 0.0001. The average gradient of the Halse Water is ~0.004. Typical ground levels in the Somerset Levels and Moors are only 3-4 m above Ordnance Datum (AOD).

Annual rainfall across the catchment varies from ~1200 mm in the upper catchment to ~675 mm in the low lying Levels and Moors, which compares to an annual average of 920 mm for England and Wales (EA, 2008b).

4.2 Reasons for selecting study area

The River Tone catchment and, particularly, the Halse Water sub-catchment were selected as the field study area for the research presented in this thesis for the following reasons:

1. The upper Tone and Halse Water are identified by the Environment Agency as 'hot-spot' catchments with significant issues associated with soil degradation and erosion, and excessive sediment delivery to the watercourses (Paul King and Louise Webb, Environment Agency, pers. comm.; and Ben Thorn, FWAG, pers. comm.) due to steep slopes and the presence of winter crops on erosion-vulnerable soil (Palmer, 2003; Palmer, 2004; Palmer *et al.*, 2006).

2. Enhanced sediment delivery from the catchment to the watercourses within the study area has been identified in a number of previous studies investigating soil degradation, sediment sources, potential impact on flooding, sediment quality, and effectiveness of land use management techniques to reduce water and sediment runoff (Palmer, 2004; Palmer *et*

al., 2006; Black and Veatch, 2005c; Owens *et al.*, 2007; Collins, 2008; Black and Veatch, 2009; Black and Veatch, 2011).

3. The vulnerability of the catchment to soil erosion, with consequent enhanced sediment delivery to watercourses, has resulted in the catchment being covered by two UK Government initiatives. The first is Catchment Sensitive Farming (supported by Soils for Profit project), which aims to work with farmers and landowners to reduce runoff and diffuse pollution. The second is a pilot study in the upper Tone catchment which is being performed under the Government's new catchment-based approach to meeting WFD targets (Environment Agency, 2011).

4. The upper catchments have the potential to supply excessive sediment loads to the lower reaches, which have been extensively modified primarily for flood risk management and navigation, including the presence of major weirs, as well as having low gradients. In addition, discharges and water levels are artificially managed using in-channel structures and adjacent riparian washlands, as well as being tidally influenced. Therefore, there is high potential for interruption of sediment supply and/or sediment deposition within the lower reaches of the River Tone, particularly associated with in-channel structures and the river banks in reaches subject to enlargement, embanking and re-sectioning.

5. There are current and on-going flood risk management issues to be resolved within the study catchment, including the need for new/upgraded flood defences within Taunton, which suffers periodic and significant flooding, to facilitate new development, and the renewal/replacement of

major weirs within Taunton which are now structurally unsound. The Parrett Catchment CFMP identifies the need to reduce runoff in the upper catchment and the need to study the natural processes of the River Tone to inform future flood risk management policy and work.

6. There is pressure from local stakeholders, including farmers and riparian owners, for the Environment Agency to continue/restore historic levels of dredging in the lower course of the River Tone. The cessation of dredging is claimed to have allowed an excessive build-up of sediment within the channel of both the fluvial and tidal sections of the River Tone, which they believe, is now a major cause of flooding and increased flood risk. There are, therefore, issues associated with local stakeholder perception of the causes of flooding and their demands for a solution that is costly (~£20,000 / km of river), potentially damaging to the environment and in contravention of legislation, and potentially unnecessary.

7. There are recognised issues relating to the status of the river under the WFD associated with excessive sediment delivery and diffuse pollution, while the CFMP identifies the need to reduce runoff in the upper catchment, reduce flood risk in Taunton and understand/work with natural processes in the lower Tone.

8. There is a perceived conflict of interest between managing floodplain washlands for agriculture and flood management (storage of flood water) in relation to water and land quality. The local farming community claim flood water, laden with silt and vegetation, which has been allowed to remain within the washlands for extended periods, stagnates and rots on

agricultural land which has adversely impacted upon productivity and increased costs.

9. The Halse Water and lower River Tone system provides a clear transition from a steeper, cobble/gravel-bedded headwater river to a low gradient, sand/silt-bedded river in the lower course. This provides ideal conditions to use SIAM, a key sediment assessment tool used in this research (see Section 5.2.3). SIAM has been specifically developed to track and assess sediment impacts associated with the transition of finer, wash-material load, sediment to bed-material load and subsequent morphological changes. There is high potential for this mechanism to occur in the study catchment.

The significant issues relating to enhanced soil erosion and excessive sediment delivery in the upper catchments combined with a high potential for sediment deposition in the lower, modified reaches and a stakeholder perception that excessive sediment deposition in these lowland river channels has increased flood risk, with its associated land quality impacts in the washlands, makes the River Tone and Halse Water an ideal test-bed for research into the potential effects of sediment loading on the morphology and flood risks in a lowland river system. The catchment is ideal for using, testing and bench-marking sediment assessment tools, including SIAM and ISIS-Sediment (see Section 5.2), which were identified in FRMRC1. There is a real and pressing need to research and understand the sediment dynamics within this catchment to facilitate current flood risk management decisions and implementation of CFMP policies/actions.

The reaches included in the sediment models, applied within this research (described in Section 5.2), extend from the tidal limit of the River Tone (at Newbridge downstream of Taunton) upstream to Norton Fitzwarren, which is the confluence of the River Tone and the Halse Water, a distance of 14.1km. The sediment models then extend up the Halse Water to Northway, a distance of approximately 12.2km (Figure 4.11).

The upper Tone is not included within the model, due to constraints imposed by the resources available to support this project, but the Halse Water is analogous to the upper Tone while being more manageable in terms of investigating, assessing and understanding links between upstream sediment sources and downstream sediment sinks.

4.3 Setting the River Tone within the context of lowland river research

There has been very little research investigating the interactions between sediment dynamics, morphology and flooding, with the only UK studies focused on upland rivers, for example The River Wharfe (Lane *et al.*, 2007) and Pontbren (Henshaw, 2009), and no research which deals with the effects on flood risk. There has, however, been extensive research investigating sediment sources, sediment management and sediment yield focused on the Parrett Catchment, which covers an area of approximately 1,700km^2 (i.e. Palmer *et al.*, 2006; Owens *et al.*, 2007; Collins, 2008; Black and Veatch, 2011). As well as the River Parrett and the River Tone, the catchment also includes the Rivers Cary, Isle, Yeo and Cam. The research presented in this thesis therefore has direct links to this large body of work and is relevant for the whole Parrett catchment.

There has been extensive research on lowland rivers, both within the UK and Europe, which has focused on a number of sediment issues pertinent to the research presented in this thesis. Sediment issues investigated can be broadly categorised as: soil erosion and sediment runoff; sediment sources and delivery pathways; river sediment yield; and fine sediment deposition in the river channel. However, these sediment issues have never been investigated in a fully-integrated manner.

Studies, encompassing a range of land use and geology/soil types, have investigated and quantified soil erosion and sediment runoff. Catchments include the River Avon in Hampshire (Withers et al., 2007) and the River Worfe, a tributary of the River Severn, in Shropshire (Fullen and Booth, 2006) as well as various sites in Somerset, Devon, Hampshire, Bedfordshire, Cambridgeshire, Dorset, Oxfordshire, Berkshire, Kent, Norfolk, Nottinghamshire, Shropshire, Staffordshire and Sussex (Evans, 2002; Boardman *et al.*, 2003; Boardman *et al.*, 2006; Evans, 2006b). In Europe many studies have focused on the silty/sandy/loamy soils of Belgium and France (for example Martin, 1999; Van Rompaey *et al.*, 2002; Bielders *et al.*, 2003; Verstraeten et al., 2003a; Martin *et al.*, 2004).

Research identifying and categorising catchment sediment sources and delivery pathways has been undertaken on various river catchments in the UK and Northern Ireland, for example, the River Leadon, Herefordshire (Grusowski *et al.*, 2003); the River Bush, County Antrim (Evans and Gibson, 2006); the River Tern, Shropshire and the Rivers Pang and Lambourn, Berkshire (Collins and Walling, 2007a); the Rivers Frome and Piddle, Dorset

(Collins and walling, 2007b); and the Hampshire Avon and River Wye (Walling *et al.*, 2008).

Much research has focused on estimating total and specific sediment yield for a number of lowland, agriculturally-dominated river catchments between 10-1000 km^2 in size. These include the Rivers Exe, Creedy, Culm and Torridge in Devon, the Humber, the River Tweed, the River Severn, the River Trent, the River Wye, the Hampshire Avon, the Ouse, the River Tyne, the River Don and the River Bush (Walling and Collins, 2005; Evans and Gibson, 2006; Walling *et al.*, 2007).

Finally, a body of research has centred on quantifying and investigating the effects of fine sediment deposition within UK rivers, such as the River Tweed (Owens *et al.*, 1999), the Little Stour, Kent (Wood and Armitage, 1999) and the River Severn (Steiger *et al.*, 2001). Work in this field has also been carried out in Europe, for example, the River Scheldt in Flanders, Belgium (Verstaeten et al., 2003b).

The River Tone catchment has characteristics that are typical of many of these lowland rivers including its size/length, geology and land use, being a moderately-sized river catchment underlain by primarily sandstone/mudstone with alluvial and terrace deposits along the river corridor and floodplain, which supports an agricultural landscape comprising mainly a mixture of pasture and arable land. Morphologically the river exhibits a typical division between less modified, semi-natural headwater reaches and more modified lowland reaches which have undergone physical alteration through urbanisation, flood defence, navigation etc. The lowest reaches of the Tone, in common with many rivers in the UK, are very low gradient and tidally influenced. Key findings and messages based on the River Tone catchment research are therefore considered to be readily transferable to many other lowland rivers, such as those listed above, while acknowledging the need to take account of catchment specificity.

In addition, it is evident that there are many lowland rivers, both within the UK and Europe, which are associated with some sediment-related research. These rivers, particularly those with reliable data relating to ‘catchment sediment sources’ and/or ‘river sediment yield’, are likely to be the priority catchments on which to further test the approach and tools for assessing sediment dynamics, morphology and flood risk, as advocated in this thesis, and to validate the conclusions from the River Tone research.

4.4 Catchment geology, soils and land use

The River Tone catchment geology is characterised by relatively permeable Devonian and Carboniferous sand-silt-mudstone, Permian basal sediments and Permo-Triassic sandstone in the upper catchment. Further downstream (upstream and downstream of Taunton across the Somerset Levels) the bedrock changes to less permeable Triassic mudstone and clay deposits (Figure 4.3). In the river valleys and floodplains the solid geology is overlain by alluvium (clay, silt and sand) and river terrace deposits (sand and gravel) (Figure 4.4).

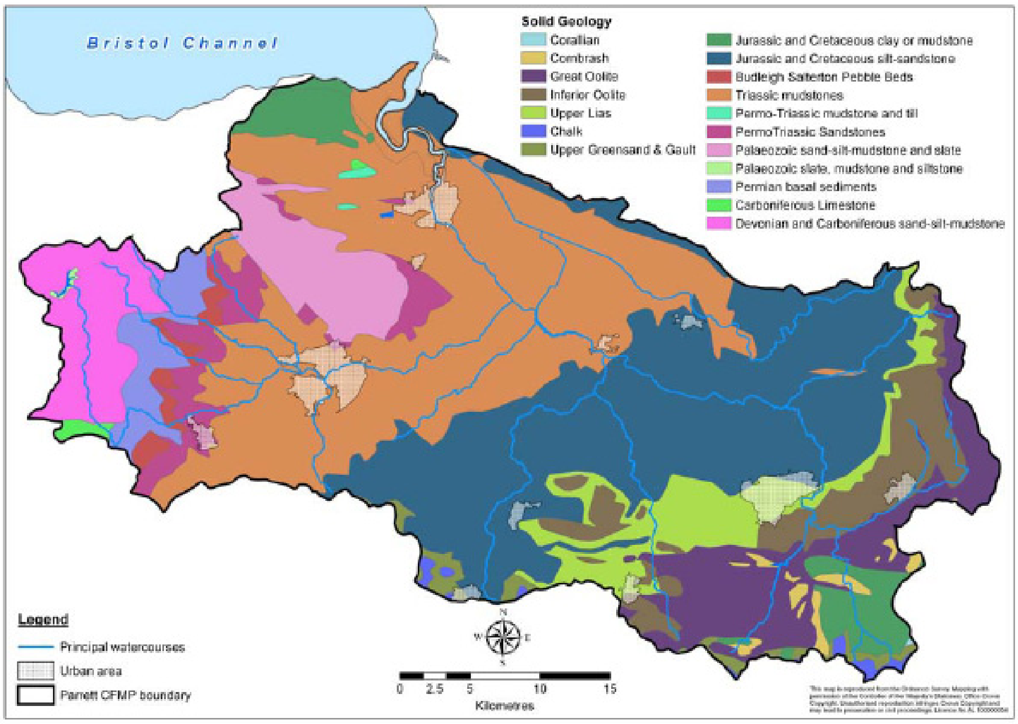


Figure 4.3 Solid geology of the Tone catchment (Source: EA, 2008b)

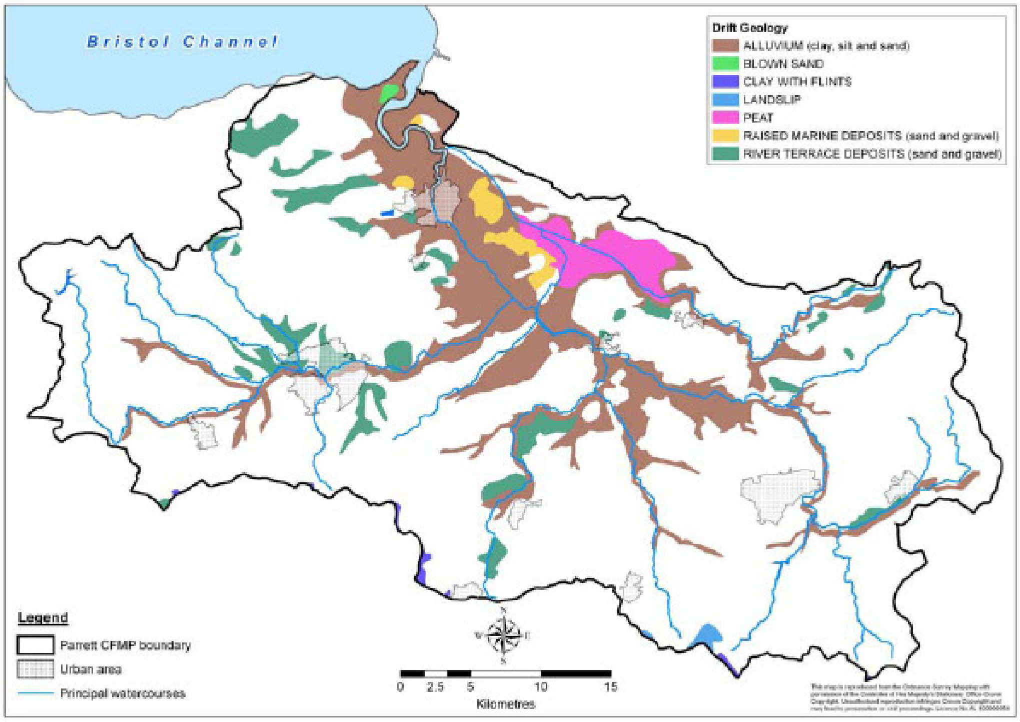


Figure 4.4 Drift geology of the Tone catchment (Source: EA, 2008b)

The National Soil Research Institute (NSRI) has undertaken a series of soil structural condition surveys in the Tone and Halse Water catchments (Palmer, 2003; Palmer, 2004; Palmer *et al.*, 2006). This work determined the soil types for the Tone and Halse Water catchments (Figure 4.5).

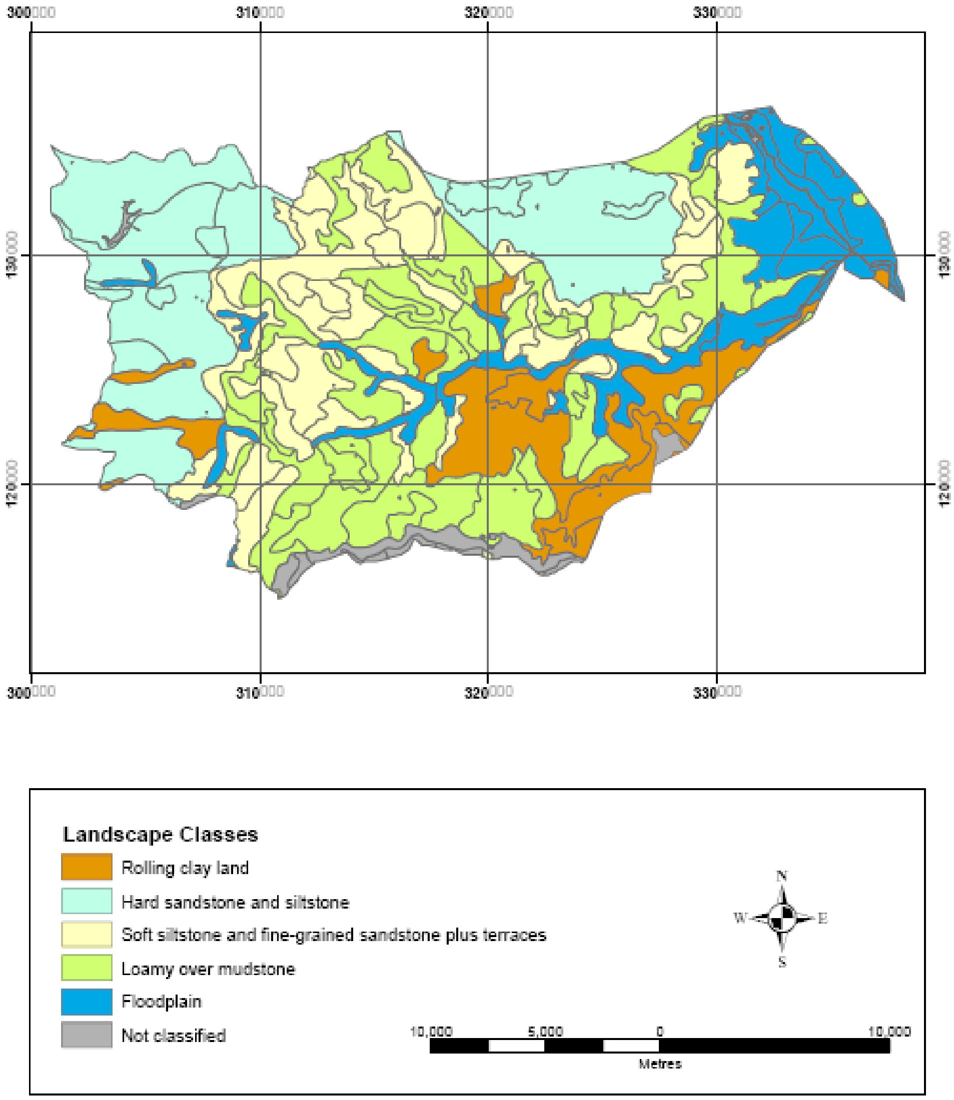


Figure 4.5 Soil types in the Tone catchment (Source: Palmer, 2003)

The Tone catchment is characterised by five main soil types, with the majority of the catchment comprising: loamy soils over Triassic reddish mudstone (26.3%); soils over hard sandstone (25.4%); and Triassic soft siltstone, fine sandstone and river terrace (21.7%). The remainder is reddish Triassic and grey Liassic clays. The Halse Water, as expected is similar, and is characterised by six soil types with the majority of the catchment characterised by: loamy soils over Triassic reddish mudstone (30.1%); and Triassic soft siltstone and fine sandstone (22.3%). The remainder of the catchment comprises: hard Devonian slates; hard Triassic breccias and sandstone, river terraces and alluvium. The soils are generally of low permeability and prone to water-logging.

Palmer (2003) reported that ~30% and ~36% of sites investigated exhibited severe/high soil degradation in 2002 and 2003, respectively. This suggests that elevated runoff and soil erosion were widespread. Approximately 75% of sample sites displayed some form of structural degradation in both years, including localised or field-scale enhancement of runoff and soil erosion. Severe/high soil degradation was almost exclusively limited to areas of loamy soils over mudstone and soft siltstone/sandstone soil type, and fields where late harvested or autumn-sown crops were grown (Palmer, 2003; Palmer *et al.*, 2006). Approximately 50% of sites in the Halse Water were found to be suffering severe/high soil degradation. Soft siltstone soils were particularly degraded, especially when associated with winter cereals (Palmer, 2004). The upper Tone, which includes the Halse Water, catchment is classed as having a high vulnerability to soil erosion (Environment Agency, 2008b).

Land use across the Tone catchment upstream of Taunton is mainly comprised of managed grassland (55%) and arable (39%) areas with urban areas and small pockets of woodland forming the remaining 6% (EA, 2008b).

Arable forms a larger percentage of land use in the Halse Water catchment (Figure 4.6).

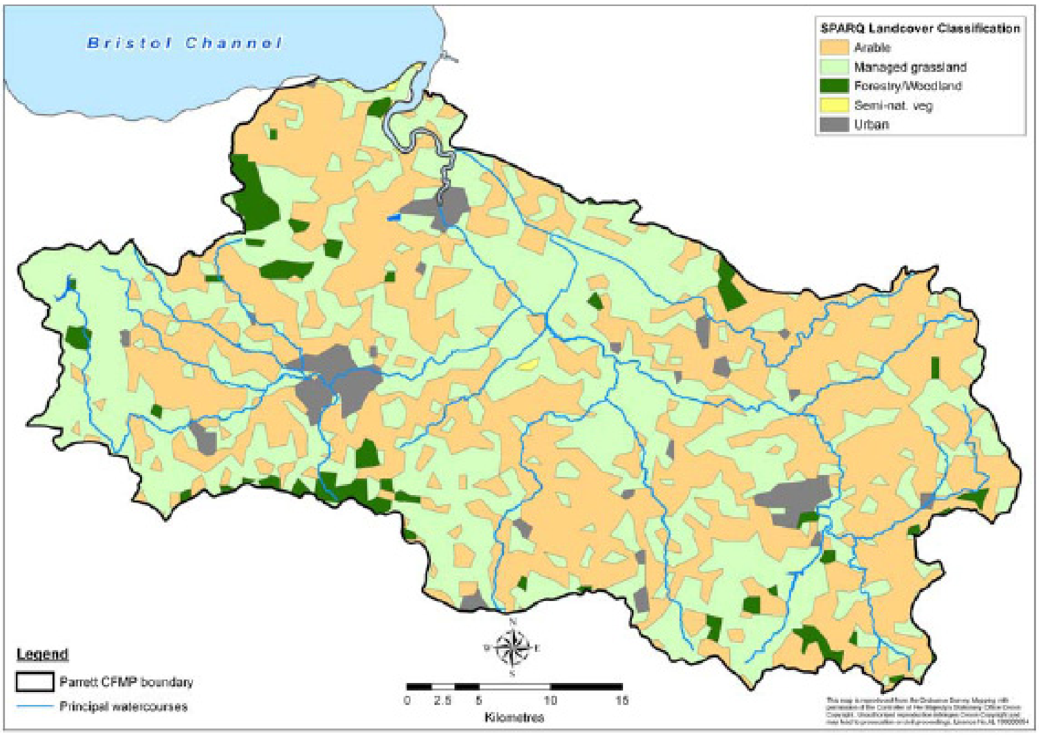


Figure 4.6 Land use in the Tone catchment (Source: EA, 2008b)

The predominant land use in the upper reaches is permanent pasture, while in the mid-reaches the land use is more intensive with grasslands, winter cereals, maize and potato crops, and sheep and cattle grazing. The floodplain of the lower reaches supports a mosaic of open moorland, pasture, grasslands, reedbeds (withy beds), and maize cultivation (Environment Agency, 2011; Palmer *et al.*, 2006).

4.5 River hydrology and morphology

Long profile information for the River Tone has been obtained via a Digital Elevation Model (DEM) and as such a number of anomalies, shown as large peaks in the profile, are present in the data. Nevertheless, the profile does establish that the River Tone long profile changes from a more convex profile in the upper catchment to concave further downstream (Figure 4.7). The convex profile is characteristic of a bedrock dominated channel, and indicates where the River Tone flows through the Brendon Hills and is unable to incise into the underlying geology. Further downstream a concave profile more typical of an alluvial stream is exhibited, which indicates a lack of geological control and suggests that the lower course is self-formed.

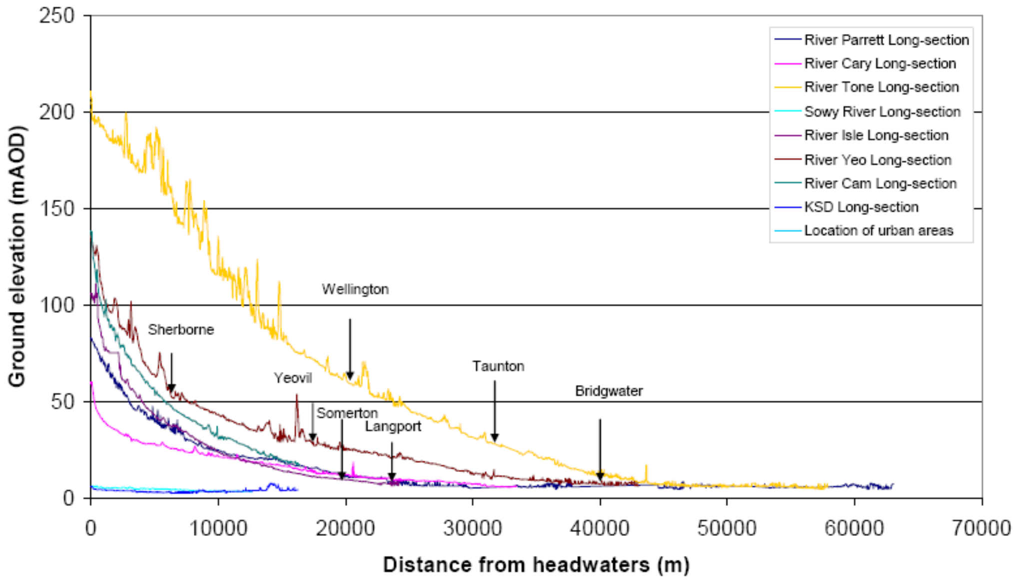


Figure 4.7 Long profile of the River Tone and other rivers in the Parrett Catchment (Source: EA, 2008b). The long profile has been obtained from a Digital Elevation Model and therefore the majority of peaks in the long profile are very likely to be anomalies in the data, although some smaller peaks in the lower reaches may be due to presence of weirs.

The upper channels are predominantly unmodified with sinuous/meandering planforms. Upper courses are generally confined within narrow floodplains. Further downstream channels have been extensively modified, and feature incised channels with unnaturally straight planforms located in broad, low-lying floodplains.

The Halse Water, although predominantly unmodified, does contain some structures. The largest structure is Norton Fitzwarren Dam, which is constructed approximately 1km upstream of Norton Fitzwarren at Wick Farm (Figure 4.8 and Plate 4.1). This structure only influences flows over a certain magnitude and is designed to have minimal impact on the 1 in 2 or more frequent annual probability flows. In addition, there are numerous small (~1m high or less) weirs located throughout the lower reaches of the Halse Water (Plate 4.2).

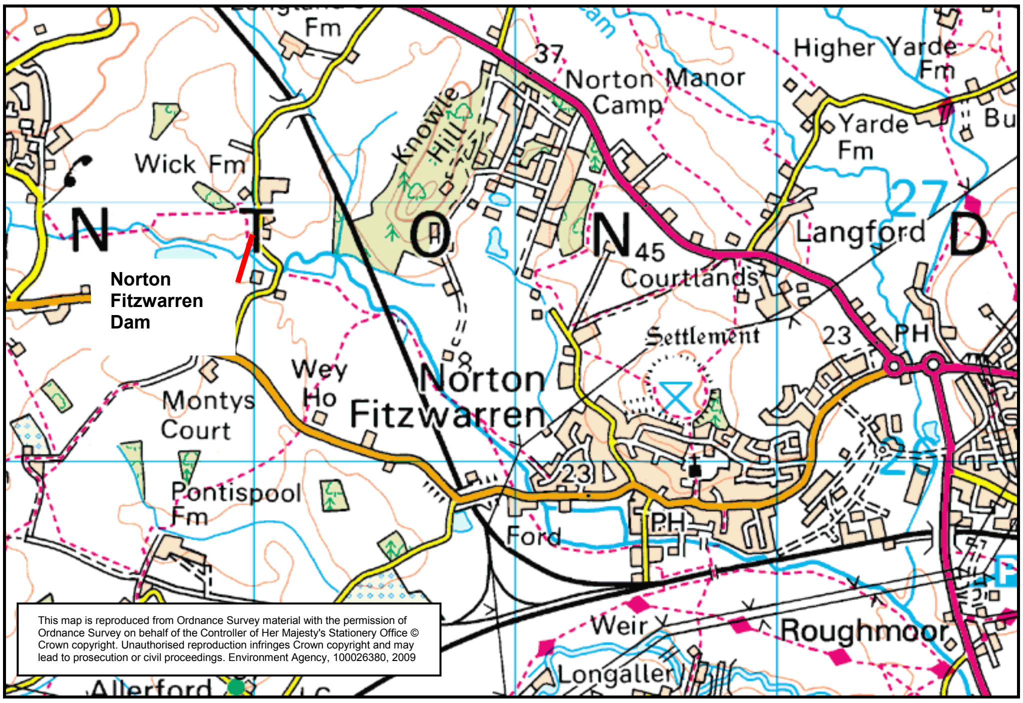


Figure 4.8 Halse Water upstream of Taunton showing location of Norton Fitzwarren Dam

Plate 4.1 Norton Fitzwarren Dam on the Halse Water

Plate 4.2 Small dams and weirs on the Halse Water

The River Tone through the centre of Taunton (Figure 4.9) has undergone significant physical alteration. Two large weirs, French Weir and Firepool Weir (Plate 4.3), have been present in some form for many years. French Weir was originally constructed to provide a head of water for a mill race feeding a large water mill historically located in the centre of Taunton and formed the upper limit of navigation since the early 18th Century. Firepool Weir was originally constructed to provide a head of water for the Bridgwater and Taunton Canal, and was upgraded to its current form in the 1960s.

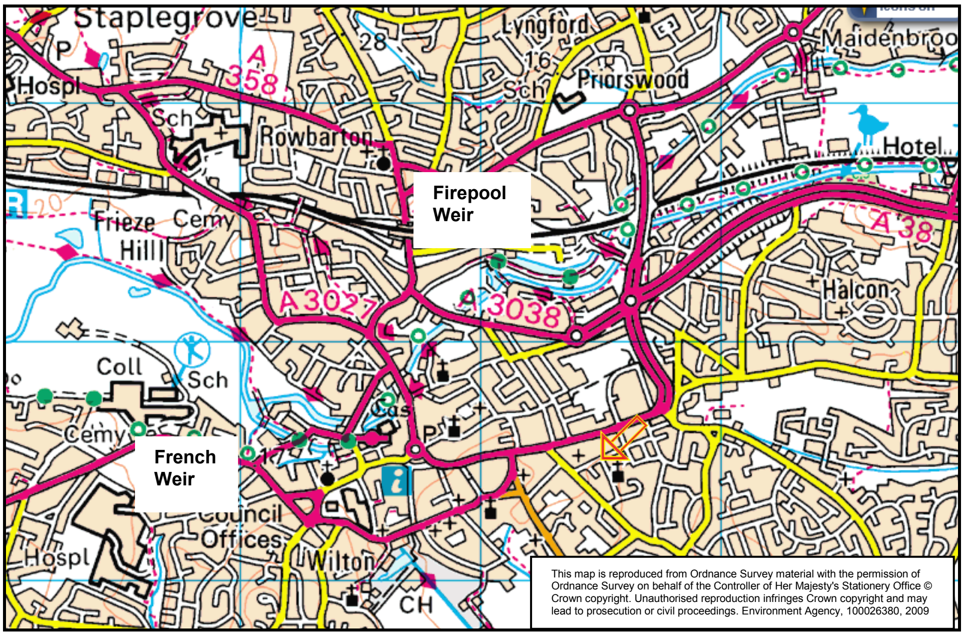


Figure 4.9 River Tone showing location of French Weir and Firepool Weir

Records of flooding go back to the 19th Century with significant events in 1889, 1929, 1960, 1968, 1997 and 2000 (Environment Agency, 2008b) and recently in 2012. In response to the biggest event of the 20th Century (1960), when flooding affected approximately 500 properties in the town, major flood defence works were carried out which included channel widening, bridge enlargement, weir reconstruction/upgrading and channel bank protection (Black and Veatch, 2005a and b). In the early 1990s the defences were further upgraded to provide a 1 in 200 year standard of protection. Recent flooding in 2012 was restricted to isolated areas within Taunton, including Vivary Park and the Taunton Deane Cricket Club, as well as villages in the upper catchment and within the Somerset Levels, which suffered re-occurring and prolonged flooding (Hill *et al.*, 2012).

Plate 4.3 French Weir (a) and Firepool Weir (b) in Taunton

These channel alterations have potentially de-stabilised the sediment dynamics and created silt traps behind the weirs. Anecdotal evidence (Francis Farr-Cox, Environment Agency Biodiversity, pers. comm.) suggests that the weir sluices were occasionally opened to allow the build-up of sediment to flush through, and it appears this has happened 2-3 times in the last 30+ years. This practice can no longer continue as the weirs are in a poor state of repair, with both Firepool Weir and French Weir scheduled for refurbishment or potential removal due to structural undermining (Jason Flagg, Environment Agency Flood and Coastal Risk Management – Wessex, pers. comm.). The Environment Agency Operations and Delivery team dredged the channel immediately upstream of Firepool Weir in the mid-2000s to ensure the entrance to the Taunton and Bridgwater Canal remained navigable, and this operation may need to be repeated again in 2012 due to perceived sediment deposition (Jason Flagg, Environment Agency Flood and Coastal Risk Management - Wessex, pers. comm.).

The lower Tone through the Levels and Moors has been extensively modified through straightening, re-sectioning (generally widening and probably some deepening), embanking and creation of weirs and sluices. Two key structures on the lower Tone include Ham Weir and New Bridge tidal sluice (Plate 4.4). Historic deposition between the embankments leading to aggradation combined with draining and lowering of the floodplain means that the channel is now perched above the floodplain.

Plate 4.4 Ham Weir (a) and New Bridge Tidal Sluice (b)

The two main flood storage areas (Moors) associated with the lower River Tone (Figure 4.10) are Currymoor (4,500ha) and Haymoor (2,000ha), which together provide 10 million m^3 of water storage.

Water enters the connected Moors via a main spillway or from the catchment area of each Moor, and either discharges back to the river via gravity outfalls or is pumped back to the river during flood conditions when the main river water level is too high to allow gravity drainage. Water levels are managed within the Moors through a network of mostly artificial ditches, known as rhynes, and are controlled by sluice structures and pumps.

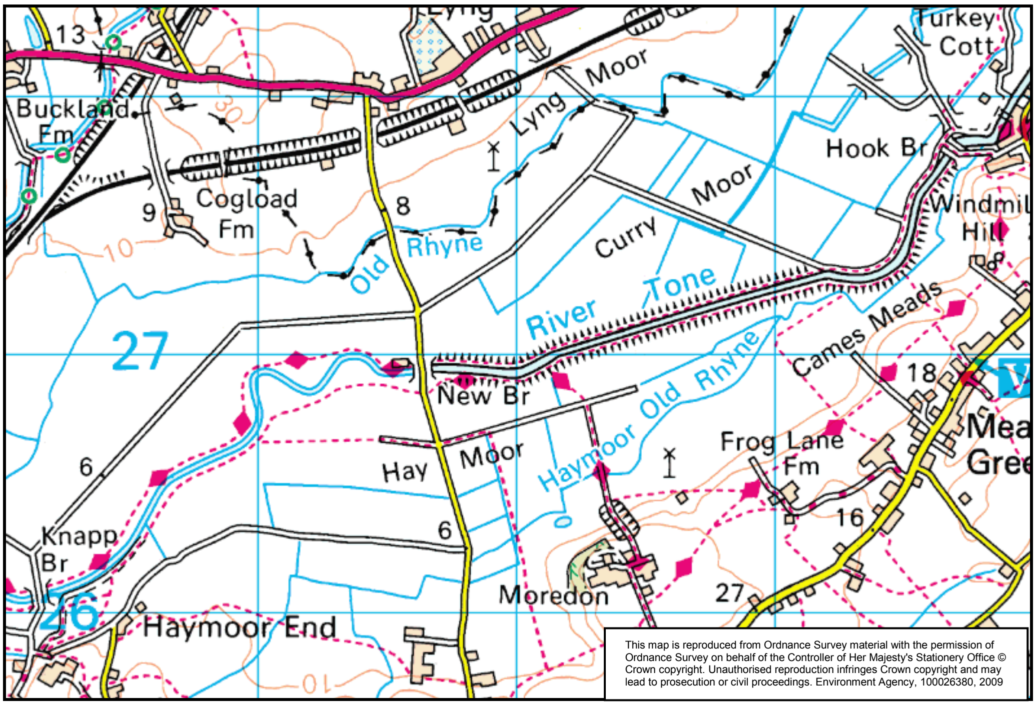


Figure 4.10 Lower River Tone showing tidal limit (New Bridge) and location of Curry Moor and Hay Moor

The steep upper catchments are generally dominated by quick runoff, and flooding tends to occur during short intense rainfall events both in the summer and winter, as a result of direct runoff or riverbank over-topping. Flooding in the lowland reaches is buffered by the flat terrain and large artificial storage areas, and is usually as a result of a longer duration storm event or the cumulative effects of a series of storms. Antecedent catchment conditions, particularly in terms of soil wetness, and volume of rainfall are critical factors in flooding on this system.

In the upper course, channel bed is characterised by coarse bed material (mainly cobbles and gravel with sand). Sediment delivery through runoff is a major issue in the upper Tone, and evidence from previous flood events has shown that under heavy rainfall large quantities of soil can be mobilised in the upper catchment (EA, 2008b). As the watercourse flows through the low lying

Somerset Levels and Moors their very shallow gradients result in lower competence and capacity for sediment transport and a high potential for sediment deposition. Sediment in these environments is characterised by fine sand and silt, much of which is kept in suspension by fluvial and tidal flows. Although the Environment Agency has identified sedimentation as a key issue for sustainable river management (EA, 2008b), recent sediment monitoring indicates that sediment deposited on the channel bed is likely to be very mobile and easily entrained during moderate flow conditions meaning the natural rates of accretion on the river bed are slow (Black and Veatch, 2011).

The morphology of the waterbodies present within the River Tone and Halse Water catchments has been assessed under the WFD (see Section 4.5). The River Tone between Wellington and the tidal limit is designated as a heavily modified waterbody, as is the downstream reach of the Back Stream. As such these waterbodies have not had a morphological assessment. The remaining river reaches including the upper Tone, Halse Water, Back Stream and Hillfarrance Brook are all deemed to have ‘good’ morphology. General ecological status is covered in Section 4.5.

River banks in the lower reaches are typically formed in homogenous very fine sand to very coarse silt, giving them very high cohesive strength. Consequently, they are unlikely to be eroded except during extremely high fluvial flow events. The lower river reaches have been enlarged and re-sectioned for flood control. As a result cross-sections are trapezoidal and do not vary greatly (Black and Veatch, 2011). The average bank top width is 30m and banks, which are approximately 4m high, have an average angle of ~30^{o}.

Given the high mobility of sediment deposited on the channel bed, sedimentation within the lower reaches of the River Tone is generally restricted to a build up of finer material (fine sand to silt) on the upper part of the bank slopes, and generally during slack water events when fluvial flow is held-up by a large tidal event (e.g. Spring Tide) or operation of tidal structures (Andy Wallis, Black and Veatch, pers. comm.). This sedimentation process is consistent with the definition of wash load material given in Section 1.3.1. The significance of fine sediment deposition is supported by studies on the River Tweed which identified floodplain sediment storage represented ~40% of the annual load of fine sediment delivered to the river (Owens *et al.*, 1999).

The sediment deposition mechanism observed on the lower Tone has dictated that 'agitation' dredging has occasionally been used to remove sediment when there is a perceived excess of build-up. Historically the agitation dredging was undertaken using water-blasting of the banks to re-suspend deposited sediment, while little attention was applied to the river bed (Black & Veatch, 2011). More recently this type of activity has been replaced by scraping banks to remove sediment and placing it in the channel flow using the bucket of a land-based or floating excavator (Plate 4.5).

Plate 4.5 Dredging in the Parrett Catchment (Source: EA)

In general, however, little dredging of the lower fluvial Tone is needed as the banks build up until they become unstable when the angle of repose is such that they material slumps into the channel (i.e. the angle of repose of sediment particles is usually 26^{o} to 42^{o}; Chanson, 2004) or until a suitable large enough fluvial event re-mobilises the material, which is then entrained and washed out of the fluvial system (Black and Veatch, 2011).

This slumping and entrainment process is probably also contributed to by other factors including seepage through banks, wave action/boat wash, poaching, animal burrowing and weight on top of the river banks through the presence of artificial embankments (Andy Wallis, Black and Veatch, pers. comm.). This process is reflected in other similar rivers in the Somerset Levels (Halcrow, 1997b) and elsewhere, for example, the River Tweed where erosion of the channel banks reintroduces about 30% of the floodplain-deposited sediment back into the channel (Owens *et al.*, 1999). This re-working of sediments is reflected in the lack of dredging needed in the lower reaches of the fluvial River Tone, with only one dredging event recorded since 1995 compared to eight events on the Parrett (Black and Veatch, 2011).

Excessive siltation in the tidal reaches of the River Tone has, however, been identified by local stakeholders, including the farming community, as a major contributor to recent flooding due to the river channel becoming choked with silt and vegetation, which is putting additional pressure on the floodplain washlands, including Currymoor (Colledge, 2012). This is then leading to water quality and land quality issues (see Section 4.5).

River morphology information was collected as part of this research based upon the Fluvial Audit methodology (Sear *et al.*, 2003) to characterise the fluvial geomorphological regime identifying relevant channel forms, sedimentary features, sediment sources, pathways and sinks. A total length of river of approximately 26.3km and encompassing the lower River Tone from the tidal limit to the confluence with the Halse Water, and the Halse Water upstream to Northway was surveyed (Figure 4.11).

The geomorphic information has been used to establish geomorphic reaches (Figure 4.11) based on source (sediment output > sediment input: predominantly degradation), exchange (sediment output ≈ sediment input: sediment stored and released in different areas of the reach), transfer (sediment output ≈ sediment input: sediment passed through the reach) and sink (sediment output < sediment input: predominantly aggradation). These geomorphic reaches have been used, in conjunction with other hydrological and hydraulic characteristics (i.e. presence of tributaries, in-channel structures), to inform the delineation and set-up of sediment models (see Sections 6.2 and 6.3).

Interpretation of a Fluvial Audit includes identification of Potentially Destabilising Phenomena (PDP), which are factors that may significantly affect channel stability (Sear *et al.*, 2003). PDP were identified for the entire Parrett Catchment by the EA in 2008, and those that are relevant to the Tone Catchment are listed in Table 4.1. Knowledge of the PDP were used to design an appropriate catchment sediment sampling strategy (Sections 5.3.4 and 5.3.5).

Scale	Increase sediment supply	Decrease sediment supply
Catchment Scale	Agricultural practises Land use changes Climate change* Soil erosion Deforestation Urbanisation	Catchment sensitive farming Climate change*1 New woodland/plantations Urbanisation Tidal exclusion structure
Reach Scale	Channel straightening Agricultural runoff Bank erosion/collapse Poaching by livestock Supply from upstream tributaries	Bank protection Dredging Structures along the watercourse Riparian vegetation Channel widening causing deposition upstream Engineered livestock watering points

* increased frequency and / or intensity of rainfall

*1 reduced frequency and / or intensity of rainfall

Table 4.1 Potentially Destabilising Phenomena for the Parrett (Tone) Catchment (Source: EA, 2008b)

4.6 River habitats

To allow characterisation and establish quality of habitat features associated with the main watercourses within the study area, and assist with the delineation of sediment-assessment reaches as part of sediment modelling, approximately 26.3km of the river encompassing the lower River Tone from the tidal limit to upstream of Taunton, and the Halse Water from its outlet upstream to Northway was surveyed using the nationally standardised River Habitat Survey [RHS] method (Environment Agency, 2003). RHS is undertaken in standard 500m survey lengths distributed along the channel either at intervals or back-to-back.

Thirty-two RHS reaches were surveyed within the study reaches, including 17 reaches on the River Tone and 15 reaches on the Halse Water (Figure 4.11). The completed survey forms, site photos and raw data are stored on the Environment Agency national RHS database and on the FRMRC legacy website (www.floodrisk.org.uk) from which they may be accessed.

The output from the RHS data are two habitat classification indices: the Habitat Quality Assessment (HQA) and the Habitat Modification Class (HMC). The RHS habitat classification indices for the lower River Tone and the Halse Water are listed in Tables 4.2 and 4.3 and the HMC scores are shown in Figure 4.11.

The Habitat Quality Assessment (HQA) scoring system is a broad measure of the diversity and hence ‘naturalness’ of the physical habitat in the survey reach, including both the channel and river corridor. The HQA scores are determined by the presence and extent of habitat features of known wildlife value. The HQA is integral to river type, and as such habitat quality can only be assessed on an intra-river basis.

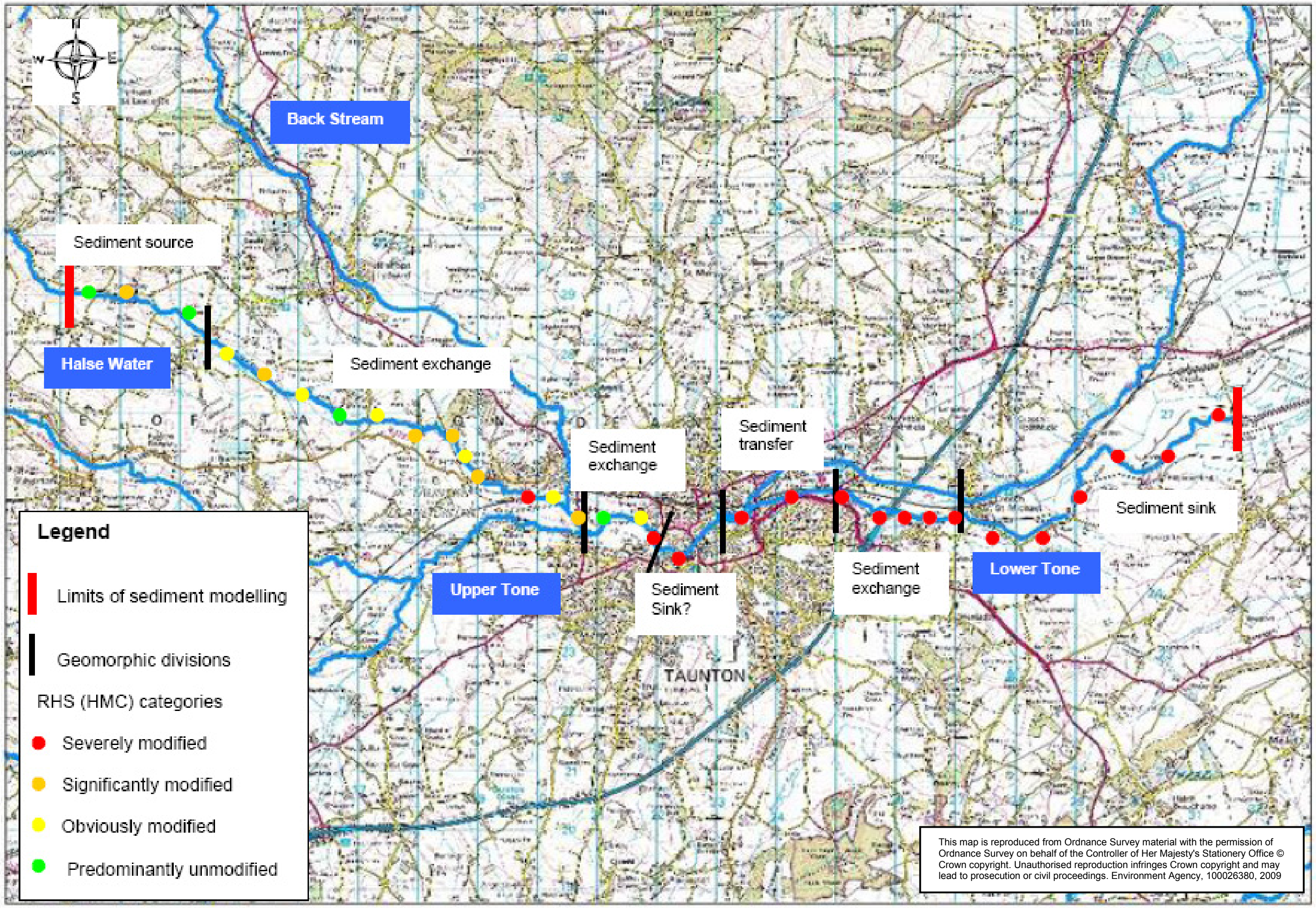


Figure 4.11 Sediment modelling limits of lower Tone and Halse Water, showing geomorphic divisions (source, pathway or sink), and RHS locations with habitat modification categories

	Site Ref	NGR (mid)	HMS	HMC	HM Descr.	HQA
Downstream	Tone-001	ST 31401 26983	3685	5	Severely modified	18
	Tone-002	ST 30641 26511	3225	5	Severely modified	12
	Tone-003	ST 29911 26124	3225	5	Severely modified	11
	Tone-004	ST 29004 25522	3325	5	Severely modified	21
	Tone-005	ST 28388 25078	3566	5	Severely modified	15
	Tone-006	ST 27924 25058	2984	5	Severely modified	18
	Tone-007	ST 27270 25185	3896	5	Severely modified	26
	Tone-008	ST 26634 25167	2890	5	Severely modified	23
	Tone-009	ST 26069 25358	2965	5	Severely modified	29
	Tone-010	ST 25551 25403	1645	5	Severely modified	33
	Tone-011	ST 25093 25732	3935	5	Severely modified	31
	Tone-012	ST 24288 25667	1967	5	Severely modified	27
	Tone-013	ST 23239 25244	3877	5	Severely modified	32
	Tone-014	ST 22456 24668	3846	5	Severely modified	17
	Tone-015	ST 22023 24873	2454	5	Severely modified	28
	Tone-016	ST 21719 25217	226	3	Obviously modified	36
Upstream	Tone-017	ST 21217 25261	145	2	Predominantly unmodified	35

Table 4.2 RHS summary data (HMC and HQA) for the lower River Tone

	Site Ref	NGR (mid)	HMS	HMC	HM Descr.	HQA
Downstream	HW-001	ST 20518 25386	1245	4	Significantly modified	40
	HW-002	ST 20136 25602	465	3	Obviously modified	44
	HW-003	ST 19141 25854	2500	5	Severely modified	38
	HW-004	ST 18792 26195	675	4	Significantly modified	54
	HW-005	ST 18508 26594	420	3	Obviously modified	58
	HW-006	ST 18155 26315	835	4	Significantly modified	48
	HW-007	ST 17737 26875	830	4	Significantly modified	46
	HW-008	ST 17391 26890	210	3	Obviously modified	51
	HW-009	ST 16750 26920	110	2	Predominantly unmodified	56
	HW-010	ST 16255 27350	470	3	Obviously modified	57
	HW-011	ST 15650 27450	580	4	Significantly modified	44
	HW-012	ST 15050 27870	400	3	Obviously modified	56
	HW-013	ST 14250 28500	100	2	Predominantly unmodified	52
	HW-014	ST 13410 28896	510	4	Significantly modified	55
Upstream	HW-015	ST 12275 29040	40	2	Predominantly unmodified	59

Table 4.3 RHS summary data (HMC and HQA) for the Halse Water

The Habitat Modification Score (HMS) assesses the degree of artificial modification in the survey river reach. The HMS is used to place the river in a Habitat Modification Class (HMC), as listed in Table 4.4. The HMS is independent of river type, and can therefore be used to describe artificial modification on an inter-river basis.

HMS	HMC	MHC Description
0-16	1	Pristine/semi-natural
17-199	2	Predominantly unmodified
200-499	3	Obviously modified
500-1399	4	Significantly modified
1400+	5	Severely modified

Table 4.4 RHS Habitat Modification Class categories

The lower River Tone, which extends for approximately 14.1km from the tidal limit to the confluence with the Halse Water just upstream of Taunton, is severely modified along the great majority of its length, with the largest contributing factor being re-sectioning of the channel cross-section (banks and bed). Other modifications include the widespread presence of embankments, bridges, weirs, bank reinforcement and outfalls. The River Tone upstream of Taunton is much less modified, mainly because the channel has not been re-sectioned. For example, the reach immediately downstream of the Halse Water confluence is 'predominantly unmodified' (Plates 4.6 to 4.9).

Habitat quality scores are 35 and 36 at the two most upstream, less modified reaches of the River Tone, while in the lower severely modified reaches habitat quality scores range from 11 to 33. The better habitat quality scores are mainly accounted for by the presence of bank vegetation/features, in-channel features, coarser substrate and the presence of trees and associated features which are generally found in the upper reaches above Taunton and in reaches upstream of the M5 road bridge. The lowland reaches generally score better on in-channel vegetation, but this is due more to the absence of shading trees which are more prevalent in the upper reaches (Plates 4.6 to 4.9).

Plate 4.6 River Tone upstream of Taunton, which is 'predominantly unmodified' with varied geomorphic and habitat features with bankside trees

Plate 4.7 River Tone in Taunton centre, which is heavily engineered and 'severely modified'

Plate 4.8 River Tone downstream of Taunton, which supports active geomorphic features and better habitat quality

Plate 4.9 River Tone on the Somerset Levels, which is embanked, perched and re-sectioned while lacking bankside trees

The study reach on the Halse Water extends upstream for approximately 12.2km from the River Tone confluence to Northway. In terms of HMS, it ranges from ‘predominantly unmodified’ to ‘severely modified’, with the majority of reaches (11 out of 15) being classed as ‘obviously modified’ or ‘significantly modified’. The three predominantly unmodified reaches are, unsurprisingly, found in the upper reaches of the river, while the severely modified reach is associated with the urban area of Norton Fitzwarren located low-down in the sub-catchment. The main factors contributing to habitat modification are re-sectioning, and the presence of bridges, weirs, reinforced banks, culverts and fords (Plates 4.10 to 4.13).

Habitat quality scores range from 38 to 59. There is an inverse correlation between modification and habitat quality scores, with the lowest HQA score associated with the severely modified reach and the three predominantly unmodified reaches all scoring above 50. Higher habitat quality scores mainly result from the presence of in-channel vegetation, bank features, and trees and their associated features (e.g. underwater roots).

Plate 4.10 Halse Water at the top of the study reach (Northway), which is 'predominantly unmodified'

Plate 4.11 Halse Water in middle reaches of study area, which supports geomorphically active river banks

Plate 4.12 Halse Water through Norton Fitzwarren, which is heavily engineered and 'severely modified'

Plate 4.13 Halse Water at downstream end, which supports some good habitat features but is affected by weirs, bridges, reinforcement and poaching

4.7 River quality

The Environment Agency has published a consultation on the Draft River Basin Management Plan – South West River Basin District (SWRBD) (EA, 2008a). The SWRBD covers 21,000 km^2 and has been divided into 12 discrete areas, one of which is the 'South and West Somerset' which includes the study areas of the River Tone and Halse Water.

The South and West Somerset area has now been split into a number of smaller catchments in line with the Government's commitment to a catchment based approach (see Section 3.4) with the Upper Tone, Lower Tone and Halse Water forming discrete catchments. The three catchments contain 9 waterbodies, and an assessment of existing (2009) status for each waterbody is shown in Table 4.5.

In Table 4.5 it can be seen that the River Tone has been split into three discrete waterbodies, with the Upper Tone the only waterbody currently achieving 'good' status. The middle and lower Tone from Wellington to the tidal limit are both classed as having an overall 'moderate' status, but both waterbodies are designated as heavily modified, mainly due to presence of flood defence infrastructure, and consequently they only need to achieve Good Ecological Potential (meaning there is no requirement to assess the naturalness of their morphologies). The key reasons for failure to achieve GES or GEP are high levels of phosphate and suppressed ecology.

Waterbody	Length (km)	Area (km^2)	Current Overall Status	Current Ecological Status	HMWB?	Fish	Inverts	Ammonia	DO	pH	Phosphate	Hydrology	Morphology
Tone (upper)	26.23	80.99	Good	Good	No	Good	High	High	High	High	High	High	Good
Tone (Wellington – Taunton)	11.12	18.96	Mod	Mod	Yes	Good	Good	Good	High	High	Poor	Not high	-
Tone (d/s of Taunton)	15.09	66.58	Mod	Mod	Yes - FD	-	High	High	High	High	Mod	Not high	-
Halse Water 1	0.67	0.22	Mod	Mod	No	Good	-	High	High	High	Mod	High	Good
Halse Water 2	23.53	41.64	Mod	Mod	No	Mod	-	High	High	High	Good	High	Good
Back Stream 1	1.23	0.67	Mod	Mod	Yes - Urban	-	-	High	High	High	Good	High	-
Back Stream 2	15.47	38.83	Mod	Mod	No	Good	High	High	High	High	Poor	High	Good
Trib. of Back Stream	2.51	12.8	Mod	Mod	No	-	-	High	High	High	Mod	High	Good
Hillfarrance Brook	19.87	49.52	Mod	Mod	No	Good	High	High	High	High	Mod	Not high	Good

Table 4.5 Waterbody status classification under WFD Cycle 1 for the River Tone catchment

The Halse Water and Back Stream are split into 5 waterbodies, with the lower reach of the Back Stream being designated as heavily modified due to urbanisation. All these waterbodies are classed as being of ‘moderate’ status with ecology/fish and phosphate being the causes of failure to achieve good status. The Hillfarrance Brook, which is the second northern tributary of the upper Tone, is classed as having an overall ‘moderate’ status, also due to high levels of phosphate and a suppressed ecology.

The South West River Basin Management Plan identifies high level outcomes for the SWRBD, which of relevance to this research include:

- *Improving rural land management and agricultural pollution control*: changes in the way land is used and managed will encourage natural sediment transport processes. This will ensure the water environment is protected… reducing sediment loss [from land] will deliver widespread ecological benefits. Responsibility for implementing measures that will improve land management falls on the agricultural sector.

- *Improving wildlife habitats*: the Environment Agency wants to remedy the impact of historic physical modifications to rivers and estuaries. Main causes of loss of habitat include agricultural land drainage, bank protection, dredging, bank erosion, river engineering, flood defence. Responsibility to secure improvements impacted by physical modification will primarily be the Environment Agency (flood risk management).

There appears to be growing evidence that nutrient enrichment, due to phosphate levels, is a problem in the Lower Tone and that it may be [excessively] eutrophic. The nutrient status of the river downstream of Wellington remains a concern for the Environment Agency, and it was submitted for designation as a 'eutrophic sensitive area' in 2009. This designation is expected to be confirmed by Defra in 2012 (Environment Agency, 2011a). An FRMRC study accompanying this PhD research investigated the quality of sediment deposited behind Firepool Weir and Ham Weir to establish whether sediment may pose a water quality risk if released, for example, through weir removal/replacement (Hooper, 2012). This study found phosphate, soluble reactive phosphorus (SRP), associated with accumulated sediment behind both weirs with an average concentration of 91.84µg/l.

In 2009 the Environment Agency commissioned a study to assess sediment quality in the lower River Tone and River Parrett (Partrac, 2009c; Partrac, 2009d; Black & Veatch, 2009). Sediments at Newbridge (River Tone tidal limit) were found to contain concentrations of heavy metals (cadmium and zinc) above FEPA Action Level 1 (requiring further consideration and testing), but within the historic range for contamination in the Severn Estuary. Polycyclic Aromatic Hydrocarbons (PAH), which are highly carcinogenic, and Total Hydrocarbons were found in concentrations above FEPA AL1. No analysis of nutrients or pesticides was undertaken. Potential sources were identified as urban areas, current and historic industrial sites, and runoff from the M5 motorway. Polychlorinated biphenyls (PCBs) were found in the older/deeper sediment accumulated behind Firepool Weir (Hooper, 2012), although at low concentrations, maximum of 6.31µg/kg (Hooper, 2012).

Water and land quality issues associated with the extended use of the floodplain washlands for flood water storage have been raised by local stakeholders, especially the farming community (Colledge, 2012). Prolonged periods of standing flood water, which is laden with silt and rotting vegetation, has led to mortality of flora and soil fauna within the washland making it temporarily unsuitable for agriculture with a subsequent loss of productivity. However, the stagnant and de-oxygenated flood water cannot be pumped back to the river as there is then a potential for fish kill. The Environment Agency must, therefore, perform a balancing act between trying to remove the flood water as quickly as possible while avoiding widespread damage to the rivers. In practice, flood water left to stand for a prolonged period requires aeration and treatment with hydrogen peroxide before it can be evacuated to the river.

4.8 Sediment sources

The River Parrett CFMP (EA, 2008b) identifies erosion of channel bank and bed sediments and sediment delivered from runoff from adjacent agricultural land as the main sediment sources in the non-tidal sections of the River Tone. Sediment delivery is particularly linked to the upper reaches and northern tributaries (Figure 4.12) which are associated with (1) loamy soils and soft siltstone soils that are prone to seasonal water-logging and erosion, and (2) steep slopes and arable land supporting winter crops (Palmer, 2003; Palmer, 2004). This is supported by findings from other studies, for example, Boardman *et al.* (2003).

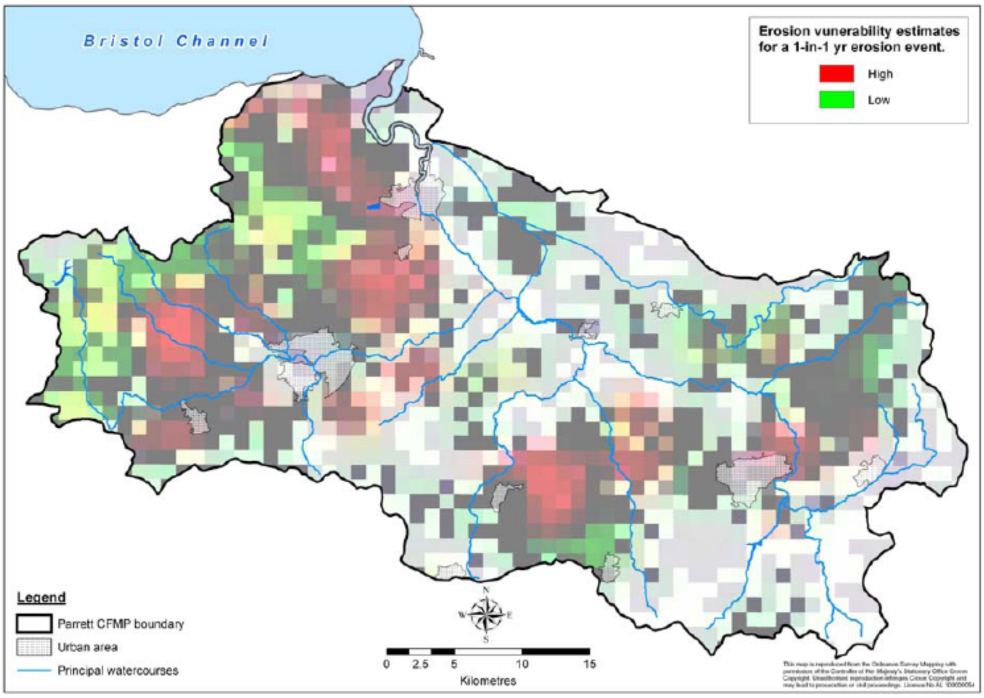


Figure 4.12 Areas at risk from soil erosion (Source: EA, 2008b)

The preponderance for soil erosion and sediment runoff on these type of soils is confirmed elsewhere in Europe. For example, in Wallonia (Belgium) and Pays de Caux (France) where agricultural soils erosion and runoff floods dominate in silt-loam and sandy loam which are highly susceptible to surface sealing and erosion when cropped (Bielders *et al.*, 2003; Martin *et al.*, 2004).

Given the issues of soil degradation, erosion and runoff, and associated water quality problems, within the River Tone and Halse Water catchments, two key catchment sediment modelling studies have been undertaken by ADAS. These studies have sought to quantify the amount of soil erosion and its contribution to the total suspended sediment flux at the catchment outlet. PSYCHIC modelling (Davison *et al.*, 2008) was used to predict diffuse losses of sediment from agricultural land in the Upper Tone catchment (above

Taunton), which was estimated to be 225 kg/ha/yr, which equates to ~6,200 tonnes/year.

In addition, catchment sediment delivery was apportioned to various land use types based on sediment fingerprinting of floodplain scrapes and suspended sediment samples (Collins, 2008). Source proportions were combined with nationally extrapolated catchment sediment yield (20-70 tonnes/km^2/yr [Cooper *et al.*, 2008]) and area of each land use type. These data are discussed more fully in Section 6.1, but in summary the mean contribution of catchment sources were predicted as follows:

- River Tone: pasture was the largest contributor (51%) followed by river banks (23%), arable land (13%) and damaged road verges (13%).

- Halse Water: arable land was the largest contributor (53-57%) followed by pasture (24-29%), damaged roads (11-16%) and river banks (3-6%).

With respect to the source of sediment transported through the fluvial outlet and into the River Tone tidal system located below Newbridge (the exact limit of tidal influence depends of prevailing fluvial flows and tides), it is considered that relatively small amounts of sediment are transported out of the fluvial system under baseline ‘normal flow’ conditions. The majority of sediment moves through on large fluvial events (which can increase sediment loads by one or two orders of magnitude). During the winter sediment is generally supplied from the upstream catchment, or erosion of banks and re-mobilisation of river bed materials. The fluvial system provides the majority of the finer material (<63μm) entering the tidal reaches, while coarser material

(>63µm) is mainly of tidal origin (Partrac, 2009a; Partrac, 2009b). With respect to the relative contribution of sediment to the tidal reaches from each fluvial sub-catchment, the River Parrett is considered to contribute ~70% of total fluvial-derived sediment compared to ~30% from the River Tone (Black & Veatch, 2011).

4.9 Catchment management

4.9.1 Land use management

The National Soil Research Institute undertook a review of soil and land management techniques to identify those that would contribute to water retention and minimisation of diffuse water pollution (including siltation) in the Parrett Catchment (Godwin and Dresser, 2000). Evidence suggests that the following practices can have a beneficial impact:

- Increasing the roughness of the soil by using mouldboard ploughing, and shallow ploughing the soil to intercept and redistribute runoff away from adjacent waterbodies.

- Grazing livestock higher up the field slope to allow runoff to infiltrate into non-compacted areas lower down.

- Improving crop rotations and applying surface litter to protect the soil from capping.

ADAS investigated the effectiveness of buffer strips in trapping sediment and phosphorus in the upper Tone catchment [and wider Parrett catchment] (Owens *et al*, 2007), the main findings of which are reported in Section 2.4.2.

Catchment Sensitive Farming covers most of the South West River Basin District and engagement with the farming community has been very good. As part of the work of Posthumus and Morris (2007) a number of farmers in the Parrett Catchment were interviewed regarding views on relevant drivers of historic, current and future land management. Although the sample was small (n = 7) general views and attitudes were extracted. The main conclusions for the Parrett catchment are as follows:

- Farmers did not feel responsible for possible increased flood risk. However, they do feel responsible for diffuse pollution and soil erosion and acknowledged they had control over pressures affecting soil erosion such as soil management and crop rotation.

- Most of the immediate benefits of soil erosion control have been off-farm, but farmers acknowledged that they derived short-term benefits, such as enhanced reputation, and long-term benefits associated with soil conservation.

4.9.2 Flood risk management

The Parrett catchment has a history of developing integrated water and flood management policies. In 1991 the Environment Agency launched its Water Level Management Action Plan for the Somerset Levels and Moors, which included actions for ‘a review of flood management practices to improve the integration of environmental targets with enhanced water management’. In 2000 a partnership of local people and organisations launched the Parrett Catchment Project (PCP) to champion integrated land and water management of the catchment to achieve sustainable benefits across the catchment. This led to the development of the PCP vision and Action Strategy; and the Parrett Catchment Water Management Strategy Action Plan (Environment Agency, 2002b; Hicklin, 2004) with identified actions, *inter alia*, including changes to agricultural land management in the upper catchment.

These strategies have now been superseded by the Parrett Catchment Flood Management Plan (Environment Agency, 2008b). Areas at risk of significant flooding from rivers include Taunton and Bridgwater, and surface water flooding, often caused by runoff from agricultural land, is also identified as an issue for parts of the upper catchment that are particularly vulnerable to soil erosion such as the upper Tone catchment.

The Tone catchment has been divided into three flood management policy units: Upper Tone (above Taunton); Taunton; and the Somerset Levels and Moors (below Taunton). Existing average Annual Expected Damages (AEDs) from flooding are estimated to be £2.6 million (approximately £2 million for Taunton and £600,000 for the Upper Tone). The CFMP concludes that changing climate and land use/management are likely to result in substantial increases in flooding both at locations currently at risk as well as introducing new locations at risk. AEDs could rise to £6.4 million (£5.2 million for Taunton and £1.2 million for the Upper Tone). The flood management policy for each policy unit is as follows:

- Upper Tone: Continue with existing or alternative actions to manage flood risk at the current level of flooding: Potential actions include encouraging best farming practices to reduce runoff.

- Taunton: Take further action to reduce flood risk. Potential actions include a review of the effectiveness of existing structural defences.

- Somerset Levels and Moors: Take action to increase the frequency of flooding to deliver benefits locally or elsewhere. Potential actions include studying the natural processes of the River Tone to inform future work.

5 STUDY APPROACH, METHODS AND DATA

5.1 Methodological research framework

The research is centred on the River Tone catchment; specifically the Halse Water, which represents a headwater sub-catchment, and the lower River Tone. The methodological research framework (Figure 5.1) seeks to elucidate information on the links between sediment sources in the upper catchment and potential sediment sinks in the lower catchment. The Tone study investigated sediment dynamics through the channel network focusing and the relationship between wash-material load, bed-material load and local sediment balance within defined hydraulic/sediment reaches.

Sediment dynamics were investigated using a series of sediment assessment tools and models, which used primary data collected during an extensive field campaign, supported by secondary data obtained from a variety of sources. The benefit of developing a model, rather than relying on direct observation, is that different simulations and scenarios can be run to answer what if…? questions (Mance *et al.*, 2002). The sediment tools and models were used to investigate a range of management and climatic scenarios, within which model input variables, such as sediment load, sediment calibre, riverbed material and flow were altered to represent different possible climate and land use futures. Comparing model outputs to field-based observations also allowed the current sedimentation regime (i.e. sediment loads and sediment yield to the tidal reaches) to be better characterised.

The response of sediment dynamics and sedimentation patterns to different land-use and catchment management scenarios were investigated, and focused on assessment of the implications for sediment continuity and connectivity, channel morphology, flood risk management, sediment continuity and habitats, and land and water quality. The information so generated provided the basis from which to establish the key components of integrated catchment management necessary to balance catchment runoff and sediment yields in a changing and uncertain future.

5.2 Tools and models

5.2.1 FRMRC1 toolbox

In Phase 1 of the FRMRC, Research Priority Area 8 on Geomorphology, Sediments and Habitats included a work package titled 'Accounting for sediment in rivers (Wallerstein *et al.*, 2006). The group undertaking this package of work was tasked with developing a quantitative tool which would build upon the qualitative Fluvial Audit with the objectives to:

- Characterise sediment source, transfer and sink areas on a reach-by-reach basis (reaches defined as geomorphologically consistent sub-units of a river drainage network);

- Represent sediment flux divergences between reaches resulting from differences between the supply of sediment and their capacity to transport sediment; and

- Predict the reach-scale response to the sediment transfer system to structural interventions and/or management actions undertaken for flood alleviation purposes [which could include catchment land use management].

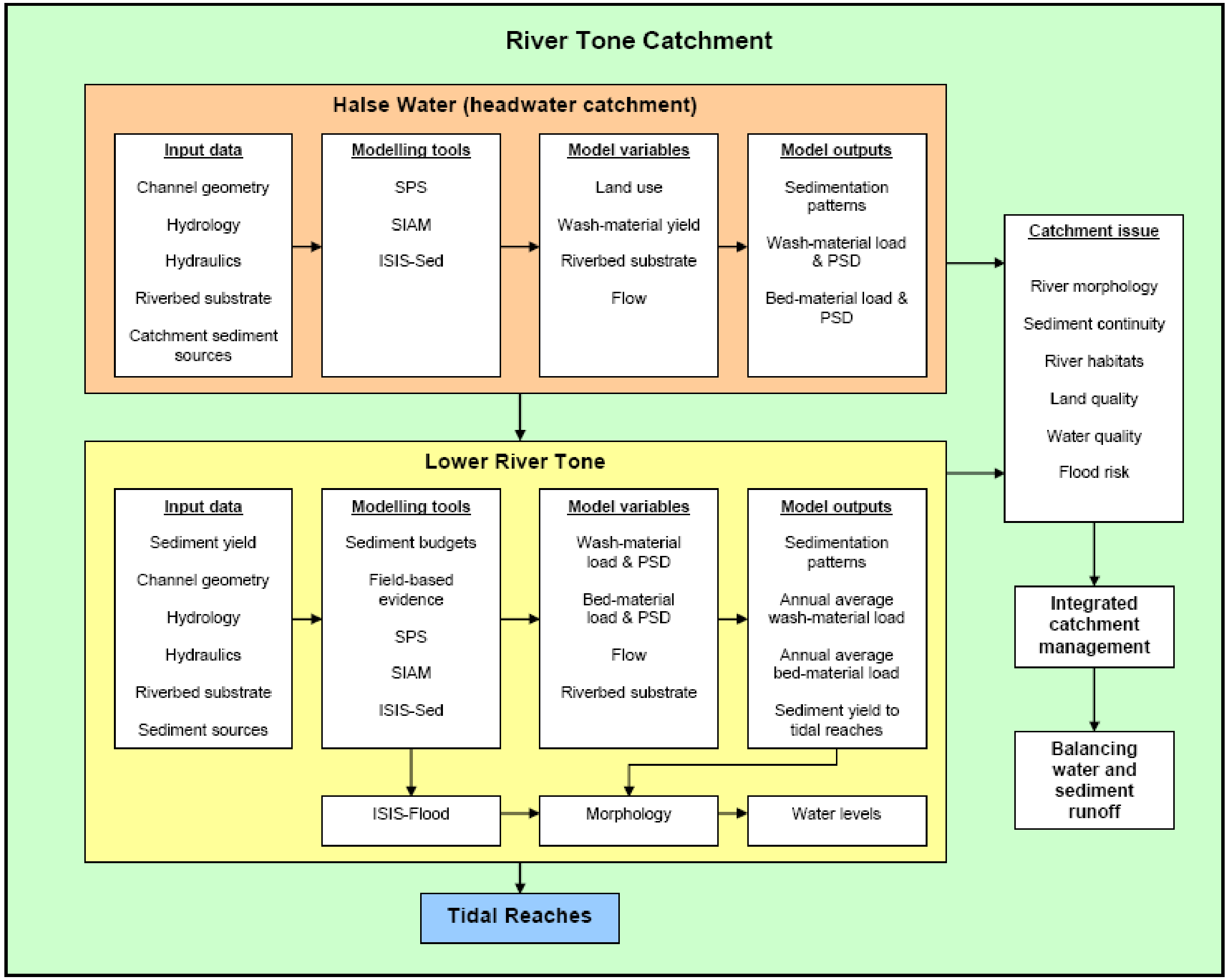


Figure 5.1 Methodological modelling and assessment framework to research sediment dynamics, morphology, flood risk and catchment interactions in the River Tone catchment

It was recognised in WP8.1 that no single approach could satisfy all situations and applications. Consequently, the output of WP8.1 was a toolbox of six methods. Specifically, methods in the toolbox are:

1. Stream power screening

2. River Energy Audit Scheme (REAS)

3. Sediment Impact Assessment Model (SIAM) – embedded within HEC-RAS (HEC-RAS: SIAM)

4. Hydraulic Engineering Centre-River Analysis System: Sediment Transport (HEC-RAS: ST)

5. ISIS Sediment

6. Cellular Automaton Evolutionary Slope and River Model (CAESAR)

These models all rely on elements of both interpretation and analysis of the sediment transfer system, but with varying contributions as shown diagrammatically in Figure 5.2.

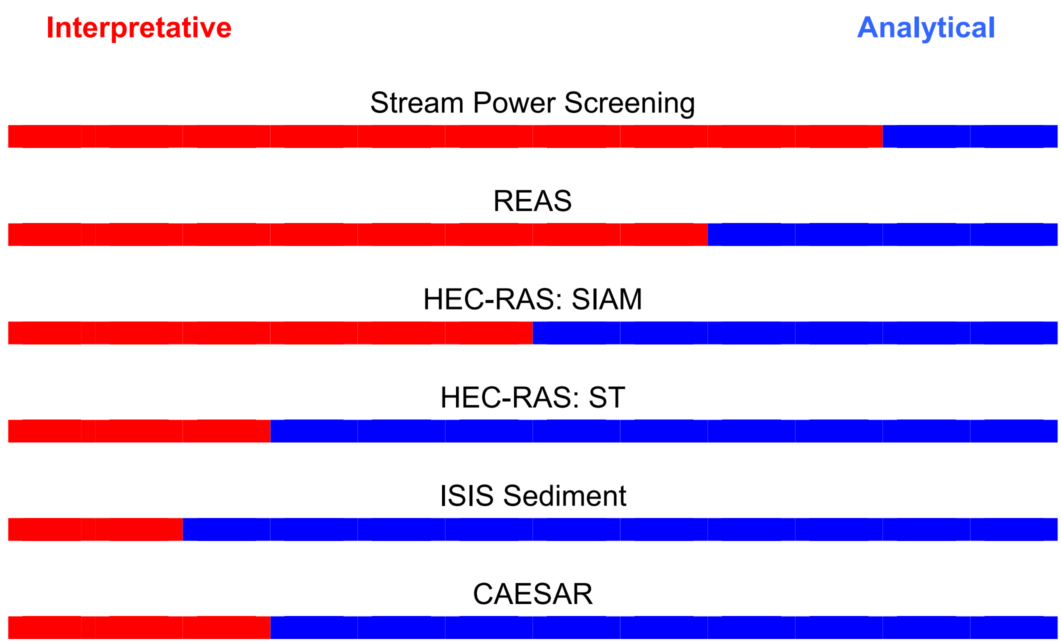


Figure 5.2 Interpretational and analytical contributions of tools included within the FRMRC sediment toolbox (Source: Wallerstein et al., 2006)

The research performed in FRMRC2, which is reported in this thesis, employed three of the methods included in the FRMRC sediment toolbox, namely: Stream power screening; SIAM; and ISIS-Sediment, and these methods are described and discussed in the following sections. These methods were chosen for a number of reasons:

- ❖ The tools range from highly interpretative to highly analytical approaches, as illustrated in Figure 5.2, allowing both a comparative benchmarking assessment to be undertaken as well as informing judgment on the level of investigation appropriate for application to sediment analysis in a lowland river system;

- ❖ ISIS and HEC-RAS hydraulic (flood) models were already available for the majority of the defined study area. These existing flood models could therefore form the basis for both SIAM and ISIS-Sediment models, facilitating use of these more data intensive models without the need for a bespoke programme of field data collection and model set-up/calibration;

- The existing hydraulic models can provide extensive hydraulic information, including bankfull width, bankfull flow, water slope and bed gradient to allow computation of stream power;

- Use was made of existing, albeit limited, sediment data available for the study area. These included suspended sediment (linked to long-term flow gauge data) and catchment sediment source data. These data were combined with primary data collected through a sediment sampling programme to allow model boundary conditions to be set;

- The study area characteristics are particularly suitable for application of these models, as the system transitions from a steeper, gravel-bed stream to low-gradient river with a silty-sand bed; and

- As discussed in Section 1.2, a component of this research is (1) to continue to test methods developed or established as part of the FRMRC Research Priority Area 8, particularly SIAM, on a lowland river system; and (2) to benchmark different methods in the toolbox to compare the outputs (in terms of similarities/differences; quality/level of detail, appropriateness etc) with respect to differing levels of inputs (in terms of data and resources).

In addition, a fourth method based on 'empirical evidence' (that is: readily available data collected via existing models, studies or bespoke survey) was also developed to firstly, begin to understand the sediment system in terms of quantification of sediment loadings and sediment continuity, and, secondly, and probably more importantly, provide input/boundary data for and allow some level of verification of the sediment models. The use of empirical evidence is not defined as a method in its own right within the FRMRC toolbox, but represents interpretation of the types of qualitative and semi-quantitative information routinely gathered during a Fluvial Audit or similar investigation. It therefore represents the basis upon which all six methods/models identified in the FRMRC toolbox are applied in practice (Thorne *et al.*, 2011). The data sets used in this component of the research are described in Section 5.3 and the outputs are discussed in Section 6.1.

5.2.2 Stream power screening

Brookes and Wishart (2006) and Thorne *et al.* (2011) provided overviews of the conceptual basis, application and issues surrounding the use of stream power screening, and hence only the key points are summarised here. The conceptual basis for the stream power screening comes from Bagnold (1966, 1980), who defines stream power as 'the rate of work done by the fluid or the rate of energy loss per unit length of stream', though an alternative definition that is more specific to sediment transport is that given by McEwen (1994) 'the rate of energy supply at the channel bed which is available for overcoming friction and transporting sediments'.

The most widely used and accepted index of stream power is specific stream power, which is the stream power per unit area of the channel bed (ω), defined by:

$$\omega = \rho g Q S / w \qquad \text{(Equation 5.1)}$$

where, p = water density (1000kg/m^3), g = acceleration due to gravity (9.81m/s^2), Q = discharge (m^3/s), S = water surface slope, and w = representative channel width (usually the width of the active bed). The units of specific stream power are Watts per square metre (W/m^2).

Investigations by Brookes (1987a and b) found that readjustment of artificially straightened channels tended to respond morphologically through deposition where bankfull specific stream power was less than ~15-25 W/m^2, and generally responded through erosion where stream power exceeded ~25-35 W/m^2. However, Brookes acknowledged that there are limitations associated with the application of stream power, and some of these are relevant to this research:

- It should not be used in isolation, but supported by other data (i.e. bed and bank material);

- It is only applicable to alluvial channels;

- It is best applied at the reach scale to avoid local anomalies but to allow capture of channel complexity; and

- There are no universal threshold values of stream power to predict morphological response and research has shown there are grey areas where rivers could respond through either erosion or deposition-led processes, and thresholds vary between rivers and catchments.

Notwithstanding this, the key strength of stream power screening is that it provides a rapid and cost-effective method of assessing sediment issues and potential continuity through a large channel network, and so provides a way to identify and prioritise reaches worthy of further, more detailed sediment investigation.

5.2.3 SIAM

SIAM is the **S**ediment **I**mpact **A**ssessment **M**odel (Biedenharn *et al.*, 2006a; Gibson and Little, 2006), although it is referred to as the Sediment Impact Analysis Methods (US Army Corps of Engineers, 2008a) or the Sediment Impact Accounting Method (Thorne *et al.*, 2011).

SIAM is a relatively new model developed at the US Army Engineers Research and Development Centre (ERDC) in collaboration with Colorado State University and the University of Nottingham. Full descriptions of the model and its data requirements are provided by Biedenharn *et al.* (2006a) and Thorne *et al.* (2011). Further information on the wash-material load: bed-material load concept, which underpins SIAM, is given in Biedenham *et al.* (2006b) and the application of SIAM in the USA is described in Biedenharn *et al.* (2006c).

SIAM supports rapid assessment and quantification of local sediment imbalances and downstream sediment yields under different river and catchment management scenarios. It is incorporated within the 'hydraulic design' module of the US Army Engineer, Hydrologic Engineering Center's River Analysis System (HEC-RAS) (Gibson and Little, 2006). Version 4.0 of HEC-RAS, which incorporates SIAM, can be freely accessed and downloaded from http://www.hec.usace.army.mil/software/hec-ras/.

SIAM splits a river network into a series of user-defined sediment reaches, which are delineated typically on observed locations of significant morphological change such as tributary junctions; changes in sediment continuity, channel gradient, planform or geometry; or changes in bed material composition. SIAM combines sediment, hydrological and hydraulic information to determine an average annual sediment budget for the river network on a reach-by-reach basis.

SIAM integrates the computed transport rates with flow duration information to compute an average annual sediment transport capacity in tonnes per year. Computed average annual sediment transport is compared with the average annual sediment load supplied by the reach upstream to evaluate the balance between sediment supply and transport capacity for each sediment reach. Sediment continuity is then used to classify reaches as sediment sources, pathways or sinks.

SIAM performs the reach averaged sediment transport computations by grain size class. Accounting for different grain size classes allows the model to track the movement of wash-material load and bed-material load through the river network. The concept of splitting and tracking wash-material load and bed-material load components of the total sediment load separately allows SIAM to identify links between sources and sinks of the relatively fine material that moves quickly through the system as wash-material load and those of the relatively coarser sediment moving as bed-material load, and it is this concept that underpins the utility of SIAM as a sediment management tool. Wash-material load, bed-material load and the basis for setting the threshold between the two have been defined in Section 1.3.1.

Application of a user-defined wash-material load: bed-material load threshold allows SIAM to treat the movement of fine and coarse material differently. A number of sediment transport functions are available in HEC-RAS 4.0 and an appropriate one is applied to calculate the bed-material load transport capacity in the reach, while the finer particles comprising the wash-material load is treated as being supply, rather than capacity limited. This decreases the total dependency on a sediment transport function for those grain class sizes that fall outside the range for which a transport function is applicable (Watson *et al.*, date unknown).

The benefit of splitting the total sediment load this way when investigating the linkages between sediment sources and sinks is demonstrated by considering a river which flows from steeper upstream reaches with coarse bed material, downstream to lower gradient reaches with finer bed material (as is the case with the River Tone). Sand particles are included in the wash-material load in the upper reaches (because their grain size is < D_{10} for the bed material), but in the lower reaches the sand becomes part of the bed-material load (because their grain size is > D_{10} for the bed material). Therefore, any increase in the supply of sand, for example due to accelerated catchment erosion, would have limited morphological impact in the upper reaches, but could have a much larger effect in the reaches further downstream.

SIAM requires the following input parameters for each sediment reach:

- *Bed material composition*: a representative and integrated bed material size gradation. Needed to define the percentage of sediment present in the bed material for each grain size class, set the wash-material load threshold diameter, and select the most appropriate sediment transport function;

- *Hydrological records*: long-term flow gauge records. These define the flow regime and corresponding flow duration curve that represents an average annual hydrologic cycle;

- *Channel form and hydraulic records*: channel geometry within HEC-RAS can use as few as 3 cross sections delineating the top, middle and bottom of a sediment reach (although usually all available cross-sections are included). Reach-averaged hydraulic parameters are generated from a quasi-steady HEC-RAS hydraulic model, to define the depth, cross-sectional area, mean velocity, hydraulic radius, wetted perimeter, top width, friction slope and roughness for each modelled discharge. The hydraulic parameters drive the calculation of bed-material sediment transport rate; and

- *Local sediment sources*: sediment calibres and loadings (tonnes/year) for a range of catchment and river sediment sources. These may include, for example, field erosion, channel bank erosion, road runoff, and inputs from tributaries and other point sources. Sediment removal, for example through dredging, can be included as a negative local source.

The six sediment transport equations available in HEC-RAS 4.0/SIAM are: Ackers-White (1973), Engelund-Hansen (1967), Laursen (1958), Meyer-Peter Müller (1948), Toffaleti (1968) and Yang (1973 and 1984).

The primary SIAM output is a local, bed-material, sediment balance (see Figure 1.2), which is defined as the difference between the annually-averaged supply of bed material sized sediment from upstream and local sources, and the average annual transport capacity for a sediment reach (negative = excess transport capacity = erosion potential; positive = excess supply = deposition potential). Other outputs include average annual transport capacities, bed-material load and wash-material load supplies, and local sediment supply totals for each reach. All outputs are listed as a total for each sediment reach as well as by grain size class.

SIAM assesses the average annual sediment balance under the defined hydrologic, hydraulic and sediment supply conditions, but the channel geometry is not updated based on the predicted net erosion or deposition. SIAM is a reached-based model that produces reach-based outputs. Consequently, it also cannot supply information on the distribution of erosion and deposition within each sediment reach, and the types of morphological adjustments (e.g. aggradation/degradation; narrowing or widening) driven by any sediment imbalance must therefore be interpreted using professional judgement and supporting evidence.

In the USA SIAM has been used on a number of river studies including Pistol Creek (Tennessee), Arkansas River (Arkansas) Bronx River (New York), Hickahala Creek (Tennessee) and Judy's Branch (Illinois). These study rivers range form 6-40 miles long and are mainly sand or cobble/gravel rivers. SIAM has generally been used to evaluate the impact of a range of catchment erosion control measures on sediment delivery to sensitive downstream sites such as wetlands (i.e. Biedenharn *et al.*, 2006a; Biedenharn *et al.*, 2006b).

In the UK the potential use of SIAM has been evaluated on a number of mainly upland rivers including the River Wharfe (Yorkshire), River Eden (Kent), River Kent (Cumbria), River Harbourne (Devon) and Pontbren Stream (North Powys), with mixed results. The model has to-date had limited success mainly due to the steepness of many of the catchments investigated (SIAM should not be used where average Froude numbers are >0.7), absence of defined/potential morphological impacts from wash-material load (most systems are bed-material load dominated), and the lack of detailed, integrated bed sediment input data, which are very rarely collected in the UK (Nick Wallerstein and Alex Henshaw, University of Nottingham, pers. comm.).

5.2.4 ISIS-Sediment

Green (2006) and Thorne *et al.* (2011) provided general overviews of 1-D sediment models in general, and ISIS-Sediment in particular. Only the key points are summarised here. In the investigations performed to support this thesis, ISIS-Sediment was used to support the core research by providing a process-based, highly analytical sediment modelling method, the outputs of which formed a key component of the sediment model benchmarking exercise. In this context, Black and Veatch were commissioned to set-up and verify the ISIS-Sediment model and to run comparative sediment management and hydrological scenarios due to their deep understanding of the model and wide experience in applying it.

Since the 1960s 1-D computational models for river flow have been used to assess and plan flood protection works, and consequently a large proportion of the main rivers in England have had at least a part of their length modelled using 1-D models, including ISIS. The hydraulic parameters needed for ISIS-Sediment are similar to those used in conventional hydraulic model calculations. Despite this sediment modelling in the UK is far less common than routine hydraulic modelling, although ISIS-Sediment has been used on occasion to identify and evaluate options for sediment management in flood defence channels (e.g. Walker, 2001).

The equations used in hydraulic and sediment transport computations are documented in the ISIS user manuals (ISIS, 1999a; ISIS, 1999b). Sediment simulation is based on a calculation of transport rates and an accounting of erosion and deposition using a concept of layers of sediment (parent layer, sub-layers and an active surface layer) with ‘well mixed’ sediment size distribution in each layer. Bank material is assumed to be the same as bed material. Channel cross-sectional geometry (bed elevation) is updated during the hydraulic simulation using one of three methods (whole section; wetted section; distributed using a user defined exponent).

Sediment transport formulae may be separately specified by size fraction (gravel, sand and silt), and different bed compositions can be specified for each cross-section. A different sediment gradation can be specified for the inflow of sediment. Available sediment transport equations are: Engelund-Hansen (1967), Ackers-White (1973), revised Ackers-White (1993) and Westrich-Jurashek (1985) [for fine silts].

Data requirements for ISIS-Sediment include: sediment inflow (specified by a time-varying rate or concentration, or as a discharge-varying concentration); hydrological data (gauged discharge or historic rainfall providing a long time series); bed material characteristic (bed material size distribution for each cross-section); bed active layer thickness (depends on whether there is a hard bed, and is based on a factor times the D_{95} value); and bed porosity (normally set to 0.4 for sand/gravel beds).

Outputs for ISIS-Sediment typically include plots of simulated bed elevation or sediment concentration as a function of time. ISIS geometry is usually based on channel cross-sections at spacings between 50-200m. Consequently, ISIS-Sediment outputs provide much more detailed information on the long-stream distribution of bed erosion/deposition than the outputs of SIAM.

5.3 Data sets

5.3.1 Sediment yield

Defining sediment yield

Sediment yield is defined as the total mass of sediment delivered to the outlet of a river catchment during a specified time period, usually on an annual basis (Parsons *et al.*, 2006; Walling *et al.*, 2008). Sediment yield is either expressed in units of weight/time (tonnes/year) or, more usually, as a specific sediment yield, which is weight/area/time (tonnes/km^2/year), calculated by dividing sediment yield by the contributing catchment area located upstream of the point of measurement.

Conventionally specific sediment yield is characterised as decreasing as catchment area increases because the river network becomes more remote from the headwater sediment sources (Birkinshaw and Bathurst, 2006). However, Parsons *et al.* (2006) point out that the area-averaged figure bears little relationship to the area from which the transported sediment itself is derived, because most sediment transported by watercourses is delivered from the bed and banks of the channel, and from alluvial and colluvial deposits within the catchment.

Birkinshaw and Bathurst (2006) investigated the scaling relationship linking specific sediment yield to river catchment area. They concluded that the sediment yield/catchment area relationship can be inverse or direct depending on catchment characteristics and the main sources of sediment. For example, if sediment is supplied predominantly from bank erosion, the sediment yield increases downstream, whereas, the reverse can be true if sediment is supplied mainly from hillslope erosion in a catchment with uniform land use. Regardless of issues related to scaling, as Walling *et al.* (2008) pointed out, the use of specific sediment yield is a powerful tool as it facilitates the comparison of sediment yield between catchments [or sub-catchments] of different sizes.

As part of the research presented in this thesis, the sediment yield at various points in the study area was established in order to estimate the input of sediment to the river from each of the discrete sediment sources identified in the catchment sediment source study (see Section 5.2.2). This was achieved by combining sediment yield data with sediment fingerprinting and point source sediment data (see Section 5.2.4) to establish typical annual loads for different sediment sources (arable, pasture, river banks, damaged road verges and tributaries). These then provided input data for the sediment model.

To facilitate a comparison between sub-catchments, and allow a comparison of estimated sediment yield outputs for the research presented within this thesis with other study outputs, specific sediment yield (tonnes/km^2/year) was calculated.

Calculating sediment yield

Walling *et al.* (2007) state that 'typical' specific sediment yields for UK rivers are in the region of 50 tonnes/km^2/year. This is supported by a recent study by Walling *et al.* (2007) who reviewed a set of 107 'high or medium quality' specific sediment yield estimates for the UK and found the average specific sediment yield to be 44 tonnes/km^2/year. The majority of these data relate to suspended sediments from agricultural catchments (76%), and are, therefore, relevant to the study area used in the research reported in this thesis.

An Environment Agency R&D project assessed sediment load as a function of catchment drainage area to derive separate equations for the annual yields of bedload (tonnes/year) and suspended sediment (tonnes/year) in small and large catchments (Sear *et al.*, 2003) as shown below.

Source areas (headwater catchments) with areas less than 100 km^2:

$$\Psi_{bed} = 5.85A^{1.08} \qquad (n = 33, r^2 = 0.31)$$

$$\Psi_{susp} = 11.64A^{1.16} \qquad (n = 60, r^2 = 0.63)$$

Large catchments with areas greater than 100 km^2:

$$\Psi_{bed} = 2.50A^{1.16} \qquad (n = 7, r^2 = 0.41)$$

$$\Psi_{susp} = 31.04A^{1.04} \qquad (n = 44, r^2 = 0.48)$$

where, Ψ_{bed} = annual bedload yield (tonnes/yr), Ψ_{susp} = annual suspended load yield (tonnes/yr), and A = catchment area (km^2).

The limited empirical database underpinning these formulae, with relatively low coefficients of explanation for the regression equations, indicates they should be used carefully. The outputs are purely indicative of the likely magnitudes of sediment yield which can be expected, and consequently the EA equations were used to provide a reality check for sediment yield generated via other methods.

Recent, nationally-extrapolated information on suspended sediment yields (Figure 5.3) suggests a specific sediment yield in the range of 20-70 tonnes/km^2/yr for the River Tone study area (Cooper *et al.*, 2008). These figures were used in a recent study to apportion sediment and nutrient sources across the Somerset Levels, which included assessing the River Tone and Halse Water (Collins, 2008).

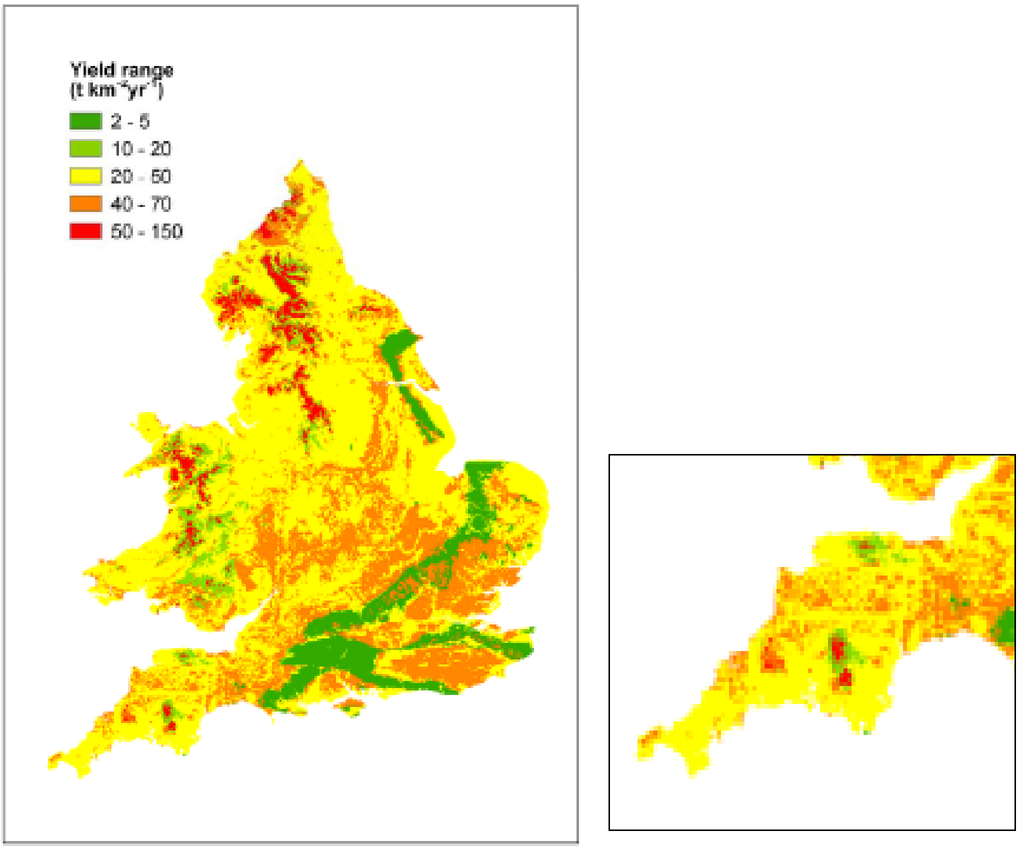


Figure 5.3 Nationally-extrapolated sediment yield classifications for the UK (Source: Cooper et al., 2008)

Walling *et al.* (2007) established the following key characteristics of suspended sediment dynamics of British rivers:

- Suspended sediment loads are almost exclusively non-capacity loads (i.e. they are supply-limited);

- Most rivers are characterised by seasonal and storm-period hysteresis, with concentrations for a given flow usually being higher on the rising stage than on the falling stage; and

- Significant suspended sediment transport is highly episodic being generally restricted to major runoff events. Typically, about 80% of the total suspended sediment is transported in about 2% of the time (equivalent to 5-10 days/year).

Cooper *et al.* (2008) stated that there is often no simple relationship between suspended sediment concentration and river discharge because:

- The same river flow can be generated by widely different spatial and temporal patterns of rainfall, which in turn can generate different levels of sediment delivery; and

- The catchment is in a different hydrological condition for each rainfall event, with differing availability of sediment.

The first point is perhaps the strongest driver of sediment delivery as recent research has shown that, although sediment delivery is strongly influenced by high-intensity, short-duration rainfall events, it is independent of the level of catchment saturation (Reid *et al.*, 2006). However, research by Palmer (2003 and 2004) identified the presence of winter crops on vulnerable soils (i.e. availability of sediment for erosion during the high, intensity rainfall events) as also being a critical factor in the study catchment.

Accurate measurement of annual sediment yield depends on continuous monitoring, which requires considerable expertise and resources in terms of installation, maintenance and calibration of sensors and samplers. Even if continuous measurement is possible, the final yield relates only to the monitoring period and may not be representative of the long-term catchment conditions (Clarke, 1995; Cooper *et al.*, 2008).

Walling *et al.* (2007) demonstrated by using simple standard error statistics that a record of about 25 years of discharge and suspended sediment would be required to estimate the long-term mean annual sediment load to within ± 20% of the actual value, at the 95% level of confidence.

The difficulties evident in collecting and using continuous data to assess sediment yield suggest that an alternative approach is needed. If continuous monitoring data are not used then an estimate of the unmeasured values is needed. A commonly used approach to dealing with temporal effects is through flow adjustment. Cooper *et al.* (2008) identify that, as a minimum, sediment yield estimation requires continuous flow measurement and large numbers of suspended sediment samples for both base flow and a range of flow events. In these circumstances, the ratio method (Cooper and Watts, 2002) may be used to calculate sediment yield. In the ratio method, the sample mean load is adjusted using the ratio of the long-term mean discharge to the sample mean discharge, as defined by:

$$L = (N m_l / m_q)\, \mu_q \qquad \text{(Equation 5.2)}$$

Where, N = the number of sample intervals with measured discharge in the period of record, m_l = the sample mean load, m_q = the sample mean discharge, and μ_q = the long-term mean discharge.

Cooper *et al.* (2008) identified that routine Environment Agency suspended sediment data which have been collected over a long timeframe are likely to include a range of flows including storm events and, consequently they should provide a large enough sample to support a reasonable estimation of sediment yield. However, it must be borne in mind that using the EA's routine sampling data alone may under-estimate sediment yield, while combining the EA's routine data together with automatic sampler data leads to over-estimation.

Environment Agency suspended sediment concentration data (mainly monthly or bi-monthly collection, but spanning 20+ years in some places) were available for a range of locations throughout the Parrett catchment, including the River Tone (e.g. Bishops Hull gauging station, major weirs and tidal limit) and the Halse Water (e.g. gauging station) (Figure 5.4).

These large data sets may provide additional information on the relationship between discharge and suspended sediment concentration through development of sediment rating curves, which can provide detailed information on the catchment response. The sediment rating curve reflects the mobilisation and availability of suspended sediment and shows how concentrations vary with discharge that explain why it is possible for catchments having the same specific sediment yield to have different temporal patterns of sediment transfer. For example, a high sediment yield may result from persistent sediment transport at low flows or very high concentrations during a few high-yield events. This is significant because it would, in turn, suggest different sediment management strategies.

Rating curves, in the broadest sense, should therefore be investigated in all cases where further understanding of the impact of sediment and a need to manage sediment inputs is required (Cooper *et al.*, 2008). Sediment rating curves are also needed to set the input boundary conditions for ISIS-Sediment modelling (see Section 6.4).

The conclusion drawn from this review of best practice literature was that establishing the sediment yield for the study area required application of all available methods of calculating sediment yield (including specific sediment yield) to compare, contrast and define acceptable upper and lower bounds. The following methods were therefore used:

- Results from meta-study data (Walling *et al.*, 2007);

- Nationally-extrapolated sediment yield (Cooper *et al.*, 2008);

- Environment Agency R&D catchment formulae to estimate bedload and suspended sediment yield;

- Environment Agency suspended sediment concentration data (routine [spot] and investigative [continuous]) and 15 minute discharge data (see Section 5.3.3) within the Ratio Method (Cooper and Watts, 2002) to estimate sediment yield and establish sediment-flow relationships (rating curves); and

- Data from previous catchment-specific investigations which have sought to determine sediment yield (i.e. Black and Veatch, 2011).

The results from the various sediment yield calculations are presented and discussed in Section 6.1. Sediment yield will be subject to sensitivity testing during the sediment modelling exercise by assessing a range of sediment yields, which fall within realistic limits, to assess implications for sediment continuity, channel morphology and potential future management.

5.3.2 Channel geometry

Two existing 1-D hydrodynamic flood models were available for use within this research:

- ISIS hydraulic flood model for the River Tone (Black and Veatch, 2005a and b) which covers the research study area from the downstream limit (Newbridge tidal sluice, NGR ST 317269) upstream to the confluence with the Halse Water as far as the West Somerset Railway crossing (NGR ST 185266), which is located to the northeast of Norton Fitzwarren; and

- HEC-RAS hydraulic flood model, developed by Hyder Consulting on behalf of Barrett Homes, which covers the study area on the Halse Water from the West Somerset Railway crossing (NGR ST 185266) upstream to the east of the road bridge at Cotford St Luke (NGR ST 170268).

Data from these two models were combined into a single ISIS model. The model was then extended further up the Halse Water to Northway (NGR ST 122290), approximately 5.5km further upstream, which linked it to the steeper, headwater catchment with its potential sediment sources. To extend the model, nine additional channel topographic cross-section profiles were surveyed and incorporated into the ISIS model (Figure 5.4).

This ISIS hydraulic model was simplified to facilitate development of the ISIS-Sediment model (see Section 6.4). The ISIS-Sediment model was then converted to HEC-RAS 4.0 format to support application of SIAM (see Section 6.3).

5.3.3 Hydrology

Discharge data from two Environment Agency gauging stations located just upstream of Taunton: Bishops Hull GS (Station ref no. 520560) on the River Tone; and Halse Water GS (Station ref no. 520580) (Figure 5.4), were collated to generate a continuous, 15-minute flow record extending from 1st January 1992 until 31st December 2009 for each gauging station. There is a good level of confidence associated with the data from the gauge on the River Tone, although there is a slightly lower confidence in the data associated with the Halse Water gauge, particularly at high flows. However, as the majority of sediment transport and morphological change in a channel occur in association with intermediate discharges, closer to the annual or Q_{med} flows, the Halse Water gauge data are considered adequate for the research reported in this thesis.

The Halse Water discharge record was used for sediment modelling in the Halse Water. However, to provide a discharge record representative of the lower River Tone, both records were first aligned, using an Information Function in excel to remove any missing values, and then combined.

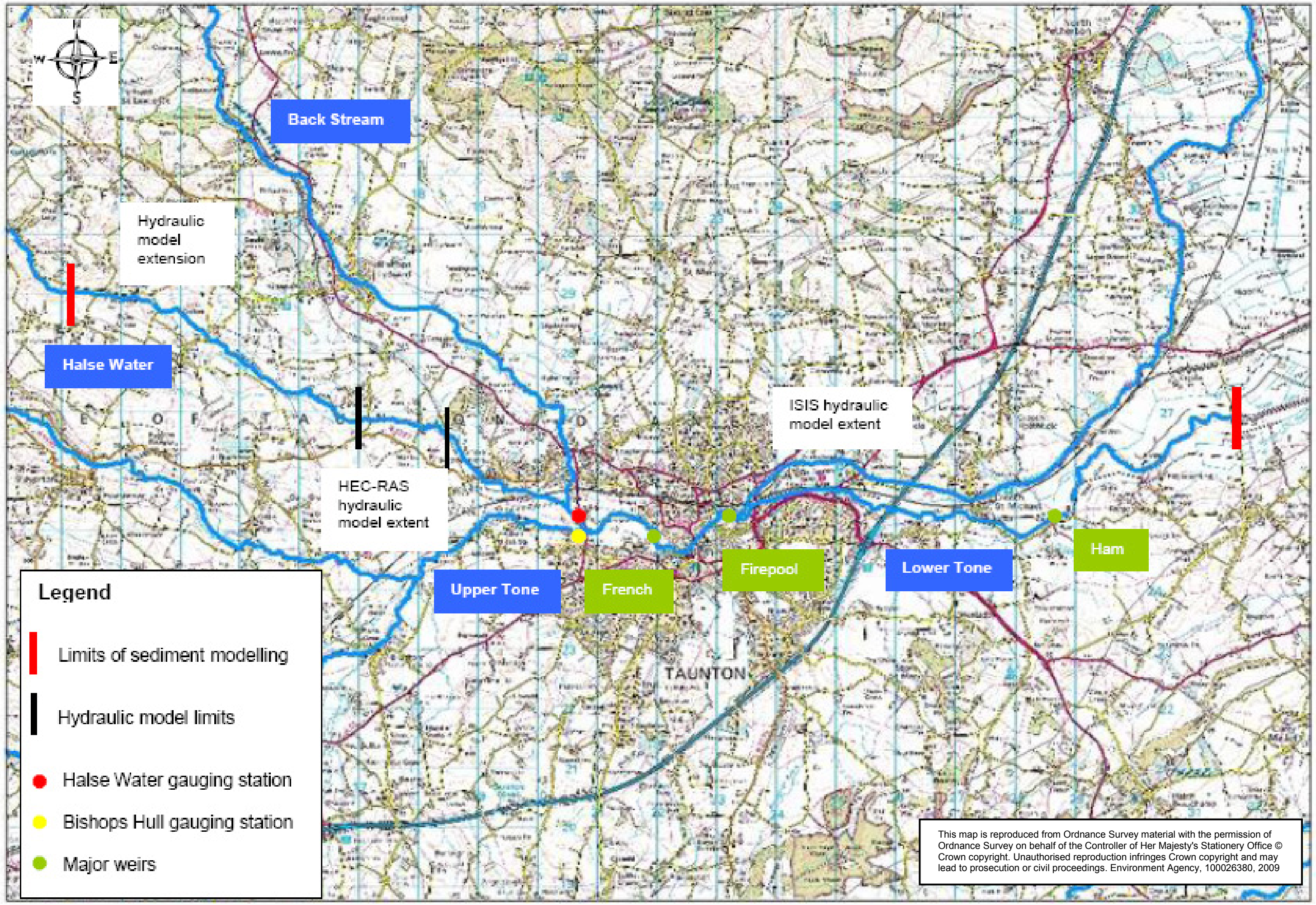


Figure 5.4 Gauging stations, major weirs and limits of hydraulic models on the lower Tone and Halse Water

The Halse Water and Lower Tone discharge records were used to generate an average annual flow duration curve for each study river. These flow duration curves were generated using arithmetic computation, with no cumulative smoothing and the minimum discharge used for computation of effective flow was set to zero. Twenty-five flow profiles were found to be the optimum number for each flow duration curve. These encompassed a range of discharges extending from 0.33 m^3/s to 16.27 m^3/s for the Halse Water, and 1.9m^3/s to 94.3m^3/s for the lower River Tone.

5.3.4 River bed material

Overview of river bed sampling

Bed material particle sizes may vary along the direction of the stream flow (longitudinally), across the width (cross-sectionally), and vertically within the bed (Bunte and Apt, 2001). Bed material sampling and analysis to define the bed material particle size is required for a variety of purposes including input parameters needed for the equations used to calculate: the threshold of bed-material motion; bed-material load transport rates; and grain/bed roughness as an input to hydraulic computations (Bunte and Apt, 2001; Kondolf *et al.*, 2003).

Bed material sampling and analysis was required to obtain information on the particle size distribution of the riverbed throughout the study area and, specifically to obtain a representative particle size distribution for each user-defined reach in the sediment models (see Section 6.3). These data were required to: provide input boundary data for the sediment models; support computations of flow hydraulics; select appropriate sediment transport equations; and enable wash-material load/bed-material load thresholds to be appropriately defined.

Sampling bed material in sand-bed (0.063-2mm) [or finer silt/clay rivers] is relatively straight forward, and usually requires an integrated sample of sediment from several locations distributed more or less systematically over the riverbed. Differentiation between surface and subsurface sediments is not usually necessary, and a shovel is often sufficient as a sampling device in exposed or shallow water sites (Bunte and Apt, 2001). Samples may be obtained using a grab sampler in deeper water sites (Kondolf *et al.*, 2003). Usually, one litre is an adequate sample size with the number and distribution of samples dependent on the spatial homogeneity of the bed material (Kondolf *et al.*, 2003).

For coarser bed material in wadeable rivers, the pebble count method is normally used (Wolman, 1954). A sample of 100-200 grains (stones) is selected from the river bed (or a bed facies such as a gravel bar), usually in a grid pattern. The stone measured at each sample point is selected randomly by the surveyor closing his/her eyes before letting a finger touch a stone on the bed. An alternative to a grid, sampling points can be selected by picking grains encountered in front of the surveyor's foot at regular intervals proceeding across/along the river bed (Kondolf *et al.*, 2003).

Alternatively bulk samples can be collected. This involves directly removing a sample from the bed, usually with a predetermined area down to a predetermined depth. When using the data for calculating bed-material load transport, subsurface bulk samples are often appropriate because it has been found that the subsurface grain size distribution more closely approximates that of the bed-material load than does the surface size distribution (Kondolf *et al.*, 2003).

In general, larger samples reduce bias and uncertainty in sampling as well as reducing the variance if the material were sampled without bias. Adequate sample size was discussed by Wentworth (1926) who recommended that samples should be large enough to include several fragments which fall into the largest grade present in the deposit, and suggested 'ideal' and practical' sample sizes (Table 5.1).

Maximum grain size (mm)	**Ideal minimum sample size (kg)**	**Suggested practical sample size (kg)**
64 – 128	256	32
32 – 64	32	16
16 – 32	4	8
8 – 16	0.5	4

Table 5.1 Ideal and practical sample sizes for bed-material sampling (Source: Wentworth, 1926)

Shirazi *et al.* (1981) recommended that the diameter of a bulk core sample should be 2-3 times the size of the largest particle and that the fraction falling in the largest size interval should not exceed 10% of the total sample weight. Church *et al.* (1987) in their review of sample size concluded that the largest grain size should constitute no more than 0.1% of the sample by bulk weight, although recognised for practical reasons that the 0.1% rule was only useful for sizes up to 32mm (a 1% criterion was used up to 128mm). Bunte and Apt (2001) suggest a sample size that is 20-100 times the mass of the D_{max} particle size.

Harvey (2006) sampled gravel (2-64mm), sand (0.063-2mm) and silts (<0.063mm) by taking 2-3kg samples collected by shovelling substrate into bags held downstream of the sample area to ensure that the finest fraction was not lost downstream. The coarser cobble fraction (64-256mm) was sampled according to a grid sampling design based on the Wolman (1954) pebble count method using a grid of approximately 0.5m x 0.5m squares across the channel.

Sampling locations must be chosen to target areas relevant to the research problem, avoid bias, and obtain a large enough sample to adequately reduce the variance of a highly variable population, while dealing with practical issues such as obtaining a manageable sample usually from under flowing water.

The first step in designing a sampling strategy is to define the sample population, which includes all the areas of the river bed that need to be represented. Secondly, the strategy should aim to minimise sample error, which is a function of population variance and sample size. Population variance can be limited by defining a more homogeneous sample population, and can be reduced by increasing sample size. Stratifying the bed according to bed-material size and sampling accordingly can reduce sample error while limiting the number of samples. Given the fact that sampling riverbed sediment is known to be prone to high uncertainty and variability it is essential that the needs of the study are continuously evaluated as data are collected (Kondolf *et al.*, 2003).

River bed sampling methodology and results

The physical dimensions of the channel, as well as its bed materials, vary throughout the study area. The lower reaches are generally unwadeable, and silt/sand dominate the bed. Both the Tone above Taunton and the Halse Water are wadeable, with mainly gravel dominated beds. Consequently, a sampling strategy was developed utilising a range of bed material sampling methods (Table 5.2). Sampling was spatially distributed to obtain a representative grain size distribution for a number of geomorphic/hydraulic homogenous reaches of the river and to minimise sampling error, as shown in Figure 5.4 and described below.

The 26.3km reach within the study area was divided into 16 geomorphologically- and hydraulically-homogeneous reaches with similar bed material characteristics, on the basis of Fluvial Audit and RHS investigations (see Section 6.3). This reduces within-reach population variance.

Within each geomorphic reach sediment was sampled using an appropriate method of collecting a suitably sized sample. In the lower reaches samples were collected using an integrated Van Veen box grab sample (Plate 5.1). In the upper reaches an integrated sample was collected by shovelling bed material into a 5-litre plastic bucket positioned downstream of the sampled area to collect fines disturbed during sampling. In addition, a Wolman (1954) pebble count (Plate 5.2) based on up to 400 stones (composed 2 or 4 sub-samples) was conducted along a longitudinal, zigzagged transect that encompassed the range of functional habitats and physical biotopes present in the reach, for example, bars, riffles, runs and pools.

Plate 5.1 Van Veen box grab used to collect river bed material samples in the lower River Tone

Plate 5.2 Bed material sampling using Wolman pebble count method showing selection of sampled stone (a) and measured using a Wolman grid with standard Wentworth openings (b)

River	Reach	Location	NGR	Bed material sampling method				
				Van Veen	Bucket	Pebble count	Probe	Russian corer
Halse Water	1	Northway	ST 1245 2905 – 1340 2880		4	400		
	2	u/s Halse Water Bridge	ST 1430 2845		2	400		
	3	u/s Woodend Bridge	ST 1525 2775		2	400		
	4	u/s Cotford St Luke Bridge	ST 1680 2680		2	400		
	5	d/s Cotford t Luke Bridge	ST 1740 2690		2	400		
	6	u/s Norton Fitzwarren	ST 1870 2630		4	400		
	7	No sampling access						
	8	u/s Halse Water G.S.	ST 2050 2550		2	400		
River Tone	1	d/s A3065 Bridge	ST 2090 2495		2	400		
	2	u/s French Weir	ST 2200 2485 – 2205 2470	2			✓	
	3	Taunton city centre	ST 2260 2475 – 2305 2520	3			✓	✓
	4	No sampling (engineered, non-erodible channel)						
	5	No sampling access						
	6	Creech St Michael	ST 2710 2540 – 2735 2535	3			✓	✓
	7	Ham Mills to Knapp Bridge	ST 2890 2530 – 3020 2610	2				
	8	Knapp Bridge to Newbridge	ST 3020 2610 – 3165 2690	2				

Table 5.2 Halse Water and lower River Tone bed material sampling locations and methods

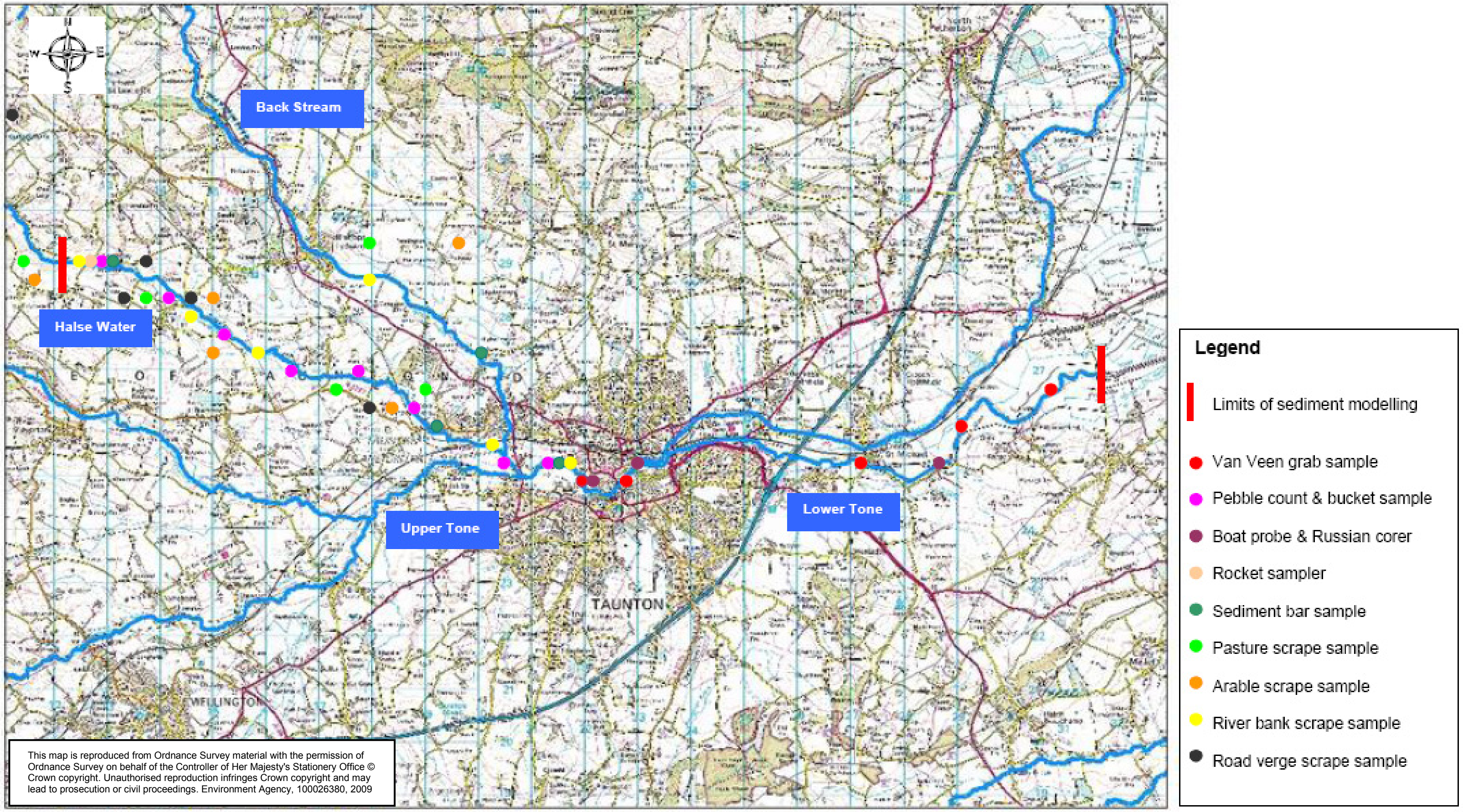


Figure 5.5 Locations and methods of river substrate, river suspended and depositional sediment, and catchment sediment source sampling on the Lower Tone and Halse Water

This method of pebble counting aims to randomly sample all the biotopes and habitat features as an integrated unit rather than representing the bed as individual cross-sections (Bevenger and King, 1995). Sample points were spaced at approximately 1m intervals along the zigzagged transect, with the sampled stone being selected from immediately in front of the surveyor's boot (Plate 5.2). Each stone was measured using a Wolman grid with standard Wentworth (1926) size openings (Plate 5.2), which means that the sizes are comparable to sieve measurements. This reduced sample variance by increasing sample size and ensuring an appropriate sample size is collected.

Multiple, integrated sediment samples were taken within each sediment reach. In the lower reaches of the River Tone grab samples were taken, predominantly from bridges. In some locations where there was no bridge and it was possible to get a grab sample from the bank this option was chosen. In the upper, wadable reaches multiple bucket samples and pebble counts were taken in representative sub-reaches. This reduced sample variance by increasing sample size.

The channel beds upstream of the three major weirs: French weir, Firepool weir and Ham weir (Plate 4.1a and b, Plate 4.2a, and Figure 5.4) were also surveyed and sampled from a boat using a pole probe, and in some locations a Russian corer (Plate 5.3), to establish extent and, where possible, depth of depositional material. This information was used to confirm or, in certain reaches, adjust the representative bed material particle size distribution.

Plate 5.3 Sampling bed material upstream of major weirs using a Russian corer from a boat

Bed material analysis

The size distribution of each integrated bulk sample, obtained using the Van Veen grab and bucket, was determined in the laboratory through Particle Size Analysis (PSA). Sample preparation and analysis included oven-drying to remove moisture, and sieving down to a sieve size of 0.088mm (Phi 3.5) using sieves at Phi 0.5 size intervals. For Van Veen grab samples, a sub-sample of the <2mm fraction was treated with hydrogen peroxide to remove organic matter and analysed in a Beckman LS Particle Size Analyser. Analysis was down to 0.00048mm (Phi 11), at either 0.5 Phi or 1 Phi intervals.

For each Van Veen grab sample, the results of the <2mm sub-sample were up-scaled using the ratio of the total wet sample weight to the particle size analyser sub-sample weight. The fine fraction was then combined with the coarser sieved fraction to produce a complete particle size distribution.

The integrated sub-samples (Van Veen grab or bucket) from within each reach were analysed separately, and then combined to provide as large a sized sample as possible for the reach as a whole. Individual and combined samples were reviewed to determine the acceptability and appropriateness of a specific particle size distribution curve for representing a given reach (Table 5.3). In all of the fine-bedded reaches the preferred particle size distribution is based on a combined, integrated sample. In three of the gravel-bedded reaches the coarser part of the integrated sample and the pebble count data corresponded well, and in these circumstances the best fit curve was chosen, which was in all cases a combined, integrated sample.

However, in five of the coarse bedded reaches the integrated sample and the pebble count data did not have a good match, and were therefore combined using the rigid combination method (Bunte and Apt, 2001, p230). The rigid method uses the percentile ratio between the integrated bucket sample and a pebble count at the lower and upper boundary of one selected particle size class to create a new cumulative frequency distribution for the fine part of the pebble count. Within the range of particle sizes common in both samples, one particle size class is sought in which the ratios between the lower and upper percentiles of the integrated sample, $P_{I\ low}$ and $P_{I\ upper}$, and the lower and upper percentiles of the pebble count, $P_{P\ low}$ and $P_{P\ upper}$, are as similar as possible. Mathematically:

$$P_{I\ low} / P_{I\ upper} \approx P_{P\ low} / P_{P\ upper} \qquad \text{(Equation 5.3)}$$

The rigid combination computes the percentiles P*ri* for each particle size Di of the fine part of the combined pebble count size distribution using:

$$P_{r\ i} = PI\ i \times P_{P\ low} / P_{I\ low} \qquad \text{(Equation 5.4)}$$

The different bed material sub-samples (type and size) collected or produced (via volumetric combination or the rigid combination method) for each geomorphic reach are shown in Table 5.3. The bed material sample used to generate the cumulative particle size distribution curve for each reach is highlighted red in Table 5.3.

Bed material in three reaches (HW7, T4 and T5) could not be sampled as the river was within private land with no access, or there were no suitable bridge and the river could not be sampled from the bank, or the river was not suitable for boat access. In these locations an assumption on bed material based on upstream or downstream sampling or a visual assessment was made. Reach T2 was sampled by Van Veen grab from the riverbank, which demonstrated that this reach was predominantly sand/silt. However, following a re-survey from a boat using a pole probe it was found that these data were unreliable as the grab, which had been used from a bank, was found to have sampled bank side sand/silt deposits (see Section 6.1). These data were not representative of the reach as a whole, which was found to be predominantly coarser gravel/cobble, as found in Reach T1 immediately upstream. The Reach T1 bed material data were, therefore, used for both reaches T1 and T2.

The representative range of particle sizes for the bed material present in each geomorphic reach were plotted as cumulative size distribution curves using the Wentworth scale (Figures 5.6 and 5.7) (Kondolf *et al.*, 2003). Grain diameters corresponding to selected percentile values were then obtained, for example, D_{50} and D_{10}, which represent the median grain size diameter and the size for which 10% of the sample is finer, respectively. The percentile values are discussed further in Section 6.1.

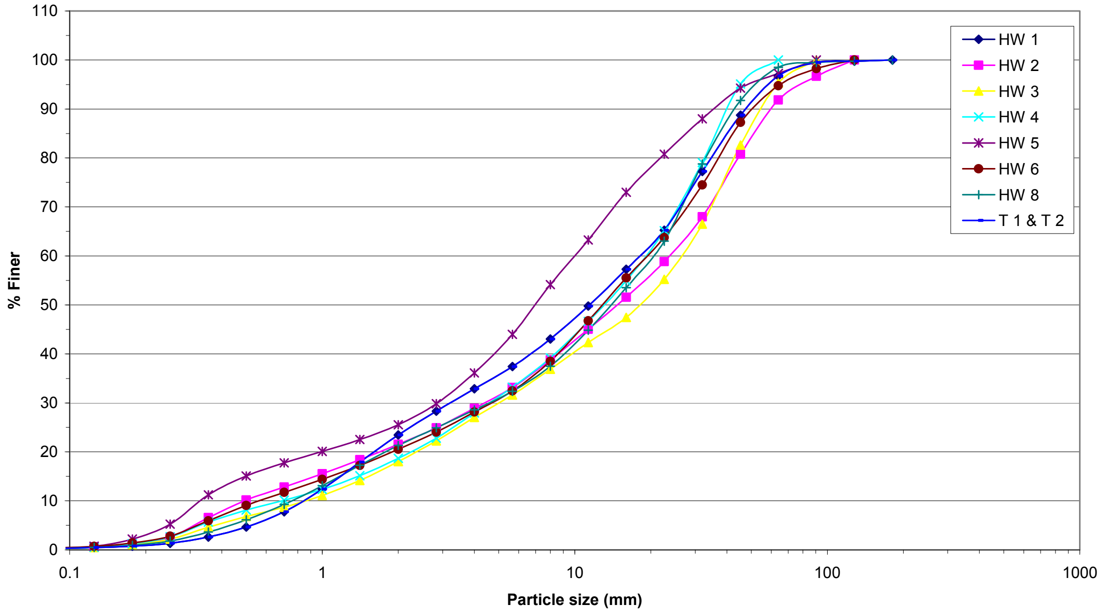


Figure 5.6 Cumulative particle size distribution curves for coarse-bedded river reaches (HW1 – HW8, and T1 / T2)

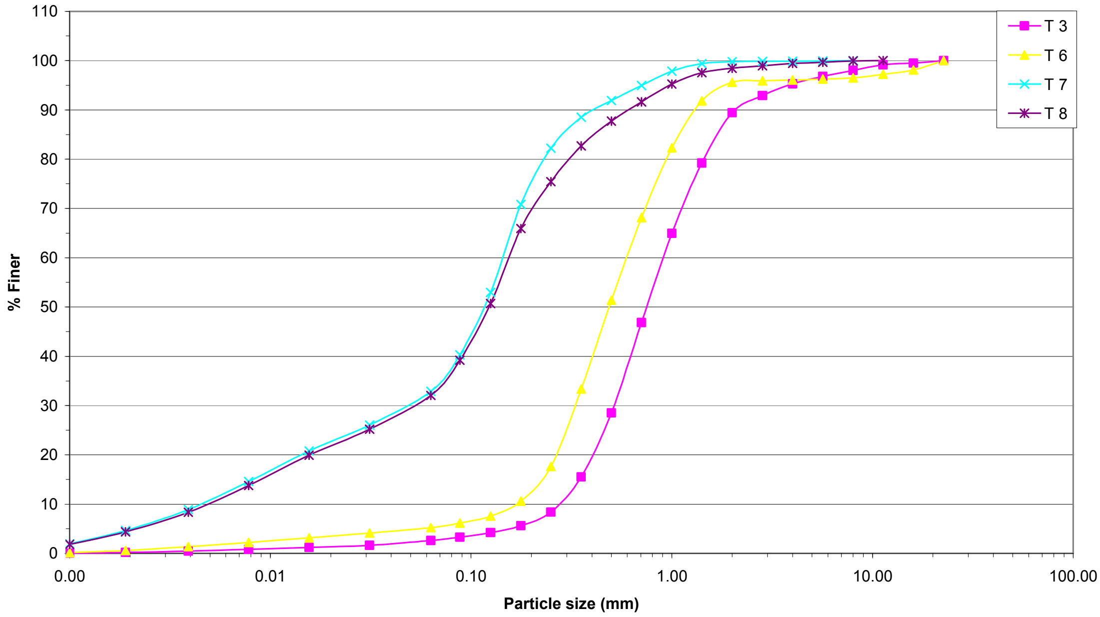


Figure 5.7 Cumulative particle size distribution curves for fine-bedded river reaches (T3 – T8)

River	Reach	Pebble count		Integrated (Van Veen or Bucket)					Rigid (lower – upper)
		200	400	A	B	c	d	combined	
Halse Water	HW1	✓	✓	✓	✓			✓	✓ (8 – 11.3)
	HW2		✓	✓	✓			✓	
	HW3		✓	✓	✓			✓	
	HW4	✓	✓	✓	✓			✓	
	HW5	✓	✓	✓	✓			✓	✓ (11.3 – 16)
	HW6	✓	✓	✓	✓	✓	✓	✓	✓ (8 – 11.3)
	HW7	No sampling access (use Reach HW8)							
	HW8	✓	✓	✓	✓			✓	✓ (22.6 – 32)
River Tone	T1	✓	✓	✓	✓			✓	✓ (32 – 45.3)
	T2	Integrated samples found to be unrepresentative (use Reach T1)							
	T3			✓	✓	✓		✓	
	T4	No sampling (engineered, non-erodible channel)							
	T5	No sampling access (use Reach T6)							
	T6			✓	✓	✓		✓	
	T7			✓	✓			✓	
	T8			✓	✓			✓	

Table 5.3 Halse Water and lower River Tone bed material samples and preferred sample (highlighted red) for generating cumulative particle size distribution curves

In addition, the representative particle size distribution for each coarse bed material reach (HW1-HW8 and T1/2) was divided into RHS substrate categories (Environment Agency, 2003) (Table 5.4 and Figure 5.8). These data were needed for model sensitivity testing (see Section 6.3) performed to compare sediment outputs against altered bed-material inputs, with the aim of establishing whether, in coarser dominated sediment source/pathway reaches, a visual assessment may be sufficient when defining the bed material.

RHS category	Particle size range (mm)	Particle size (mm)	Percentage Finer							
			HW1	HW2	HW3	HW4	HW5	HW6	HW8	T1/2
Boulder	256-512	256	100	100	100	100	100	100	100	100
Cobble	64-256	128	99	96	98	100	99	98	99	99
		64	98	92	95	100	97	95	98	97
Pebble	16-64	32	86	72	71	78	85	75	76	77
		16	74	51	47	55	73	55	53	57
Gravel	2-16	8	57	41	37	43	57	43	42	46
		4	39	31	28	31	41	32	32	34
		2	22	21	18	19	25	20	21	23

Note: values highlighted in yellow have been estimated using linear interpolation between the upper and lower values

Table 5.4 Particle size distributions for coarse-bedded river reaches converted into RHS substrate categories

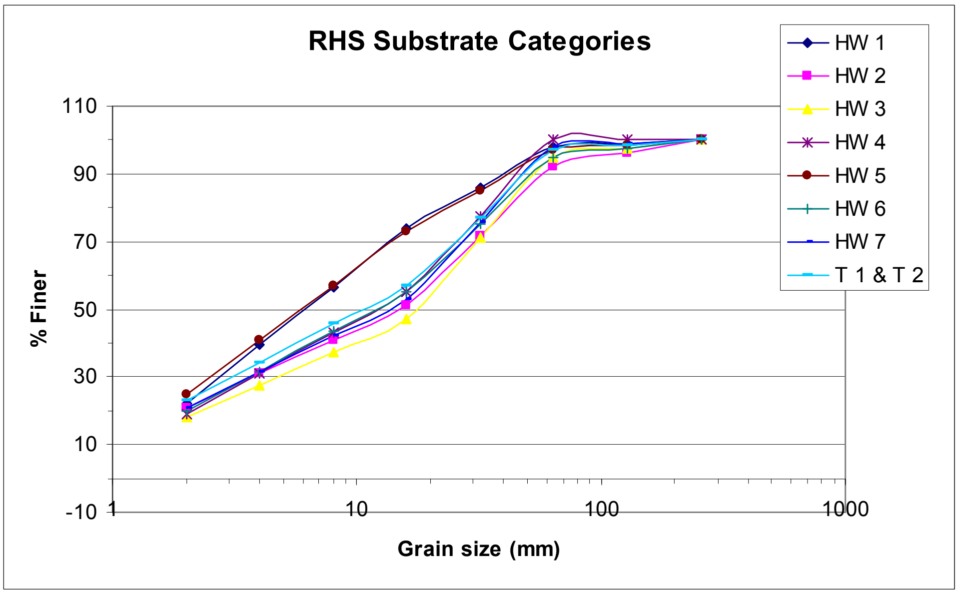


Figure 5.8 *Cumulative particle size distribution curves for coarse-bedded river reaches converted into RHS substrate categories*

The pebble counts for reaches HW4, HW5, HW6 and HW8 were split into 100 pebble sub-samples to facilitate a review of the minimum number of pebbles to provide a robust sample for this particular bed type. The size distributions were plotted and the median grain diameter (D_{50}) and various sorting coefficients (representing different ways of calculating dispersion around the median) were calculated (Table 5.5).

River Reach	Pebble Count	Mean (D_{50})	Sorting Coeff[1]	Sorting Coeff[2]	Sorting Coeff[3]
HW4	100	8.52	-	-	-
	200	12.63	2.37	-	-
	300	13.68	2.43	-	-
	400	13.12	2.34	-	-
HW5	100	8.72	-	-	-
	200	6.85	-	-	-
	300	7.52	-	-	-
	400	8.15	-	-	-
HW6	100	19.50	2.45	-	-
	200	14.02	2.61	-	-
	300	12.79	2.55	-	-
	400	12.87	2.61	-	-
HW8	100	24.44	2.14	3.41	0.53
	200	20.81	2.01	2.95	0.47
	300	19.08	1.84	2.63	0.42
	400	18.34	1.83	2.61	0.42

1 Trask (1932) $(D_{75}/D_{25})^{0.5}$
2 Yang (1996) $(D_{84}/D_{16})^{0.5}$
3 Inman (1952) $(\log_{84}-\log_{16})/2$

Table 5.5 Comparison of particle mean diameter and sorting coefficients for various pebble count samples on the Halse Water

The Halse Water, as described in Section 4, represents a predominantly unmodified watercourse with a sinuous/meandering channel approximately 5-8m wide, with an average gradient of 0.004, and a gravel-bed, which provides a variety of functional habitats and physical biotopes including bars, riffles, runs and pools. From these, albeit limited, samples it appears that at least 300 stones should be collected to reduce differences in the particle size distribution for a given reach to an acceptable level. Sampling beyond 300 stones makes minimal difference to the mean grain diameter or degree of sorting for the particle size distribution. Using 100 stones can lead to the particle size distribution curve being too fine or too coarse, and either under-estimating or over-estimating the D_{50}, and can provide a sample that is not as well sorted. This finding supports Kondolf (1997) who found that a sample size of 100, which is the minimum recommended by Wolman (1954), was inadequate to yield accurate size data and to develop representative size distribution curves.

5.3.5 Catchment sediment sources

Overview of sediment fingerprinting

Traditionally, information on sources of suspended sediment within a catchment has been collected using a range of indirect measurement or monitoring techniques, aimed at either identifying areas from which sediment is being mobilised or comparing rates of soil or sediment mobilisation from potential source areas to assess their likely relative contribution to a total sediment yield (Walling *et al.*, 2008). Various techniques have been employed including field observations and mapping, deployment of erosion pins in riverbanks, use of profilometers, terrestrial and aerial photogrammetry to monitor bank erosion and gullying, bounded and unbounded soil erosion plots, and remote sensing (Collins, 2008; Walling *et al.*, 2008).

However, use of these traditional methods and the data produced is frequently constrained and hampered by issues relating to representativeness of data collection in space and time, operational and logistical problems, and high costs (Collins and Walling, 2004). Therefore, robust and reliable techniques are required that give unequivocal results relating to soil erosion and sediment dynamics and provenance, as source control options for sediment management are likely to assume greater importance as part of effective and sustainable future catchment management strategies (Owens and Collins, 2006).

Evans (2006a) noted that it is easier to identify sources of sediment than to measure absolute sediment loads. Consequently, and to overcome some of the problems discussed above, sediment fingerprinting was developed as an alternative. This approach provides a relatively simple and cost-effective basis for assembling spatially- and temporally-integrated data for catchments (Collins and Walling, 2004). Walling *et al.* (2008) and Collins (2008) provide overviews of the development and implementation of the sediment fingerprinting approach, but a brief summary is included here for completeness.

The basis for sediment fingerprinting is the link between the geochemical properties of a sediment sample and the properties of its potential sources. The procedure assumes that sediment samples can be distinguished on the basis of their constituent properties (specific fingerprint profile) and as such the provenance of any sediment sample (suspended or deposited) can be established by comparing its specific properties with those of the potential sediment sources (Collins, 2008). The procedure also assumes that the selected fingerprint properties are readily transported and deposited in association with suspended sediment, and that properties are not transformed (via enrichment, depletion, dilution etc) beyond what can be corrected for using appropriate procedures (Collins, 2008).

It is now accepted that a single diagnostic property is inappropriate for sediment fingerprinting studies. Instead, composite fingerprints are used which comprise a range of different diagnostic properties, and to satisfy dimensionality the number of fingerprint properties should exceed the number of potential sediment sources being discriminated (Collins, 2008). Composite fingerprints should be identified using statistical verification, and used in conjunction with a multivariate numerical mixing model.

Various corrections and weightings are required during the sediment source ascription process. These include correcting for differences in particle size and organic matter content. Accounting for particle size differences usually involves restricting laboratory analysis to <0.063mm sediment fraction and correcting using specific surface area information. Differences in organic content are accounted for using an adjustment based on the ratio between the organic carbon contents of the source material and the sediment sample. The varying levels of precision of laboratory analyses for individual sediment properties is also taken into account to ensure greater emphasis is not placed on those properties affording greater precision. Finally, equifinality (i.e. different source combinations could produce the same goodness of fit in the mixing model) and the natural variability of source material properties are dealt with by incorporating uncertainty testing within the quantitative source apportionment procedure using Bayesian statistics and Monte Carlo routines.

Sediment sources can be defined in a number of ways, as described in Section 2.2. In larger catchments it is generally more meaningful to identify spatially-defined sources (i.e. sub-catchments or discrete geological zones), whereas in smaller catchments it is more common to identify source-type.

Sediment fingerprinting can provide information on the relative importance of potential sediment sources contributing to the overall sediment yield of a river system. This is clearly of considerable value when designing sediment control strategies, since it will assist in identifying those sources that should be targeted for control measures (Walling, 2006).

The sediment fingerprinting approach has been used in numerous studies to identify and apportion catchment sediment sources both in the UK and overseas (e.g. Clarke, 1995: Gruszowski *et al*, 2003; Collins and Walling, 2007a and b; Walling *et al*, 2008; Minella *et al*, 2008; Evans *et al*, 2006a; Evans and Gibson, 2006), including a recent study on the Parrett catchment, which included the River Tone and Halse Water (Collins, 2008).

Implemented methods and results

This research builds upon the initial sediment fingerprinting data for the Rivers Tone and Halse Water, which were collated as part of the sediment apportionment study for the Parrett Catchment (Collins, 2008). The research methodology therefore closely follows that employed in the 2008 study to ensure consistency of data.

Sediment source samples were collected from four land use types (pasture, arable, river bank, and road verge) from around the Halse water catchment (Plates 5.4 to 5.7). Twenty samples from each land use type were collected from the catchment. Samples were collected as surface scrapes (up to 20mm depth of topsoil) with each source sample comprising a composite sample of up to 10 individual scrapes per location (approximately 100g per sample). Eroding bank samples were taken over the full vertical extent of the bank face.

All samples were taken with a non-metallic trowel, which was repeatedly cleaned between samples to avoid cross contamination.

Plate 5.4 Pasture land in the Halse Water catchment showing vehicle wheel rutting (a) and severe soil poaching by livestock (b)

Plate 5.5 Arable land in the Halse Water catchment, which slopes down to the river

Plate 5.6 Eroding river banks in the Halse Water catchment

Plate 5.7 Damaged/eroding road verges in the Halse Water catchment

It was initially proposed to use suspended sediment samples from the Halse Water as the basis for sediment fingerprinting and apportionment of source sediment type in the catchment. However, sediment transport is highly episodic and samples need to be collected during storm events, when the vast majority of suspended sediment transport occurs. However, this approach is notoriously difficult to use in practice on small, flashy streams because it requires accessing the river at short notice during intermittent spates. Often it results in a collection of 'snapshot' samples which may not be representative of sediment origins because these vary significantly both during individual storm hydrographs and between storm events.

To avoid these issues, simple, *in situ*, time-integrated suspended sediment samplers (Phillips *et al.*, 2000), known as 'rocket samplers' are now used in many sediment studies. The device comprises a PVC pipe (98 mm internal diameter, 1 m length) with two end caps containing a 4 mm internal diameter inlet/outlet pipe (Figure 5.9 and Plate 5.8). The sampler is orientated parallel to the flow and positioned so that it is submerged during sediment transport events. It accumulates a suspended sediment sample over the period between visits by the researcher, when sediment is collected from the sampler for laboratory analysis. The sampler collects and composites a heterogeneous mix of the primary particle sizes comprising the local suspended sediment load, suitable for creating a representative particle size distribution and supplying fine sediment that can be fingerprinted.

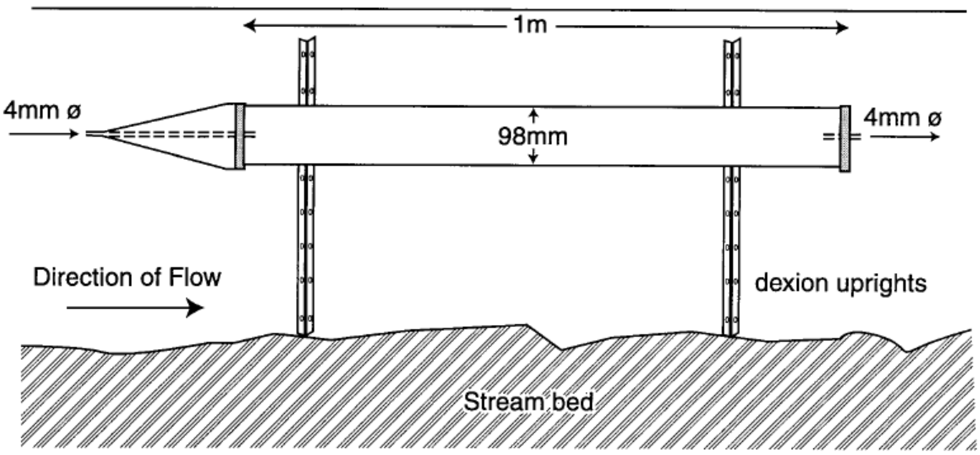


Figure 5.9 Cross-section of a suspended sediment 'rocket' sampler (Source: Phillips et al., 2000)

Plate 5.8 Rocket sampler in situ within the Halse Water catchment

Four rocket samplers were installed within the Halse Water catchment during the autumn and winter 2009/2010 as follows:

- Upstream limit of the modelled reach of the Halse Water (Northway, NGR ST 12217 29028);

- In the Halse Water just upstream of its confluence with the River Toine (downstream of the gauging station, NGR ST 20622 25263);

- In the Back Stream just upstream of its confluence with the Halse Water (Norton Fitzwarren, NGR ST 20491 26386); and

- In a small tributary of the Halse Water (upstream of Cotford St Luke, NGR ST 16028 27246).

Unfortunately, unusually high flows during winter 2009/10 destroyed three of the four rocket samplers. However, the Northway sampler survived to provide a usable suspended sediment sample.

Following the loss of the rocket samplers, an alternative approach to collecting sediment for PSA and fingerprinting was discussed and agreed with ADAS. The new approach involved collecting recently deposited, fine sediment from exposed bars located at selected points along the Halse Water and River Tone (top of model reach, at same location as rocket sampler; and at Norton Fitzwarren, NGR ST 19130 25910), Back Stream (Barham's Bridge, NGR ST 20103 27151) and River Tone (downstream of confluence with Halse Water, NGR ST 21374 25355) (Figure 5.4 and Plates 5.9 to 512).

Plate 5.9 Sediment bar at Northway on the Halse Water, which was used to supply a sample for sediment fingerprinting

Plate 5.10 Sediment bar at Norton Fitzwarren on the Halse Water, which was used to supply a sample for sediment fingerprinting

Plate 5.11 Sediment bar on the River Tone, which was used to supply a sample for sediment fingerprinting

Plate 5.12 Sediment bar on the Back Stream, which was used to supply a sample for sediment fingerprinting

A vertical sample was taken through the bar, with any coarse clasts being discarded to create a time-integrated sample of the suspended sediment load deposited to form the bar. The sample size was approximately 100g.

Laboratory analysis and sediment source discrimination/ascription modelling was undertaken by Prof. Adrian Collins under a collaborative research agreement between ADAS and the University of Nottingham. The procedures are fully documented elsewhere (e.g. Collins and Walling, 2007; Collins, 2008), however, for completeness the methodology is re-produced here. Due to resource constraints at ADAS a random sub-set of 5 source samples per land use were selected for analysis (Figure 5.5 for locations).

Laboratory analysis

Land use source samples were oven-dried at 40^{o}C, manually disaggregated and dry sieved down to 0.063mm. Suspended sediment and sediment bar samples were de-watered using centrifugation then freeze-dried and sieved down to 0.063mm. Particle size distributions were derived for sediment samples (Figures 5.10 to 5.13).

A total of 47 properties were included in the analytical fingerprinting. These include concentrations of Al, As, Ba, Bi, Cd, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Fe, Ga, Gd, Ge, Hf, Ho, K, La, Li, Ln, Mg, Mn, Mo, Na, Nd, Ni, Pb, Pd, Pr, Sb, Sc, Sm, Sn, Sr, Tb, Ti, Tl, U, V, Y, Yb, Zn and Zr. Concentrations were determined by ICP-MS, following direct digestion with nitric and hydrochloric acid.

Absolute grain size compositions for all samples were measured using a Micrometrics laser diffraction granulometer following pre-treatment with hydrogen peroxide to remove organics, chemical dispersion with sodium hexametaphosphate and exposure to ultrasound. Particle size analysis assumed spherical particles in the estimation of specific surface area.

The phosphorus content (organic, inorganic and total) of the <63 μm fraction of all soil and sediment samples was determined colourimetrically using a Pye Unicam UV/Visible spectrophotometer following chemical extraction with hydrochloric acid and sodium hydroxide using the molybdenum blue method. Carbon and nitrogen content was measured directly by pyrolysis using an automatic C/N analyser.

Sediment source discrimination

A two-stage statistical procedure was used to test the ability of fingerprint properties to discriminate between the individual source types. The first stage used the Kruskal-Wallis H-test to examine the ability of individual constituents to distinguish source types (pasture, arable, riverbank and road verge) in an unequivocal manner. Deployment of the Kruskal-Wallis H-test is founded on the logical assumption that the selection of robust composite fingerprints requires confirmation of the power of individual constituents to discriminate the source samples under scrutiny.

The Kruskal-Wallis H-test is the non-parametric equivalent of analysis of variance and provides a distribution-free procedure for examining contrasts between sample sets. It has a power efficiency of ca. 95.5%, thereby rendering it suitable for testing in conjunction with relatively small sample sets. Greater inter-group contrasts generate larger test statistics and where these exceed the critical value, Ho (i.e. the null hypothesis stating that measurements of the fingerprint property exhibit no significant differences between the source type categories) is rejected. The Kruskal-Wallis H-test is applied to the values of a specific property for the source material dataset as a whole. Consequently, a statistically significant output is suggestive of source inter-category contrasts, rather than confirming differences between all possible pairs of source categories. Stage 1 eliminated redundant fingerprint properties.

The second stage of source discrimination used a multivariate Discriminate Function Analysis (DFA) to test the ability of properties to discriminate the source material samples into the correct categories. DFA estimates discriminant function coefficients indicative of the explanatory power of fingerprint properties. A multivariate stepwise selection algorithm, based on the minimisation of Wilks' lambda, was used to identify the optimum (i.e. smallest) combination of properties, or composite fingerprint, for discriminating the source samples collected. During the stepwise selection procedure, properties satisfying two principal test criteria, i.e. the partial F ratio and tolerance level, are entered in order of their explanatory power. Default values were used for both the partial F ratio (1.0) and tolerance level (0.001). As a means of avoiding the preferential selection of individual properties for inclusion in the final composite fingerprint, all parameters were assigned the default inclusion level (1.0). Stepwise selection ceases when all source material samples are classified correctly, or when none of the remaining constituents available for inclusion in the composite signature improve sample discrimination.

Sediment source ascription

A multivariate mixing model was used to apportion sediment sources. The model is founded on the assumption that the concentrations of the properties comprising the composite fingerprint, measured in sediment samples, represent the product of the corresponding concentrations in the original sources and the relative inputs contributed by those sources.

Potential sources are represented in the mixing model using the mean concentrations of fingerprint properties. Use of the mean concentration value to represent a particular source can be justified since the sediment collected from the catchment outlet will inevitably represent a mixture of material mobilised and delivered from numerous locations upstream. As a result, the collection of representative source material samples from a range of locations throughout the catchment and the use of these samples to derive mean fingerprint property concentrations can be assumed to be analogous to natural sediment mixing during the sediment delivery process. The use of mean fingerprint property values is therefore physically meaningful.

Two linear boundary conditions are imposed on the mixing model iterations to ensure that the relative contributions (P_s) from the individual sediment sources are non-negative and that these contributions sum to unity.

$$0 \le P_s$$

$$\sum_{s=1}^{n} P_s = 1$$

The mixing model algorithm optimises estimates of the relative contributions from the potential sediment sources by minimising the sum of squares of the weighted relative errors, but includes revised weightings, viz.:

$$\sum_{i=1}^{n} \left\{ \left(C_i - \left(\sum_{s=1}^{m} P_s S_{si} Z_s O_s SV_{si} \right) \right) / C_i \right\}^2 W_i$$

where: C_i = concentration of fingerprint property (i) in catchment outlet time-integrated suspended sediment sample or sediment bar sample; P_s = the optimised percentage contribution from source category (s); S_{si} = mean concentration of fingerprint property (i) in source category (s); Z = particle size correction factor for source category (s); O = organic matter content correction factor for source category (s); SV_{si} = weighting representing the spatial variation of fingerprint property (i) in source category (s); W_i = tracer discriminatory weighting; n = number of fingerprint properties comprising the optimum composite fingerprint; *m* = number of sediment source categories.

The particle size correction factor is included in the sediment mixing model since it is widely understood that grain size exerts an important influence on element concentrations in soil and sediment samples. In consequence, the fingerprint properties of source material and sediment samples cannot be directly compared, even after sieving, unless a correction factor is utilised. Due to particle size selectivity during sediment transportation from source to river channel, the typical sediment sample is enriched in fines compared to the corresponding samples collected to represent the individual sources. In order to calculate a particle size correction factor, specific surface area (m^2/g) is used as a surrogate measure for grain size composition because it exerts a key control on element concentrations.

During the application of the mixing model for source type apportionment, the ratio of the mean specific surface area of the sediment bar samples or time-integrated sediment sample to the corresponding mean value for each individual source type was used. Although this approach assumes a linear relationship between fingerprint property concentration and specific surface area, it provides a pragmatic means of addressing the need to take explicit account of particle size selectivity.

The mixing model algorithm also includes an organic matter content correction since the latter also influences element concentrations in soil and sediment samples. This correction is calculated in the same manner as the equivalent for particle size, but using information on organic carbon content. Because the influence of particle size and organic matter content on element concentrations can be closely related, the combined use of the correction factors was carefully examined in order to ensure that the over-correction of the source material datasets was avoided.

A weighting to reflect the spatial variation of individual tracers in each source was incorporated in the mixing model. This weighting was included to ensure that the fingerprint property values for a particular source characterised by the smallest standard deviation exerted the greatest influence upon the optimised solutions. It is logical that as the standard deviation of the fingerprint property values increases, the uncertainty associated with the source ascription also increases. The weighting was calculated using the inverse of the root of the variance associated with each fingerprint property measured for each source. The spatial variation weighting provided a means of representing the compound effect of a number of sources of uncertainty, including the variance of the tracer datasets for specific sources and the differing levels of precision associated with laboratory measurements of those tracers.

The mixing model algorithm also incorporated a weighting to reflect tracer discriminatory power. This weighting was based on information on the discriminatory efficiency of each individual tracer included in any given composite fingerprint provided by the results of the DFA.

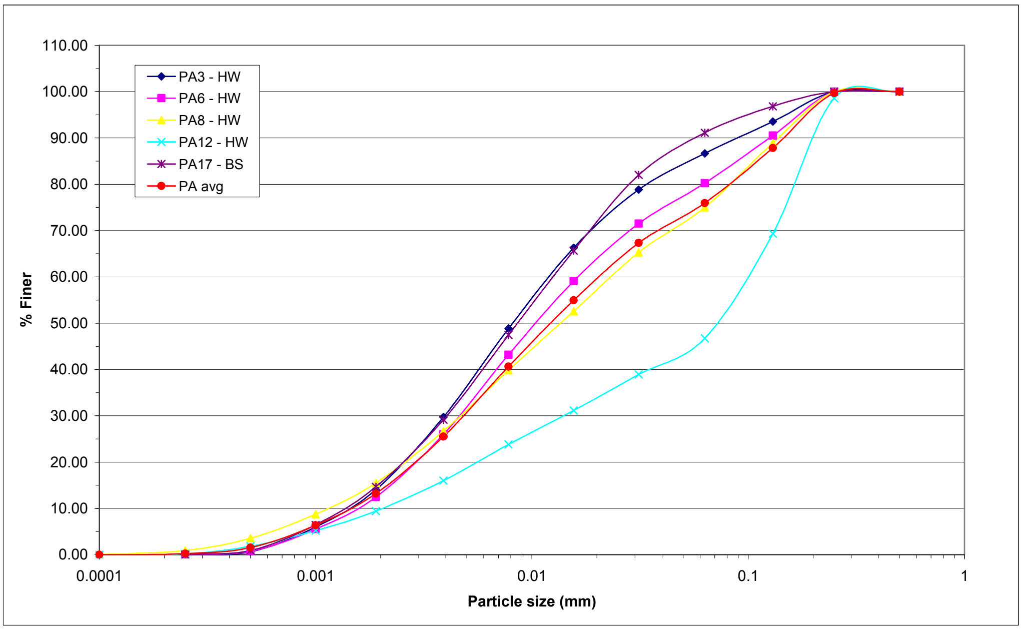


Figure 5.10 Cumulative particle size distributions for pasture sediment source samples in the Halse Water catchment

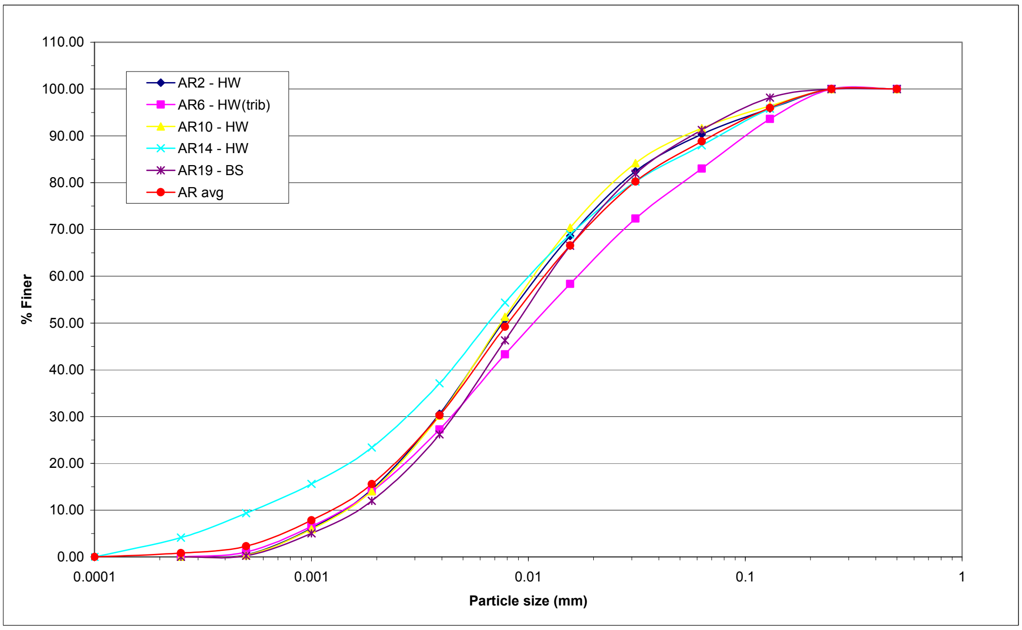


Figure 5.11 Cumulative particle size distributions for arable sediment source samples in the Halse Water catchment

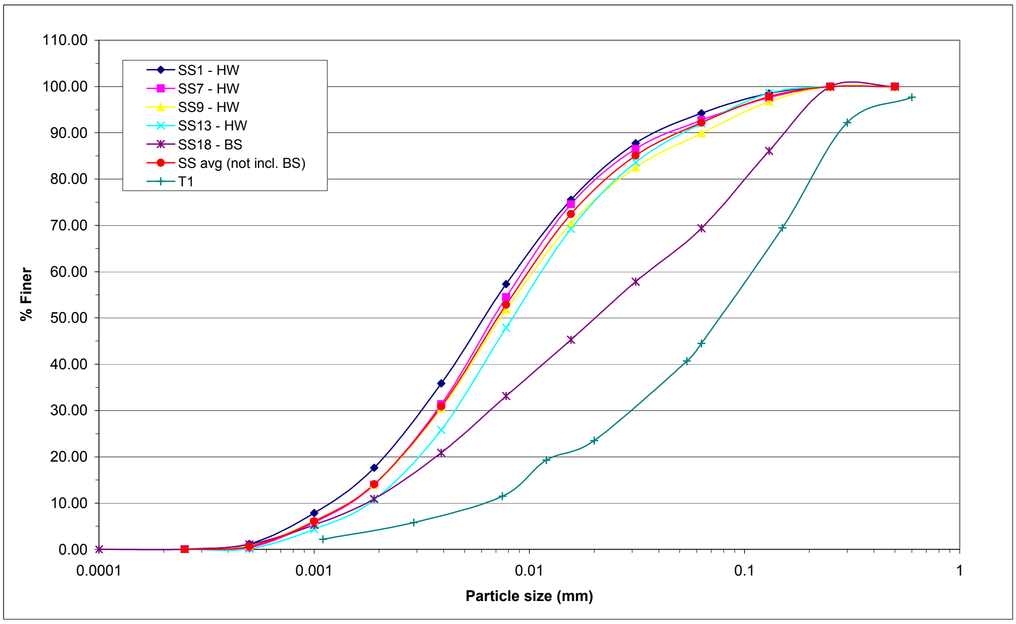


Figure 5.12 Cumulative particle size distributions for sub-surface (riverbank) sediment source samples in the Halse Water catchment

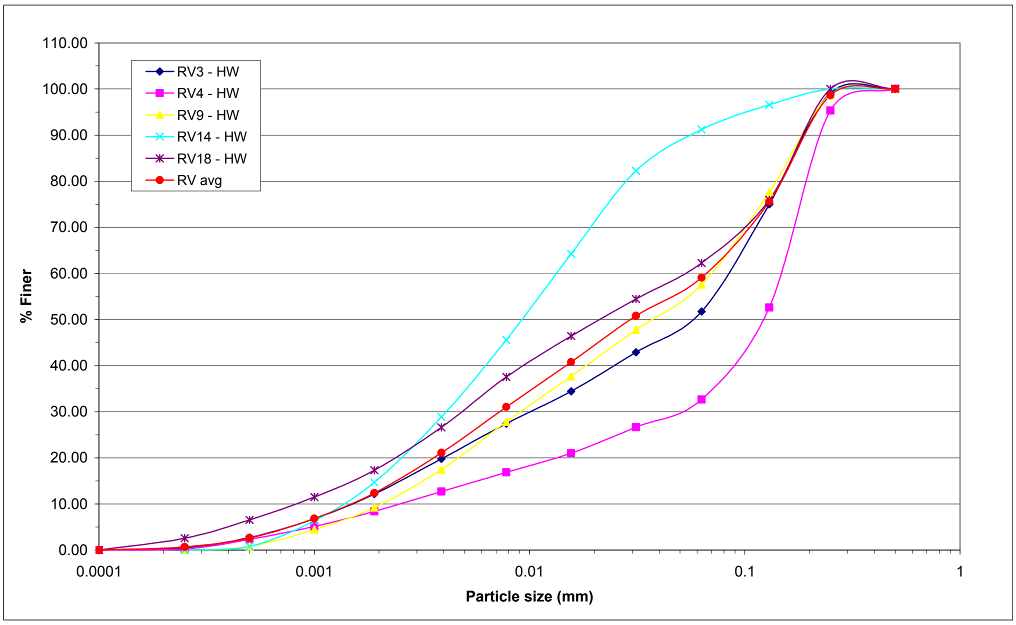


Figure 5.13 Cumulative particle size distributions for damaged road verge sediment source samples in the Halse Water catchment

Following application of these techniques, sediment fingerprinting outputs were expressed as the mean relative contribution to the suspended sediment or sediment bar samples from each source type (i.e. arable, pasture, riverbank, road verge). Table 5.6 presents the results for the Halse Water obtained from the original Collins (2008) study and those generated by the collaborative research.

Sediment fingerprinting indicates that, within the Halse Water catchment, the mean average contribution of sediment is greatest from arable land (37%), followed by eroding river banks (25%) then pasture (22%) with damaged road verges providing the smallest contribution (16%). However, it must be noted that the mean percentage contribution of each land use type can differ both temporally and depending on which sediment sample (i.e. rocket, bar, floodplain) is used. For example, arable land provided the largest contribution in 2007/08, whereas eroding river banks provided the largest contribution in

2009/2010. Acknowledging these issues it is clear that sediment fingerprinting data must be used with caution, with any assessment of land use contribution to sediment yield preferably using as many data as possible.

The mean contribution of sediment from arable land ranged between 5-57%. The equivalent figure for pasture was 12-29%, eroding river banks was 2-61%, and damaged road verges was 11-22%. For arable and pasture fields the lowest contributions were associated with the 2009/2010 suspended sediment sample, while the greatest contributions were associated with the 2008 floodplain scrape sample.

In contrast, the lowest contributions from river bank and road verge were linked to the 2008 floodplain scrape sample, and the greatest contributions were linked to the 2009/2010 suspended sediment sample. Reasons for differences in sediment contributions from different sources could be linked to timing/location of rainfall occurring during or prior to sampling periods, antecedent conditions in the catchment regarding wetness and crop status, and/or the location or type of river sediment sample used for comparative analysis (i.e. floodplain deposit, in-channel deposit or suspended sediment).

Furthermore, the percentage contributions of sediment quoted in Table 5.6 are given as the ‘mean’, and consequently the ‘true’ contribution figure could be higher or lower. For example, the total range for each land use type linked to the 2009/2010 suspended sediment sample is: arable (0-94%), pasture (3-95%), river bank (0-97%) and road verge (0-96%). This demonstrates that there can be a wide band of uncertainty associated with the sediment fingerprinting outputs, which must be taken into consideration when interpreting the results. Nevertheless, the range of mean contributions for each land use type do fall within ranges quoted in research literature (see Section 2.2) or identified through discussion with ADAS.

As a point of comparison, the 2008 sediment apportionment study also estimated the percentage contribution of the four land use types for the entire Tone catchment as: arable (13% ± 2%); pasture (51% ± 1%); river bank (22% ± 1%); and road verge (13% ± 2%). Although this is a single point in space and time for the Tone catchment, it appears that contributions for river banks and road verges are consistent with the Halse Water catchment, while pasture plays a greater role in sediment delivery than does arable land. This probably reflects the wider extent of pasture in the Tone catchment compared to the Halse Water catchment.

	Mean percentage contribution									
Sample	Rocket	Rocket	Rocket	Floodplain	Rocket	Bar	Bar	Study mean range	Study mean average	Literature range
Source	Oct – Dec 2007	Dec 2007 – Jan 2008	Jan 2008	2008	Sept 2009 – Feb 2010	2010	2010			
Pasture	28 (± 2)	20 (± 2)	20 (± 2)	29 (± 2)	12 (± 1)	20 (± 1)	21 (± 1)	12 – 29	22	1 – 78
Arable	56 (± 2)	55 (± 2)	44 (± 2)	57 (± 2)	5 (± 1)	21 (± 1)	21 (± 1)	5 – 57	37	
River bank	4 (± 1)	4 (± 1)	13 (± 1)	2 (± 1)	61 (± 1)	46 (± 1)	46 (± 1)	2 – 61	25	5 – 80
Road verge	12 (± 1)	20 (± 1)	22 (± 1)	11 (± 1)	22 (± 1)	13 (± 1)	12 (± 1)	11 – 22	16	10 – 50

Table 5.6 Mean percentage contribution of sediment from each land use type compared to various spatial and temporal sediment samples within the Halse Water catchment

Finally, in addition to the source-type fingerprinting, the relative contribution of sediment from the Halse Water compared to its tributary the Back Stream was also assessed. This was undertaken by comparing source samples from the Halse Water and Back Stream to the River Tone sediment bar sample. Results indicate a mean contribution of 81% ± 1% (range 44-100%) from the Halse Water, with the Back Stream making a mean contribution of 19% ± 1% (range 0-56%). However, as shown with the land use data, caution must be exercised when using these data as it is likely that relative contributions will vary through time.

As Evans (2006a) pointed out identifying sources of sediment is easier than measuring absolute sediment loads (which is discussed in detail in Section 5.3.1), and sediment fingerprinting certainly provides a practicable and cost-effective solution to collecting and analysing both spatially- and temporally-integrated sediment source data for catchment sediment studies. The method also avoids some of the problems associated with more traditional sediment-source sampling methods such as operator error during field mapping, the need for spatially-extensive monitoring over long timescales to reduce uncertainty regarding representativeness of data, and the need for hi-tech equipment, and also avoids logistical and cost issues.

It is also true, as identified by Collins and Walling (2004), that there is a need for robust and reliable techniques that give unequivocal results relating to soil erosion and provenance. Sediment fingerprinting is certainly robust and reliable, and is subject to continued application to a range of catchments and improvement in the analytical method of sediment discrimination and ascription (Prof. Adrian Collins, ADAS, pers. comm.), which will continue to increase confidence in its applicability. However, sediment fingerprinting (or for that matter any other method) is unlikely ever to provide unequivocal results, and this has been demonstrated for the Halse Water catchment where percentage contributions vary through time and depend on which method of river sediment sampling was employed. Therefore, as with all methods and models, the need for expert user input and the need to exercise caution when using the output data remains paramount, particularly in relation to prioritising and implementing potentially expensive catchment management measures targeted on specific sediment sources and delivery issues.

The relative sediment source contributions and particle size distributions generated by the collaborative research with ADAS were used to set up the Halse Water SIAM model (see Section 6.3) as well as being used to assess linkages between sediment sources, pathways and sinks for a range of predicted land use sediment contributions.

5.3.6 Incorporating climate change

The influence of climate change on catchment hydrology and its implications for fluvial geomorphology were discussed by Goudie (2006) who identified that, historically, geomorphologists tended to examine the effects of a range of anthropogenic processes on river systems, such as land use change, dam construction and water abstraction within a present-day context. However, he established that we are now in an era when such processes will be joined by changes caused by climate change. The influence of climate change or its predicted impacts (i.e. changes in rainfall or flood flow) is now routinely incorporated into geomorphological research or flood risk studies, for example, see Coulthard and Ramirez (2011), Henshaw (2009) and Lane *et al.* (2007).

The amount of sediment delivered to rivers or mobilised/transferred through rivers may increase in the future as climate modelling suggests that the types of rainfall/runoff that are effective in delivering and transferring sediment to rivers are likely to occur more frequently (Reid *et al*., 2006; Lane and Thorne, 2007). Changes in rainfall patterns are also likely to increase peak river flows in the future.

Planning Policy Statement 25 (PPS25) (Table B.2, Annex B) provided guidance on the sensitivity allowances for testing flood designs against projected changes in climate (peak rainfall and peak flow) out to 2115 (Communities and Local Government, 2006; Wilby *et al.*, 2007) (Table 5.7).

Parameter	**2025**	**2055**	**2085**	**2115**
Peak rainfall intensity	+5%	+10%	+20%	+30%
Peak river flow volume	+10%		+20%	

Table 5.7 National predicted changes in peak rainfall and peak river flow

Predicted climate changes to future river flood flow (1 in 50 return period), which are now divided by river basin district, and extreme rainfall have recently been updated with new projected change factors (Environment Agency, 2011b) (Table 5.8).

Parameter	**2020s**	**2050s**	**2080s**
Peak rainfall intensity	+5%	+10%	+20%
Peak river flow volume	+15%	+20%	+30%

Table 5.8 Predicted changes to river flood flow (SW England) and extreme rainfall intensity (national)

Changes in flood flows are expressed in comparison with the 1961-1990 baseline flows. However, this baseline period represents a period which does not include many large flood events on this catchment (only the flood of 1968) and misses three large, recent flood events which occurred in 1997, 2000 and 2012. Therefore, it is considered that the change factor may be an over-estimation for the River Tone catchment. Within FRMRC Phase 1 SIAM was deployed on an upland river catchment, and the modelling took account of future climate change by using the PPS25 2085 allowance (20% increase), but due to model limitations the whole range of river flows was increased as opposed to just peak flows (Nick Wallerstein, pers. comm.).

For the research presented on this thesis the whole flow regime has been altered by a factor of -20% and -10%, to take account of potential future land management activities that may reduce run-off, and by a factor of +10% and +20%, to represent predicted future flows under climatic conditions predicted for the periods 2020-2050s and 2050-2080s. Increasing the whole flow regime to represent climatic change is supported by research which has identified several significant, mainly positive, trends observed at high and low flows in western Britain (Dixon *et al.*, 2006). With hydrodynamic flood models, such as ISIS, a different approach can be taken with the historic rainfall record being adjusted and scaled using the allowances for peak [extreme] rainfall intensity, an approach which has frequently been used due to its simplicity (e.g. Lane *et al.*, 2007).

In addition to changes in river flow, which will influence the river's ability to mobilise and transport sediment available within the channel, climate change is also likely to lead to increases in catchment sediment erosion and the delivery of eroded sediment to watercourses (Reid *et al.*, 2006; Evans *et al.*, 2008), as well as potentially increasing the calibre of sediment mobilised as more intense rainfall and surface runoff has the potential to move larger sediment particles, particularly in the sand size fraction (Prof. Adrian Collins, ADAS, pers. comm.).

The research performed here therefore accounts for the potential for increased amounts of larger calibre sediment to enter the river system by modelling low to increased wash-material loads and recognises the possibility that alterations to the particle size distribution of wash-material load by including a larger sand fraction based on ratios taken from existing sand-rich river banks on the system.

6 ASSESSMENTS OF SEDIMENT TRANSFER AND INTERACTIONS BETWEEN WASH-MATERIAL AND BED-MATERIAL LOADS

6.1 Empirical evidence

To understand how changes in catchment conditions affect channels and what the sequence and timescale of responses are likely to be requires an understanding of how a river collects, transports and deposits sediment. The starting point for gaining an understanding of how the River Tone sediment system operates is the construction of a sediment budget, which can be defined as the description of the input, transport, storage and export of sediment from a defined geomorphic system (Reid and Dunne, 2003). All sediment budgets are conceptually based on a simple continuity equation for sediment, where all terms are expressed as quantities per unit time:

Sediment input = sediment output + change in sediment storage

The sediment budget concept provides an effective basis for representing the key components of the sediment delivery system within a catchment and for assembling the necessary data to elucidate, understand and predict catchment sediment delivery (Walling and Collins, 2008). Estimates of sediment yield at various locations through the River Tone system are presented in Table 6.1. These are based on a range of methodologies as described in Section 5.3.1.

When applying the ratio method, 23 years of Environment Agency suspended sediment monthly/bi-monthly spot-sample data (1985 to 2008) and, where available, corresponding 15-minute flow gauge data were combined and analysed. For the Halse Water, flow gauge data were only available from 1992 and, therefore, pre-1992 flow data were calculated on a ratio of the long-term mean flows for the River Tone at Bishops Hull. The range of sediment yields was estimated for selected sites using actual flows (1992-2008), estimated flows (1985-2008) and different time-frames to investigate the influence of weirs and whether sediment trapping efficiency may have changed through time. Finally, at the Bishops Hull gauging station site continuous [investigative] suspended sediment data were also available increasing the number of individual sediment sample points from 309 to 609. At this location sediment yield was estimated using both routinely collected data alone and routinely collected data combined with investigative data.

Finally, as part of an Environment Agency channel monitoring project on the Rivers Parrett and Tone, sediment fluxes (in-flows and out-flows in tonnes/day) were monitored at Newbridge over two discrete time periods: summer (18^{th} July – 7^{th} August 2009); and winter (23^{rd} November – 7^{th} December 2009) (Partrac, 2009a; Partrac, 2009b). During the summer average (baseline) sediment yield was 62 tonnes/day, while during the winter the average (baseline) sediment yield was 5 tonnes/day, increasing to 173 tonnes/day during a high flow event. These figures have been used to estimate an annual sediment yield under both baseline conditions and with some flood events (5% of time) included.

These sediment yield estimates were used to construct a sediment budget schematic of the lower River Tone and the two main upstream inputs: the upper River Tone [including the Hillfarrance Brook] and the Halse Water (Figure 6.1). Sediment mobilisation, transport and storage are characterised by appreciable spatial and temporal variability, and it is necessary to take account of this variability when constructing a sediment budget (Walling and Collins, 2008). The sediment yield schematic shows both lower (green) and upper (black) bound sediment yield estimates taken from any of the methods used to calculate sediment yield (see Section 5.3.1). Sediment yield estimates based on the ratio method (pink) are also included for comparison.

Nationally extrapolated data and EA equations (defined in Section 5.3.1) suggest that the upper Tone contributes more sediment than the Halse Water. Given its larger catchment size, and the fact that estimated sediment yield depends entirely on the size of the contributing catchment, this is to be expected. The annual sediment yield in the Tone at its confluence with the Parrett downstream of Newbridge is estimated to be between ~8,000 and 29,000 tonnes/year. The upper bound figure is probably an over-estimation as it relies on there being a significantly enhanced sediment loading from the entire catchment, which is not the case in this system as the river is perched and has few catchment sediment inputs downstream of Taunton. The EA equations suggest ~19,000 tonnes/year, but again this could be an over-estimation for the reasons given above. Frequently, sediment yield per unit area decreases downstream because the delivery ratio decreases markedly. This is because average catchment slopes decrease and because more of the eroded sediment goes into long-term colluvial and floodplain storage (Reid and Dunne, 2003).

		Sediment Yield Estimation Method								
		Meta-study	Nationally extrapolated		EA R&D equations			Ratio method	Project monitoring	Range
			Low	High	Bed	Suspended	Total			
Halse Water (Gauging Station)										
88km^2	Total	3872	1760	6160	737	2097	2834	1584		1584 – 6160
	Specific	44	20	70	8.4	23.8	32.2	18		18 – 70
Upper Tone (Bishops Hull Gauging Station)										
202km^2	Total	8888	4040	14140	1181	7753	8934	4319 – 15681		4040 – 15681
	Specific	44	20	70	5.9	38.4	44.2	21.4 – 77.6		20 – 77.6
River Tone (upstream French Weir)										
290km^2	Total	12760	5800	20300	1796	11293	13089	21455 – 25761		5800 – 25761
	Specific	44	20	70	6.2	38.9	45.1	74 – 88.9		20 - 88.9
River Tone (Firepool Weir)										
290km^2	Total	12760	5800	20300	1796	11293	13089	12222		5800 – 20300
	Specific	44	20	70	6.2	38.9	45.1	42.2		20 – 70
River Tone (Bathpool)										
290km^2	Total	12760	5800	20300	1796	11293	13089	10300 – 12951		5800 – 20300
	Specific	44	20	70	6.2	38.9	45.1	35.5 – 44.7		20 – 70
River Tone (Knapp Bridge)										
350km^2	Total	15400	7000	24500	2234	13733	15967	3257 – 3874		3257 – 24500
	Specific	44	20	70	6.4	39.2	45.6	9.3 – 11.1		9.3 – 70
River Tone (Newbridge tidal limit)										
414km^2	Total	18216	8280	28980	2714	16353	19067	7740 – 7928	12227 – 14739	7740 – 28980
	Specific	44	20	70	6.6	39.5	46.1	18.7 – 19.2	29.5 – 35.6	18.7 – 70

Table 6.1 Total and specific catchment sediment yield estimations for the River Tone and Halse Water

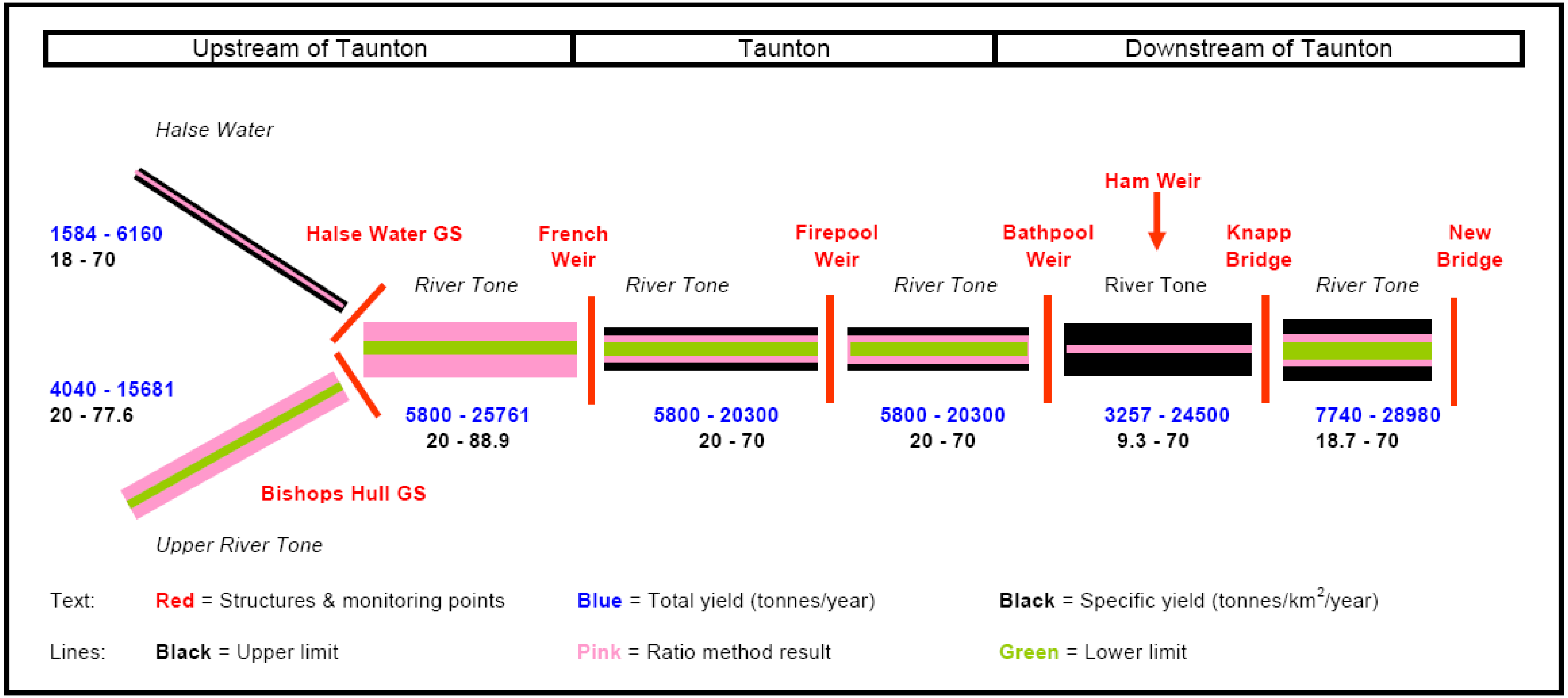


Figure 6.1 Schematic showing total and specific sediment yield ranges for the River Tone and Halse Water catchments

When reviewing sediment budgets based on the Ratio Method (i.e. long-term, catchment specific data) it can be seen that the upper Tone is still predicted to contribute more sediment to the lower system than the Halse Water, at ratios ranging between 3:1 and 10:1. The true value is likely to be somewhere in between these two extremes because as using EA routine sampling data alone under-estimates sediment yield, while combining EA routine data with automatic sampler data leads to over-estimation (Copper *et al.*, 2008).

The Ratio Method calculated sediment yield downstream of the confluence of the upper River Tone and Halse Water to be between ~21,500 and 25,800 tonnes/year. When reviewed against the estimates from the upper catchment (~6,000 to 17,000 tonnes/year) this is either (1) an over-estimation, or (2) one or both of the tributaries is/are being under-estimated. Anecdotal evidence from the Environment Agency, FWAG and landowners suggests that the Halse Water is potentially contributing more sediment than the ratio method has estimated. This is possible given the limited number of suspended sediment data points (No. 142) available for the Halse Water, which leads to a higher level of uncertainty in the output.

The sediment budget suggests annual yields in the River Tone decrease by ~50% (~10,000 – 13,000 tonnes/year) between the confluence with the Halse Water and Taunton. This indicates significant deposition and long-term storage of sediment in the intervening reach, which includes the large French and Firepool Weirs. The reach immediately downstream of Taunton is indicated as acting as a sediment transfer reach, with no significant erosion or deposition. This would be expected as this reach is heavily engineered with non-erodible boundaries. As the river flows across the Somerset Levels there appears to be a further significant reduction in sediment yield due to long-term storage either in-channel or on the floodplain, and this reach includes a third large weir at Ham. At the tidal limit sediment yield is estimated to be ~8,000 tonnes/year, suggesting a further reduction of approximately 30% from that measured downstream of Taunton.

Relationships between suspended sediment concentration and discharge, presented as log-log plots, for three key sites on the River Tone system are presented in Figures 6.2-6.4. As discussed previously, the wash-material component of suspended sediment transport is governed by the rate of supply rather than the transporting capacity of the flow. Conversely, the bed material component of the suspended load is governed by transport capacity. Consequently, high suspended sediment concentrations are generally associated with periods of intense rainfall that drive catchment runoff and increased river flows. Empirical sediment concentration-discharge relationships typically represent the increase in suspended sediment concentration (C) as a power function of discharge (Q):

$$C = aQ^b. \qquad \text{(Equation 6.1)}$$

However, given that the dominant control on wash-material load (which makes up most of the suspended load) is its supply, and given the highly variable character of the catchment sediment supply, it is unsurprising that plots often show a wide degree of scatter, and this is the case here (Figures 6.2-6.4). Much of the scatter is theorised as being due to hysteresis, which is produced as the sediment wave is not synchronised with the water wave. Hysteretic relationships, where the sediment wave precedes the water wave, giving higher sediment concentrations on the rising limb, are the most common outcome. Perhaps of more interest are seasonal differences in sediment concentration, which can again add to scatter. Figures 6.2-6.4 generally show higher sediment concentrations in the autumn/winter compared to spring/summer, and this probably reflects the preponderance for vulnerable catchment soils to become degraded and eroded at this time, as discussed in Section 4.6.

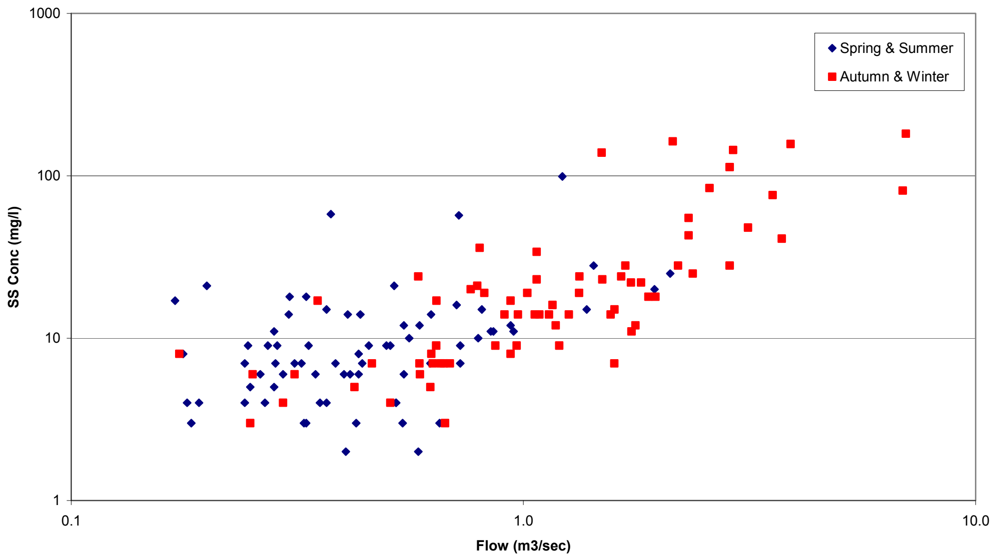


Figure 6.2 Relationship of suspended sediment concentration to discharge (log-log plot), differentiated in relation to seasons, for the Halse Water (gauging station)

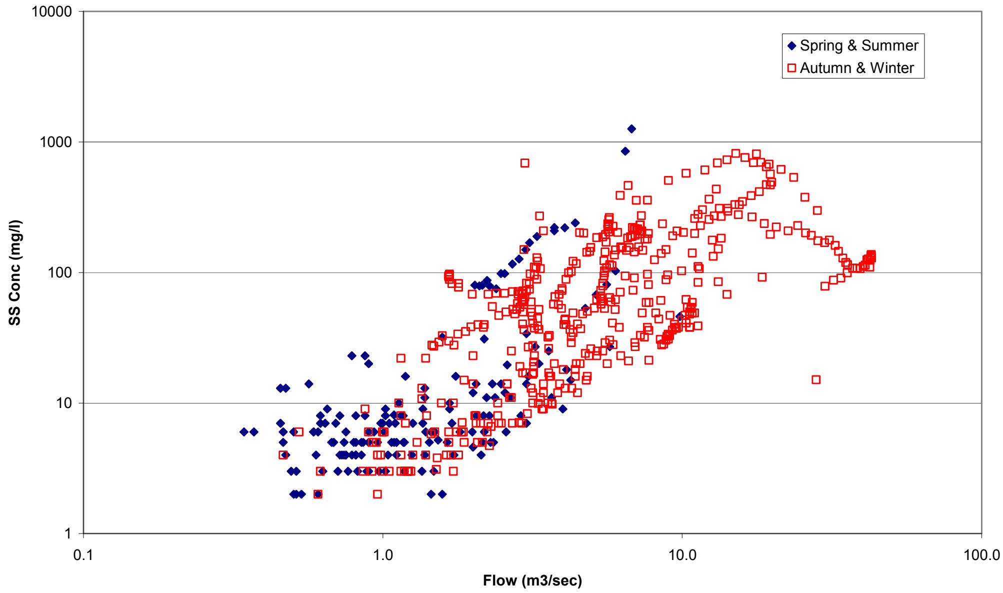


Figure 6.3 Relationship of suspended sediment concentration to discharge (log-log plot), differentiated in relation to seasons, for the upper River Tone (Bishops Hull gauging station)

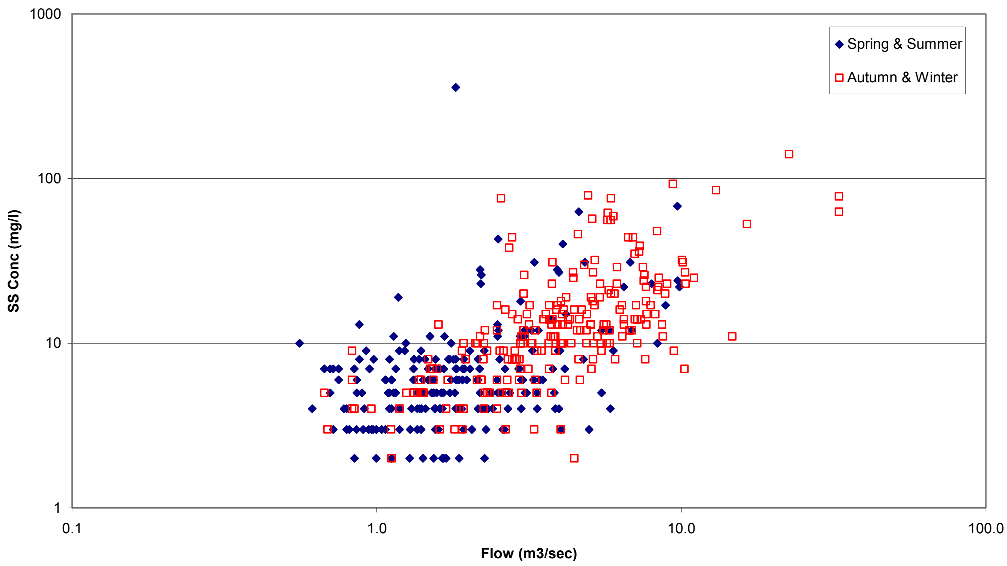


Figure 6.4 Relationship of suspended sediment concentration to discharge (log-log plot), differentiated in relation to seasons, for the River Tone (Knapp Bridge)

These sediment concentration-flow relationships underpinned derivation of sediment yield estimates made using the Ratio Method (Cooper and watts, 2002). Project-specific monitoring was also used, in combination with linear regression analysis, as the boundary input data for the ISIS-Sediment model. However, assessments of sediment yield have shown that sediment-rating assessed yields can be in error by a factor of 10 (Walling and Webb, 1988). Such errors can arise because of sampling errors/bias and because the regression model provides a poor fit to the high flow end of the relationship where it may be data sparse and where the bulk of the sediment is transported. Sediment yields derived from sediment concentration-flow relationships must therefore be used with extreme caution.

The sediment budget information predicts significant (~10,000 tonnes/year) long-term sediment storage in the River Tone downstream of Halse Water confluence and within the centre of Taunton. If this amount of sediment was deposited annually for a decade (which is an approximate and conservative estimate of the interval since the weir sluices were last drawn-down) then a significant reduction in channel capacity would be expected. This is because 10,000 tonnes is equivalent to ~6,700m^3 (using a 1.5 tonnes/m^3 average silt density conversion rate) which, if deposited evenly over an area of the channel bed approximately 20m wide by 1400m long would equate to a bed elevation rise of 0.24m/year or 2.4m over a ten year period. If sediment deposition was restricted to behind weirs and areas of the river channel subject to further over-widening, as the longitudinal profile (Figure 6.6) suggests, then river bed elevation rises would be even more pronounced.

It appears very unlikely that sedimentation has or is occurring at this scale. However, to try to verify this, an assessment of volume and cross-sectional changes of the river channel through Taunton (approximately 1400m) was completed. This was undertaken by comparing present-day channel cross-sections (taken from the latest ISIS model) against channel cross-sections derived from the 1960s flood channel engineering drawings (as-built cross-sections). The latest ISIS hydraulic model was used to generate data on cross-sectional flow area (m^2) and, thus, the volume of water the channel could hold (m^3).

Due to the 1960s as-built flood channel drawings only providing indicative channel dimensions, especially channel width, the assessment of channel volume also included a set of as-built cross-sections that (1) had the left bank level increased to reflect modern day standards of defence, and (2) had the banktop width increased by 2.3m to reflect existing channel dimensions. The results of the channel volume assessment are shown in Tables 6.2-6.5, with coloured cells representing those existing model cross-sections that closely match in location to the available as-built cross-sections.

Latest version of ISIS hydraulic model							
Cross-Section	**Chainage (m)**	**Cumulative Chainage (m)**	**Left Bank (mAOD)**	**Right Bank (mAOD)**	**Channel width (m)**	**Flow Area (m^2)**	**Volume (m^3)**
RT10373	116.00	0.00	15.03	16.13	34.17	50.85	5,898.19
RT10257	227.70	116.00	15.03	16.76	34.17	70.33	16,014.78
RT10029	251.10	343.70	15.77	17.09	29.22	92.11	23,129.35
RT9778	55.00	594.80	14.73	15.85	24.55	62.61	3,443.73
RT9723d	42.80	649.80	14.73	15.85	24.55	62.32	2,667.40
RT9680	55.00	692.60	14.82	15.95	28.07	76.00	4,180.09
RT9625d	149.00	747.60	16.06	16.23	39.89	148.64	22,147.03
RT9476	194.80	896.60	14.65	15.58	27.35	76.10	14,823.39
RT9281	95.90	1,091.40	14.90	15.24	26.67	77.10	7,393.87
RT9186d	205.40	1,187.30	14.96	15.07	28.69	92.34	18,966.33
Total	**1,393**	**1,393**					**118,664**

Table 6.2 Total channel volume through Taunton based on latest ISIS hydraulic model cross-sections

As-built 1960s cross-sections							
Cross-Section	Chainage (m)	Cumulative Chainage (m)	Left Bank (mAOD)	Right Bank (mAOD)	Channel width (m)	Flow Area (m^2)	Volume (m^3)
RT10373	48	0	15.03	16.13	34.17	50.85	2,440.63
18-18	135	48	14.02	15.95	24.17	42.88	5,788.88
17-17	64	183	15.50	15.50	23.61	79.72	5,102.12
16-16	74	247	15.87	15.87	26.22	81.18	6,007.61
15-15	71	321	15.78	15.78	26.91	84.44	5,995.42
14-14	65	392	15.35	16.00	24.39	75.75	4,923.93
13-13	87	457	14.85	16.00	24.80	63.85	5,554.76
12-12	66	544	14.79	15.63	25.42	66.03	4,358.11
11-11	25	610	14.68	16.00	23.62	61.71	1,542.83
10-10c	38	635	14.68	14.68	25.18	66.01	2,508.28
10-10	55	673	14.68	14.68	25.18	66.01	3,630.41
8-8c	45	728	14.38	16.00	36.31	103.91	4,676.05
8-8	78	773	14.38	16.00	36.31	104.57	8,156.44
7-7	64	851	16.00	15.41	24.43	85.24	5,455.46
6-6	63	915	16.00	15.38	25.91	91.55	5,767.71
5-5	64	978	15.33	15.33	24.08	79.49	5,087.67
4-4	159	1,042	14.62	15.22	24.19	66.14	10,515.54
2-2	160	1,201	15.00	15.00	27.44	86.85	13,896.61
Total	**1,361**	**1,361**					**101,408**

Table 6.3 Total channel volume through Taunton based on 1960s 'as-built' flood channel cross-sections

As-built 1960s cross-sections (with raised left bank)							
Cross-Section	Chainage (m)	Cumulative Chainage (m)	Left Bank (mAOD)	Right Bank (mAOD)	Channel width (m)	Flow Area (m^2)	Volume (m^3)
RT10373	48	0	15.03	16.13	34.17	50.85	2,440.63
18-18	135	48	14.02	15.95	24.17	42.88	5,788.88
17-17	64	183	15.50	15.50	25.04	79.72	5,102.12
16-16	74	247	15.87	15.87	26.22	81.18	6,007.61
15-15	71	321	15.78	15.78	26.91	84.44	5,995.42
14-14	65	392	15.35	16.00	24.39	75.75	4,923.93
13-13	87	457	15.63	16.00	27.86	85.57	7,444.55
12-12	66	544	15.63	15.63	30.71	91.82	6,060.12
11-11	25	610	15.54	16.00	26.88	84.82	2,120.49
10-10c	38	635	15.50	14.68	25.18	66.01	2,508.28
10-10	55	673	15.50	14.68	25.18	66.01	3,630.41
8-8c	45	728	16.00	16.00	39.77	168.33	7,574.74
8-8	78	773	16.00	16.00	39.77	168.99	13,180.84
7-7	64	851	16.00	15.41	24.43	85.24	5,455.46
6-6	63	915	16.00	15.38	25.91	91.55	5,767.71
5-5	64	978	15.33	15.33	24.08	79.49	5,087.67
4-4	159	1,042	14.62	15.22	24.19	66.14	10,515.54
2-2	160	1,201	15.00	15.00	27.44	86.85	13,896.61
Total	**1,361**	**1,361**					**113,501**

Table 6.4 Total channel volume through Taunton based on 1960s 'as-built' flood channel cross-sections with left bank raised to reflect existing levels

As-built 1960s cross-sections (increased in width by 2.3m)							
Cross-Section	Chainage (m)	Cumulative Chainage (m)	Left Bank (mAOD)	Right Bank (mAOD)	Channel width (m)	Flow Area (m^2)	Volume (m^3)
RT10373	48	0	15.03	16.13	34.17	50.85	2,440.61
18-18	135	48	14.02	15.95	26.47	47.47	6,408.59
17-17	64	183	15.50	15.50	25.91	88.07	5,636.48
16-16	74	247	15.87	15.87	28.52	90.43	6,691.82
15-15	71	321	15.78	15.78	29.21	93.76	6,656.82
14-14	65	392	15.35	16.00	26.69	84.13	5,468.13
13-13	87	457	14.85	16.00	27.10	71.19	6,193.10
12-12	66	544	14.79	15.63	27.72	69.71	4,600.99
11-11	25	610	14.68	16.00	25.92	69.07	1,726.83
10-10c	38	635	14.68	14.68	27.48	73.48	2,792.35
10-10	55	673	14.68	14.68	27.48	73.48	4,041.57
8-8c	45	728	14.38	16.00	38.62	111.47	5,016.15
8-8	78	773	14.38	16.00	38.62	111.47	8,694.66
7-7	64	851	16.00	15.41	26.73	94.67	6,059.01
6-6	63	915	16.00	15.38	29.21	103.06	6,492.72
5-5	64	978	15.33	15.33	26.38	88.97	5,694.14
4-4	159	1,042	14.62	15.22	26.49	74.16	11,791.76
2-2	160	1,201	15.00	15.00	29.74	96.22	15,394.40
Total	**1,361**	**1,361**					**111,800**

Table 6.5 Total channel volume through Taunton based on 1960s 'as-built' flood channel cross-sections with channel width increased by 2.3 m to reflect existing widths

Present-day channel volume is calculated to be 118,664 m^3, whereas volume of the channel based upon the 1960s flood channel as-built cross-sections is calculated to be 101,408 m^3. This represents an increase in volume of 17,256 m^3 (~17%) from the 1960s baseline.

When the 1960s as-built cross-sections are adjusted, to better represent present-day bank heights and widths, the 1960s channel volume is, as expected, increased (111,800 m^3 if channel widened or 113,501 m^3 if banks raised). However, compared to present-day channel volume there is still an increase in channel volume of 5,163 m^3 (~5%) or 6,864 m^3 (~7%) from the 1960s baseline.

Therefore, instead of seeing a significant reduction in volume, as sediment budgeting suggests due to significant sediment deposition in the channel, in fact the channel capacity appears to have slightly increased since the 1960s. This suggests the channel is subject to some long-term degradation.

A review of the cross-sectional area plots for the five close-matching cross-sections (Figure 6.5 for one example, and Appendix A for all five cross-sections) supports this conclusion by showing a general increase in channel depth or width since the flood channel was constructed in the 1960s.

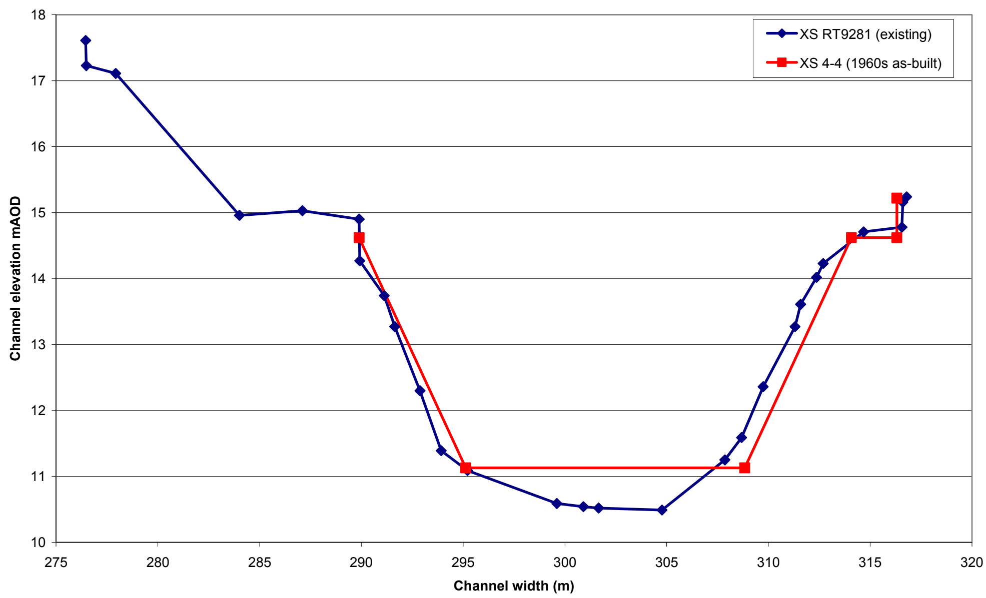


Figure 6.5 Comparison of a 1960s 'as-built' flood channel and existing channel cross-sectional area for a single location on the River Tone in Taunton

The longitudinal profile for the study area (Figure 6.6), obtained from the ISIS hydraulic model, appears to show that bed elevations have risen at a number of key locations, specifically: upstream of French Weir, A3027 road bridge (Town Bridge in Taunton), upstream of Firepool Weir and upstream of Ham Weir, which could represent aggradation in areas upstream of in-channel structures and where the channel is at its widest. The increase in bed elevation could be natural variation in the bed topography or could be linked to deposition of sediment, including either coarse- or fine-grained material or a combination of both.

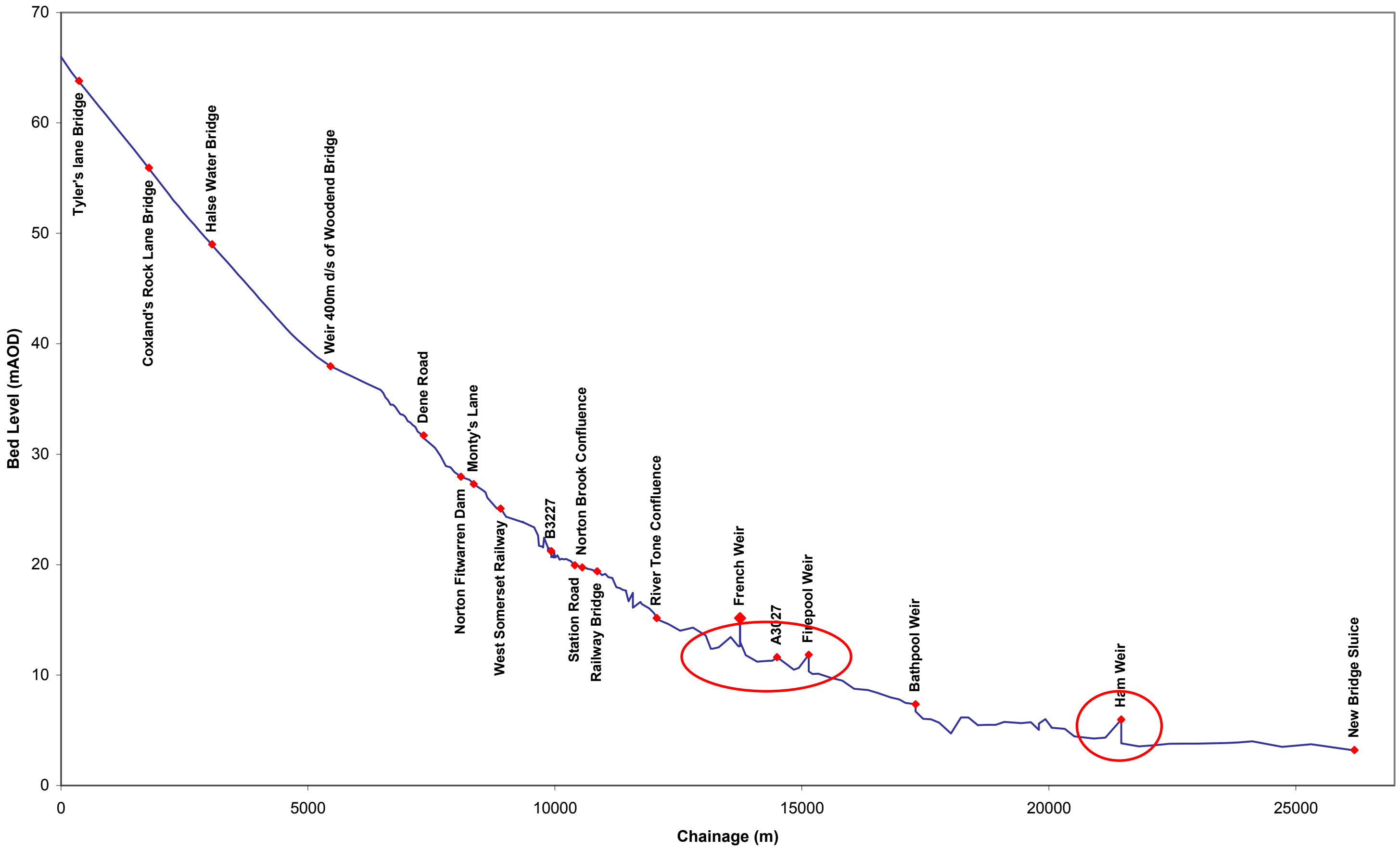


Figure 6.6 Longitudinal profile of Halse Water (Northway to confluence) and lower River Tone (confluence to Newbridge) derived from ISIS hydraulic model

The extent of sediment potentially deposited at the key locations within Taunton was estimated from a review of the river longitudinal and channel cross-sectional profiles. This allowed an estimation of the potential annual sedimentation rate (tonnes/year) to also be made. Fine sediment potentially deposited behind French Weir and Firepool Weir was estimated to be a wedge 1.5m deep at the thickest point, which extended across the entire 20m width of river bed and 200m upstream of each weir. At Town Bridge the sediment deposition was estimated to be a wedge 0.5m deep at the thickest point, which extended across the entire 20m width of river bed and 100m along the channel.

Based on a conservative assumption that the fine sediment has been deposited over at least a decadal period (since the last flushing) coupled with a total volumetric estimate of 6,500m^3 (representing approximately 5% of the current total channel volume through Taunton, see Table 6.2) of material that has been deposited indicates a sedimentation rate in the order of ~1,000 tonnes/year (using an average silt density of 1.5 tonnes/m^3), of which ~400 tonnes/year is estimated to be deposited upstream of Firepool Weir.

To further elucidate information on sedimentation in Taunton, an investigation into river bed material composition and the extent of sediment deposition behind the three major weirs was undertaken. The investigation involved using a metal probe from a boat to investigate the occurrence, extent and depth of loose sediment deposits over the consolidated river bed substrate. In some locations cores of the finer substrate were taken using a Russian corer. Summary results for each weir are presented in Figures 6.7 to 6.9, while supporting tables and photographs providing more detailed information on composition of loose and consolidated substrate are presented in Appendix B. Samples are labelled A to R, with A samples located nearest to the weir with subsequent samples taken upstream. Each sample generally comprises a transect across the channel width (left bank, mid-point and right bank), and each point is presented as a water depth, depth of a loose bed material and minimum depth of consolidated material.

At French Weir (Figure 6.7) sampling extended approximately 500m upstream. At the majority of sample points bed material comprised consolidated cobble or gravel, with a shallow layer of loose material (approximate depth of 0.2m) comprising mainly sand/fine gravel lying over the top. At a few locations loose material, comprising mainly silt and sand, with an approximate depth of 0.6-1.0m was present. These deposits were generally associated with discrete sediment bars located along the channel margins. The channel upstream of French Weir is, therefore, characterised by a cobble/gravel substrate overlain by a discontinuous layer of fine sediment arranged in depositional bars.

At Firepool Weir (Figure 6.8) sampling extended approximately 250m upstream. The first two sets of sample points were taken within 50m of the weir crest, where the channel is also very over-widened. Bed material comprised consolidated material, of unknown composition, covered with an approximate 1.5m deep layer of loose material comprising a mixture of fine gravel, sand and silt. These deposits, which shelve up to the channel margins and in front of the canal entrance, have created islands supporting mature vegetation. Further upstream, river bed composition consistently comprised 0.3-0.6m of loose material (mainly silt, sand and fine gravel but including some cobbles) forming a continuous layer blanketing a consolidated bed of generally unknown composition. The channel upstream of Firepool Weir is therefore characterised by a layer of coarse sand/fine gravel blanketing the consolidated bed, which has a significant thickness immediately upstream of the weir.

At Ham Weir (Figure 6.9) sampling extended approximately 1,250m upstream. River bed composition consistently comprised a 0.5-1.5m thick layer of loose sediment over a consolidated clay bed. Usually the loose material is asymmetrically deposited, with a deeper layer on one or the other side of the channel. The top layers of the loose material are generally clay, silt and sand, but in some locations a band of gravel is also found (see Appendix B). The channel upstream of Ham Weir is therefore characterised by clay/silt/fine sand deposition, which appears to have blanketed a gravel-dominated bed.

An accompanying FRMRC study investigated the quality of sediment deposited behind Firepool Weir and Ham Weir to establish whether sediment may pose a water quality risk if released, for example, through weir removal/replacement (Hooper, 2012). Digital elevation models for both weirs were created using the sediment depth data collected (Figures 6.8 and 6.9), from which total volumes of silt were calculated.

The accumulation of sediment behind Firepool Weir was calculated to be 14,550m^3 (representing approximately 12% of the current total channel volume through Taunton, see Table 6.2), which takes into account all sediment deposited in front of the canal entrance as well as 250m of the main river channel. This could be an over-estimation as it includes consolidated sediment, which could represent natural bed topography as opposed to overlying deposits. Nevertheless, given this estimated volume of sediment plus evidence that the deeper/older deposits contain PCB, the use of which was prohibited in the 1970s, suggests sediment accumulation began prior to this (i.e. for the last 50 years). On this basis annual sediment accumulation is estimated to be 291m^3/year or approximately 440 tonnes/year. As stated previously, this is likely to be a maximum depositional rate.

The accumulation of sediment behind Ham Weir was calculated to be 35,544m^3. This total volume includes consolidated sediment, which could represent natural bed topography as opposed to overlying deposits, but also sampling of material covered approximately 1,000m upstream of the weir and it is likely that sediment deposits extended further upstream. Therefore, this total volume is probably a fair representation of the sediment accumulation behind the weir. Given this estimated volume of sediment plus evidence that sediment accumulation began in the 1960s, annual sediment accumulation is estimated to be 711m^3/year or approximately 1,070 tonnes/year.

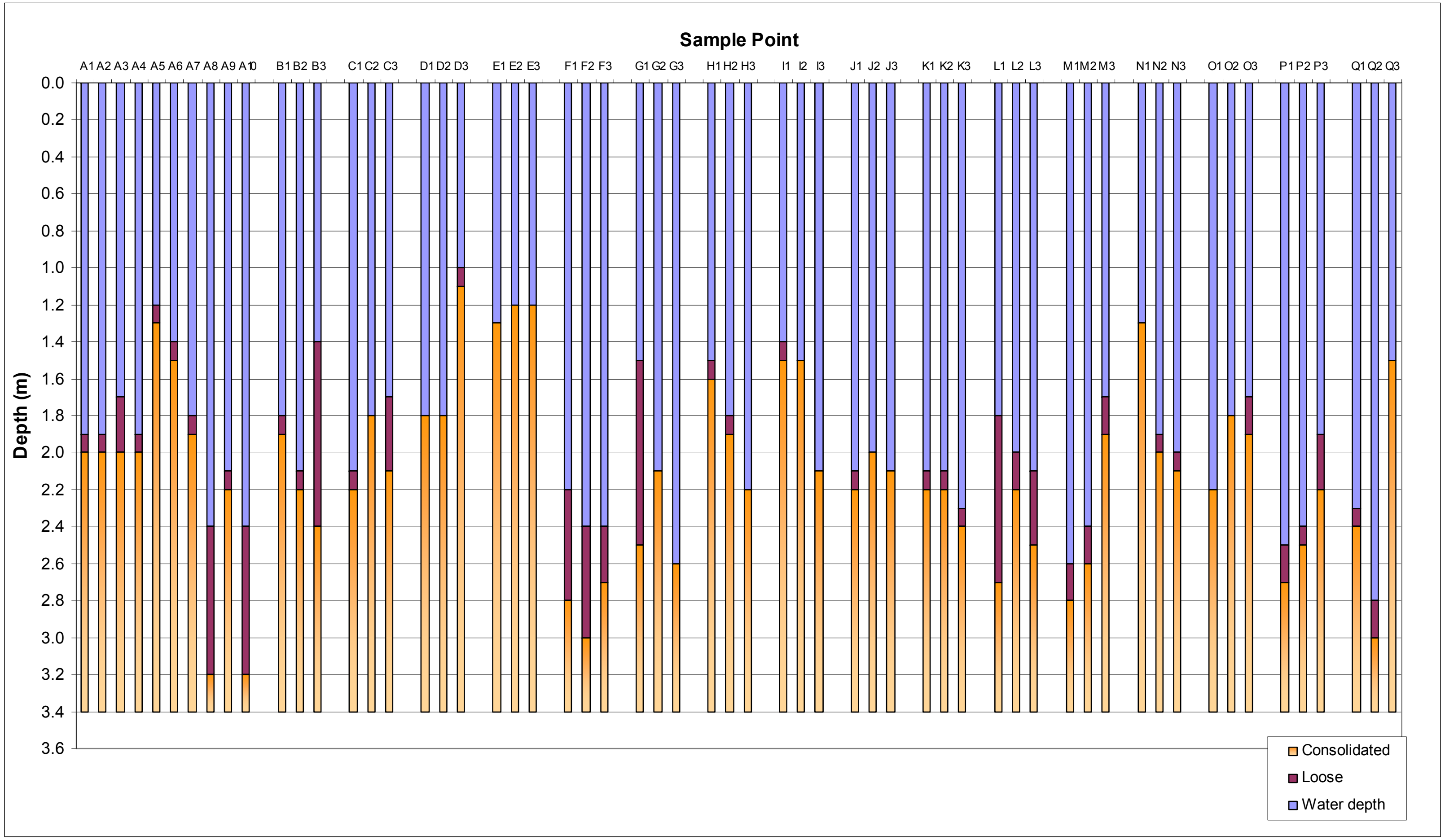


Figure 6.7 Assessment of river bed material and sediment deposition upstream of French Weir on the River Tone

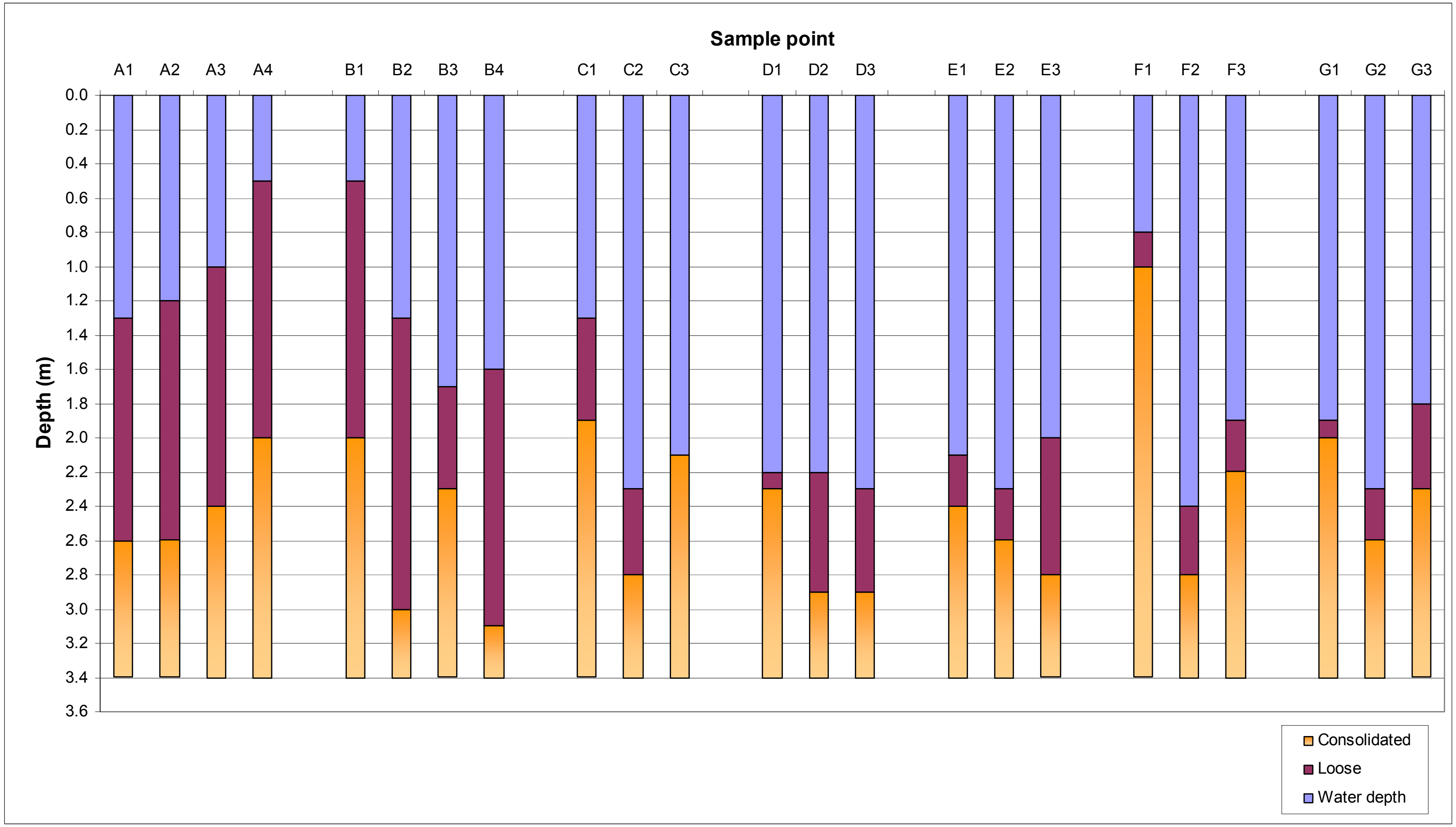


Figure 6.8 Assessment of river bed material and sediment deposition upstream of Firepool Weir on the River Tone

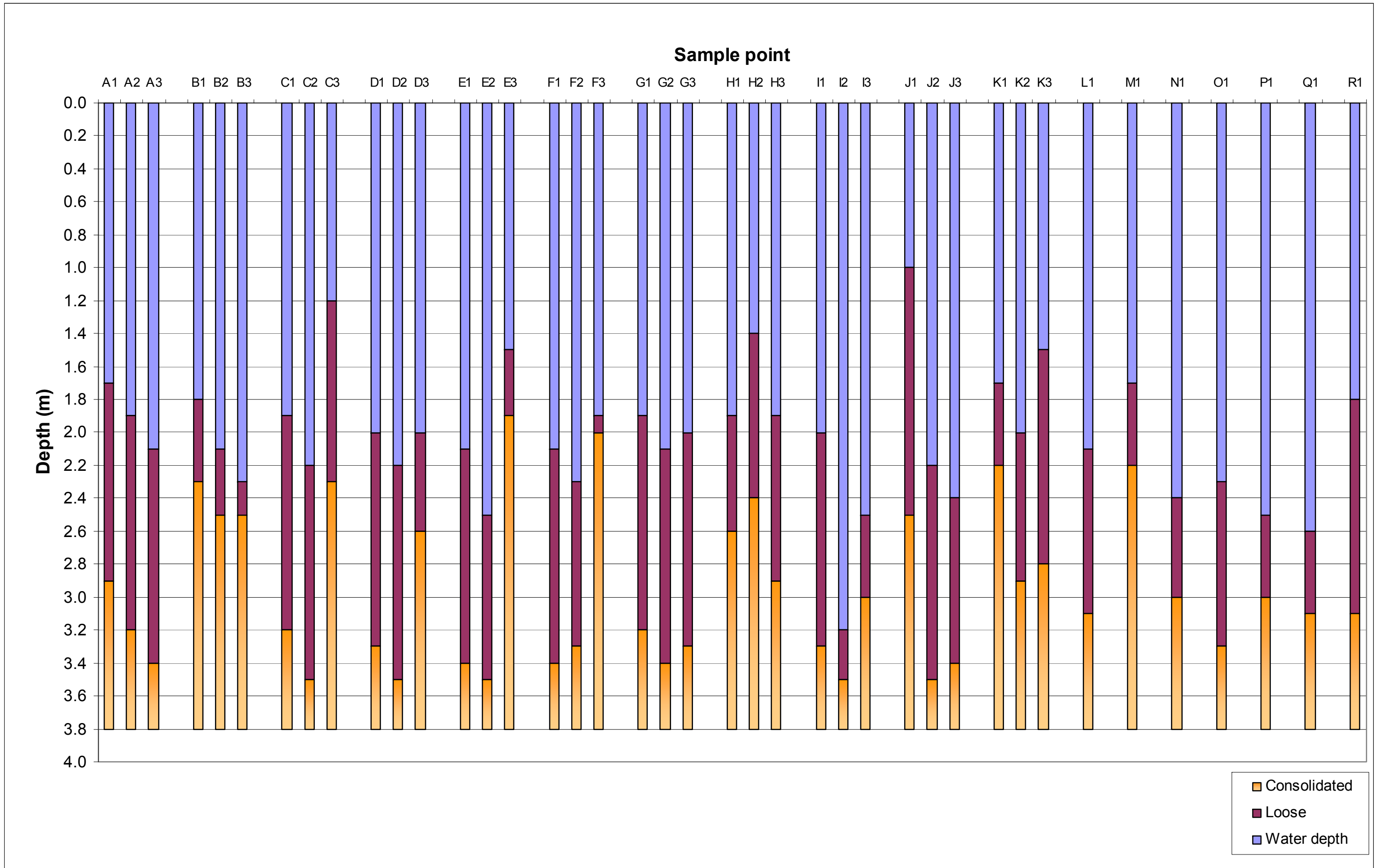


Figure 6.9 Assessment of river bed material and sediment deposition upstream of Ham Weir on the River Tone

Changes in the D_{50} through the river system from the Halse Water downstream through the lower River Tone, are shown in Figures 6.10 and 6.11. Locations of major in-channel structures and tributaries are marked. The Halse Water and upper reaches of the lower River Tone are characterised by a gravel bed, which generally shows a downstream fining from coarse gravel to medium-sized gravel.

There are localised changes in the riverbed composition within the Halse Water, which are probably due to natural changes in river gradient/channel dimensions or due to sampling bias, but could also be due to the presence of structures including the Norton Fitzwarren Dam, although this structure should have minimal impact on the 1 in 2 or more frequent annual probability flows, and numerous small (~1m high) weirs located throughout the lower reaches of the Halse Water.

The most dramatic change in bed material can be seen in the lower River Tone between Reaches T2 and T3. These reaches are separated by French Weir (the first major weir in Taunton). Here the D_{50} changes from 11.4mm (medium gravel) to 0.8mm (coarse sand). Downstream of Firepool Weir the D_{50} reduces further to 0.5mm (medium sand), while in the Somerset Levels downstream of Ham Weir the D_{50} is 0.1mm (very fine sand). These major weirs have fixed crests, giving them the potential to interrupt downstream transfer of bed-material load.

The major influence on the downstream transfer of bed-material load therefore appears to be French Weir, which is the key factor in the abrupt conversion of the lower River Tone from a gravel-bedded to a sand-bedded river.

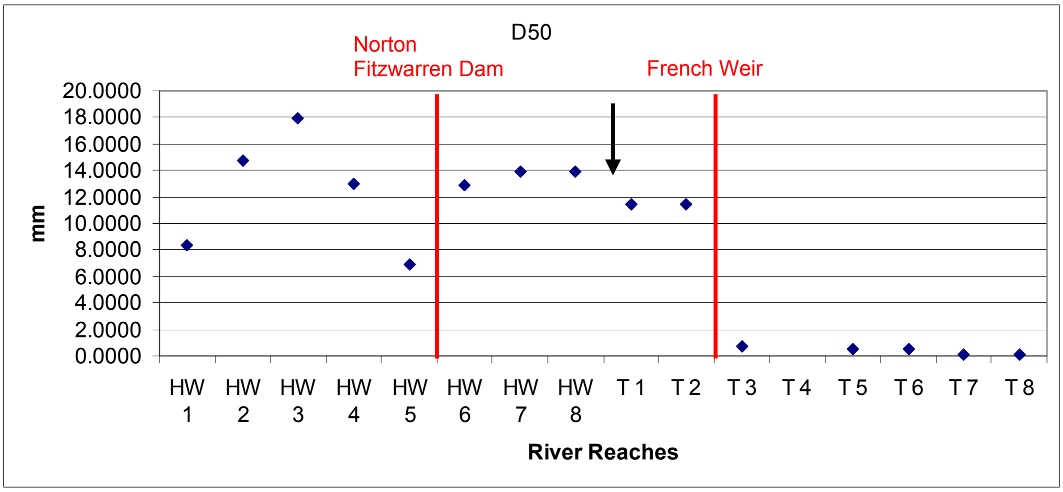


Figure 6.10 Median (D_{50}) grain size for bed material in the Halse Water and lower River Tone showing location of structures (red bars) and tributaries (arrows)

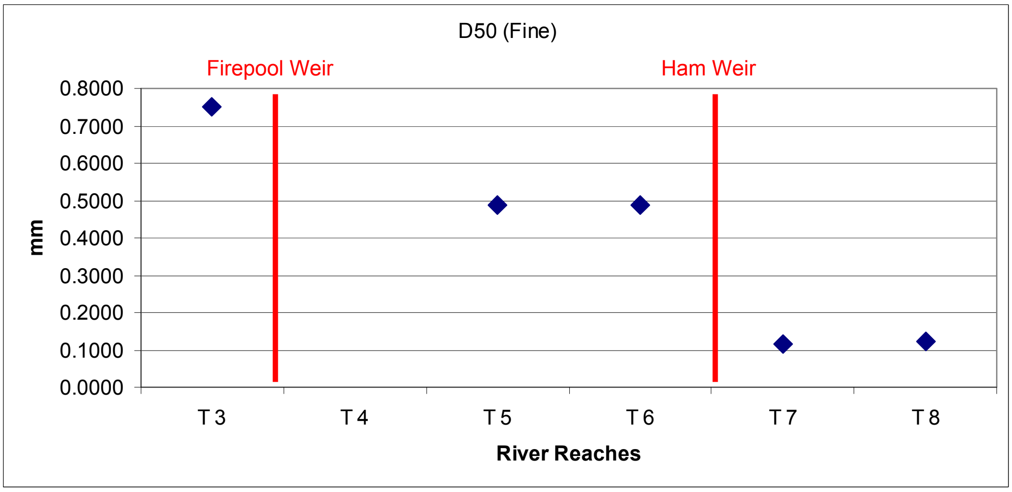


Figure 6.11 Median (D_{50}) grain size for river reaches in the lower River Tone with fine bed material showing location of structures (red bars)

The key messages from the review of available empirical sediment data are:

- Sediment budget analysis suggests a high sediment yield from the upper catchment with high suspended sediment concentrations occurring in the autumn/winter, which is probably reflecting fine sediment availability;

- Sediment budgets suggest significant long-term storage of fine sediment through Taunton as well as downstream in the low gradient Somerset Level reaches. However, sediment budgets must be used with extreme caution due to potentially large errors associated with the collection of underpinning sediment data and uncertainties inherent to sediment analysis;

- Assessment of channel volume and cross-sectional area changes, longitudinal channel profile and sedimentation behind French Weir and Firepool Weir indicates there is no evidence of significant deposition of fine sediment and subsequent aggradation in Taunton, which contradicts the sediment budget predictions. Sediment accumulation appears to be localised with bars and wedges of sand/fine gravel being restricted to locations affected by hydraulic structures, especially immediately upstream of Firepool Weir where the channel has been significantly over-widened;

- Assessment of the longitudinal channel profile and sedimentation behind Ham Weir suggests there is potential for long-term aggradation of fine sand and silt sized sediment on the river bed, which appears to have blanketed the fine gravel-dominated substrate; and

- French weir appears to be the major control on downstream transfer of bed-material load, causing an abrupt change in river bed composition in the lower River Tone from gravel-dominated to sand-dominated. There is evidence of the coarser, bed-material load depositing as sediment bars further upstream of French Weir, which occurs when the material meets the backwater effect from the weir.

6.2 Stream power screening

The pre-existing ISIS hydraulic model was used to extract data on channel dimensions and flows for a range of cross-sections within the Halse Water (104 cross-sections along the 12.2km modelled reach) and lower River Tone (87 cross-sections along the 14.1km modelled reach). The specific stream power at bankfull discharge was calculated for each cross-section using Equation 5.1. A range of other parameters were also calculated including hydraulic depth (cross-sectional area / wetted perimeter) and average velocity, and the complete data set is presented in Appendix C.

The longstream distribution of specific stream power in the Halse Water features a general reduction with distance downstream of Northway (Figure 6.12). Based on the broad categories suggested by Brookes (1987 a and b), the upper reaches have sufficient stream power to respond to disturbance through erosion, while bankfull stream powers in the remaining, majority of the Halse Water are consistent with the watercourse acting as a sediment transfer pathway. However, discrete spikes and troughs in the stream power profile for the lower-middle reaches of the Halse Water are related to local changes in gradient and/or channel dimensions that suggest the presence of sub-reaches individually dominated by erosion, sediment exchange and deposition.

Comparison of specific stream power against bankfull width (Figure 6.13) and hydraulic depth (Figure 6.14) reveals an inverse relationship between stream power and both width and hydraulic depth. This is particularly clear in part of the lower course (10,400m – 11,000m) where the river has been re-sectioned and enlarged as part of flood risk management for a new housing development in Norton Fitzwarren immediately upstream of the mainline railway crossing (Figure 6.20). An inverse relationship with width is to be expected, but an inverse relationship with depth is more unusual. The explanation stems from an artificial, two-stage cross-section that dissipates velocity and energy very effectively at high, in-bank flow. Based on stream power analysis, it appears that re-sectioning for flood defence has created an extensive and efficient sediment trap in the lower Halse Water.

The longstream distribution of specific stream power in the lower River Tone shows a generally decreasing trend from the Halse Water confluence above Taunton down to the tidal limit at Newbridge (Figure 6.15). The most upper reaches of the modelled reach appear to have some potential to function as a sediment transfer pathway, although they transition quickly into a deposition reach upstream of Taunton due to the backwater effects of French Weir. Within Taunton, a spike of higher stream power suggests the potential for localised erosion. Specific stream power decreases steadily downstream of Taunton, and the potential for the river to function as a deposition sink increases. Below Ham Weir (at about 10,000m) specific bankfull stream powers are very low.

Comparing specific stream power against bankfull width (Figure 6.16) and hydraulic depth (Figure 6.17) it appears that there is a positive relationship with both. This is particularly clear in the Taunton reaches (2,000m – 3,000m) where the river flow is controlled by weirs and constrained between flood walls. It appears that specific stream power in this reach is, therefore, controlled by its heavily modified, engineered condition within the urban area. In the downstream reaches, the very low values of specific stream power result primarily from the extremely small slope, which is low naturally, rather than artificially altered channel dimensions.

In accordance with guidance in Thorne *et al.* (2011) regarding application of the stream power screening tool, the available cross-sections were grouped into geomorphologically- and hydraulically-homogeneous reaches (see Section 6.3) producing 8 reaches on each of the Halse Water and lower River Tone. This provided the basis for application and assessment of specific stream power at the reach scale (Figure 6.18). Average specific stream power is calculated for each geomorphic/hydraulic reach, which is generally analogous to the SIAM reached-based model (see Section 5.2.3). The average specific stream power is categorised in terms of sedimentation process potential (erosion, transfer or deposition) based on the indicative values described by Brookes, namely: erosion (>35 W/m^2); transfer (15-35 W/m^2); and deposition (<15 W/m^2). In addition, a qualitative assessment establishes the general composition of each geomorphic/hydraulic reach in terms of sedimentation potential.

In Figure 6.18 it can be seen that within-reach specific stream powers generally decrease from the upper Halse Water catchment down through the lower River Tone with, in general, a high potential for erosion in the upper reaches of the Halse Water, the potential for sediment transfer through the middle reaches and deposition in the lower reaches (Plates 6.1 to 6.3). The River Tone is indicated as being an erosion/transfer zone as far downstream as Bathpool Weir, a small check weir constructed by the Environment Agency.

Beyond this location sedimentation potential in the Tone is predominantly for deposition. The stream power screening tool also suggests the possibility of some reaches having the potential for reach-scale erosion (e.g. HW4, HW6 and T3). Conversely, other reaches have the potential for deposition, for example, reaches HW7 & HW8. This most likely reflects the impacts of re-sectioning, with the over-widened river reach associated with the new housing development, and tributary inputs from the Back Stream.

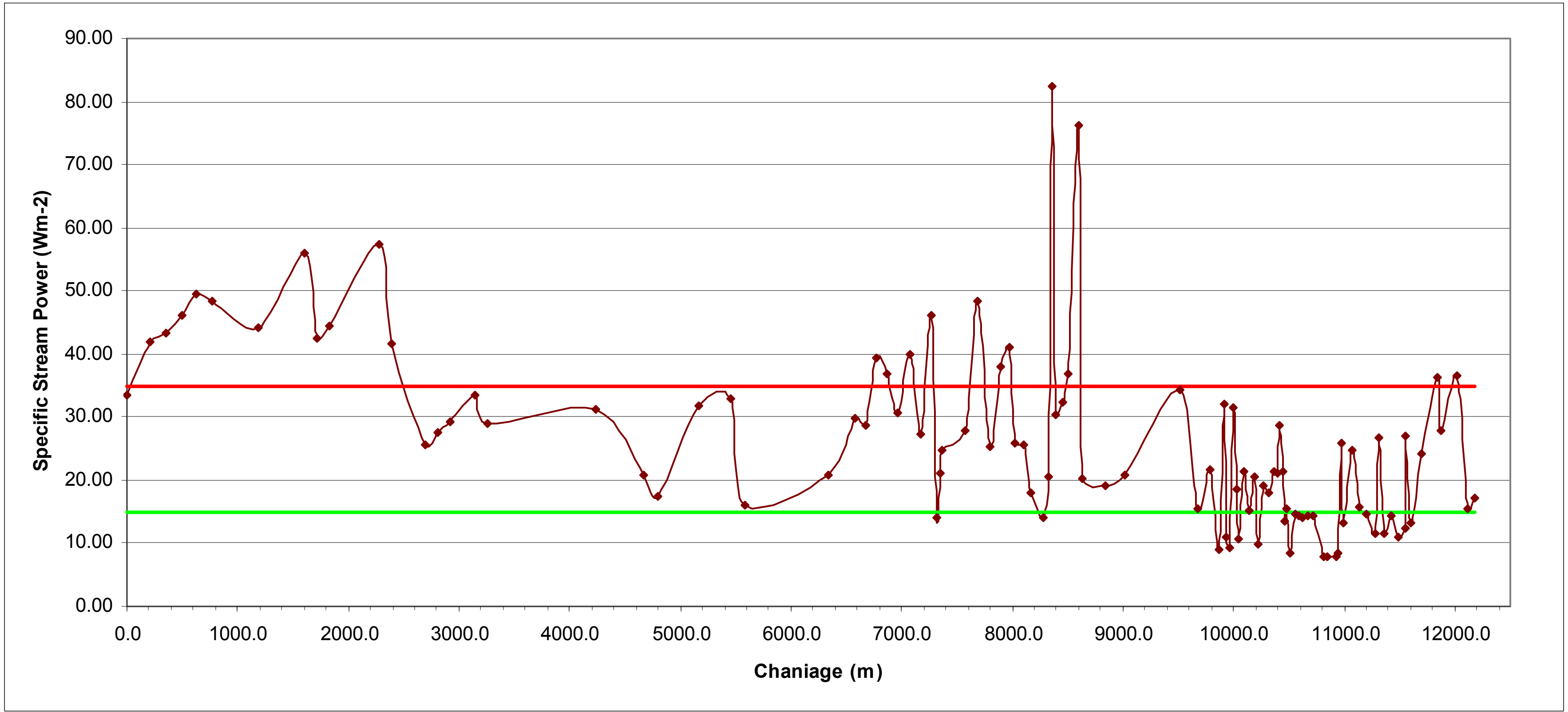


Figure 6.12 Change in specific stream power along the Halse Water with bands of sedimentation potential shown (above red = erosion; below green = deposition)

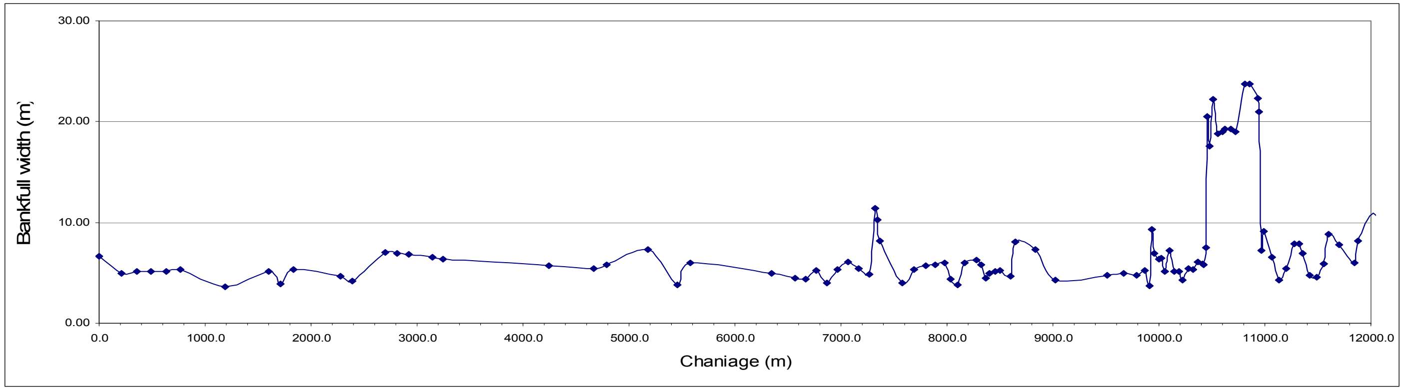


Figure 6.13 Change in bankfull width along the Halse Water

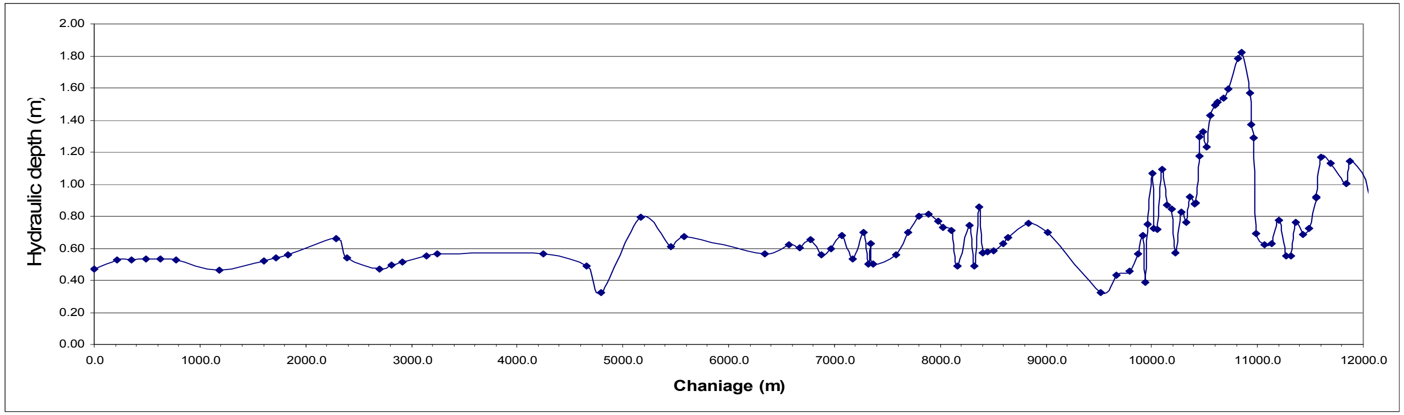


Figure 6.14 Change in hydraulic depth along the Halse Water

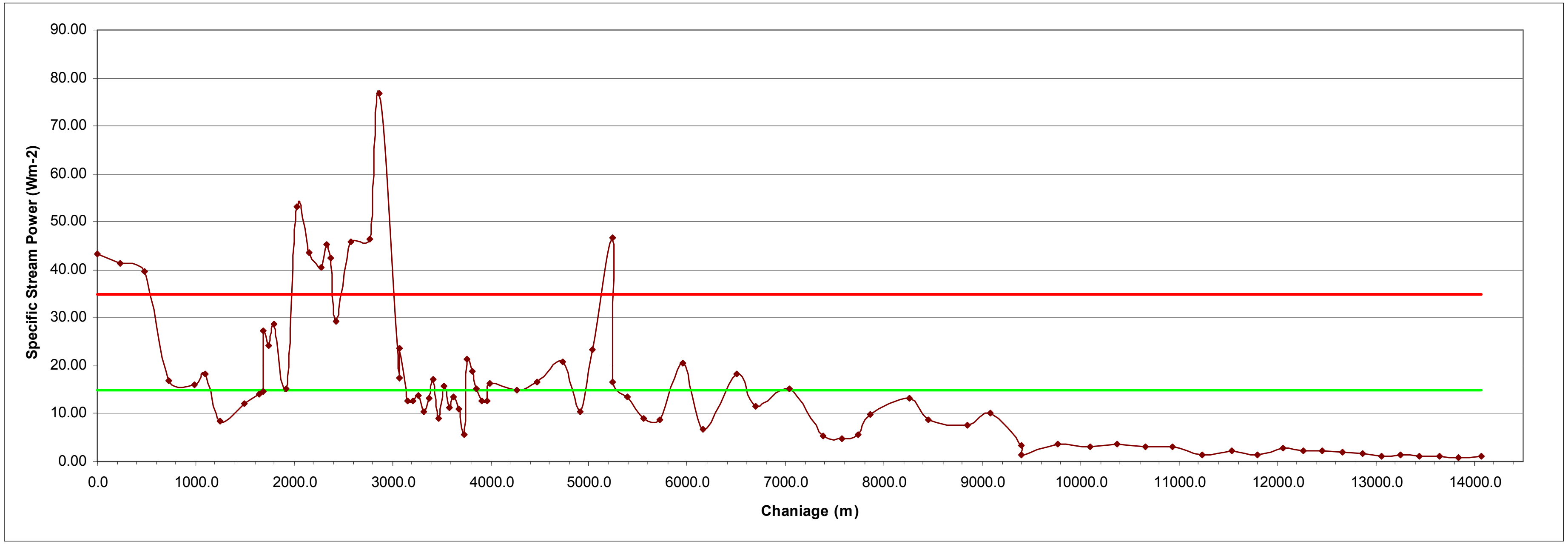


Figure 6.15 Change in specific stream power along the lower River Tone with bands of sedimentation potential shown (above red = erosion; below green = deposition)

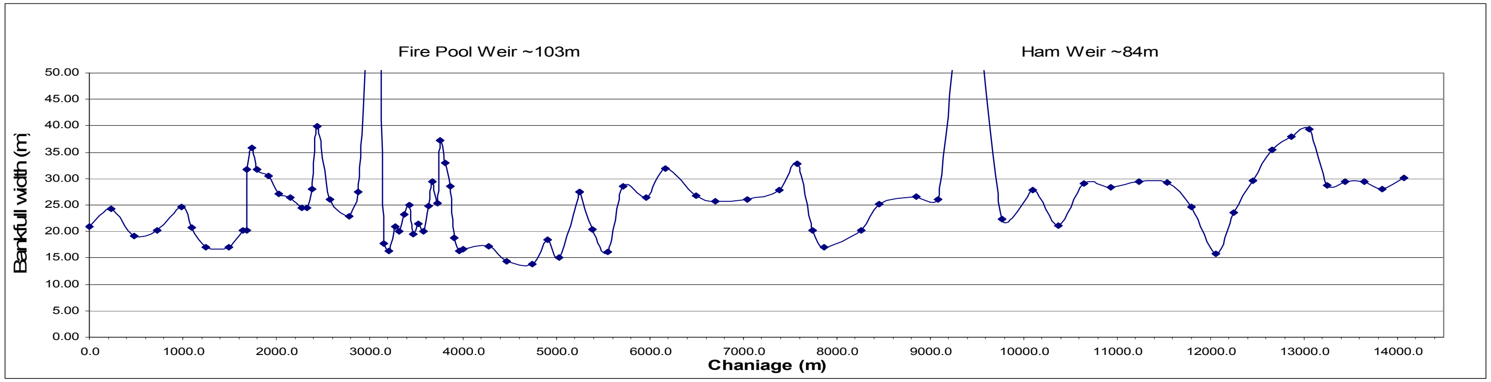


Figure 6.16 Change in bankfull width along the lower River Tone

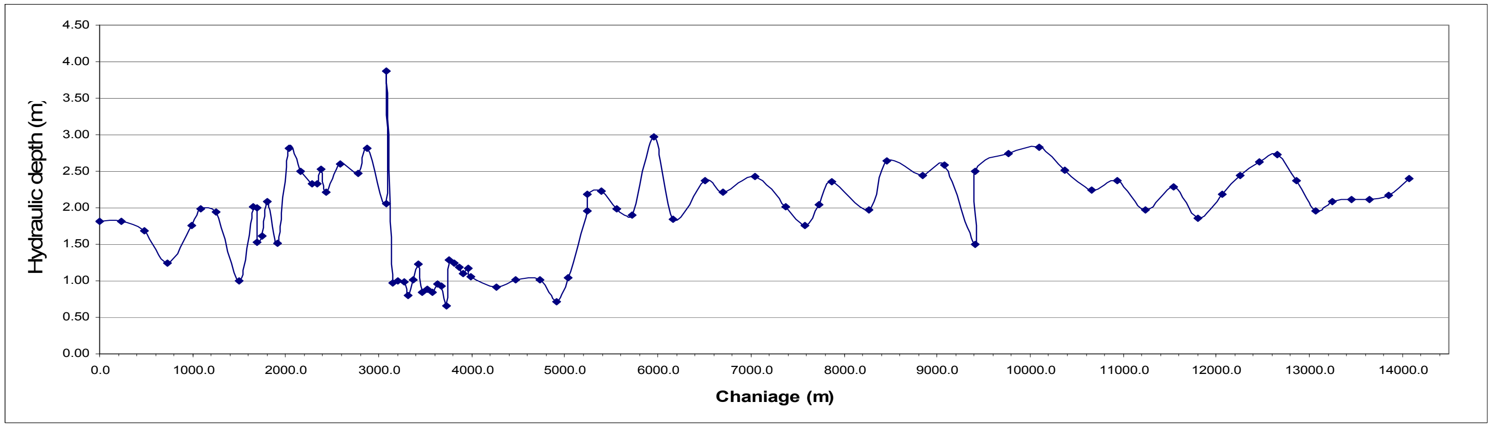


Figure 6.17 Change in hydraulic depth along the lower River Tone

River	Flow Direction	Reach	Location	Stream Power Range	Stream Power Average	Sedimentation Potential		
						Erosion	Transfer	Deposition
Halse Water	Upstream	HW 1	u/s limit (Tyler's Bridge) to Coxland's Rock bridge	33.40 to 55.96	45.34			
Halse Water		HW 2	Coxland's Rock bridge to King's Moor (ford)	25.55 to 57.34	37.71			
Halse Water		HW 3	King's Moor (ford) to Burge Farm	17.53 to 32.97	27.22			
Halse Water		HW 4	Burge Farm to Cotford St Luke bridge	13.94 to 46.02	28.84			
Halse Water		HW 5	Cotford St Luke bridge to Norton Fitzwarren Dam	17.89 to 48.29	31.23			
Halse Water		HW 6	Norton Fitzwareen Dam to u/s Norton Fitzwarren	13.97 to 82.29	32.63			
Halse Water		HW 7	Norton Fitzwarren to Mainline Railway	7.80 to 32.16	16.37			
Halse Water		HW 8	Mainline Railway to Confluence	10.83 to 36.46	19.75			
Tone		T 1 & T 2	Confluence to French Weir	10.78 to 33.73	21.78			
Tone		T 3	French Weir to Firepool Weir	15.11 to 76.74	38.28			
Tone		T 4	Firepool Weir to Bathpool Weir	5.69 to 46.66	15.97			
Tone		T 5	Bathpool Weir to M5 Bridge	8.60 to 20.48	13.61			
Tone		T 6	M5 Bridge to Ham Weir	3.30 to 18.17	9.24			
Tone		T 7	Ham Weir to Knapp Bridge	1.33 to 3.67	2.55			
Tone	Downstream	T 8	Knapp Bridge to New Bridge (Tidal Limit)	0.96 to 2.68	1.63			

Figure 6.18 Summary of specific stream power showing average stream power per reach and qualitative assessment of sedimentation potential within each reach. Potential is based upon indicative values defined by Brookes (1987a and b)

Plate 6.1 Upper (a) and middle (b) reaches of the Halse Water, which are dominated by erosional processes

Plate 6.2 Lower reaches of the Halse Water, showing new two-stage channel for flood risk management (a), and lower reaches of the River Tone, showing presence of a mid-channel sediment bar (b), both of which are dominated by depositional processes

Plate 6.3 Reach T1 (a) and Reach T4 (b) of the River Tone, which are dominated by sediment exchange and sediment transfer processes, respectively

6.3 SIAM

The evidence provided by field reconnaissance and application of the stream power screening tool indicates that the Halse Water is likely to be primarily a source and pathway for sediment, whereas the lower River Tone is likely to be primarily a sediment pathway and sink. This finding, combined with technical challenges of constructing and running a fully integrated river model for the entire ~26km study area, led to the decision to split the SIAM (and ISIS-Sediment) models into two discrete models:

1. Halse Water model. Primarily focused on linking the catchment sediment sources identified through sediment fingerprinting to the river, and investigating the fate of wash-material and bed-material components of the sediment load moving through the upper part of the river system; and

2. Lower River Tone model. Primarily focused on investigating the fate of wash-material and bed-material components of the sediment load, and understanding exchanges between wash-material and bed-material loads in the lower river system.

6.3.1 SIAM 1: Halse Water

Input data and boundary conditions

A sediment model of the Halse Water was constructed using SIAM. The model encompasses the river from upper-middle reaches at Northway downstream to the confluence with the River Tone, a river distance of 12,180m. The modelled reach was divided into eight sediment reaches (Figures 6.19 and 6.20):

❖ Reach HW1: a very short ‘dummy’ reach included to generate the upstream wash-material and bed-material loads supplied from upstream to Reach HW2. Reach HW1 is not included in analysis of sediment dynamics and loads reported in the following sections.

- Reach HW2: furthest upstream reach, extending to below Halse (Kingsmoor) and linked geomorphically to the steep, narrow upper catchment. This reach features a morphologically active channel with eroding banks.

Plate 6.4 Reach HW2 (furthest upstream reach) on the Halse Water showing river connected to sediment sources (poaching and eroding banks)

- Reach HW3: Kingsmoor to upstream of Cotford St Luke, which features a meandering, sediment exchange channel which is linked to sediment sources from river banks and surrounding arable land.

Plate 6.5 Reach HW3 (upstream of Cotford St Luke) on the Halse Water showing river connected to sediment sources (eroding banks) and supporting deposition bars

❖ Reach HW4: downstream to Cotford St Luke (Dene Road bridge), featuring a sinuous channel with sediment exchange linked to pasture and amenity grassland. A small, un-named, tributary enters this reach.

Plate 6.6 Reach HW4 (upstream of Dene road bridge) on the Halse Water showing sinuous channel within pasture

❖ Reach HW5: upstream of the Norton Fitzwarren dam, with a sinuous channel, which is affected by back-water effects from the dam under higher flow conditions.

Plate 6.7 Reach HW5 (upstream of Norton Fitzwarren dam) on the Halse Water showing sinuous channel

❖ Reach HW6: sinuous channel downstream of the dam and upstream of the urbanised channel through Norton Fitzwarren.

Plate 6.8 Reach HW6 (upstream of Norton Fitzwarren) on the Halse Water showing sinuous channel and one of numerous small weirs

❖ Reach HW7: artificially-modified, urbanised section of river including an over-widened, two-stage channel located upstream of the mainline railway crossing.

Plate 6.9 Reach HW7 (through Norton Fitzwarren) on the Halse Water showing urbanised and modified river channel

- Reach HW8: sinuous section downstream to confluence, which is morphologically active including sediment bars, riffles and eroding banks. The Back Steam, which is estimated to supply, on average, 20% of the total wash-material load, enters the Halse Water within this reach.

Plate 6.10 Reach HW8 (upstream of confluence with River Tone) on the Halse Water showing sinuous river channel with active morphology (eroding banks and deposition bars) with Back Stream entering in this reach

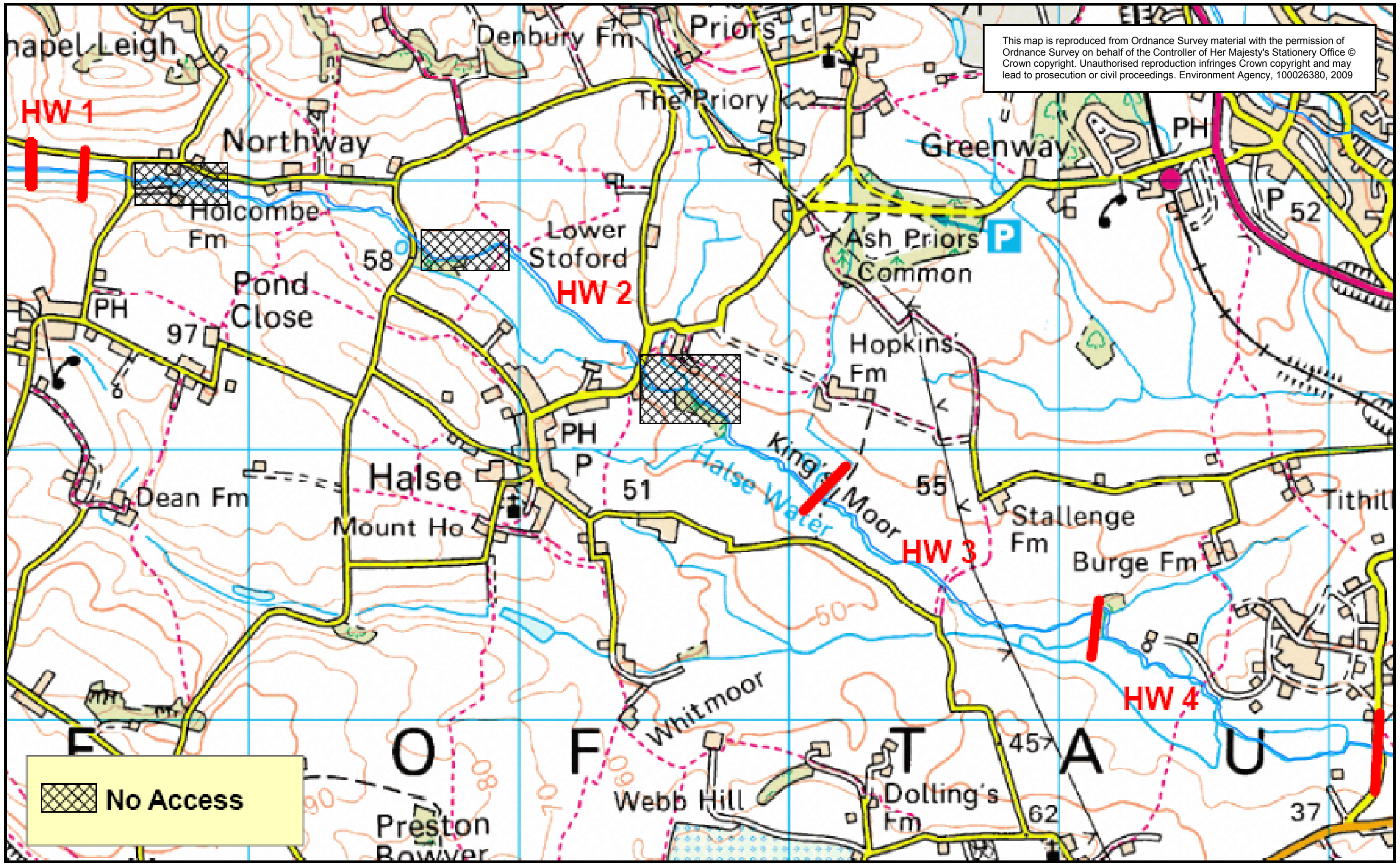


Figure 6.19 SIAM sediment reaches on the upper Halse Water

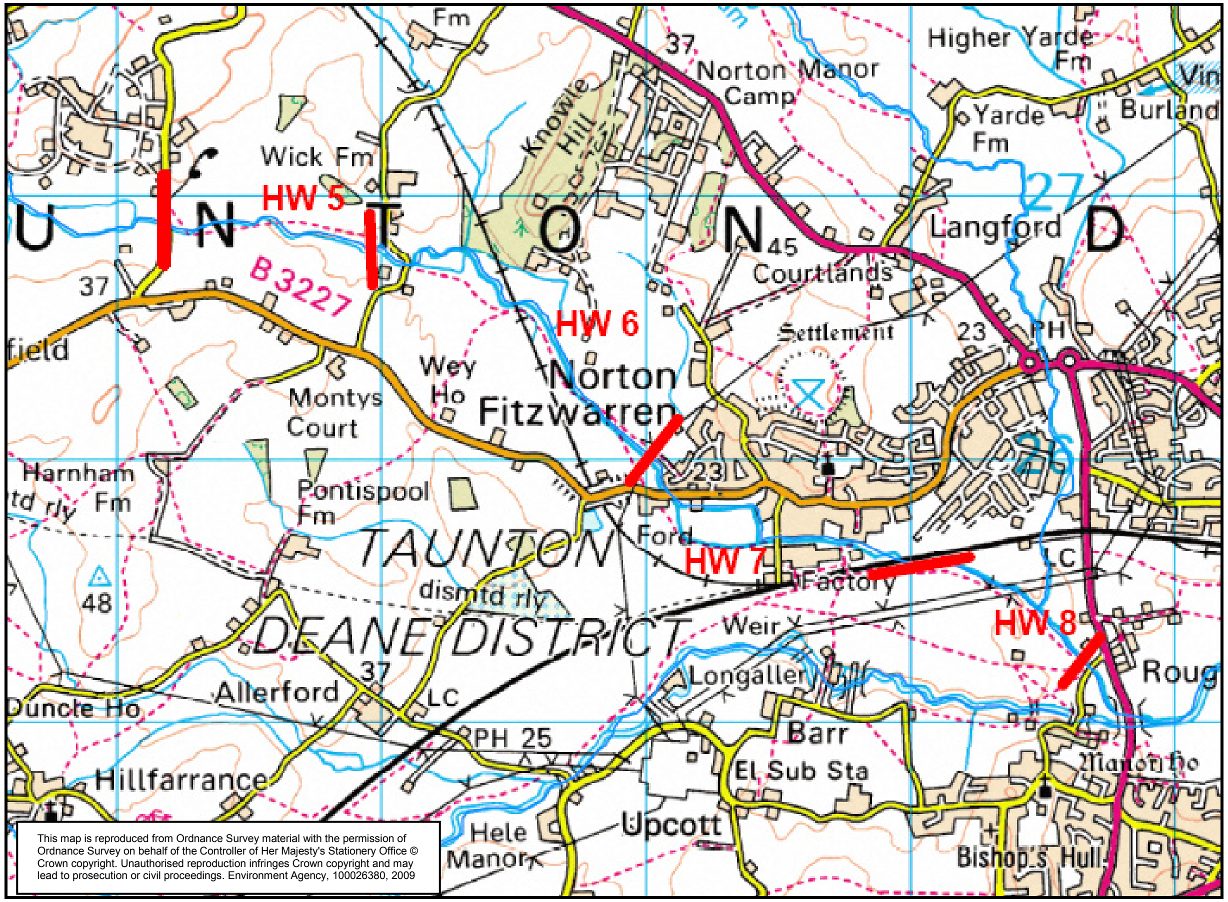


Figure 6.20 SIAM sediment reaches on the lower Halse Water

The Halse Water SIAM uses the following input data:

Channel geometry. The ISIS hydraulic model covering the Halse Water was used as the basis to develop a HEC-RAS (Version 4.0) hydraulic model of the study reach. One hundred and seventy-five cross sections were included within the model, which equates to an average spacing of ~70m. The model was simplified by removing interpolated cross-sections, but it included significant in-channel structures, such as Norton Fitzwarren dam, and bridges/culverts (Dene Road bridge, Wick Road bridge, West Somerset railway culvert, Mainline railway culvert and agricultural access bridge culvert). The hydraulic model did not include footbridges, small (~1m high) weirs or tributaries. The model did not include out of bank flow routes and storage areas.

Bed material and wash-material load threshold. A representative bed material particle size distribution was defined for each sediment reach (see Section 5.3.4). The wash-material load:bed-material load threshold value for each sediment reach was based on the D_{10}. However, as SIAM only prescribes a set of standard grain sizes, the best fit upper value was selected (after a comparison between best fit upper D_{10} and the closest-matching D_{10}, see Model Run 1 below). Wash-material load threshold values ranged from 0.5mm to 1mm. In addition, each representative bed material particle size distribution was re-categorised using the RHS bed material classes (see Model Run 5 below), and based on these particle size distributions the wash-material load threshold was set as 1mm for all reaches.

Hydrological and hydraulic records. A continuous 15-minute flow record from 1st January 1992 until 31st December 2009 was obtained, and used to generate an average annual flow duration curve, as described in Section 5.3.3. Twenty-five flow profiles encompassed a wide range of flows from 0.3m^3/sec to 16.3m^3/sec. The water surface long profile, under different flows, was visually checked to assess for anomalies (i.e. abrupt changes in water level, afflux at structures etc.). The point velocity range for all discharges at all 175 cross-sections was 0 – 3.3 m/sec, and the average velocity range was 0.5 – 1.4 m/sec. Average Froude numbers ranged from 0.28 to 0.50. The hydraulic model was found to be correctly representing the Halse Water, with velocities and average Froude numbers falling within the limits for reliable sediment modelling using SIAM.

Local sediment sources. Six sediment sources were simulated in the Halse Water model:

1. Upstream wash-material sources (8% of total catchment wash-material yield) entering Reach HW1;

2. Upstream bed-material load entering Reach HW1;

3. Small tributary sediment loads (8% of total catchment wash-material yield) entering Reach HW4;

4. Back Stream tributary catchment wash-material sources (20% of total catchment wash-material yield) entering Reach HW8;

5. Back Stream bed-material load entering Reach HW8; and

6. Wash-material sources from total catchment (64% of total catchment wash-material yield, divided evenly across all eight sediment reaches).

The division of total catchment sediment yield into that sourced from the Halse Water and Back Stream sub-catchments was based on sediment fingerprinting results (see Section 5.3.5). Catchment sediment yield was derived from arable, pasture, river bank and road verge sources.

Present day (baseline) catchment wash-material sediment inputs were based on the particle size distributions, co-produced with ADAS (see Section 5.3.5). Present-day (baseline) bed-material inputs used the particle size distributions obtained from the riverbed sampling (see Section 5.3.4).

The sediment impacts of different relative proportions of each land use type, based on sediment fingerprinting results (see Section 5.3.5), for a mid-range total catchment sediment input (10,000 tonnes/year), were investigated to simulate alternative future land use scenarios.

In addition, three catchment sediment yield futures were simulated, using a realistic mix and relative contributions of the four different land use types defined from Table 5.6, to investigate alternative future land use scenarios. Future catchment wash-material inputs were based on a low (5,000 tonnes/year), medium (10,000 tonnes/year) or high (15,000 tonnes/year) yield from the total catchment and tributary sources. Bed-material inputs were represented as percentages of the corresponding wash-material inputs.

Bed material transport equation. Six sediment (bed material) transport equations are available in SIAM (Ackers-White; Engelund-Hansen; Laursen; Meyer-Peter Müller; Toffaleti; and Yang) and all six were applied to elucidate the differences between them (Table 6.6).

These model runs were applied using a medium catchment wash-material yield (10,000 tonnes/year) derived from the total catchment and tributary sources. Within SIAM the transport of wash-material load is assumed to be supply limited, which means this sediment passes through the watercourse and does not feature in any of the transport calculations that underpin the data listed in Table 6.6.

Reaches	Ackers-White	Laursen-Copeland	Toffaleti	Yang	MPM	Engelund
HW2	1,903	-22,600	503	3,006	-840	6,910
HW3	1,426	30,900	219	2,595	7,180	6,712
HW4	2,688	84,000	699	7,444	20,000	17,600
HW5	2,585	27,100	-140	-2,448	446	-68,300
HW6	177	11,200	268	1,262	10,000	29,300
HW7	250	26,600	301	4,180	-1,198	41,200
HW8	-20	-12,100	-89	-2,860	-2,894	-17,900

Table 6.6 SIAM l*ocal sediment balances (tonnes/year) for Halse Water sediment reaches using different bed material transport equations*

Predicted sediment loads are extremely sensitive to the choice of bed-material transport equation, differing by an order of magnitude or more in some instances. The Ackers-White, Toffaleti and Yang equations were considered to be the more applicable in terms of their theoretical basis and they did in fact generate sediment balances in SIAM that compared favourably to field observations. Of these three plausible equations, Ackers-White was selected as this also emerged as the best performing bed-material transport equation in the ISIS-Sediment model and is the UK industry standard for hydraulic and sediment modelling. Using the same bed-material transport function in the SIAM and ISIS-Sediment models also facilitated comparison of model outcomes.

Model run scenarios

The Halse Water SIAM was run for the following scenarios:

1. *Altered wash-material:bed-material threshold.* To test model sensitivity to variability in the value specified for the wash-material:bed-material load threshold grain size. The threshold value was selected as either: the upper class boundary of the bed material size class containing the measured D_{10}; and the closest class boundary. This investigation used a single, realistic land use mix option (LU1, see Model Run 2) and a medium (10,000 tonnes/year) catchment wash-material sediment yield.

2. *Altered land use mix options for a single catchment sediment yield*. Three different land use mix options, based on the results of the sediment fingerprinting, were assessed for a medium (10,000 tonnes/year) catchment wash-material sediment yield to test sensitivity to different land use mixes in the catchment (e.g. more or less arable land). This scenario used the actual (baseline) flow record.

3. *Altered catchment sediment yield for a single land use mix option.* For a single land use mix option (LU1), three catchment wash-material sediment yields (5,000; 10,000 and 15,000 tonnes/year) were modelled to test the sensitivity of sediment impacts to changes in the magnitude of catchment

sediment yield, which could be brought about by altering land use types (e.g. converting pasture to arable) or land use management (e.g. removal of buffer strips). This scenario used the actual (baseline) flow record.

Model outputs, in terms of the particle size distribution of wash-material and bed-material loads supplied to the most downstream reach (HW8), were used to define sediment inputs to the lower River Tone model (see Section 6.3.2).

4. *Altered hydrology*. A scenario with a single, realistic land use mix option (LU1) and a medium (10,000 tonnes/year) catchment wash-material sediment yield was modelled with actual and altered annual runoff (baseline, +10%, +20%, -10% and -20%) to represent the hydrological impacts of climate change (increased runoff) or enhanced land use management for runoff control (reduced run-off).

5. *Altered river bed material*. For a single, realistic land use mix option (LU1) and three catchment wash-material sediment yields (5,000; 10,000 and 15,000 tonnes/year), altered bed material particle size distributions (based on RHS size classes) were modelled. The aim was to evaluate whether visual assessment and classification of the river bed material size might be sufficient to support application of SIAM.

1. ***Assessing the sensitivity of SIAM to the selected value of the wash-material:bed material threshold***

In advance of modelling to assess impacts of altered land use mix and management, and altered catchment hydrology, the sensitivity of SIAM outputs to the choice of wash-material:bed-material load threshold value was investigated. The threshold value was changed for a run simulating a scenario with a catchment wash-material sediment yield of 10,000 tonnes/year. The tenth percentile (D_{10}) of the bed sediment size class for each sediment reach was established through PSA of bed samples collected during fieldwork.

To test model sensitivity two wash-material:bed-material load threshold values were used. Firstly, the threshold was specified as the upper boundary of the bed sediment size class in HEC-RAS that included the actual D_{10}. Secondly, the threshold was specified as the nearest boundary value to the actual D_{10} (i.e. closest upper of lower value). This resulted in the threshold being reduced in reaches HW4 (1mm to 0.5mm), HW5 (0.5mm to 0.25mm) and HW6 (1mm to 0.5mm). The impacts of altering these wash-material load threshold values in these three reaches are presented in Table 6.7.

Reducing the wash-material load threshold in Reach HW4 results in SIAM treating a lot more of the sediment load as bed-material rather than wash-material load. As the bed-material load is transport capacity (rather than supply) limited, according to SIAM a lot more of the sediment supplied from upstream and local sources is deposited in this reach. The result is to more than double the positive sediment imbalance in Reach HW4.

River Reaches		Wash material:bed-material load threshold	
		Upper D_{10}	Nearest D_{10}
Local sediment balance (tonnes/year)	HW2	1,903	1,903
	HW3	1,426	1,426
	HW4	2,688	6,063
	HW5	2,585	-7,176
	HW6	177	484
	HW7	250	250
	HW8	-20	-20
Wash-material load output to River Tone (tonnes/year)		11,200	17,300

Table 6.7 SIAM local sediment balances for Halse Water sediment reaches and wash-material load output to the River Tone, modelled for upper boundary and nearest boundary values of the wash-material:bed-material threshold (blue highlighted cells identify where local sediment balance has changed)

Retention of more sediment in Reach HW4 reduces the sediment input to Reach HW5, which, according to SIAM, switches from a sediment sink to a major source of sediment, despite the reduction in the wash-material load threshold in this reach. Although scour in Reach HW5 increases the sediment load supplied to Reach HW6, the sediment balance in that reach is less strongly affected, with only minor increases in sediment deposition predicted. This is because much of the additional sediment supplied from scour of Reach HW5 is classed as wash-material load for Reach HW6 and the remaining lower reaches of the Halse Water. This increase in wash-material load results in a 50% increase in the quantity of fine sediment (wash-material load) predicted to enter the River Tone.

These results demonstrate the sensitivity of SIAM outputs to uncertainty in bed material particle size distributions and the importance of the value that the model user selects to represent the wash-material:bed-material threshold grain size. The representative threshold value can not therefore be selected using a generic rule, but is specific to each river under investigation and its associated SIAM.

Based on the results of this model run, it was concluded that the upper boundary of the bed sediment size class would be used for the remainder of the SIAM run scenarios on the Halse Water. This is because the model outputs based on the upper threshold value, when compared to field observations and other sediment assessment information, most closely reproduced baseline conditions in the Halse Water.

2. ***Assessing the impact of different catchment land use mixes on sediment dynamics in the Halse Water***

The results of simulations representing different land use mixes are shown in Table 6.8. The land use mix options are based on results from the sediment fingerprinting and provide a range of land use proportions derived from assessing sediment obtained by sampling in-channel bar deposits (LU1), the suspended sediment sample (LU2), and a floodplain sediment deposit (LU3).

River Reaches		Catchment land use mix options		
		LU1	LU2	LU3
Local sediment balance (tonnes/year)	HW2	1,903	1,903	1,903
	HW3	1,426	1,426	1,426
	HW4	2,688	2,688	2,688
	HW5	2,585	2,585	2,585
	HW6	177	177	177
	HW7	250	250	250
	HW8	-20	-20	-20
Wash-material load output to River Tone (tonnes/year)		11,200	11,200	11,200

Land use	Land use mix options		
	LU1	LU2	LU3
Pasture	21%	12%	29%
Arable	21%	5%	57%
Bankside	46%	61%	3%
Road verge	12%	22%	11%

Table 6.8 SIAM local sediment balances for Halse Water sediment reaches and wash-material load output to River Tone, modelled for three land use mix options with medium (10,000 tonnes/year) catchment wash-material sediment yield

In these simulations, altering the mix of different land uses does not affect the total catchment sediment yield, but does alter the size distribution of sediment supplied to the fluvial system. SIAM indicates that neither local sediment balances (reach-scale erosion, transfer or deposition) or wash-material loads supplied to the River Tone are affected. This is to be expected because the maximum grain sizes derived from catchment sources other than the bed are all smaller than 0.5mm, which is below the wash-material load:bed-material load threshold throughout the Halse Water. In this respect SIAM outputs concur with those of the Stream Power Screening tool (see Section 6.2) in characterising the Halse Water as a source and transfer pathway for fine sediment (that is material smaller than ~1mm).

SIAM and the Stream Power Screening tool both indicate that the Halse Water does not store fines for long or in any appreciable quantity. Consequently, if 10,000 tonnes/year of catchment-derived wash-material enter the river system, SIAM predicts that around 11,200 tonnes/year of wash-material load is supplied to the River Tone, regardless of the mix of sediment sources. The additional 1,200 tonnes/year of fine sediment is derived from erosion of the river bed and lower banks. Field-based evidence supports this in that stream reconnaissance found no extensive areas of fine sediment accumulation.

That is not to say that the channel is free from sediment deposition. There are areas of coarse sediment deposition, which are in long-term flux, such as in-channel gravel bars, and there are discrete locations of fine sediment storage, such as the wedge-shaped deposits of sand upstream of a number of small weirs in the Halse Water. It is important to remember that these structures and the local sand accumulations they prompt are not represented in SIAM, and also to recognise they play no significant role in medium to long-term sediment impacts and balances when these are considered at the catchment-scale.

In summary, SIAM suggests that altering the mix of land use types in the catchment has no significant sediment impacts in the Halse Water because all catchment-derived sediment that enters the fluvial system is transferred to the River Tone. This conclusion is very likely to hold true for the upper River Tone as well. This, however, is unlikely to be the whole story as the mix of land use types will undoubtedly play an important role in determining the total amount of catchment wash-material sediment entering the Halse Water [and upper River Tone] and ultimately entering the lower River Tone as wash-material load. This concept is explored in the next model run scenario.

Furthermore, changes in the relative contributions of different land uses would also have to be taken account of when selecting an appropriate sediment management strategy. For example, in sediment source option LU1, where riverbanks contribute the largest amount to total catchment sediment yield, sediment control measures might best be focused on fencing to prevent stock access and allow a riparian corridor to develop. This would reduce sediment inputs by allowing vegetation to naturally stabilise some eroding riverbanks. Conversely, in sediment source option LU3 where arable land contributes 57% of the total catchment sediment yield, a better strategy would be to take the most erosion-vulnerable land out of arable production, alter crops or ploughing regimes on the remaining arable fields, and plant vegetated buffer strips to intercept sediment carried by surface runoff before it enters the fluvial system.

The selection of a possible sediment management strategy relies on having a good understanding of the relative contribution of each land use to total catchment sediment yield. This, therefore, also clearly demonstrates why robust sediment fingerprinting data, which ideally should be underpinned by a range of different sediment samples across a number of flood events, must be used to establish the relative contribution of different land uses, as discussed in Section 5.3.5.

3. Assessing the impact of altered catchment wash-material sediment yields on sediment dynamics in the Halse Water

The mix of land use types in a catchment will undoubtedly impact upon the total amount of catchment wash-material sediment entering a river system and ultimately leaving it as wash-material load. For example, soil vulnerability to erosion and its availability for transport and delivery into a river system will be greater in an arable-dominated catchment as opposed to pasture-dominated. Thus the total amount of catchment wash-material sediment entering a river, and the subsequent wash-material sediment load generated, would be expected to be greater in an arable-dominated catchment and lower in a pasture- or woodland-dominated landscape. This is supported by the findings of Van Rompaey *et al.* (2002) who concluded that a relatively small increase in arable land results in a relatively large change in sediment delivery to rivers. Furthermore, changes in the management and/or intensity of use of existing land uses can also result in changes in the quantity of sediment derived from a catchment. For example, removal of buffer strips may increase sediment yield while implementing a reduced animal stocking regime may decrease sediment yield.

The model results from altering catchment wash-material yield are shown in Table 6.9. The model runs are based on land use mix option LU1, which best represents the calculated average percentage contribution for the study area (Table 5.6). SIAM predicts that altering the quantity of catchment-derived sediment entering the fluvial system makes no difference to local sediment balances because all of the material is finer than or equal to 0.5mm. Transport of such material by the Halse Water is supply-limited (as opposed to transport-limited). Consequently, any additional sediment derived from catchment sources passes through the Halse Water as wash-material load, to enter the River Tone. This explains why increasing (or decreasing) the catchment sediment yield in the Halse Water, which could be achieved through a change in land use mix or altered land management, simply alters the amount of wash-material load output to the River Tone. This conclusion will very likely hold true for the upper River Tone as well.

River Reaches		Catchment wash-material sediment yield (tonnes/year)		
		5,000	10,000	15,000
Local sediment balance (tonnes/year)	HW2	1,903	1,903	1,903
	HW3	1,426	1,426	1,426
	HW4	2,688	2,688	2,688
	HW5	2,585	2,585	2,585
	HW6	177	177	177
	HW7	250	250	250
	HW8	-20	-20	-20
Wash-material load output to River Tone (tonnes/year)		6,229	11,200	16,200

Table 6.9 SIAM local sediment balance for Halse Water sediment reaches and wash-material load output into the River Tone, modelled for three catchment wash-material sediment yields

This finding reinforces the finding that the Halse Water [and upper River Tone] is a source-transfer system for fine sediment, and explains why the sediment-related impacts of changes in either the sources or amounts of catchment-derived sediment would be expected to occur further downstream in the lower River Tone. The results reinforce the importance of controlling accelerated catchment erosion at source rather than trying to manage the resulting elevated sediment loads within the Halse Water [upper Tone] fluvial system, should sedimentation in the lower River Tone need to be reduced. Clearly, once fine sediment gets into the upper catchment watercourses it is very likely to pass quickly into the lower Tone and it would be very difficult to influence this natural process through channel management, maintenance or other intervention.

4. *Assessing the impact of changing the annual runoff on sediment dynamics in the Halse Water*

The sediment impacts of changes in annual runoff from the Halse Water catchment that might result from changes in climate or land use change/management are listed in Table 6.10. In the table, the baseline (current conditions) is compared to scenarios for increased (+10% and +20%) and decreased (-10% and -20%) annual runoff with no change in catchment sediment yield (10,000 tonnes/year).

River Reaches		Flow				
		Minus 20%	Minus 10%	Actual	Plus 10%	Plus 20%
Local sediment balance (tonnes/year)	HW2	1,360	1,568	1,903	2,186	2,536
	HW3	1,021	1,210	1,426	1,650	1,872
	HW4	1,958	2,325	2,688	3,080	3,477
	HW5	1,934	2,249	2,585	2,940	3,290
	HW6	134	156	177	200	222
	HW7	191	221	250	278	302
	HW8	7	-5	-20	-34	-49
Wash-material load output to River Tone (tonnes/year)		11,000	11,100	11,200	11,300	11,500

Table 6.10 SIAM local sediment balances for Halse Water sediment reaches and wash-material load output to the River Tone, modelled for different flow regimes

Annual sediment loads are directly proportional to runoff and so alterations to the flow regime affect the sediment loads predicted throughout the Halse Water. Increasing runoff has the effect of amplifying accretion, while reducing runoff has the opposite effect. However, changing the flow regime does not alter the pattern of sedimentation predicted using SIAM because the classification of individual reaches as sediment sources, transfers and sinks in

Table 6.10 is unaffected. This conclusion is likely to be true for the upper River Tone as well.

Altering catchment runoff does, however, impact the sediment yield to the River Tone, with an increase in runoff leading to slightly greater amounts of both bed-material load and wash-material load being exported from the Halse Water and *vice versa*. Again, this conclusion can be directly transferred to the upper River Tone.

5. ***Assessing the impact of altered bed-material particle size distribution on sediment dynamics in the Halse Water***

SIAM results presenting the impacts of altering the river bed material particle size distribution from that actually measured to one which is re-configured using RHS particle size classes are shown in Table 6.11. The model runs are based on catchment wash-material sediment yields of 10,000 and 15,000 tonnes/year.

RHS-based particle size-class distributions are based on size classifications that could be obtained from pre-existing records in the RHS database or from visual assessment of the bed material, either of which would be quicker and cheaper than conventional bed-material sampling. What SIAM suggests is that reach-scale sediment imbalances are generally magnified using size classes based on the RHS data. However, the sense of the balance is only altered in one reach (HW5), which flips from being a sediment sink to a source. This occurs because the bed material actually sampled in this reach was relatively fine (see Section 5.3.4) and this is not properly represented when the observed size classes are grouped to produce RHS categories.

River Reaches		Catchment wash-material sediment yield (tonnes/year)			
		10,000		15,000	
		Norm PSD	RHS PSD	Norm PSD	RHS PSD
Local sediment balance (tonnes/year)	HW2	1,903	2,826	1,903	2,826
	HW3	1,426	4,091	1,426	4,091
	HW4	2,688	4,923	2,688	4,923
	HW5	2,585	-474	2,585	-474
	HW6	177	327	177	327
	HW7	250	804	250	804
	HW8	-20	-283	-20	-283
Wash-material load output to River Tone (tonnes/year)		11,200	10,000	16,200	15,000

Table 6.11 SIAM local sediment balances for Halse Water sediment reaches, including bed-material load output (HW8) and wash-material load output into the River Tone, modelled for two catchment wash-material sediment yields and actual and RHS-based bed material particle size distributions

A more significant impact of using RHS categories is that the fine end of the bed material particle size distribution (that is everything finer than gravel) is no longer represented and, consequently, the wash-material load threshold (D_{10}) is substantially increased. Consequently, SIAM classifies everything finer than gravel as wash-material load and the bed ceases to include any fines whatsoever. The result is that scour of the bed does not yield any wash-material load at all. Therefore, using RHS-size categories turns the channel exclusively into a sediment transfer pathway in which whatever material enters from the catchment passes through but nothing is added from erosion of the channel bed. The use of RHS categories also increases the predicted bed-material load leaving the Halse Water, in this case by an order of magnitude. This clearly represents a loss of fidelity in the model.

Despite this, and given the inherent uncertainties in sediment sampling and modelling, it is considered that the error introduced using RHS categories to represent the bed are not unmanageable and might be dealt with by applying a correction factor, for example, by adding 10% to the modelled, wash-material load to allow for fines derived from bed scour, and reducing the amount of bed-material load. It is therefore concluded that use of existing RHS data or visually observed bed material size categories to apply SIAM may be acceptable in gravel, cobble and boulder-bedded streams.

6.3.2 SIAM 2: Lower River Tone

Input data and boundary conditions

A separate SIAM was constructed for the lower River Tone. The model extended from the Halse Water confluence to the tidal limit at Newbridge, a river distance of 14,080m. The modelled reach was divided into the following eight sediment reaches (Figure 6.21):

❖ Reach T1: furthest reach upstream, featuring a semi-natural channel which is active and free to adjust its morphology and in-channel habitats.

Plate 6.11 Reach T1 (furthest upstream reach) on the River Tone showing semi-natural channel with active morphology and range of habitats

❖ Reach T2: semi-natural reach immediately upstream of the first major in-channel structure (French Weir). The water surface profile in this reach is influenced by the backwater effects of French Weir.

Plate 6.12 Reach T2 (upstream of French Weir) on the River Tone showing channel influenced by back-water effects of weir

❖ Reach T3: extending from French Weir to Firepool Weir (the second major in-channel structure), which is located in the centre of Taunton. The channel in this reach has been heavily modified for flood defence and it is enlarged, stabilised, embanked and disconnected from its floodplain. The river bed is erodible.

Plate 6.13 Reach T3 (French Weir to Firepool Weir, in Taunton centre) on the River Tone showing modified channel for flood defence

❖ Reach T4: extending downstream from Firepool Weir to Bathpool Weir. This is another heavily modified channel, which is assumed to have a non-erodible, engineered bed based on field-observations.

Plate 6.14 Reach T4 (Firepool Weir to Bathpool Weir, downstream of Taunton centre) on the River Tone showing engineered channel

❖ Reach T5: this reach extends from Bathpool Weir to a point downstream of the M5 road bridge where the river becomes heavily modified and constrained within embankments. Reach T5 is morphologically-active and is incised into its floodplain in reach T5.

Plate 6.15 Reach T5 (Bathpool Weir to M5 Road Bridge) on the River Tone showing morphologically-active channel

❖ Reach T6: extends downstream to a third major in-channel structure (Ham Weir). The water surface profile in this reach is influenced by back water effects from Ham Weir. The channel has been re-sectioned and modified for flood defence, which is disconnected from the floodplain by embankments. The river bed is erodible.

Plate 6.16 Reach T6 (M5 road bridge to Ham Weir) on the River Tone showing re-sectioned and modified channel

❖ Reach T7: has been re-sectioned and modified for flood defence. It features a very low gradient channel that is perched and disconnected from its floodplain by embankments. It extends downstream from Ham Weir to the tidal limit (Newbridge).

Plate 6.17 Reach T7 (Ham Weir to tidal limit) on the River Tone showing embanked river perched above the floodplain

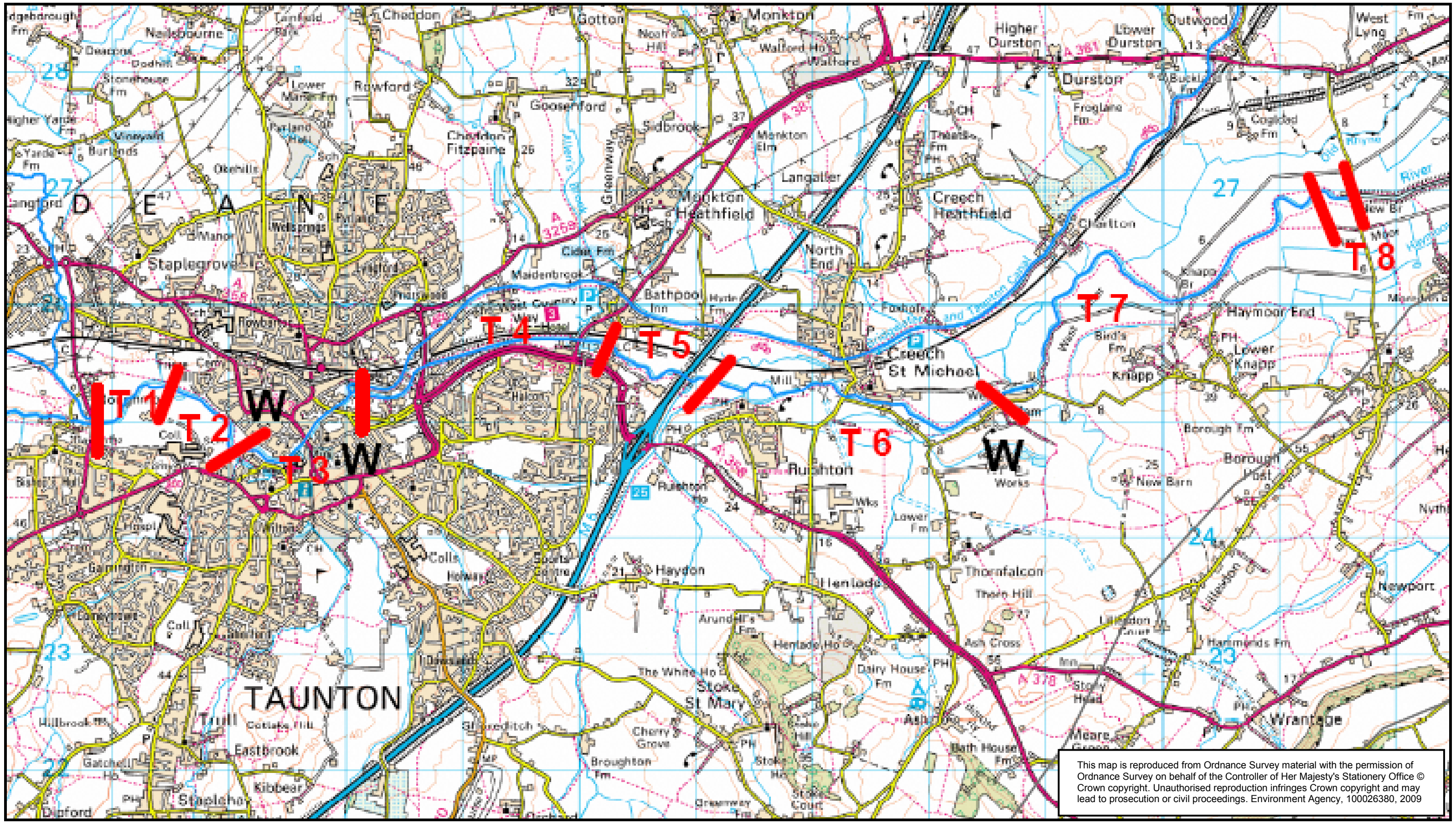


Figure 6.21 SIAM sediment reaches on the lower River Tone, showing major weirs (W)

- Reach T8 is a very short ‘dummy’ reach, which is included to allow quantification of downstream sediment outputs of wash-material and bed-material loads from SIAM into the tidal river. This dummy reach is necessary as SIAM only outputs data on sediment supply to each sediment reach. SIAM does not explicitly give the sediment yield from each reach.

The River Tone SIAM uses the following input data:

Channel geometry. The ISIS model was used as the basis to develop a HEC-RAS (Version 4.0) hydraulic model of the study reach of the lower River Tone. Removal of interpolated cross-sections meant that ninety-seven survey cross sections were included within the HEC-RAS model, with an average spacing of ~150m.

The ISIS model included significant in-channel structures, such as the French, Firepool, Bathpool and Ham weirs, the Town Bridge in Taunton, and old canal and road bridges in Creech St Michael. However, it excluded footbridges, small tributaries, side loops, and the Taunton and Bridgwater Canal. Consequently, none of these were represented in the HEC-RAS model. The tidal sluice gate at Newbridge was also omitted, because SIAM could not account for seasonal effects of this structure, which is open in the winter and closed in the summer. Finally, the HEC-RAS model did not include over-bank flow routes and storage areas.

Bed material and wash-material load threshold. A representative bed material particle size distribution was defined for each sediment reach (see Section

5.3.4). Reach T4 alone was defined as having a bed formed exclusively in large cobbles to mimic the behaviour of the non-erodible, engineered channel in this reach. The wash-material load:bed-material load threshold size value for each sediment reach was based on the D_{10} of the bed material but, as SIAM prescribes a set of standard grain sizes, the best fit value was selected (i.e. the nearest of the immediately lower or higher standard grain values). This value was selected following a model run assessing sensitivity to altered threshold value, similar to that undertaken for Run 1 for the Halse Water SIAM, which is described in Section 6.3.1. The resulting washload threshold values ranged from 1mm (medium sand) to 0.004mm (very fine silt).

Hydrological and hydraulic records. A continuous 15-minute discharge record, constructed from a combination of measured discharge at the Halse Water and Bishops Hull gauging stations (as discussed in Section 5.3.3) between 1st January 1992 and 31st December 2009 was used to generate an average annual flow duration curve (as described in Section 5.3.3). The flow duration curve was divided into twenty-five classes, which encompassed a range of discharges between 1.9m^3/sec and 94.3m^3/sec. The water surface long profiles for selected discharges were examined visually to check for anomalies (i.e. abrupt changes in water elevation, unrealistic flow profiles at in-channel structures etc.). The minimum and maximum point velocities simulated in the model were 0.01 and 1.98m/sec, respectively. The minimum and maximum average velocities were 0.25 and 1.02m/sec, respectively. Average Froude numbers ranged between 0.10 and 0.23. These velocities and Froude numbers are consistent with what would be expected in the lower River Tone, and they fall within the range for which SIAM is applicable.

Local sediment sources. The significant sources of sediment entering the modelled reach of the River Tone are: upstream wash-material load; upstream bed-material load; and channel bank erosion inputs. Outputs from the Halse Water SIAM simulation were used to define particle size distributions for the wash-material and bed-material loads input from upstream (see Section 6.3.1). The particle size distribution of locally-sourced sediment from bank erosion was established by sampling and analysing exposed bank materials (see Section 5.3.5). According to the sediment budgeting exercise, described and discussed in Section 6.1, the annual wash-material load supplied to the modelled reach of the River Tone is between 2,500 and 25,000 tonnes/year. The associated bed-material loads were estimated as percentages of the modelled wash-material loads. The quantity of sediment supplied by bank erosion was estimated, based on direct observations of bank retreat made during field data collection.

Sediment transport equation. Six bed-material transport equations are available in SIAM (Ackers-White; Engelund-Hansen; Laursen; Meyer-Peter Müller; Toffaleti; and Yang). The Ackers-White equation was selected because it produced model outputs that best fitted field-based evidence, maintained continuity with upstream Halse Water SIAM and the corresponding ISIS-Sediment model, and is the UK industry standard for hydraulic and sediment modelling.

Model run scenarios

The lower River Tone SIAM was run for the following scenarios:

1. *No wash-material load*. This provided the baseline against which to assess the predicted effects of varying wash-material loads on sediment balances and reach-scale channel morphologies (see Section 7.1). Under this scenario, the actual discharge record was used and the upstream bed-material load input was 1,000 tonnes/year. Bank material inputs of 600 tonnes/year were included for Reaches T1 and T5, to represent the local supply from eroding banks observed in those reaches.

2. *Altered upstream wash-material loads.* These simulations were performed to test the sensitivity of the lower Tone to changes in land use type and/or management in the upper Tone and Halse Water sub-cathments (see Section 6.1). Annual upstream inputs of wash-material load of 2,500; 5,000; 10,000; 15,000; 20,000 and 25,000 tonnes/year were modelled. In addition, the same range of annual wash-material loads was modelled with a coarser size distribution, to investigate downstream sensitivity to bank instability in the fluvial system upstream. The actual discharge record was used in all runs and the upstream input of bed-material load was held constant at 1,000 tonnes/year. Local inputs from bank bank erosion of 600 tonnes/year were again included in Reaches T1 and T5.

3. *Altered hydrology*. To investigate the sensitivity of the lower Tone to future climate change effects (increased runoff and flow) or land use management effects (reduced runoff and flow), four wash-material load scenarios (5,000; 10,000, 20,000 and 25,000 tonnes/year) were modelled

together with an altered discharge regime (baseline, +10%, +20%, -10% and -20%). Bed-material load and channel bank inputs were unchanged from those used in the previous scenarios. Model runs were also repeated using the coarser wash-material load, which in this case represented the potential impact of increased rainfall intensity (see Section 5.3.6).

4. *Altered upstream bed-material load*. The sensitivity of the lower Tone to changes in the upstream supply of bed-material load was investigated using simulations with input loads of: 0; 500; 1,000; 2,000; and 4,000 tonnes/year. In addition, the same range of bed-material loads was modelled with a coarser particle size distribution to investigate downstream sensitivity to bank instability in the fluvial system upstream. The actual discharge record was used throughout, with a constant wash-material load input of 10,000 tonnes/year and the same local bank inputs to reaches T1 and T5 as those in the previous simulations.

5. *Altered channel substrate in Reach T7*. In the simulations described above, the bed material in this reach is represented as fine to very fine silt based on field sampling. Sediment samples were collected from the channel banks rather than the bed, and these samples were used to characterise the bed-material load:wash-material load (rather than basing this on an estimate of the size of the un-sampled bed material). This decision was based on the observation that the majority of sedimentation takes place on the banks rather than the bed in this reach (see Section 4.3). However, using the fine sediment from the banks probably results in SIAM over-estimating the annualised rate of deposition in the lower reach of the River Tone.

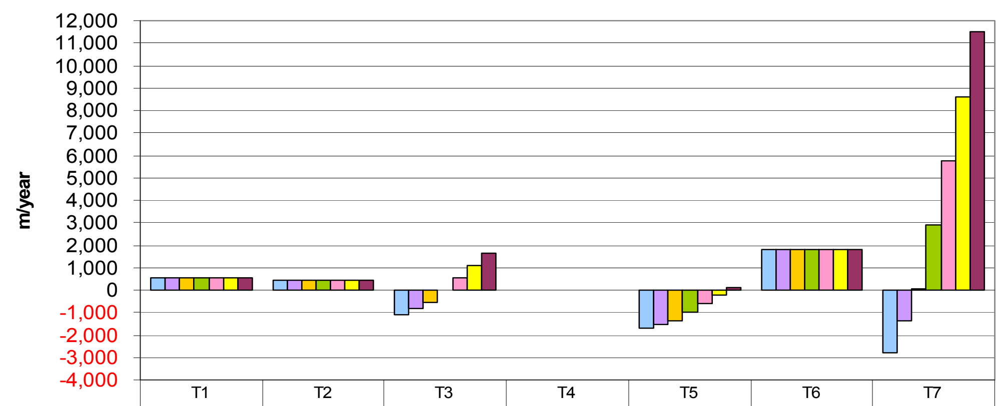
To investigate the sensitivity of the sediment balance in the lower reach to the decision to use bank material to characterise the wash-material:bed-material load threshold, SIAM was used to simulate both actual and coarser bed materials in Reach T7. This was based on substituting the sampled bank material with the sandier bed material sampled in Reach T6, which is likely to be more representative of the bed material in this lowest reach.

Simulations were performed for a range of wash-material loads (0; 5,000; 10,000; 15,000, 20,000; and 25,000 tonnes/year). This matrix of SIAM runs was created to extend the investigation of the sediment balance in the lower Tone to high fluvial discharge conditions when sediment transport is less affected by tidal effects or through the strategic use of the tidal sluice. Under these conditions it is believed that the silt behaves as wash-material load throughout the fluvial Tone. In this context, altering the bed-material load:wash-material load threshold value is the only parameter that can be altered to simulate this behaviour, as the influence of seasonal sluice operation or tidal back-up cannot be simulated explicitly using SIAM.

In considering the outcomes of SIAM simulations, this section deals with implications for sediment dynamics. Discussion of the morphological and flood risk implications of predicted changes in local sediment follows in Sections 7.1 and 7.2.

1. *Assessing the sediment impacts of different wash-material loads in the lower River Tone*

SIAM was used to assess the effect of changing the annual wash-material load (0; 2,500; 5,000; 10,000; 15,000; 20,000; and 25,000 tonnes/year) on the sediment balance in each of the reaches in the lower Tone. The results are listed and graphed in Figure 6.22.



	T1	T2	T3	T4	T5	T6	T7
0 wash load	548	443	-1,103	0	-1,726	1,809	-2,808
2.5k wash load	548	443	-826	0	-1,540	1,809	-1,378
5k wash load	548	443	-548	0	-1,355	1,809	51
10k wash load	548	443	5	0	-984	1,809	2,912
15k wash load	548	443	559	0	-613	1,809	5,771
20k wash load	548	443	1,112	0	-242	1,809	8,630
25k wash load	548	443	1,666	0	129	1,809	11,500

Figure 6.22 SIAM local sediment balances (tonnes/year) for sediment reaches in the lower River Tone under different annual wash-material loads, with the 'normal' calibre, and actual flow conditions

The results indicate that the sediment impacts of changing the annual wash-material load are limited to sediment reaches T3, T5 and T7.

According to SIAM, Reach T3 (in the centre of Taunton) would experience a net loss of sediment of ~1,000 tonnes/year, if no wash-material load were supplied from the catchment and river upstream. A wash-material load supply of 10,000 tonnes/year is required to balance the sediment input and output for this reach while at higher wash-material load supplies, the reach increasingly acts as a sediment sink. Under the maximum wash-material load likely (25,000 tonnes/year), based on analysis of the sediment budget (see Section 6.1), deposition of approximately 1,600 tonnes/year is predicted in Reach T3.

SIAM's prediction of sedimentation in Reach T3 under all but the lowest wash-material load scenarios is generally consistent with field observations that some coarse sand supplied from the Halse Water and upper Tone sub-catchments upstream has been deposited within some locations of this reach since channel works were completed in the 1960s. Sediment accumulation appears to be concentrated upstream of Firepool Weir. Since the 1960s there appears to have been a cycle of sedimentation involving periods of rising bed levels and the creation of islands, that reduced the trapping efficiency in the pool upstream of the weir to such an extent that a condition of dynamic equilibrium was reached, interspersed by periodic dredging and sluicing of sediment that temporarily lowered bed levels to partially restore the trapping efficiency, renewing sedimentation and island building. Table 6.12 presents the size distribution for wash-material load in each sediment reach under the normal calibre input scenario. The table illustrates that the wash-material load retained in Reach T3 is coarse sand.

Reach	Total	1, Clay 2	2, Clay 1	3, VFM	4, FM	5, MM	6, CM	7, VFS	8, FS	9, MS	10, CS	11, VCS	12, VFG
T1	10,300	1,246	1,248	1,594	1,452	1,176	782	890	810	49	1,077	0	0
T2	10,300	1,246	1,248	1,594	1,452	1,176	782	890	810	49	1,077	0	0
T3	10,300	1,246	1,248	1,594	1,452	1,176	782	890	810	49	1,077	0	0
T4	10,300	1,246	1,248	1,594	1,452	1,176	782	890	810	630	435	72	2
T5	10,500	1,263	1,266	1,618	1,464	1,238	819	927	810	630	435	72	2
T6	8,595	1,263	1,266	1,618	1,464	1,238	819	927	0	0	0	0	0
T7	8,595	1,263	1,266	1,618	1,464	1,238	819	927	0	0	0	0	0
T8	2,528	1,263	1,266	0	0	0	0	0	0	0	0	0	0
%	100	50.0	50.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 6.12 SIAM wash-material load by grain size for sediment reaches on the River Tone (10,000 tonnes/year with the normal calibre wash-material load)

Reach T5 is downstream of Taunton centre. It is the first reach where the channel is not completely constrained by historic engineering works. This reach is a net source of sediment under all but the highest wash-material load scenario (25,000 tonnes/year), with a net sediment imbalance decreasing from -1,700 tonnes/year under the zero wash-material load input to just -200 tonnes/year under a 20,000 tonnes/year wash-material load input scenario. Table 6.12 indicates that sedimentation in Reach T5 may be accounted for by material ranging from fine to coarse sand transitioning from wash-material load into bed material load within this reach.

In Reach T7, the lower Tone has the very low gradient and wide, deep, embanked, slow-flowing channel typical of a river crossing the Somerset Levels. The sediment balance predicted for this reach is -2,800 tonnes/year under the zero wash-material load input scenario. The reach is balanced for a wash-material load of 5,000 tonnes/year. It acts as a sediment sink under larger wash-material load inputs, with sediment accumulation rates increasing from ~3,000 tonnes/year for 10,000 tonnes/year input, to ~11,500 tonnes/year for a wash-material load input of 25,000 tonnes/year. This increase in deposition rate is accounted for by the transition of silt and very fine sand from wash-material to bed-material load within this reach (Table 6.12).

It is notable that Reach T6 is predicted to be a sediment sink under all wash-material load scenarios, with ~1,800 tonnes/year of material accumulating there annually. Taken together, Reaches T6 and T7 generally reflect the outcomes of the sediment budgeting, which suggest net storage of wash-material in this stretch of the lower River Tone. Indeed, the results in Table 6.12 indicate that under average annual flow conditions only the clay fraction of the wash-material load passes through the fluvial reaches of the lower River Tone to enter the tidal reaches downstream.

The results of modelling to assess the effects on local sediment balances of coarsening the wash-material loads are shown in Table 6.13. Comparing the model outputs against the normal calibre wash-material load scenarios (Figure 6.22) reveals that coarsening the wash-material load only affects local sediment balances in the three key sediment reaches: T3, T5 and T7.

River Reaches	Actual Flow						
	wash off	2.5k wash	5k wash	10k wash	15k wash	20k wash	25k wash
T1	548	547	547	547	547	547	547
T2	443	443	443	443	443	443	443
T3	-1,103	-722	-344	416	1,174	1,935	2,693
T4	0	0	0	0	0	0	0
T5	-1,726	-1,577	-1,429	-1,130	-833	-535	-237
T6	1,809	1,809	1,809	1,809	1,809	1,809	1,809
T7	-2,808	-1,448	-89	2,631	5,348	8,067	10,800

Table 6.13 SIAM local sediment balances (tonnes/year) for sediment reaches in the lower River Tone with actual flow conditions and different 'coarse' calibre wash-material load inputs

Reach T3 still acts as a sediment source under low wash-material load inputs and continues to be a sediment sink under high wash-material loads. However, enhanced deposition of coarse sand (Table 6.14) results in balance being attained at a wash-material load of ~7,500 tonnes/year (as opposed to 10,000 tonnes/year for the normal calibre wash-material load). For a high wash-material load (25,000 tonnes/year) sediment deposition increases to ~2,700 tonnes/year.

Enhanced deposition in Reach T3 reduces the supply of sediment to Reach T5 (Table 6.14), which becomes a net source of sediment under all wash-material load scenarios. The calibre of sediment supplied by T5 is, however, finer than it was under the previous scenarios.

Reach	Total	1, Clay 2	2, Clay 1	3, VFM	4, FM	5, MM	6, CM	7, VFS	8, FS	9, MS	10, CS	11, VCS	12, VFG
T1	10,300	1,213	1,244	1,622	1,457	1,115	678	740	664	400	1,137	0	0
T2	10,300	1,213	1,244	1,622	1,457	1,115	678	740	664	400	1,137	0	0
T3	10,300	1,213	1,244	1,622	1,457	1,115	678	740	664	400	1,137	0	0
T4	9,871	1,213	1,244	1,622	1,457	1,115	678	740	664	630	435	72	2
T5	10,100	1,230	1,261	1,646	1,470	1,178	715	777	664	630	435	72	2
T6	8,276	1,230	1,261	1,646	1,470	1,178	715	777	0	0	0	0	0
T7	8,276	1,230	1,261	1,646	1,470	1,178	715	777	0	0	0	0	0
T8	2,491	1,230	1,261	0	0	0	0	0	0	0	0	0	0
%	100	49.4	50.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 6.14 SIAM wash-material sediment supply by grain size for sediment reaches on the River Tone (10,000 tonnes/year coarse calibre wash-material load scenario)

The pattern established in Reaches T3 and T5 continues downstream in Reach T7, where a decrease in the input of silt and fine sand (which is partly offset by a slight increase in clay) results in reduced deposition and more of the wash-material load being exported to the tidal Tone downstream.

In summary, the effect of coarsening the wash-material load is to decrease the supply of wash-material load required to balance sediment inputs to outputs in Reach T3, while a slight increase in the supply of wash-material load is required to balance sediment inputs to outputs in Reaches T5 and T7.

The outcomes of exploratory runs involving altered wash-material load inputs and/or calibres demonstrate how connectivity between upstream and downstream sediment reaches leads to inter-actions and knock-on effects in the sediment transfer system. This emphasises the need to adopt a catchment-wide approach when managing sediment, to avoid interventions that solve a sediment problem in the project reach at the expense of triggering further problems in other reaches further downstream.

2. Assessing the impacts of different flows on sediment dynamics in the lower River Tone

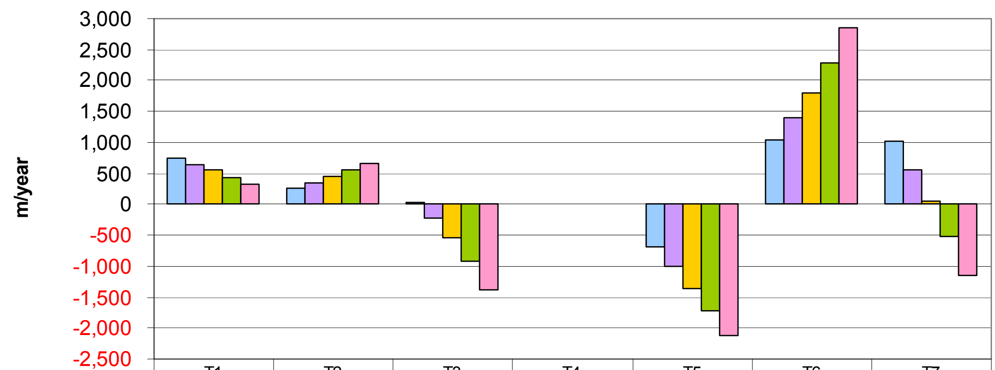
The results from the sediment modelling assessing the effects of altered flow regimes on local sediment balance within each sediment reach are shown in Tables 6.15 and 6.16 and Figures 6.23 to 6.26. SIAM results obtained using baseline 'actual flow' scenarios are compared to those for reduced and increased flows under the four 'normal' calibre wash-material load inputs (5,000; 10,000; 20,000 and 25,000 tonnes/year).

River Reaches	Actual flow				Flow plus 10%				Flow plus 20%			
	5k wash	10k wash	20k wash	25k wash	5k wash	10k wash	20k wash	25k wash	5k wash	10k wash	20k wash	25k wash
T1	548	548	548	548	437	437	437	437	317	317	317	317
T2	443	443	443	443	547	547	547	547	660	660	660	660
T3	-548	5	1,112	1,666	-927	-373	733	1,288	-1,373	-819	287	842
T4	0	0	0	0	0	0	0	0	0	0	0	0
T5	-1,355	-984	-242	129	-1,728	-1,357	-615	-244	-2,117	-1,746	-1,004	-633
T6	1,809	1,809	1,809	1,809	2,294	2,294	2,294	2,294	2,842	2,842	2,842	2,842
T7	51	2,912	8,630	11,500	-524	2,337	8,055	10,900	-1,159	1,703	7,421	10,300

Table 6.15 SIAM local sediment balances (tonnes/year) for sediment reaches in the lower River Tone under increased flows and four, 'normal' calibre, wash-material load scenarios

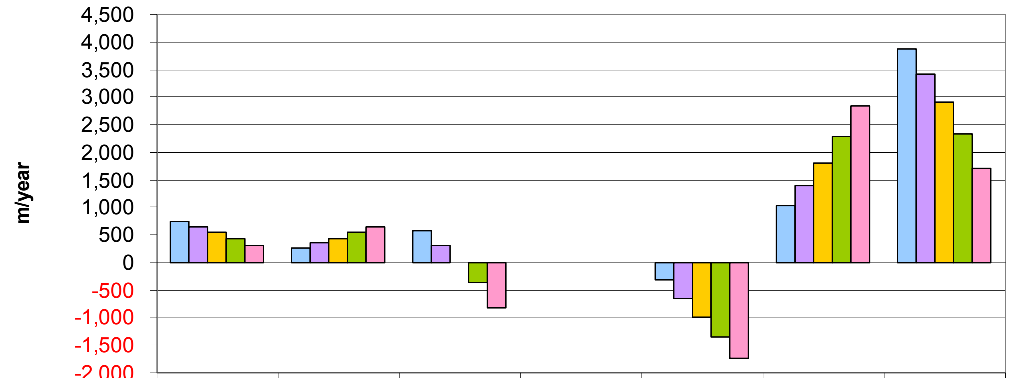
River Reaches	Actual flow				Flow minus 10%				Flow minus 20%			
	5k wash	10k wash	20k wash	25k wash	5k wash	10k wash	20k wash	25k wash	5k wash	10k wash	20k wash	25k wash
T1	548	548	548	548	648	648	648	648	735	735	735	735
T2	443	443	443	443	349	349	349	349	265	265	265	265
T3	-548	5	1,112	1,666	-230	323	1,430	1,984	26	579	1,686	2,240
T4	0	0	0	0	0	0	0	0	0	0	0	0
T5	-1,355	-984	-242	129	-1,011	-640	102	473	-684	-313	429	800
T6	1,809	1,809	1,809	1,809	1,393	1,393	1,393	1,393	1,032	1,032	1,032	1,032
T7	51	2,912	8,630	11,500	557	3,419	9,137	12,000	1,023	3,884	9,602	12,500

Table 6.16 SIAM local sediment balances (tonnes/year) for sediment reaches in the lower River Tone under decreased flows and four, 'normal' calibre, wash-material load scenarios



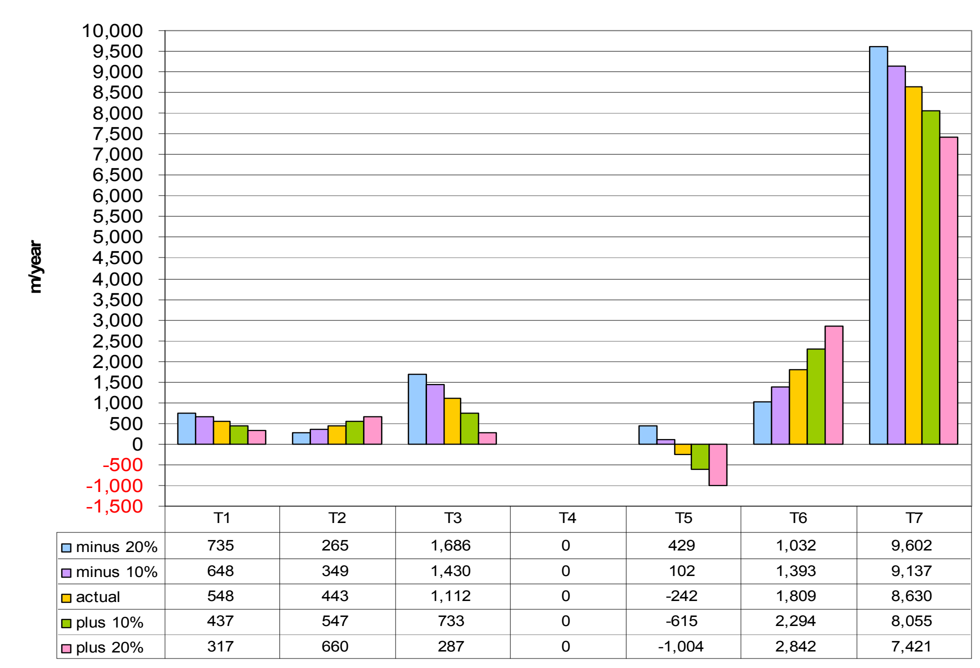
	T1	T2	T3	T4	T5	T6	T7
minus 20%	735	265	26	0	-684	1,032	1,023
minus 10%	648	349	-230	0	-1,011	1,393	557
actual	548	443	-548	0	-1,355	1,809	51
plus 10%	437	547	-927	0	-1,728	2,294	-524
plus 20%	317	660	-1,373	0	-2,117	2,842	-1,159

Figure 6.23 SIAM local sediment balances (tonnes/year) for sediment reaches in the lower River Tone under different flow scenarios with 5,000 tonnes/year of 'normal' calibre wash-material load



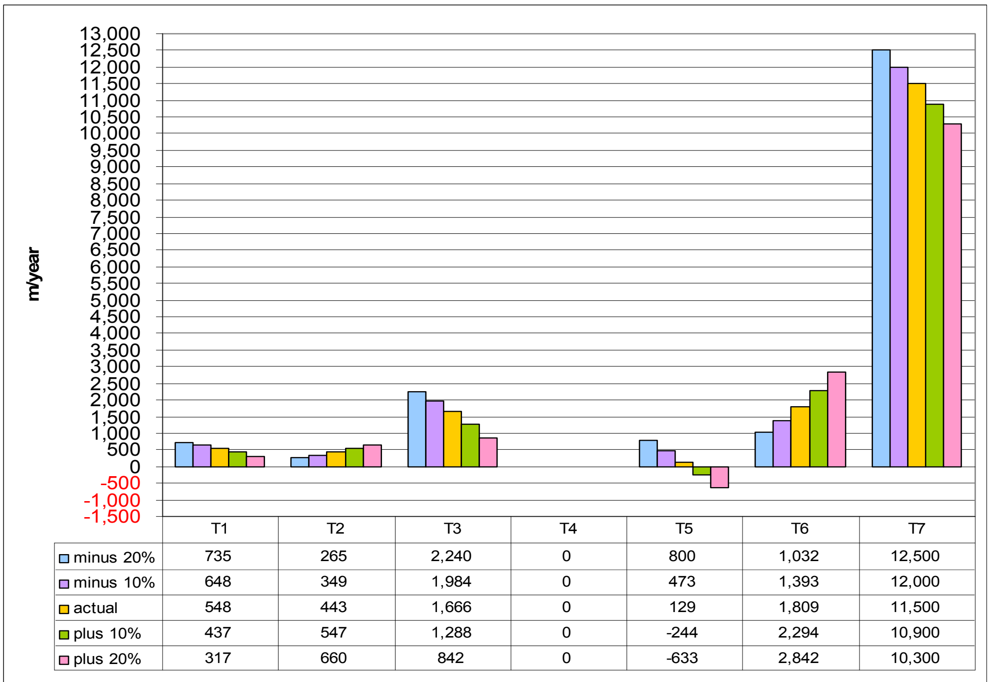
	T1	T2	T3	T4	T5	T6	T7
minus 20%	735	265	579	0	-313	1,032	3,884
minus 10%	648	349	323	0	-640	1,393	3,419
actual	548	443	5	0	-984	1,809	2,912
plus 10%	437	547	-373	0	-1,357	2,294	2,337
plus 20%	317	660	-819	0	-1,746	2,842	1,703

Figure 6.24 SIAM local sediment balances (tonnes/year) for sediment reaches in the lower River Tone under different flow scenarios with 10,000 tonnes/year of 'normal' calibre wash-material load



	T1	T2	T3	T4	T5	T6	T7
minus 20%	735	265	1,686	0	429	1,032	9,602
minus 10%	648	349	1,430	0	102	1,393	9,137
actual	548	443	1,112	0	-242	1,809	8,630
plus 10%	437	547	733	0	-615	2,294	8,055
plus 20%	317	660	287	0	-1,004	2,842	7,421

Figure 6.25 SIAM local sediment balances (tonnes/year) for sediment reaches in the lower River Tone under different flow scenarios with 20,000 tonnes/year of 'normal' calibre wash-material load



	T1	T2	T3	T4	T5	T6	T7
minus 20%	735	265	2,240	0	800	1,032	12,500
minus 10%	648	349	1,984	0	473	1,393	12,000
actual	548	443	1,666	0	129	1,809	11,500
plus 10%	437	547	1,288	0	-244	2,294	10,900
plus 20%	317	660	842	0	-633	2,842	10,300

Figure 6.26 SIAM local sediment balances (tonnes/year) for sediment reaches in the lower River Tone under different flow scenarios with 25,000 tonnes/year of 'normal' calibre wash-material load

Altering the flow affects sediment balance throughout the river, with the exception of Reach T4, which is unresponsive due to being heavily engineered. For a given wash-material load input, altering the flow can change either the direction (i.e. eroding or depositing) or the magnitude (accelerated erosion or deposition) of sediment imbalance in a reach. Responses are reach-specific depending on both the quantity of wash-material load entering the system and the magnitude/direction of change in the flow.

For example, with 10,000 tonnes/year of wash-material load entering the lower River Tone, a 10% increase in flow does not uniformly increase erosion and decrease deposition throughout the sediment reaches. Deposition is reduced in Reach T1, but the transfer of additional sediment to Reach T2 increases deposition in that reach. Increased flow enhances erosion in Reach T3 and T5, with the additional sediment derived from Reach 3 passing through Reaches 4 and 5 to be deposited in Reach T6. Deposition in Reach T7 is reduced resulting in more sediment being exported to the tidal Tone downstream. These findings further highlight how local sediment imbalances interact to influence the direction and magnitude of impacts further downstream in the sediment transfer system.

While altering the flow affected sediment balances in all reaches, interest is focused on the three critical reaches that are directly influenced by changes in wash-material load as these are most likely to be most strongly influenced by catchment land management. Hence, further discussion concentrates on these key reaches.

- Reach T3: depending on the supply of wash-material load, increasing the flow results in either reduced deposition or increased erosion. Conversely, reducing the flow results in either increased deposition or reduced erosion. It follows that altering the flow can change Reach T3 from a sediment supply to a sediment sink, or *vice versa*, depending on the supply of wash-material load entering the lower River Tone.

- ❖ Reach T5: increasing the flow results in accelerated erosion for all the modelled wash-material loads, whereas reducing the flow results in decreased erosion with the reach becoming a sediment sink under the two largest wash-material loads.

- ❖ Reach T7: increasing the flow with a low (5,000 tonnes/year) wash-material load supply results in reduced deposition or increased erosion, while reducing the flow enhances deposition for all wash-material loads.

Tables 6.17 and 6.18 compare local sediment balances generated by altering the flow for ‘coarser’ calibre wash-material loads. The results, when compared to the ‘normal’ calibre wash-material outputs (Tables 6.15 and 6.16), show that coarsening the wash-material load only affects sediment balances in the three key sediment reaches: T3, T5 and T7.

River Reaches	Actual flow				Flow plus 10%				Flow plus 20%			
	5k wash	10k wash	20k wash	25k wash	5k wash	10k wash	20k wash	25k wash	5k wash	10k wash	20k wash	25k wash
T1	547	547	547	547	437	437	437	437	316	316	316	316
T2	443	443	443	443	547	547	547	547	660	660	660	660
T3	-344	416	1,935	2,693	-723	38	1,556	2,315	-1,169	-408	1,110	1,869
T4	0	0	0	0	0	0	0	0	0	0	0	0
T5	-1,429	-1,130	-535	-237	-1,802	-1,504	-908	-611	-2,191	-1,892	-1,297	-1,000
T6	1,809	1,809	1,809	1,809	2,294	2,294	2,294	2,294	2,842	2,842	2,842	2,842
T7	-89	2,631	8,067	10,800	-664	2,056	7,492	10,200	-1,298	1,421	6,857	9,576

Table 6.17 SIAM local sediment balances (tonnes/year) for sediment reaches in the lower River Tone under increased flows and four ‘coarse’ calibre wash-material load scenarios

River Reaches	Actual flow				Flow minus 10%				Flow minus 20%			
	5k wash	10k wash	20k wash	25k wash	5k wash	10k wash	20k wash	25k wash	5k wash	10k wash	20k wash	25k wash
T1	547	547	547	547	647	647	647	647	734	734	734	734
T2	443	443	443	443	349	349	349	349	265	265	265	265
T3	-344	416	1,935	2,693	-26	734	2,253	3,011	230	990	2,509	3,267
T4	0	0	0	0	0	0	0	0	0	0	0	0
T5	-1,429	-1,130	-535	-237	-1,085	-786	-191	107	-757	-459	136	434
T6	1,809	1,809	1,809	1,809	1,393	1,393	1,393	1,393	1,032	1,032	1,032	1,032
T7	-89	2,631	8,067	10,800	418	3,137	8,573	11,300	883	3,603	9,039	11,800

Table 6.18 SIAM local sediment balances (tonnes/year) for sediment reaches in the lower River Tone under decreased flows and four 'coarse' calibre wash-material load scenarios

The patterns of change in sediment balances are the same as those with 'normal' calibre wash-material loads. Differences are restricted to the magnitude of erosion or deposition, and in Reach T3 the increase in flow needed to change the reach from a sediment source to a sediment sink with moderately high (i.e. 10,000 tonnes/year) wash-material load input.

3. Assessing the impacts of changing the bed-material loads on sediment dynamics in the lower River Tone

Table 6.19 compares sediment balances resulting from changes to the input of bed-material load to the lower River Tone from the upper River Tone and Halse Water sub-catchments upstream. Changes to the bed material supply could result from climate change or changes to land and/or catchment management.

The impacts of changing the supply of bed-material load is restricted to the first sediment reach, T1. This reach represents the river upstream of the heavily engineered reaches within Taunton, which maintains a semi-natural channel featuring actively eroding banks and mobile sediment bars.

River Reaches	Actual Flow				
	0 bed	0.5k bed	1k bed	2k bed	4k bed
T1	-455	46	548	1,551	3,556
T2	443	443	443	443	443
T3	5	5	5	5	5
T4	0	0	0	0	0
T5	-984	-984	-984	-984	-984
T6	1,809	1,809	1,809	1,809	1,809
T7	2,912	2,912	2,912	2,912	2,912

Table 6.19 SIAM local sediment balance (tonnes/year) for River Tone sediment reaches under various 'normal' calibre bed-material load scenarios

If the supply of bed-material load is cut off, Reach T1 becomes a sediment source (~500 tonnes/year), but an input of bed-material load of just 500 tonnes/year is sufficient to bring the reach close to being in balance. Further increases in bed-material load (1,000 – 4,000 tonnes/year), which could result from increased bed scour, bank erosion and bed material transport capacity in the upper River Tone and/or Halse Water, turn the reach into a sink for coarse sediment with deposition rates increasing progressively from 500 to 3,500 tonnes/year.

The model reflects the fact that relatively coarse bed material is deposited as soon as it meets the backwater effect from French Weir, which extends upstream into Reach T1. Field observations support this contention, although coarse deposition would likely prograde into Reach T2, as no significant differences were detected between the bed material characteristics in these two reaches. In that sense, coarsening of the bed-material load would be unlikely to alter the location or extent of bed material deposition.

4. Assessing the impact of altering the bed material in Reach T7 of the lower River Tone

Tables 6.20 and 6.21 compare the sediment impacts of altering the bed material size in Reach T7. The aim of doing this is to investigate situations where the characteristic bed size changes, for example, summer low flows when the reach may be back-watered by tidal influence and/or operation of the tidal sluice, and under high winter flows that over-ride the tidal influence.

With a finer bed material Reach T7 becomes a sediment source under the zero wash-material load scenario, but adding even the lightest of wash-material load inputs to the lower River Tone (5,000 tonnes/year) is sufficient to achieve sediment balance, because any silt and very fine sand that arrives as wash-material load still transitions into bed-material load (Table 6.22), for which this reach has no transport capacity. Consequently, making the bed finer results in only the clay fraction passing through to the tidal river downstream.

Conversely, coarsening the bed to represent exposure of the sandier material, results in Reach T7 becoming a weakly aggrading sediment sink that (like Reach T6 immediately upstream) is unaffected by changes in quantity of the wash-material load supplied to the lower Tone. The cause of this behaviour is apparent from Table 6.23, where it can be seen that with coarser bed material clay, silt and very fine sand pass through Reach T7 and on into the downstream tidal river, rather than the silt and very fine sand transitioning into bed-material load that is deposited within the reach.

River Reaches	Actual Flow and finer bed material in Reach T7					
	wash off	5k wash	10k wash	15k wash	20k wash	25k wash
T1	548	548	548	548	548	548
T2	443	443	443	443	443	443
T3	-1,103	-548	5	559	1,112	1,666
T4	0	0	0	0	0	0
T5	-1,726	-1,355	-984	-613	-242	129
T6	1,809	1,809	1,809	1,809	1,809	1,809
T7	-2,808	51	2,912	5,771	8,630	11,500

Table 6.20 SIAM local sediment balances (tonnes/year) for sediment reaches in the lower River Tone, with finer bed material in Reach T7, under various wash-material loads, normal wash-material calibres and actual flow conditions

River Reaches	Actual flow and coarser bed material in Reach T7					
	wash off	5k wash	10k wash	15k wash	20k wash	25k wash
T1	548	548	548	548	548	548
T2	443	443	443	443	443	443
T3	-1,103	-548	5	559	1,112	1,666
T4	0	0	0	0	0	0
T5	-1,726	-1,355	-984	-613	-242	129
T6	1,809	1,809	1,809	1,809	1,809	1,809
T7	612	612	612	612	612	612

Table 6.21 SIAM local sediment balances (tonnes/year) for sediment reaches in the lower River Tone, with coarser bed material in Reach T7, under various wash-material loads, normal wash-material calibres and actual flow conditions

Reach	Total	1, Clay 2	2, Clay 1	3, VFM	4, FM	5, MM	6, CM	7, VFS	8, FS	9, MS	10, CS	11, VCS	12, VFG
T1	10,300	1,246	1,248	1,594	1,452	1,176	782	890	810	49	1,077	0	0
T2	10,300	1,246	1,248	1,594	1,452	1,176	782	890	810	49	1,077	0	0
T3	10,300	1,246	1,248	1,594	1,452	1,176	782	890	810	49	1,077	0	0
T4	10,300	1,246	1,248	1,594	1,452	1,176	782	890	810	630	435	72	2
T5	10,500	1,263	1,266	1,618	1,464	1,238	819	927	810	630	435	72	2
T6	8,595	1,263	1,266	1,618	1,464	1,238	819	927	0	0	0	0	0
T7	8,595	1,263	1,266	1,618	1,464	1,238	819	927	0	0	0	0	0
T8	2,528	1,263	1,266	0	0	0	0	0	0	0	0	0	0
%	100	50.0	50.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 6.22 SIAM wash-material supply by grain size for sediment reaches in the lower River Tone. Note: wash-material load calibre = normal, wash-material load quantity = 10,000 tonnes/year, and Reach T7 has finer bed material

Reach	Total	1, Clay 2	2, Clay 1	3, VFM	4, FM	5, MM	6, CM	7, VFS	8, FS	9, MS	10, CS	11, VCS	12, VFG
T1	10,300	1,246	1,248	1,594	1,452	1,176	782	890	810	49	1,077	0	0
T2	10,300	1,246	1,248	1,594	1,452	1,176	782	890	810	49	1,077	0	0
T3	10,300	1,246	1,248	1,594	1,452	1,176	782	890	810	49	1,077	0	0
T4	10,300	1,246	1,248	1,594	1,452	1,176	782	890	810	630	435	72	2
T5	10,500	1,263	1,266	1,618	1,464	1,238	819	927	810	630	435	72	2
T6	8,595	1,263	1,266	1,618	1,464	1,238	819	927	0	0	0	0	0
T7	8,595	1,263	1,266	1,618	1,464	1,238	819	927	0	0	0	0	0
T8	8,595	1,263	1,266	1,618	1,464	1,238	819	927	0	0	0	0	0
%	100	14.7	14.7	18.8	17.0	14.4	9.5	10.8	0.0	0.0	0.0	0.0	0.0

Table 6.23 SIAM wash-material supply by grain size for sediment reaches in the lower River Tone. Note: wash-material load calibre = normal, wash-material load quantity = 10,000 tonnes/year, and Reach T7 has coarser bed material

In reality conditions probably alternate somewhere between the two extremes represented above, probably being closer to the coarser bedded situation more often than the finer one. This is especially likely during winter, when the supply of wash-material load from the sub-catchments upstream is high and flows are easily capable of carrying clay, silt and fine sand through into the tidal reaches (i.e. the situation represented in Tables 6.21 and 6.23). However, there will be occasions, particularly during high intensity, short duration summer storm events, when elevated loads of wash-material is delivered to the river in sufficient concentrations to overwhelm the transport capacity of flows that are either tide locked or held back by sluices and gated structures that have been closed to maintain water levels in the wetlands for wildlife conservation management. Under these circumstances, the system operates as indicated in Tables 6.20 and 6.22, with the fine sand and silt fractions of the wash-material load accumulating on the river banks in Reach T7.

5. Assessing sediment outputs from the fluvial system into the tidal reach of the River Tone

Table 6.24 and Figure 6.27 present modelled sediment outputs from the fluvial Tone into the tidal reach, split into the constituent bed-material and wash-material loads, for a range of 'normal' calibre wash-material load inputs, a constant (1,000 tonnes/year) bed-material load input, and actual flow conditions. The results indicate that changing the supply of wash-material load alters the amount of wash-material load leaving the fluvial system (the range being 69 to 6,215 tonnes/year), but it has no effect on output of bed-material load, which remains constant at 4,370 tonnes/year. Hence, the overall sediment output range between 4,439 and 10,585 tonnes/year.

Altering the flow has no effect on the output of wash-material load, but may increase or decrease the output of bed-material load (Table 6.28). Coarsening the wash-material and bed-material supplies (Table 6.25) has no effect on bed-material load output, but slightly reduces the wash-material load output (range 69 to 6,124 tonnes/year) because more of the sand fraction transitions into capacity-limited bed-material load in the upstream reaches.

Wash-material load input (t/yr)	Bed-material load input (t/y)	Wash-material load output (t/yr)	Bed-material load output (t/yr)	Total sediment load output (t/yr)
0	1000	69	4370	4439
2500	1000	683	4370	5053
5000	1000	1298	4370	5668
10000	1000	2528	4370	6898
15000	1000	3757	4370	8127
20000	1000	4986	4370	9356
25000	1000	6215	4370	10585

Table 6.24 SIAM wash-material, bed-material and total sediment load outputs from the fluvial system into the tidal River Tone under various 'normal' calibre wash-material load inputs, and with actual flow

Wash-material load input (t/yr)	Bed-material load input (t/y)	Wash-material load output (t/yr)	Bed-material load output (t/yr)	Total sediment load output (t/yr)
0	1000	69	4370	4439
2500	1000	675	4370	5045
5000	1000	1280	4370	5650
10000	1000	2491	4370	6861
15000	1000	3702	4370	8072
20000	1000	4913	4370	9283
25000	1000	6124	4370	10494

Table 6.25 SIAM wash-material, bed-material and total sediment load outputs from the fluvial system into the tidal River Tone under various 'coarse' calibre wash-material load inputs, and with actual flow

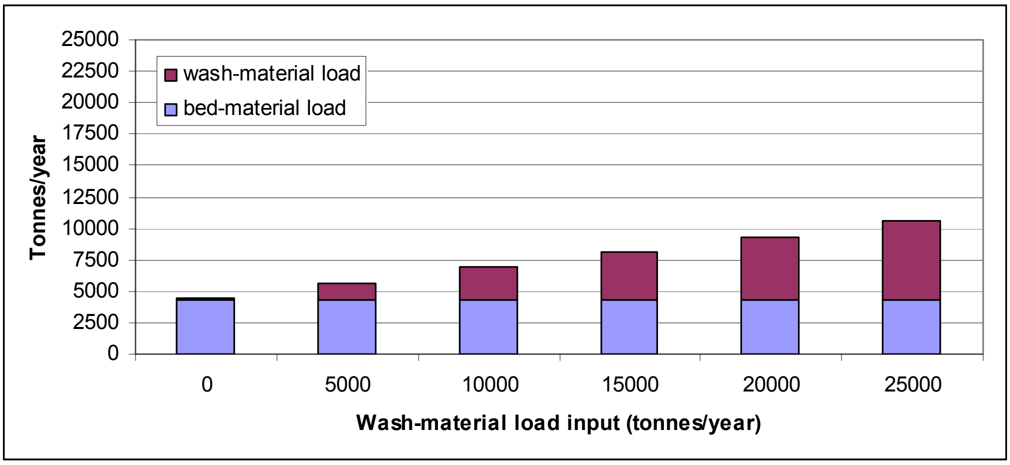


Figure 6.27 SIAM wash-material and bed-material load outputs from the fluvial system into the tidal River Tone under various 'normal' calibre wash-material load inputs and with actual flow

A change in total sediment output is apparent when the bed material in Reach T7 is coarsened to better reflect the characteristics of the bed as opposed to the banks (Table 6.26 and Figure 6.28), as described in the previous section (model run 4). Under these conditions, bed-material load output is greatly reduced and maintains a constant value of 604 tonnes/year, because none of the wash-material load transitions into bed-material load in this reach. The quantity of wash-material load is greatly increased because the silt and fine sand fractions pass through as wash-material load. Consequently, the output of wash-material load increases to its maximum of 20,900 tonnes/year, while the total output of sediment ranges from 673 to 21,504 tonnes/year.

Wash-material load input (t/yr)	Bed-material load input (t/y)	Wash-material load output (t/yr)	Bed-material load output (t/yr)	Total sediment load output (t/yr)
0	1000	69	604	673
5000	1000	4503	604	5107
10000	1000	8595	604	9199
15000	1000	12700	604	13304
20000	1000	16800	604	17404
25000	1000	20900	604	21504

Table 6.26 SIAM wash-material, bed-material and total sediment load outputs to the tidal River Tone for actual flows and various 'normal' calibre wash-material load inputs, but with coarser bed material in Reach T7

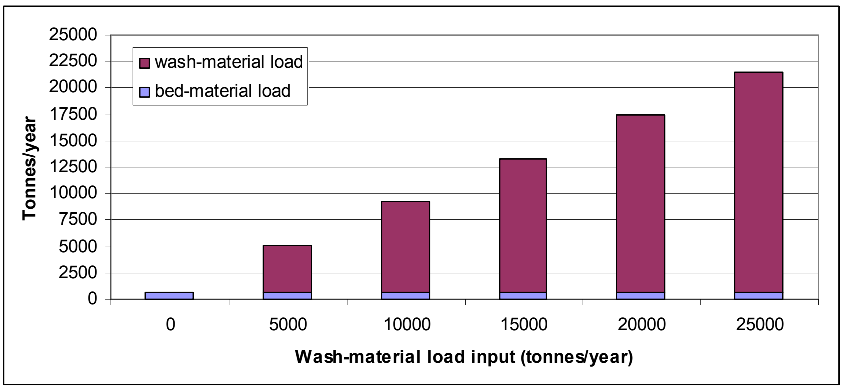


Figure 6.28 SIAM wash-material and bed-material load outputs to the tidal River Tone with actual flows and various 'normal' calibre wash-material load inputs, but with coarser bed material in Reach T7

The wash-material load outputs, expressed as percentages of the wash-material load inputs for model runs with finer and coarser bed materials are listed in Table 6.27. The results show that only ~25% of wash-material leaves the fluvial system when the bed material in Reach T7 has a finer particle size distribution (which is representative of the river banks). This rises to 84 to 90% when a coarser particle size distribution is used, which is more representative of the actual river bed.

Wash-material load input (t/yr)	Finer substrate in Reach T7		Coarser substrate in Reach T7	
	Wash-material load output (t/yr)	Wash-material load output (%)	Wash-material load output (t/yr)	Wash-material load output (%)
5000	1298	26	4503	90
10000	2528	25	8595	86
15000	3757	25	12700	85
20000	4986	25	16800	84
25000	6215	25	20900	84

Table 6.27 SIAM wash-material load outputs to the tidal River Tone, expressed as rates and percentages of the wash-material load input for model runs with both finer and coarser substrate in Reach T7

Flow	Bed-material output (tonnes/year)
Plus 20%	6,147
Plus 10%	5,218
Actual	4,370
Minus 10%	3,612
Minus 20%	2,920

Table 6.28 SIAM bed-material load outputs to the tidal River Tone under various flow regimes

According to SIAM, varying wash-material load inputs between 10,000 and 25,000 tonnes/year produces a range of total sediment outputs to the tidal River Tone of 6,861 to 21,504 tonnes/year, based on model runs with both finer and coarser bed material in Reach T7. This range of sediment outputs is very similar to that based on sediment budgeting, which predicts a total suspended sediment output range between 7,740 and 28,980 tonnes/year. This is encouraging as it demonstrates that the SIAM outputs are closely aligned to the outputs from the alternative sediment budgeting methods, which increase confidence in SIAM and its results/conclusions.

Furthermore, predicted total suspended sediment outputs based on the two sediment budgeting methods with a higher level of confidence on their outputs, the Ratio Method and project-specific sediment flux monitoring, are ~8,000 and ~13,000 tonnes/year, respectively. When these predicted outputs are compared to the SIAM results it is found to be the equivalent of a wash-material load input of 15,000-25,000 tonnes/year (with finer bed material in Reach T7) or 10,000-15,000 tonnes/year (with a coarser bed material in Reach T7), which is likely to represent the more common scenario. These results, taken in combination and compared against field-based morphological evidence, would, therefore, indicate that the annual average quantity of wash-material sediment load entering the lower River Tone from upstream sub-catchments is between 10,000 and 15,000 tonnes/year. This is equivalent of a specific sediment yield of ~35 to 52 tonnes/km^2/year, which closely aligns with typical national and local specific sediment yield estimates calculated by Walling *et al.* (2007), who calculated a national average of 44 tonnes/km^2/year, and Copper *et al.* (2008), who calculated a local range of 20-70 tonnes/km^2/year. These findings provide greater confidence in the efficacy of SIAM to estimate annual sediment yields.

Revised, best-fit sediment budget schematics of the lower River Tone have been developed, which represent an annual average wash-material load entering the lower Tone ranging between 10,000 and 15,000 tonnes/year with a bed-material load of 1,000 tonnes/year. Two schematics have been presented representing (1) a winter flood event [with coarser bed material in Reach T7] (Figure 6.29), and (2) a summer, tide-locked flood event [with finer bed material in Reach T7] (Figure 6.30).

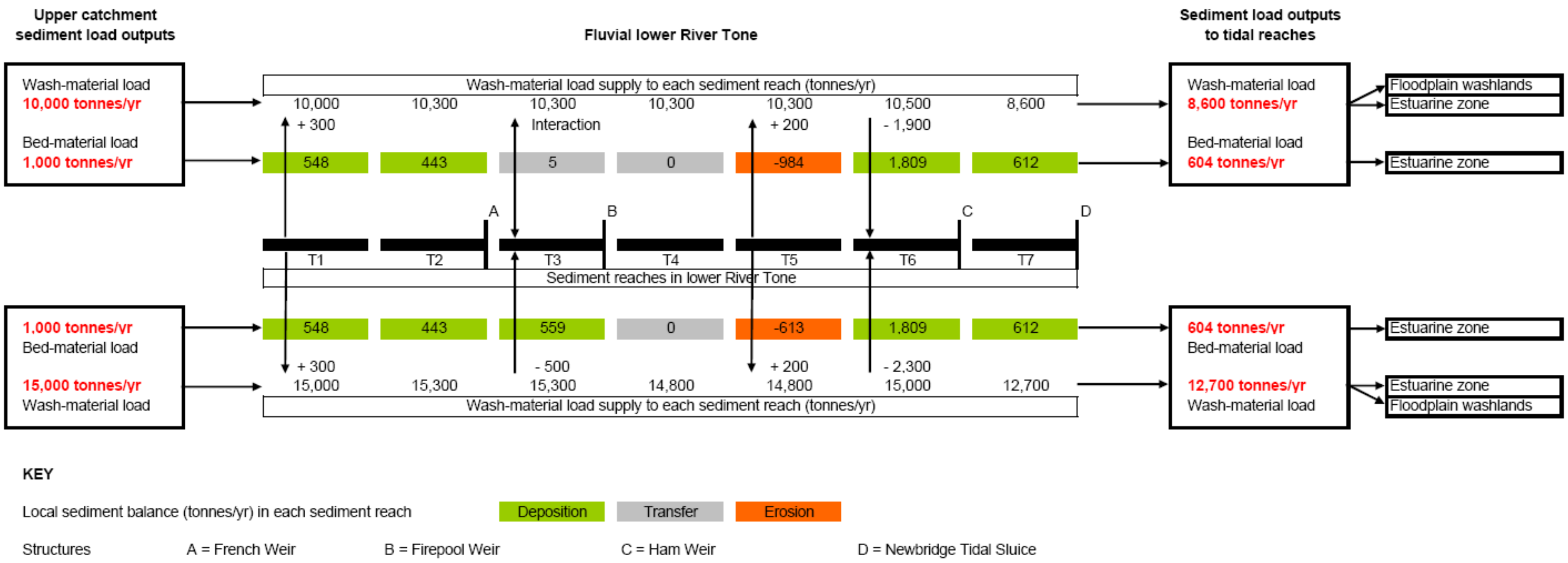


Figure 6.29 Schematic showing sediment load inputs to, sediment load outputs from, local sediment balances, and interaction between bed-material and wash-material loads within the lower River Tone under winter flood conditions (coarser bed material in Reach T7)

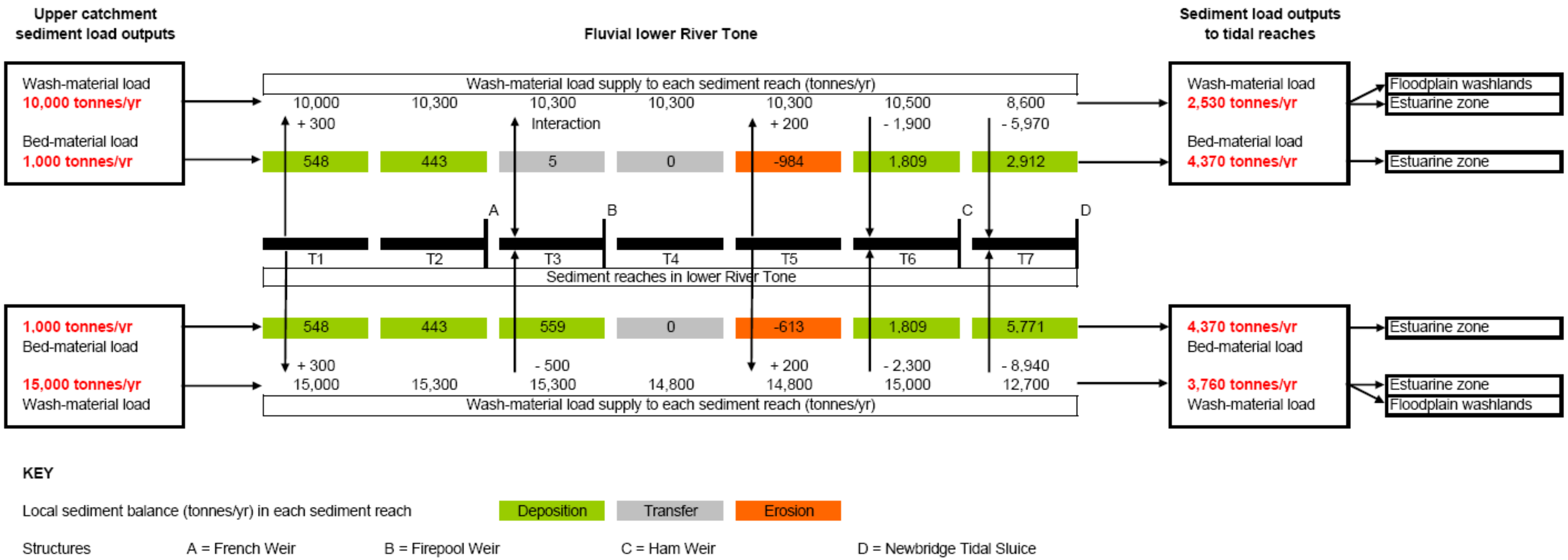


Figure 6.30 Schematic showing sediment load inputs to, sediment load outputs from, local sediment balances, and interaction between bed-material and wash-material loads within the lower River Tone under summer, tide-locked flood conditions (finer bed material in Reach T7)

6.4 ISIS-Sediment

Input data and boundary conditions

The ISIS-Sediment model was constructed by simplifying an existing ISIS (Version 3.5) hydraulic model (see Section 5.3.2), and splitting it into two discrete models: one for the Halse Water and one for the lower River Tone. Model features included:

- The Tone model extended from the Bishops Hull gauging station downstream to the Newbridge tidal sluice, with all tributaries, except the Halse Water, removed. The river was divided into five sediment reaches, which are generally analogous to the SIAM reaches;

- The Halse Water model extended from Northway downstream to the confluence with the River Tone, with all tributaries removed. The river was divided into two sediment reaches: Northway to Back Stream tributary, and Back Stream to the confluence with the River Tone;

- All out-of-bank flow routes and storage areas that were not directly connected to the main channel were removed;

- The number of in-channel structures was reduced and made consistent with SIAM. Consequently, only key weirs, dams, culverts and bridges were included;

- Channel cross-sections were simplified where this did not impact the results; and

❖ Interpolated channel cross-sections were removed, so that the models only contained actual, surveyed cross-sections.

Sediment data inputs to the model include: (1) bed material size distribution for each channel ISIS reach (these are analogous to SIAM sediment reaches); and (2) sediment inflow to the model at its upstream boundary limits. Bed material sizes were based on particle sampling and size analyses, as described in Section 5.3.4. The observed particle size distributions were simplified into ten grain diameters (Table 6.29), with the final bed material gradation for each reach being represented as the weighted average of the nearest field samples.

River Reach	Grain diameter (mm)									
	0.001	0.063	0.125	0.25	0.5	1	2	8	16	32
HW1	0.003	0.014	0.087	0.076	0.085	0.125	0.451	0.135	0.024	0.000
HW2	0.003	0.009	0.053	0.063	0.056	0.065	0.202	0.138	0.220	0.191
HW3	0.002	0.008	0.036	0.041	0.054	0.081	0.201	0.129	0.274	0.174
HW4	0.004	0.020	0.071	0.062	0.111	0.157	0.348	0.090	0.058	0.079
HW5	0.002	0.010	0.044	0.045	0.050	0.077	0.238	0.186	0.299	0.049
HW6	0.005	0.026	0.126	0.092	0.067	0.102	0.468	0.099	0.015	0.000
HW7	0.002	0.006	0.027	0.034	0.033	0.040	0.130	0.118	0.321	0.289
HW8	0.003	0.007	0.028	0.060	0.085	0.081	0.211	0.193	0.277	0.055
T1	0.000	0.003	0.005	0.020	0.053	0.105	0.108	0.223	0.160	0.323
T2	0.011	0.146	0.224	0.279	0.210	0.107	0.023	0.000	0.000	0.000
T3	0.002	0.031	0.023	0.099	0.313	0.324	0.137	0.063	0.008	0.000
T6	0.006	0.056	0.044	0.227	0.348	0.237	0.041	0.013	0.028	0.000
T7	0.046	0.357	0.269	0.182	0.080	0.047	0.010	0.009	0.000	0.000

Table 6.29 Bed material gradations used in the ISIS models of the Halse Water and River Tone

The bed material size distribution for Reach T2 in Table 6.29 (which is based on grab sampling) appears anomalous as it is much finer than that in adjacent reaches. The implications for this are discussed below in the results section.

To maintain consistency with SIAM, 15-minute discharge records extending from 1st January 1992 until 31st May 2009 were collated for the Halse Water and Bishops Hull gauging stations. These data were used to generate 3-hour flow series.

The only gauging station on the Halse Water is the one near its confluence with the River Tone. The Halse Water drainage basin above the gauging station was divided into six sub-catchments, some of which add significant flows (e.g. Back Stream). Inflows from the sub-catchments were estimated by distributing flows measured at the gauging station between them according to the ratios of their areas to the overall area of the Halse Water catchment. A timing adjustment based on the calculated time of travel to the Halse Water gauge was also applied to each inflow. Sediment concentrations at each inflow point were set equal to those measured at the Halse Water gauge. The resulting flows and sediment contributions were verified by using the model to check that their cumulative outputs matched the discharges and loads observed at the Halse Water gauge.

Sediment concentrations entered into the ISIS-Sediment model were estimated using sediment rating curves fitted to measured load data from the EA gauging stations on the Halse Water and the River Tone at Bishops Hull (Table 6.30).

River Tone	
Flow (m^3/s)	Sediment conc. (ppm)
10	104.4
20	227.0
30	357.7
40	493.9
50	634.3
60	778.2
70	925.0
80	1074.4
90	1226.1
100	1379.9

Halse Water	
Flow (m^3/s)	Sediment conc. (ppm)
2	28.8
4	51.1
6	71.4
8	90.6
10	109.0
12	126.7
14	143.9
16	160.7
18	177.1
20	193.2

Table 6.30 ISIS sediment concentrations for the River Tone at Bishops Hull gauging station and Halse Water gauging station

As previously discussed, scatter is evident in these data (see Section 6.1) and consequently there is considerable uncertainty in sediment inflows estimated using the rating curve fitted to them, which limits the accuracy of the sediment model, because a small error in estimated sediment concentration can have a major impact on the model's output.

ISIS-Sediment includes the Ackers-White equation to calculate the flow's capacity to transport non-cohesive sediments and the Westrich-Jurashek equation for cohesive sediments (which are considered to be any sediment finer than 0.063mm in diameter).

The 'Hard bed' option in ISIS-Sediment was used to simulate reaches where the channel bed was believed to have been rendered non-erodible due to hard engineering, such as in the River Tone between Firepool Weir and the A38 road bridge at Bathpool.

ISIS-Sediment offers several options for updating bed elevations and cross-profiles, and the Tone model used the most realistic option in which elevations along the part of the bed that is inundated are adjusted according to the cross-stream distribution of bed shear stress. However, the steep gradient of the Halse Water precluded this option and bed elevation changes were uniformly distributed across the wetted width instead.

Model run scenarios

The models were run for a range of wash-material load and flow scenarios, comparable to those investigated using SIAM (see Section 6.3). These were:

- *Baseline scenario*: this used flows and wash-material loads actually observed to generate present day model outputs against which comparisons can be made.

- *Altered hydrology*: this run used an altered flow record (baseline, +10%, +20%, -10% and -20%) to assess potential changes in sediment dynamics due to future changes in climate or land use management.

- *Altered wash-material load yields from the Halse Water catchment*: this used reduced wash-material loads in the Halse Water model (-25% and -50%) to assess potential changes in sediment dynamics and the net output of sediment associated with changes in land use management in the Halse Water catchment

- *Altered wash-material load yields from the upper Tone catchment*: the wash-material load input to the lower River Tone model from the upper basin was reduced (-10%, -25%, -50% and -100%) to assess potential changes in sediment dynamics associated with changes in land use management in the upper Tone catchment.

Initially, these scenarios were simulated using all seventeen years of available flow data. In the River Tone model, the entire flow record was used successfully, but the Halse Water model was unstable during the first few years of record, exhibiting rapid fluctuations in bed elevation that were unrealistic. It was therefore decided to remove the first four years of record in the Halse Water simulations, limiting run durations to just thirteen years.

Though shortening the duration of model runs is not ideal, it did increase confidence in the model outputs. Also, unrealistic results obtained for the Halse Water were a reminder that its relatively steep gradient (slope > 0.004) was a challenge to ISIS-Sediment and reinforced the importance of checking model outputs manually to verify their plausibility.

Results

The results of the ISIS-sediment modelling for the Halse Water are listed in Table 6.31. The results for the baseline scenario are generally as expected, with erosion predicted in the upper reaches of the modelled stream and deposition in the lower reach.

The Halse Water model was calibrated to give a sediment output of approximately 1,200 tonnes/year under the baseline scenario, based on the sediment rating curve developed for the Halse Water gauging station (Table 6.30). Multiple calibration runs were required before the target sediment output was achieved, and it became clear that changes in channel roughness well within theoretically acceptable ranges resulted in significant change in modelled sediment transport rates and annual loads.

This highlights how sensitive a detailed sediment model can be to very small changes in model input parameters, especially on steep or moderately steep watercourses. Without a large amount of accurate calibration data, which will very rarely if ever be available, confidence bounds on the results from the ISIS-Sediment model will be large.

River Reaches	Baseline	Wash-material load		Flow			
		<25%	<50%	-10%	-20%	+10%	+20%
U/S input	70	14	8	62	57	77	85
Northway to Back Stream	-2,337	-2,515	-2,529	-1,627	-1,236	-3,390	-4,692
Back Stream to Confluence	1,628	1,574	1,559	798	-64	2,007	1,958
D/S output	1,203	1,137	1,071	991	797	1,437	1,687

Table 6.31 Annual balances (tonnes/year) for sediment reaches in the Halse Water obtained by running ISIS-Sediment under different wash-material load and flow scenarios

Results obtained using ISIS-Sediment suggest that sediment dynamics in the Halse Water are insensitive to reductions in the input of wash-material load sized sediment from catchment erosion. According to Table 6.31, changes are minor in both the pattern of erosion and sedimentation, with the upper and middle reaches (Reaches HW2 to HW7 in SIAM) remaining a sediment source and the lowest reach (Reach HW8 in SIAM) remaining a sediment sink. Net delivery of sediment to the lower River Tone only decreases marginally.

Sediment dynamics in the Halse Water are more responsive to changes in catchment runoff. A 10% reduction in runoff acts to decrease erosion in the upper and middle reaches, sedimentation in the lower reaches, and the output of sediment to the lower River Tone. A more extreme, 20% reduction in runoff produces a further decrease in erosion upstream while eliminating deposition in the lower reach of the Halse Water and markedly decreasing the output of sediment to the lower River Tone. Conversely, a 10% increase in runoff amplifies both upstream erosion and downstream deposition while also elevating output to the lower Tone. A 20% increase in runoff further increases erosion in the upper and middle reaches but hardly affects downstream deposition, with additional sediment flushed through to further increase output to the lower River Tone.

ISIS-Sediment suggests that, in the Halse Water, catchment runoff is a stronger driver of sediment dynamics and output to the lower River Tone than is the yield of wash-material load sized sediment. For example, a 20% reduction on runoff generates a 34% reduction in sediment output and a 20% increase results in a 40% increase in sediment output. In comparison, decreases of 25% and 50% in catchment wash-material load inputs produce reductions of sediment output of only 5% and 10%, respectively.

The results of the ISIS-Sediment modelling for the lower River Tone are listed in Table 6.32. Under the baseline scenario, some reaches perform as would be expected based on field observations, while others, such as Bishops Hull to French Weir, and Ham Weir to Knapp Bridge, do not.

River Reaches	Baseline	Wash-material load				Flow			
		<10%	<25%	<50%	<100%	-10%	-20%	+10%	+20%
U/S input	9,593	9,417	9,149	8,703	7,811	7,725	6,072	11,688	14,004
Bishops Hull to French Weir	-2,995	-3,246	-3,506	-3,726	-3,912	-3,256	-2,879	-3,283	-3,686
French Weir to Firepool weir	41	226	129	83	12	421	584	77	-49
Firepool Weir to Ham Weir	2,225	2,425	2,395	2,434	2,580	2,107	2,105	2,873	4,271
Ham Weir to Knapp Bridge	-994	-940	-925	-843	-413	-559	-399	-1,380	-1,814
Knapp Bridge to Newbridge	100	133	229	434	1,067	192	183	-155	-399

Table 6.32 Annual balances (tonnes/year) for sediment reaches in the lower River Tone obtained by running ISIS-Sediment under different wash-material load and flow scenarios

ISIS-sediment consistently predicts that the River Tone upstream of French Weir (Reaches T1 and T2 in SIAM) is a net source of sediment. Although some bank erosion was observed in this reach, the bed elevation was found to be stable (see Section 6.3.2) and therefore this model outcome is unrealistic.

The baseline ISIS-Sediment model used the very fine bed material sampled by a sediment grab in Reach T2, which was subsequently found to be incorrect. When the bed material in this ISIS-Sediment reach was altered to reflect the bed material sampled in Reach T1, the reach upstream of French Weir switches to a major net sediment sink, with deposition predicted to drive rapid aggradation at levels which were unrealistic.

This suggests that the ISIS-Sediment model is unable to accurately represent the sediment impacts of complex flow and sediment transport patterns in the River Tone upstream and associated with French Weir.

Failure of ISIS-Sediment to accurately model the most upstream reach, with both finer and coarser bed material, has consequences for its predictions of sediment balances in the reaches further downstream. Specifically, characterising the Bishops Hull to French Weir reach as an erroneous major sediment source, leads to the reach immediately downstream from French Weir to Firepool Weir in Taunton centre (Reach T3 in SIAM) predicted to be a mild sediment sink. However, when the upper reach is predicted to be a major sediment sink, which has an unrealistic rate of aggradation, the French Weir to Firepool Weir also changes and becomes a net source of sediment [not shown numerically]. The sensitivity of ISIS-Sediment outputs to small changes in bed material characteristics, coupled with the model's inability to predict a realistic sediment balance in the upper reach, greatly reduces confidence that ISIS-Sediment can reliably predict sediment dynamics in the fluvial system further downstream.

The sediment impacts of reducing the supply of wash-material load and of altering runoff are, perhaps, more revealing. Results listed in Table 6.32 indicate that reducing the input of wash-material load from the upper River Tone and Halse Water or increasing the volume of runoff generally promotes erosion and decreases deposition, while reducing runoff generally reduces both erosion and deposition, although there are some anomalous results. This is discussed further in the following paragraphs.

The French Weir to Firepool Weir reach (Reach T3 in SIAM) maintains a balanced condition, which is consistent with field observations and empirical data (see Section 6.1). The relatively small amount of predicted deposition is consistent with observed sediment aggradation within the over-widened channel upstream of Firepool Weir. Deposition at this location would have been significant following the construction of the flood defences in the 1960s, however, the channel is now observed to be fairly stable.

Reducing the supply of wash-material load generally results in increased deposition, but this is functionally linked to increased erosion in the reach immediately upstream, which is inconsistent with field observations and records, and should, therefore, be discounted. It is possible to have more confidence in the sediment impacts predicted to result from changes in runoff. Increased deposition under reduced runoff, and reduced deposition with increased runoff both align with the observed behaviour of the lower Tone.
The ISIS-Sediment reach between Firepool Weir and Ham Weir (Reaches T4, T5 and T6 in SIAM) is consistently predicted to be a sediment sink, which aligns with empirical evidence showing finer material passing through the upstream part of this reach and depositing upstream of Ham Weir. Sediment responses to reductions in runoff and wash-material load are muted, though the reach is more responsive to increased runoff, with a 20% increase, resulting in a 92% increase in sediment deposition.

The reach between Ham Weir and Knapp Bridge (the upper stretch of Reach T7 in SIAM) is predicted to remain a sediment source under all wash-material load scenarios. However, this reach is predicted to be more responsive to changes in runoff, in that net erosion varies more widely with runoff-induced changes than it does with changes in wash-material load.

The reach between Knapp Bridge and Newbridge Tidal Sluice (the lower stretch of Reach T7 in SIAM) is predicted to remain a sediment sink under all wash-material load scenarios, with sediment deposition increasing as more material is eroded from the upper reaches. The reach is responsive to changes in runoff with the reach becoming a greater sediment sink with reduced runoff and becoming a sediment source with enhanced runoff.

The ISIS-Sediment model may be capable of simulating sediment dynamics and subsequent bed level changes in the lower reaches of the River Tone under high, winter flows, but it is difficult to see how it can represent the system under summer, low flows and, particularly, when the flows are controlled by tidal influences or the operation of the tidal sluice. At such times, sediment dynamics are predicted to be dominated by deposition of fine sediment on the upper channel banks (see Section 4.3). This is not reflected in the model outputs in Table 6.32, where erosion generally dominates the lower reaches.

Key findings

The river network, in particular the River Tone, is complex in both in terms of the number of in-channel structures and the downstream connectivity of sediment reaches, as well as the transport of sediment through the network and the interaction between wash-material load and bed-material load, which it appears ISIS-Sediment is unable to accurately represent. There are several possible reasons for this including uncertainties and sensitivity of input parameters, particularly bed-material and channel roughness, and equations determining sediment transport. The model also appears not to be able to accurately model the complex flow and sediment patterns at major structures, such as French Weir, and also cannot represent the way sedimentation occurs in the lower reaches of the Tone where sediment builds up on the banks rather than the channel bed during periods when fluvial flow is tidally influenced or controlled by sluice operation.

The ISIS-Sediment model has the ability to provide sediment outputs in the form of changes in channel profile over time. However, following the review of ISIS-Sediment model outputs it was found that the baseline and predicted changes in annual sediment balance, in terms of aggradation and degradation, especially in the most upstream and lowest reaches of the River Tone, did not match field observations and the predictions from SIAM.

Given the high level of uncertainty associated with the annual sediment balances and erroneous predictions from ISIS-Sediment, which obviously have a knock-on effect for predicted morphological change, it was concluded that the channel profile outputs from ISIS-Sediment would not be used to (1) compare predicted morphological changes against SIAM outputs, or (2) provide the basis for the assessment of flood risk described in Section 7.2.

6.5 Discussion

The sediment transfer system in a river is made up of links connecting sediment supply, transport and storage reaches that operate at a range of scales in space and time (Sear *et al.*, 2003). In headwater reaches, such as those in the Halse Water, the sediment system is dominated by supply and transport. Wash-material load is supply limited and alterations to the supply have little or no impact on local sediment balances because all the available wash-material load entering the river is transferred downstream and exported to the mainstream river (in this case into the lower River Tone). However, in a sediment impact model, the quantity of sediment exported as wash-material load is sensitive to categorisation of the bed-material load:wash-material load threshold and changes to the size distribution of sediment supplied to the river by catchment erosion. Consequently, changes to either of these factors will directly impact the quantity and calibre of sediment predicted to be exported from headwater reaches and streams.

Headwater sediment yield is also intrinsically linked to the volume of runoff from the catchment (Collins and Owens, 2006). However, while changes to the amount of runoff alter the magnitude of reach-scale erosion and deposition, and the output of sediment downstream, they do not change the pattern of sedimentation within and between sediment reaches in headwater systems.

In contrast to headwater streams, the sediment system in the lower courses of rivers, such as the lower River Tone, is dominated by the sediment transfer and storage. Alterations in the quantity of wash-material load entering the lower course due to changes in the headwater basins can affect local sediment balances where what was wash-material load in the upper reaches transitions to bed-material load in the lower course as the water gradient slackens either naturally or artificially due to in-channel structures.

Often, the size fraction that has the most influence on local sediment balances is medium to coarse sand, and in this respect the lower Tone is typical. Sediment modelling suggest that while medium to coarse sand is deposited in the fluvial lower Tone, the fine sand, silt and clay fractions usually pass through to the tidal river downstream. However, modelling also predicts that when tide-locking or the closure of sluices create back water conditions, the fine sand and silt fractions may be deposited to affect local sediment balances in the lower reaches of the fluvial River Tone.

The results of sediment modelling, verified by field observations, suggest that transitions of fine sediments from wash-material to bed-material load are spatially and temporally variable. Wash-material load deposition is strongly linked to the occurrence of back water effects, which can be either in-channel (for example, in sub-reaches immediately upstream of weirs, especially if these are over-wide, and in sub-reaches pooled by tide locking), or out-of-channel (for example, during over-bank floods or in sub-reaches where flow that is pooled upstream of closed structures spills onto the floodplain or into adjacent wash- and wetlands).

Clearly, the relationship between wash-material and bed-material loads, and, ultimately, the local sediment balance, is affected by the quantities and calibres of wash-material and bed-material loads, and the volume and temporal distribution of runoff moving through the drainage network. However, the sediment impacts of changes in either runoff or sediment load are specific to each sediment reach and depend on the response in the reach immediately upstream as well as the original, causal change in runoff and/or sediment yield. Interactions between sediment outputs and local sediment balances control the connectivities of different size fractions between the upper and lower course of the river, dictating that runoff and sediment dynamics must be managed in an integrated manner and at the catchment (i.e. drainage network) scale.

The original definition of wash-material load adopted in the research presented in this thesis was defined in Section 1.3.1 based upon definitions given by Biedenharn *et al.* (2006b and c) and Church (2006). This definition can now be expanded, based on consideration of the field observations and model outcomes reported and discussed herein:

Wash-material load: Sediment which is not found in appreciable quantities in the river bed and/or lower banks, and which is finer than bed-material load. Once entrained wash-material load generally moves in suspension and travels for relatively long distances during individual transport events. Wash-material load sized sediments usually make up by far the greater part of the sediment load and their deposition dominates upper bank, riparian and floodplain sedimentation. In addition, and particularly in the lower course of a river, wash-material load may dominate deposition in slack water and back water areas associated with over-wide channels, flows impounded by tide-locking or hydraulic structures, and spilling of flow into marginal washlands and wetlands.

Sediment modelling has proven useful in providing information on the sediment impacts of alterations to the inputs of sediment and runoff, with responses being expressed in terms of changes in the local sediment balance (tonnes/year) within sediment reaches. However, taken in isolation model outputs cannot provide an adequate basis from which to select appropriate river management solutions to sediment-related problems in terms of channel instability, flood risk, infrastructure or ecosystem services. Model-based predictions of impacts of changes in climate and catchment land use on sediment dynamics must, therefore, be considered within a user-developed, multi-disciplinary understanding of the fluvial system that links channel process, form (morphology) and stability to targets for key river functions including flood risk management, navigation, heritage, recreation and biodiversity etc. This will be considered and discussed in Chapter 7.

6.6 Comparison of sediment assessment tools

6.6.1 Comparison of predicted sedimentation patterns

Sediment balances predicted for individual or grouped sediment reaches of the Halse Water, based on the outputs of field observations, Stream Power Screening (SPS), SIAM and ISIS-Sediment under the baseline scenario, are shown in Figure 6.31.

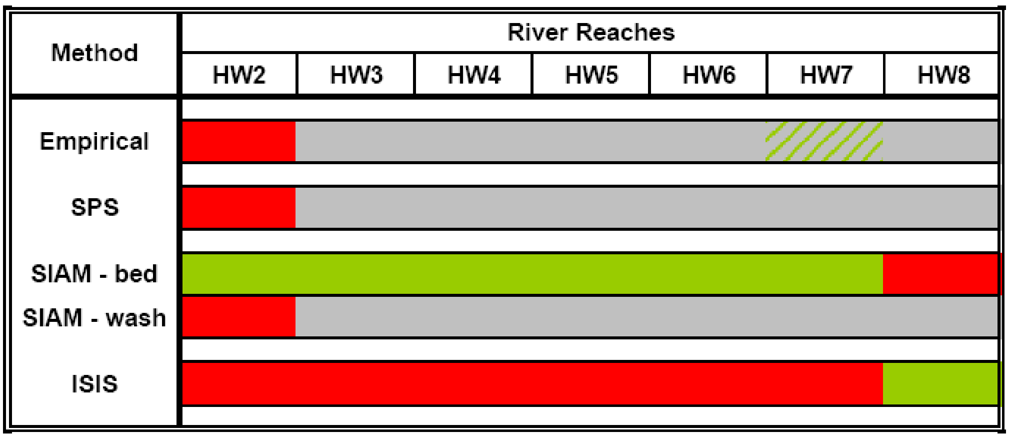


Figure 6.31 Comparison of sediment balances predicted by empirical/field-based evidence, SPS, SIAM and ISIS-Sediment for the Halse Water under the baseline scenario (red = source; grey = transfer; green = sink). For SIAM wash-material load, red = sediment added to wash-material load from bed-material load, green = sediment added to bed-material load from wash-material load, and grey = no exchange between wash-material and bed-material loads. Hatching represents two sediment balances in each reach

In Figure 6.31 outputs from SIAM show both imbalances in the bed-material load (i.e. the local sediment balance, which classifies the reach as a sediment source (red), transfer (grey) or sink (green)) and exchanges of sediment between the wash-material and bed-material loads (i.e. sediment added to wash-material load from the bed-material load (red) or sediment added to the bed-material load from the wash-material load (green)).

SPS predicts erosion in Reach HW2, with the remainder of the Halse Water transferring eroded sediment to the lower River Tone. The pattern for wash-material load predicted by SIAM is identical, with fine material acquired from the upstream headwater sub-catchment and in Reach HW2 being transported through the Halse Water and into the lower River Tone without any major transitioning to the bed-material load to accumulate in the channel on the way. Both SPS and wash-material load predicted by SIAM match field observations, which established areas of channel erosion in the upper reaches of the Halse Water with the majority of the middle and lower reaches dominated by sediment transfer with no major areas of fine sediment aggradation identified (although there is now potential for some fine sediment accumulation in Reach HW7 due to the construction of a wide two-stage channel as part of flood defence works). This suggests that the SPS is able to correctly predict the dynamics of fine sediment supplied to and moving through the Halse Water, particularly in relation to the interaction between the wash-material and bed-material loads.

SIAM predicts net accumulation of bed-material load in Reaches HW2 to HW7, with HW8 being the only reach to experience net scour. ISIS-Sediment predicts the exact opposite, with Reaches HW2 to HW7 shown as sediment sources and only Reach HW8 predicted to act as a net sediment sink. The difference between predictions of bed material patterns using SIAM and ISIS-

Sediment is difficult to state with any certainty. Possible reasons include the fact that sediment reaches are divided up differently in each model, with ISIS-Sediment modelling Reaches HW2 to HW7 as a single sediment reach. This could act to dampen any intra-reach variation in sediment patterns by presenting just the dominant process, which in this case could be erosion from the upper part of the channel network. Alternatively, it could be the fact that SIAM treats bed-material load separately from wash-material load, whereas ISIS-Sediment predicts a total sediment load. This could result in ISIS-Sediment identifying erosion throughout, which is linked to fine sediment erosion rather than erosion of bed material sized sediment.

In reality, the Halse Water is predominantly a sediment transfer / exchange system for bed-material sized sediment, as described in Section 4.3 and predicted by SPS. At the reach-scale the river supports areas of erosion (particularly basal river bank scour) and coarse sediment deposition (in-channel bars), which are in long-term flux. Therefore, reality lies somewhere between the predicted outputs from SIAM (bed-material load patterns) and ISIS-Sediment.

Sediment balances predicted for sediment reaches in the lower River Tone, based on the empirical and field-based evidence, and applications of Stream Power Screening, SIAM and ISIS-Sediment for the baseline scenario are shown in Figure 6.32. SIAM outputs are again divided to show local (bed-material load) balances and exchanges of sediment between the wash-material and bed-material loads. Outputs from sediment budgeting have not been examined in this section, as sediment budget outputs have potentially large errors associated with them (as discussed in Section 6.1) and did not well represent the upper reaches (T1 to T3) of the River Tone.

In general, the models predict a general pattern of sediment transfer in the upper reaches (above and through Taunton, Reaches T1 to T4), and net deposition in the lower reaches (Reaches T6 and T7). However, in detail the various patterns of sediment sources, transfers and sinks plotted in Figure 6.32 differ markedly.

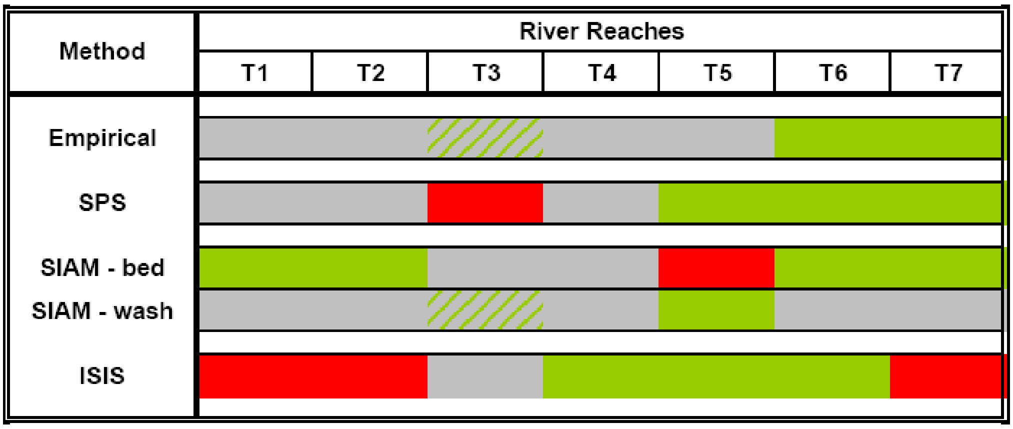


Figure 6.32 Comparison of sediment balances predicted by empirical/field-based evidence, SPS, SIAM and ISIS-Sediment for the lower River Tone under the baseline scenario (red = source; grey = transfer; green = sink). For SIAM wash-material load, red = sediment added to wash-material load from bed-material load, green = sediment added to bed-material load from wash-material load, and grey = no exchange between wash-material and bed-material loads. Hatching represents two sediment balances in each reach or alternative sediment exchange mechanisms

A key difference is that ISIS predicts net erosion in Reaches T1 and T2 (upstream of French Weir), while empirical evidence and SPS predict a sediment balance (transfer) and SIAM predicts new deposition of bed-material load. In fact, as discussed above, in Section 6.4, the results of ISIS-Sediment should be discounted because the bed material sizes used in the baseline model were too fine resulting in the erroneous prediction of net erosion. Re-running ISIS-Sediment with a coarser substrate produced net deposition, in accordance with SIAM's prediction, but at an unrealistic rate that would fill the channel in a few years. It must be concluded that the ISIS-Sediment model produces unreliable predictions in Reaches T1 and T2, due to its inherent sensitivity to very small changes in the input variables. Empirical and field evidence supports the predictions of SIAM and SPS that Reaches T1 and T2 are net sediment sinks that store bed-material load supplied from upstream and derived from within the reach from local scour of the bed and banks, while transferring fine sediment to downstream reaches. This is consistent with the physical barrier and associated back water effects of French Weir (at the downstream limit of Reach T2), which prevent downstream transfer of relatively coarse bed-material load, except probably during exceptionally high flow events.

Discrepancies also occur between the sediment balances predicted for Reach T3 (within Taunton centre). SPS predicts net erosion, while SIAM and ISIS-Sediment both predict a balanced throughput of sediment with the latter model indicating that some of the incoming wash-material load transitions into bed-material load. Empirical evidence and field-based observations support SIAM and ISIS-Sediment in that the channel appears to be stable with net deposition only being observed under low and intermediate flows, at locations where the channel has been further over-widened for flood control/navigation purposes.

Like ISIS-Sediment's error in Reaches T1 and T2, the SPS erroneous prediction in Reach T3 can be explained by a problem with its input data. SPS uses the bankfull discharge to calculate reach-averaged stream power and identifies reaches as potential sediment sources, transfers or sinks based on a user-defined threshold, in this instance based on the work of Brookes (1987a and b). In Reach T3 the channel has been enlarged and high flows are constrained by flood walls that result in an unnaturally high bankfull discharge, approximating to the 1 in 100-year flood. The effect is to skew the SPS prediction for the reach strongly towards erosion when the stream power associated with the 1 in 100-year flood is compared with that for a much lower flow in the more natural channel in Reaches T1 and T2 upstream.

The lesson to be learned from Reach T3 is that care must be taken when defining the appropriate reference flow for application of the SPS method. In heavily modified channels with exaggerated bankfull capacities, the median discharge (Q_{med}) should be used as this will more closely correspond to the bankfull discharges used in natural or semi-natural alluvial reaches.

Good agreement in the predictions for Reach T4 (the reach immediately downstream of Taunton centre) should be expected as this is a heavily engineered reach with fixed boundaries and non-erodible bed. Field observations, SPS and SIAM all concur that T4 is a sediment transfer reach. ISIS-Sediment, however, predicts net deposition in this reach. This outcome is very likely due to the fact that ISIS-Sediment modelled Reach T4 as part of a longer sediment reach extending from Firepool Weir downstream to Ham Weir (encompassing Reaches T4, T5 and T6). Overall, this long reach does indeed experience net deposition, especially in Reach T6, which is the longest sub-reach located upstream of Ham Weir.

Reach T5 (the first reach downstream of Taunton) is less heavily engineered and features a more natural channel that is incised into its floodplain. Based on field observations it may be concluded that incision has ceased and the reach transfers incoming sediment to the depositional reaches downstream. However, none of the models predict this. SPS and ISIS-Sediment label Reach T5 as being net depositional, while SIAM predicts net erosion, with some of the sediment in transport transitioning from wash-material load to bed-material load. Given that the supply of bed-material load from the upstream reaches (T1 to T4), due to being heavily engineered and the presence of significant barriers of French Weir and Firepool Weir, is actually likely to be small, SIAMs prediction is not unreasonable. However, this is not corroborated by strong field evidence, although there is bank erosion in this reach.

Within this reach SPS appears to be correctly predicting the dynamics of fine sediment, particularly in relation to the interaction between the wash-material and bed-material loads, as opposed to bed-material load patterns. In this context SPS outputs corroborate the SIAM predictions that some wash-material load transitions into bed-material load in this reach. The erroneous ISIS-Sediment prediction, of net deposition for Reach T5, is likely to occur for the same reason as described for Reach T4. As ISIS-Sediment models Reaches T4 to T6 together, it is possible that the dominant depositional process in the larger Reach T6 dampens any intra-reach variability which may occur.

Field observations, SPS, SIAM and ISIS-Sediment all agree that Reach T6 in the lower River Tone upstream of Ham Weir accumulates sediment, with SIAM predicting wash-material sized sediment passing through to the lowest reaches of the River Tone.

Field observations, SPS and SIAM (with a coarser bed material in this reach, see Section 6.3) all agree that Reach T7 in the lower River Tone as it crosses the Somerset Levels either transfers or accumulates sediment. Only ISIS-Sediment disagrees, predicting overall net erosion in this reach, especially in the upper part of this reach (above Knapp Bridge). The reason for this erroneous prediction was discussed earlier, in Section 6.4, and may be attributed to the model's inability to simulate the dominant depositional process (i.e. sediment accumulation on the banks rather than the bed of the channel). The net erosion predicted by ISIS-Sediment does happen, but only during high flows that are neither tide-locked nor ponded behind closed hydraulic structures. Under these circumstances, deposits of fine material on the banks are either (1) eroded and re-suspended, or (2) slump from the banks to the bed and re-suspended to be transported into the tidal reaches downstream.

When reviewing the overall pattern of sedimentation predicted by SPS and the wash-material load component of SIAM through Reaches T1 to T7 it is again, as with the Halse Water, interesting to note the similarity particularly for the upper and middle reaches (T1 to T5) of the river. The obvious discrepancy is Reach T3 where the full range of river flows are constrained within channel leading to SPS being skewed towards erosion, as discussed above. In the lowest reaches, SPS predicts deposition while SIAM predicts a transfer of wash-material load. However, this is under the coarser bed material option (see Section 6.3, and Tables 6.21 and 6.23), which aims to replicate winter conditions, when the supply of wash-material load is high and flows are capable of carrying the finer material through into the tidal reaches (the more likely scenario). However, when a finer bed material option is used (Tables 6.20 and 6.22), which aims to replicate conditions of high wash-material load but where flows are held back by tidal influence or operation of structures (i.e. summer storm event), SIAM predicts deposition. This suggests that the SPS is, in general, able to correctly predict the dynamics of fine sediment supplied to and moving through the River Tone, particularly in relation to the interaction between the wash-material and bed-material loads, and especially in more semi-natural alluvial river reaches.

6.6.2 Practical use of sediment assessment tools

Routine EA suspended sediment data will be probably continue to be the only long-term sediment data available for most river systems with which to start to categorise the sediment system, identify potential sediment imbalances and establish potential sediment yields. However, sediment budgets based on routinely collected data should be used with extreme care, particularly when interpreting sedimentation patterns and sediment continuity through a river network, as the results for the Halse Water and lower River Tone do not particularly compare well with field-based observations and other empirical data. The only way to reduce uncertainty associated with these data is to undertake a concerted programme of suspended and bed material sediment sampling across the UK, or at the very least, within a sub-set of known 'hot-spot' catchments. Nevertheless, estimating sediment budgets based on the best available sediment data and a range of techniques is a useful exercise to start to understand realistic lower and upper boundaries for annual average sediment loads, which could be expected to occur on a given river system, plus potentially identifying reaches worthy of more detailed investigation. Sediment budgets are probably most important for helping to set an appropriate and realistic range of sediment loads which can be investigated via more detailed sediment modelling.

SPS has been shown to be rapid and robust method for assessing sediment continuity and potential imbalances through a large channel network, with outputs generally corresponding well with field-based observations and other empirical evidence. Care must be taken when using SPS, as already identified by Thorne *et al.* (2011), but also when selecting input data for the SPS calculation particularly in relation to selecting an appropriate flow and especially in river reaches which are highly constrained by flood defences that can artificially elevate bankfull flow. Of interest is the similarity between the predictions of sediment patterns of SPS and the wash-material load component of SIAM, which suggests that SPS is able to correctly predict the dynamics of fine sediment supplied to and moving through a river system, particularly in relation to the interaction between the wash-material and bed-material loads, and especially in semi-natural alluvial river reaches. This suggests that SPS may be useful in identifying reaches that may be sensitive to altered wash-material load that may arise, for example, from changes to catchment land use management.

Field-based observations and other empirical evidence relating to sediment dynamics, patterns and yields (i.e. fluvial audit, river geometry, sediment monitoring) should always be collected/collated and assessed to support and underpin other sediment assessment tools and models, and is particularly useful in verifying SIAM outputs. Field-based evidence is critical in establishing the current sedimentation status, which should be cross-referenced to driving variables such as land use or flow to identify whether it is representative of recent aberrations in the system or of a long-term average condition.

Although the above tools are valuable in categorising the sediment system and starting to understand sediment continuity, sediment imbalances and sensitivity of the system to changes in sediment and flow inputs they are restricted in their ability to answer ’what if?’ questions and forecast predicted sediment dynamics under different future scenarios. This can only be achieved through the use of a sediment model. Sediment models represent one of the most useful tools as they can provide representations of sediment fluxes and transfers in river systems. As such they allow the evaluation of different scenarios including the role of diffuse [and point source] sediment inputs and the response of the river system to change in, for example, policy, land use, land management and climate (Owens *et al.*, 2004). However, there are some key differences between the two sediment model used within this research (SIAM and ISIS-Sediment) in terms of performance and practical application.

In the Halse Water and lower River Tone SIAM proved to be both appropriate and robust in representing river sediment dynamics in a lowland river system, and allowing the rapid assessment of various management interventions which could affect both sediment inputs and flows. Although it is a reduced complexity model, SIAM’s outputs have been shown to be closely aligned to field-based observations, and are supported by rapid screening techniques such as SPS. This is the first successful application of SIAM in the UK.

ISIS-Sediment was found to be unable to appropriately represent sections of the channel network, especially reaches associated with complicated structures (e.g. French Weir downstream of Reach T2) where the model could not seemingly represent the complex interactions between flow and sediment, and therefore predicted unrealistic sediment patterns which did not align with field-based observations. Furthermore, although ISIS-Sediment is a detailed sediment model, the findings from the research presented in this thesis indicate that it is generally still only suitable for establishing trends on a reach-by-reach basis when assessing a large river network. Where ISIS-Sediment may be better suited is to undertake discrete, localised assessments of sediment dynamics and bed elevation changes associated with, for example, the impacts of physical alterations to channels (i.e. re-sectioning) or structures (i.e. removal of a weir, impoundment etc), an application which has been successfully demonstrated in the past (e.g. Walker, 2001).

Results from both sediment models are linked to a wide range of uncertainties. These uncertainties stem from lack of knowledge of sediment transport mechanics, a sparse availability of field-derived data such as bed material and sediment yields, a wide range of uncertainty associated with sediment sampling and limitations in the performance of the models themselves (Thorne *et al.*, 2011). As demonstrated by application of SIAM and ISIS-Sediment on the Halse Water and lower River Tone, the range of model outputs can be further influenced, sometimes by orders of magnitude, depending on the choice of model input data and boundary conditions, especially sediment transport function, bed material and channel roughness. To have any confidence in the outputs from the sediment models requires a very large amount of sediment/flow input data and sediment calibration/verification data, which is very rarely, if ever, available or is very costly to collect. Given these limitations, it is suggested within this thesis that outputs from any sediment model, including ISIS-Sediment, should only be used to predict and assess the relative direction and magnitude of change, rather than placing undue faith in absolute sediment loads and/or rates of aggradation or degradation. As with all complex models the requirement for experienced operators in constructing, running and interpreting the model is paramount.

Setting up a detailed sediment model, such as ISIS-Sediment, is a very time consuming and expensive process. As noted previously many rivers (especially lowland rivers) have an ISIS flood model (or equivalent) associated with them. Therefore, the construction of a model from scratch should not be the norm. Nevertheless, the conversion of a hydraulic flood model into a sediment model still requires a significant input of additional resources. A benefit of SIAM is that model construction can be speeded-up because, although it still needs to be created within a HEC-RAS model framework, the number of cross-sections representing the channel geometry can be significantly reduced. For example, the minimum number of cross-sections needed for each defined sediment reach, which could be many kilometres in length, could be as few as three. However, it is probable that an ISIS flood model, with all available cross-sections, will be converted into HEC-RAS format and used to underpin SIAM, and under these circumstances resources needed for model construction may not differ significantly.

The biggest differences between ISIS-Sediment and SIAM relate to the calibration/verification of the model, running model scenarios and generated outputs. Use of ISIS-Sediment on the steeper Halse Water headwater catchment found that the model was unstable, and as such required a large amount of time to verify the model by altering model variables/input parameters to produce sensible and realistic outputs, which were comparable to field-based observations. SIAM, being a reduced complexity model, seemingly provided a more stable modelling platform, which was verified against field-based observations in a straight forward manner, using two key variables, namely sediment transport function, and wash-material load:bed-material load threshold value.

Within this research, when modelling both the Halse Water and lower River Tone, it was found that each ISIS-Sediment model run scenario took between 2-3 days computing time on a standard desk-top computer. This is compared to SIAM, which computes outputs for each model run scenario in a few seconds. This is considered to be one of the biggest benefits of using SIAM, in that multiple model runs can be undertaken very quickly, which allows various model parameters and/or model scenarios to be tested quickly and efficiently. This is particularly useful for bracketing certain parameters, such as sediment yield, which are associated with a high level of uncertainty to understand and test the sensitivity of the response of the river system. For example, within this research approximately 250 model runs were generated and tested within SIAM (with many runs being abortive work and therefore not reported within this thesis). Using ISIS-Sediment this would have taken approximately 500-800 computing days on an equivalent desk-top computer. This is not to say ISIS-Sediment cannot or should not be used, but instead highlights the need to carefully consider which model is appropriate for a given sediment assessment. Importantly this also suggests that, perhaps, ISIS-Sediment should only be used when a small number of model run scenarios are required at a discrete location on the river system (i.e. to investigate a specific problem at a specific location).

Outputs are also generated differently, with ISIS-Sediment generating overly-large amounts of data. For this research approximately 100GB of data was created by ISIS-Sediment, compared to a few GB of data from SIAM generated as excel spreadsheets. This makes it difficult to manipulate ISIS-Sediment data and share it with others, whereas SIAM data can be easily accessed, reviewed, manipulated and shared.

Thorne *et al.*, 2011 when reviewing the applicability of ISIS-Sediment, concluded that given the uncertainties surrounding sediment modelling, the use of simple, fast-running 1-D sediment models within a stochastic or probabilistic framework may at present be the best way to handle uncertainty when predicting future sediment dynamics. This is a key strength of SIAM, the ability to rapidly run multiple scenarios which allows sensitivity testing to better understand uncertainties surrounding aspects of a study which are data poor. This is especially true for sensitivity testing and assessing the implications for a range of sediment wash-material and bed-material loads, which are data that will usually be absent or sparse for most UK river systems and cannot be easily or cheaply collected on a project-by-project basis. This in turn provides a greater level of confidence for catchment managers when starting to make decisions on where best to commit resources.

The complex and detailed ISIS-Sediment routing model does not appear to provide clear benefits over a more simple sediment continuity model such as

SIAM. Indeed, the perception that ISIS-Sediment is the better/detailed/more robust sediment model may actually be a key weakness of using ISIS-Sediment in that there is a belief that more detail equates to greater confidence in outputs. Paradoxically, this may in fact be the reverse unless very large amounts of calibration and verification data are available, which is rarely the case. In addition, use of a more complex sediment model may actually lead to a reduced reliance on the need for an experienced modeller and geomorphologist to be involved, leading to a lack of expert user interpretation of outputs or field reconnaissance-based checking of model data inputs and outputs. As has been discussed, the need for expert user involvement and interpretation/checking data is paramount in the successful application of a sediment model and the subsequent performance of any sediment study.

To conclude, this research indicates that the majority of studies assessing lowland river sediment dynamics at the catchment scale or over a large river network should implement a range of sediment assessment tools and models to adequately categorise the sediment system, bracket and test sensitivity to parameters associated with a high level of uncertainty, establish current sediment dynamics and predict future sedimentation patterns for a range of management scenarios. Therefore, not only is there no single approach that satisfies all situations and applications (as reported by FRMRC WP8.1, see Section 5.1) there is also no single tool that satisfies a single application. Studies should collate and review all existing and empirical data including establishing sediment budgets and collecting field-based data. It is recommended that the Stream Power Screening tool should be used to undertake a rapid assessment of the system and potentially identify areas at risk from imbalances in the sediment load, while SIAM should be used to investigate the effect of land and water management scenarios on sediment dynamics and to answer the what if? questions. In the long-term these models should be supported with improved and more extensive sediment yield data for river catchments in the UK.

Outputs from SIAM in terms of sediment balances and patterns should be converted into a format that is consistent with other river (ecosystem) services to allow river users and managers to compare and assess implications of different management scenarios/strategies. For example, bed material imbalances can be converted to channel dimensional changes (to assess morphological implications), which can then provide inputs for a flood model to investigate implications for water elevations and flood risk (as described in Section 7.1).

This research suggests that ISIS-Sediment should not be used for large-scale, complex or long-term studies, or studies which are sediment data scarce and therefore associated with a high level of uncertainty, which will be the majority of cases in the UK unless a concerted programme of sediment monitoring is implemented. However, ISIS-Sediment is considered to be appropriate for localised, highly-detailed sediment studies where there is a need to assess bed elevation changes over time due to discrete changes to in-channel management or installation removal of in-channel structures.

Finally, although ISIS-Sediment is not advocated for the majority of catchment-wide sediment studies it is acknowledged that in the UK the majority of rivers are covered by an ISIS flood model. At present SPS needs to be calculated by hand, however, as with this research, the SPS input parameters (water slope, flow and width) can be provided by the hydraulic (ISIS) model. Similarly, although SIAM can be set-up from scratch in HEC-RAS, it is likely that in the majority of cases an existing ISIS hydraulic model will be converted into HEC-RAS format to provide the modelling platform for SIAM.

It is therefore recommended that the ISIS modelling suite is adapted and updated to be able to provide both SPS and a SIAM equivalent (i.e. sediment continuity) as discrete packages within the overall ISIS modelling package. This would further integrate sediments into ISIS, and provide a range of sediment assessment tools that can be accessed as part of industry standard water / flood investigations in the UK. As Newson (2010b) states… practical modelling platforms, compatible with those available to water managers' will detract from any remaining isolationist image accruing to geomorphology.

7 IMPLICATIONS FOR FUTURE RIVER AND CATCHMENT MANAGEMENT

7.1 River channel morphology

7.1.1 Introduction

As predicted by Stream Power Screening and confirmed by SIAM, the Halse Water is a wash-material load sediment source and pathway with no significant areas of deposition of fine material. Consequently, assessment of channel morphological implications associated with altered river sediment dynamics focuses on the lower River Tone, where river reaches are potentially impacted via the transition of wash-material load to bed-material load (within Reaches T3, T5 and T7) and/or deposition of some or all of the increased bed-material load (within Reaches T1 and T2).

The implications for river morphology are discussed under the same sub-headings used to discuss sediment dynamics in Section 6.3.2.

SIAM, being a reached-based model, cannot define specific locations of erosion and deposition with each reach or provide information on the extent or type of morphological change expected to result from sediment imbalances. However, the results of the local sediment balance calculations were used to derive indicative channel changes based on the channel dimensions used within the hydraulic model.

The dominant sediment deposition locations within sediment reaches, either channel bed or channel banks, was made based on field-based observations and/or other empirical evidence (as reported in Section 4.3). Deposition within reaches T1, T2 and T3 is on the channel bed, Reach T5 is assessed as being able to deposit on both the bed and banks, and deposition in Reach T7 is on the channel banks.

7.1.2 Assessing the impact of changing wash-material load

Reach T3 is predicted to be a net supplier of sediment with low wash-material loads, before acting as a sediment sink with wash-material loads greater than 10,000 tonnes/year (Figure 6.22). It can be seen from Tables 7.1 and 7.2 that with 'normal calibre' wash-material the channel bed elevation in Reach T3 is predicted to lower by 0.03m/year (an increase in average hydraulic depth by 1.3%), under the zero wash-material load scenario, maintain parity under the 10,000 tonnes/year wash-material load scenario, and rise by 0.04m/year (a reduction in average hydraulic depth by 2%) under the 25,000 tonnes/year wash load scenario.

Reach T3 therefore demonstrates a muted response to changes in wash-material load, with the channel morphology never predicted to change by a large amount (+/- 3-4cm), and as such maintains the ability to quickly adjust and 'return to mean'. Based upon field-based evidence it would appear that the majority of any deposition of the sand fraction that does occur is restricted to immediately upstream of Firepool Weir and, potentially at the Town Bridge road crossing; both locations where further over-widening of the channel has occurred. For example, immediately upstream of Firepool Weir the channel increases from approximately 30m to 100m to account for the canal entrance.

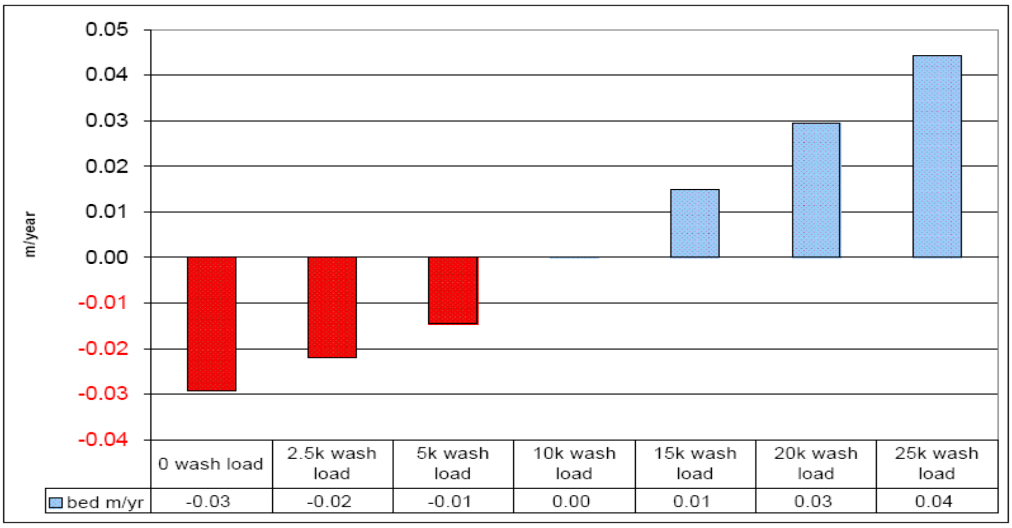


Figure 7.1 Predicted rates of bed elevation change within the River Tone Reach T3 under various 'normal' calibre wash-material load scenarios

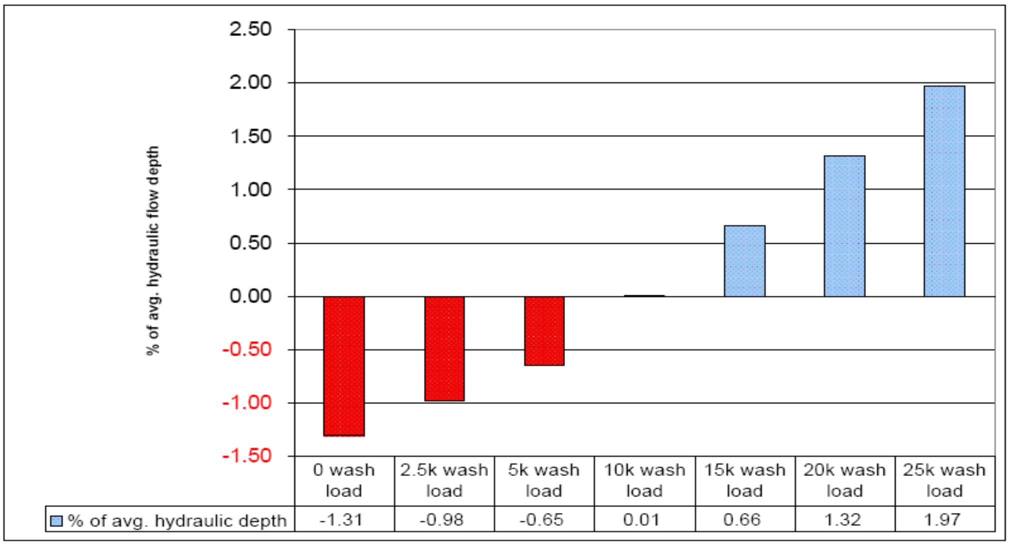


Figure 7.2 Predicted percentage change in average hydraulic depth within the River Tone Reach T3 under various 'normal' calibre wash-material load scenarios

Coarsening the wash-material load was predicted to result in deposition of greater amounts of coarse sand, which results in a sediment balance within the reach being obtained under a reduced wash-material load.

The morphological response to a coarsening wash-material load is shown in Figure 7.3. It can be seen that the river bed elevation is predicted to lower by 0.03m/year under the zero wash-material load scenario, but reach parity with an input of 7,500 tonnes/year. Under the highest wash-material load the river bed elevation is predicted to rise by 0.07m/year as opposed to 0.04m/year with a normal calibre wash-material load of the same amount.

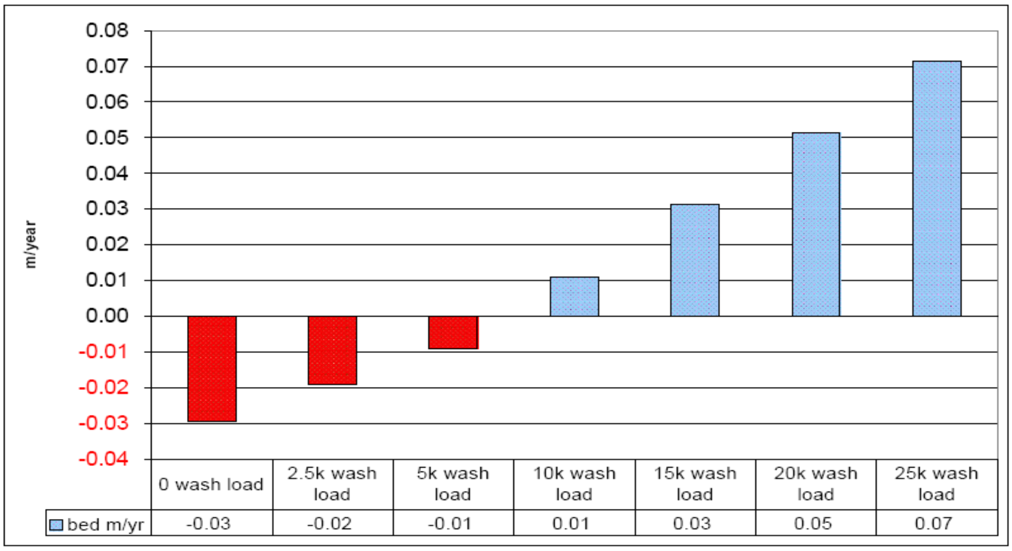


Figure 7.3 Predicted rates of bed elevation change within the River Tone Reach T3 under various 'coarser' calibre wash-material load scenarios

Reach T5 is predicted to be generally a net supplier of sediment under all but the highest wash-material loads (Figure 6.22). An assessment of altered morphology associated with (1) SIAM predicted sediment balance affecting primarily the banks (Figures 7.4 and 7.5), and (2) SIAM predicted sediment balance affecting primarily the bed (Figures 7.6 and 7.7) has been undertaken.

From Figures 7.4 and 7.5 it can be sent that each bank is predicted to erode by 0.2 m/year (an increase in average bankfull width by 1.7%) under the zero wash-material load scenario, which steadily decreases with the introduction of greater wash-material loads. With a 10,000 tonnes/year wash-material load bank erosion is reduced to 0.1 m/year (an increase in average bankfull width by 1%), and the reach maintains morphological equilibrium with approximately 23,000 tonnes/year of wash-material load.

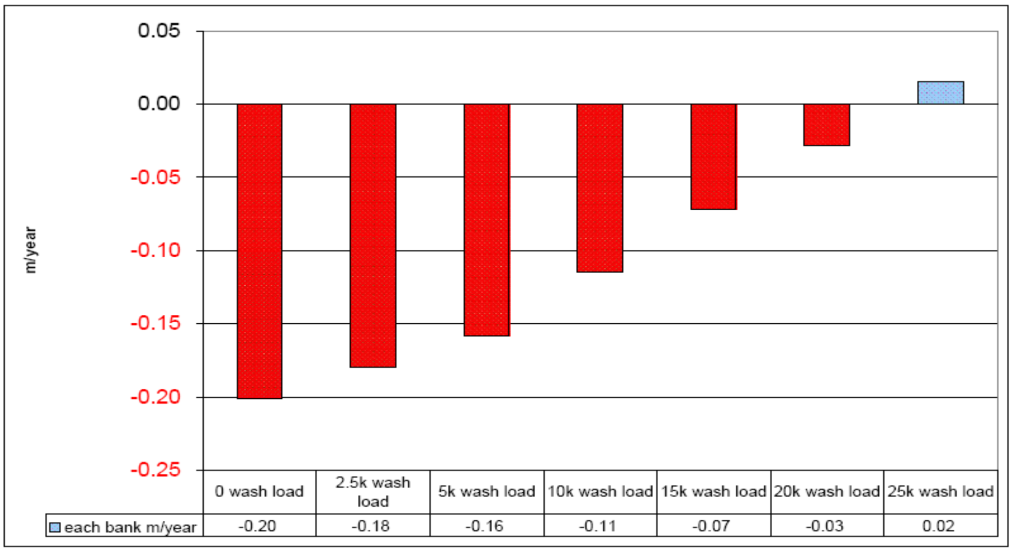


Figure 7.4 Predicted rates of bank advance or retreat within the River Tone Reach T5 under various 'normal' calibre wash-material load scenarios

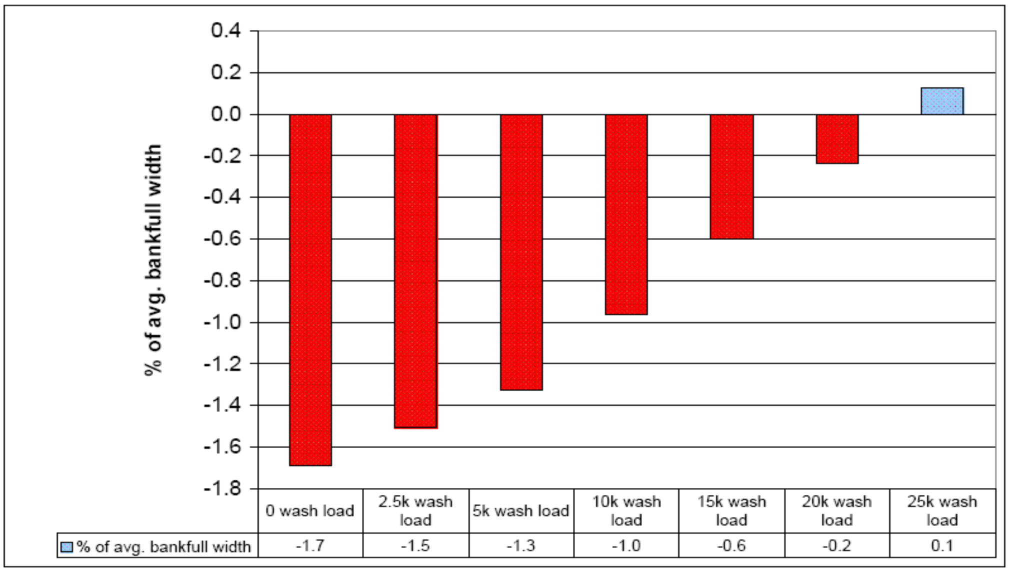


Figure 7.5 Predicted percentage change in average bankfull width within the River Tone Reach T5 under various 'normal' calibre wash-material load scenarios

From Figures 7.6 and 7.7 it can be seen that bed elevation is lowered by 0.1 m/year (an increase in average hydraulic depth by 4.7%) under a zero wash-material load, with the bed elevation maintaining equilibrium with approximately 20,000 tonnes/year of wash-material load.

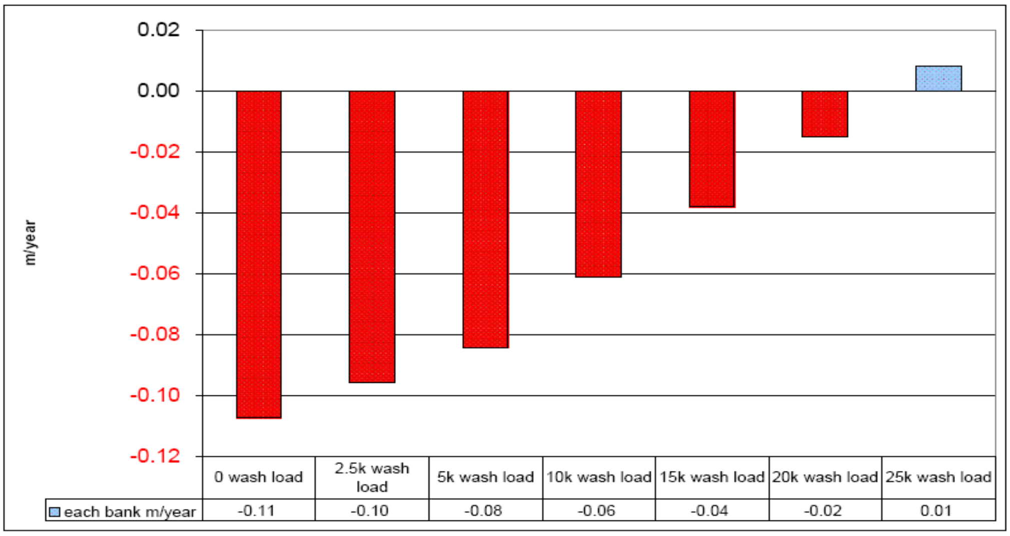


Figure 7.6 Predicted rates of bed elevation change within the River Tone Reach T5 under various 'normal' calibre wash-material load scenarios

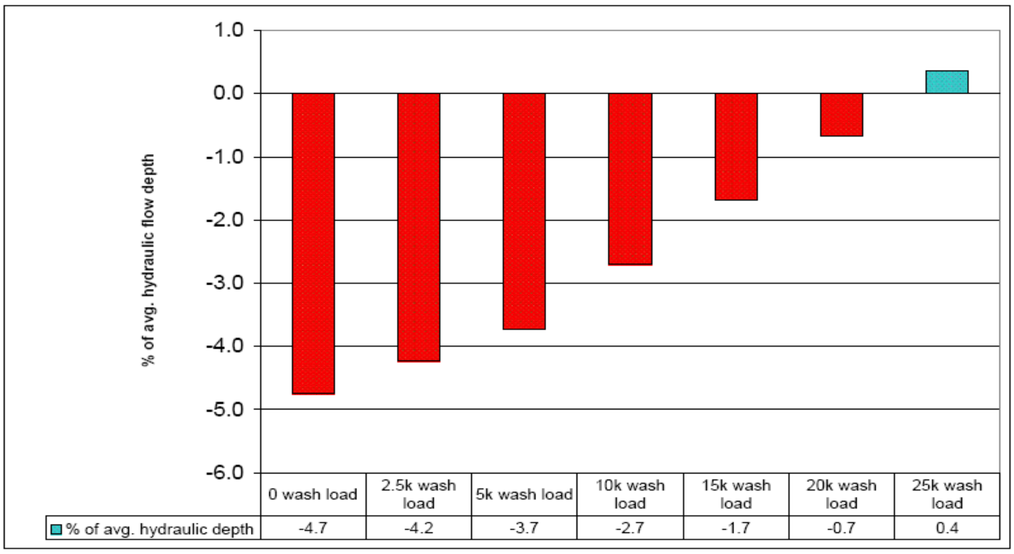


Figure 7.7 Predicted percentage change in average hydraulic depth within the River Tone Reach T5 under various 'normal' calibre wash-material load scenarios

Coarsening the wash-material load has no additional morphological effect at low wash-material loads, but leads to increased bank or bed erosion for wash-material loads greater than 5,000 tonnes/year. Figure 7.8 shows rates of bank change with a coarser wash-material load, and bed morphology follows the same pattern.

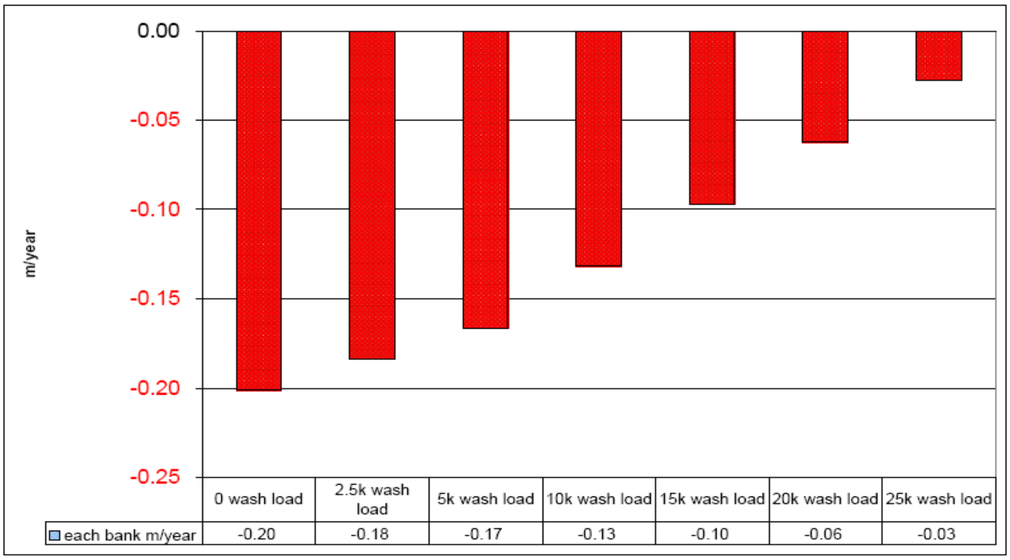


Figure 7.8 Predicted rates of bank retreat within the River Tone Reach T5 under various 'coarser' calibre wash-material load scenarios

Reach T7 is predicted to be a net source of sediment under low wash-material loads, which then acts as a sediment sink with wash-material loads greater than ~5,000 tonnes/year (Figure 6.22). It can be seen from Figures 7.9 and 7.10 that the channel banks in Reach T7 are predicted to erode by 0.06 m/year (an increase in average bankfull width by 0.4%) under the zero wash-material load scenario, maintain equilibrium under the 5,000 tonnes/year wash-material load scenario, and accrete by 0.07 m/year (a reduction in average bankfull width by 0.5%) under the 10,000 tonnes/year wash-material load scenario and 0.26 m/year (a reduction in average bankfull width by 1.8%) under the 25,000 tonnes/year wash-material load scenario.

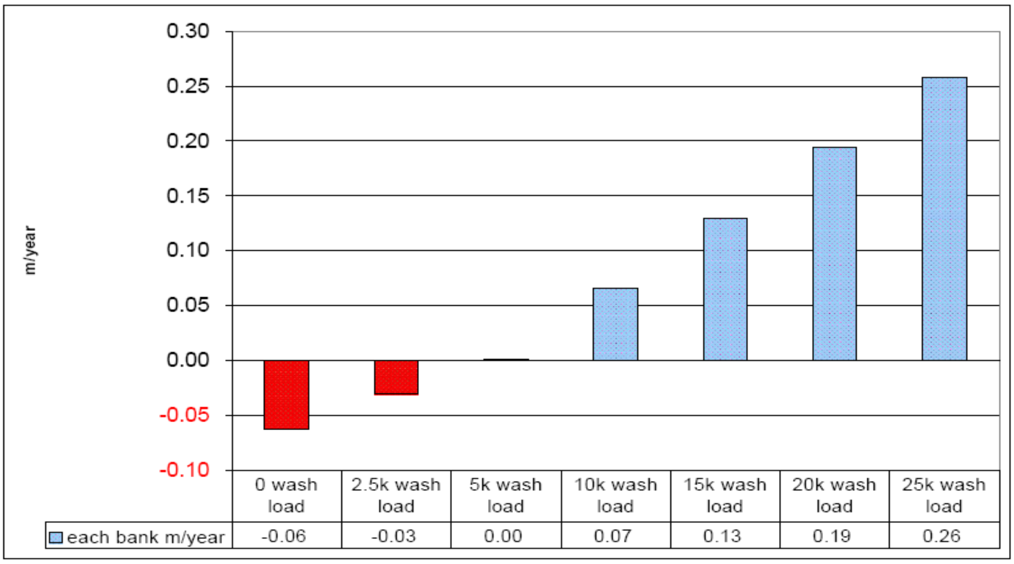


Figure 7.9 Predicted rates of bank advance or retreat within the River Tone Reach T7 under various 'normal' calibre wash-material load scenarios

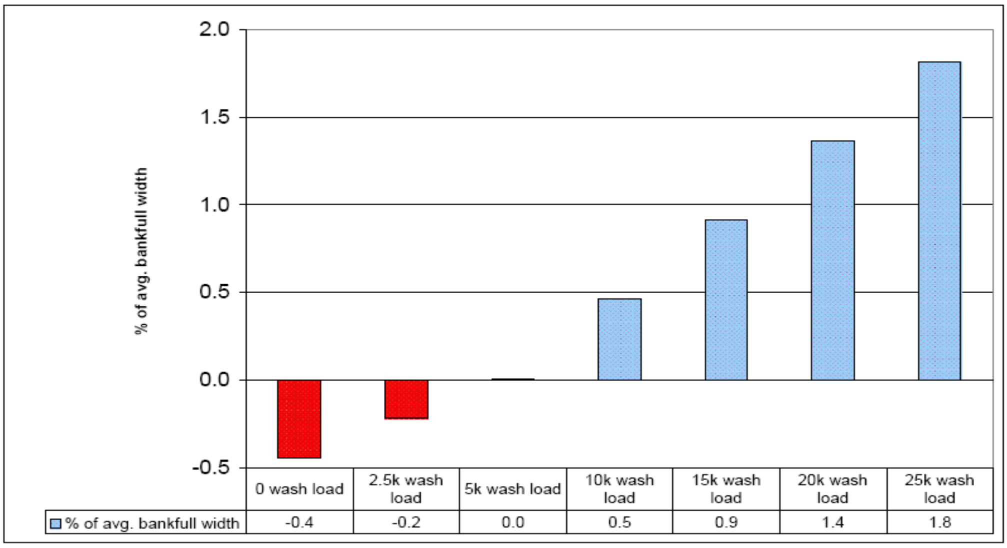


Figure 7.10 Predicted percentage change in average bankfull width within the River Tone Reach T7 under various 'normal' calibre wash-material load scenarios

Coarsening the wash-material load is predicted to result in a reduced supply of sand and silt to Reach T7, resulting in slightly less deposition. The morphological response to a coarsening wash-material load is shown in Figure 7.11, which as expected shows a slight reduction in sediment accumulation on the banks. For example, 0.06 m/year bank deposition is predicted for a coarser calibre wash-material load of 10,000 tonnes/year, as opposed to 0.07 m/year for a normal calibre wash-material load.

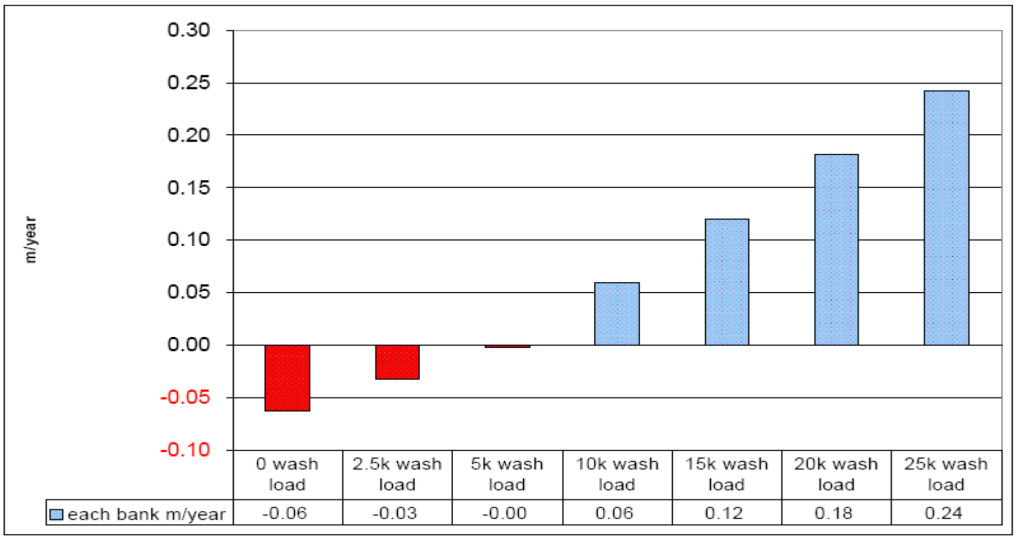


Figure 7.11 Predicted rates of bank advance or retreat within the River Tone Reach T7 under various 'coarser' calibre wash-material load scenarios

Within Reach T7 the results are based on an average annual flow condition and they assume a continued pattern of deposition. However, as discussed in Section 4.3 and Section 6.3.2, in reality the silt and fine sand fraction of the sediment is likely to be transported out of the fluvial system into the tidal reaches during moderate-high flows, which is when the majority of the finer sediment is moving through the system. When deposition of silts and fine sand is predicted to occur (i.e. when flow and water levels are held up due to tidal influence or operation of the tidal sluice) it is predicted to build up on the banks until it either reaches a critical angle/thickness and slumps into the river channel, or is re-mobilised *in situ* by spate flows. Either way the fine sediment is re-entrained and washed downstream into the tidal reaches during those high flow events that are neither tide-locked nor backed-up by the tidal sluice, which prevents long-term accumulation of fine sediment in the lowest reaches of the fluvial system. The morphological implications for this regime are discussed in Section 7.1.5.

As discussed previously, in Section 6.6.2, SIAM provides a quick tool for sensitivity testing and comparing different sediment loads against field-derived morphological and sediment data to predict a likely average annual sediment yield. In the absence of large amounts of reliable sediment yield data (which is likely to be the situation in the UK for the majority of river sediment studies for the immediate/medium-term future at least) which could be used for model calibration/validation, SIAM instead uses channel morphological information to validate the model outputs (in terms of sediment budgets). In effect, SIAM is 'reverse engineering' an average annual sediment yield based on field-based morphological observations, which are data that can be obtained relatively easily and cheaply using well-documented methods, and are far more reliable than current sediment yield data.

For the lower River Tone a wash-material load input of approximately 10,000 – 15,000 tonnes/year best fits other empirical evidence collated during this research (see Section 6.1). Thus, with some degree of confidence, it can be concluded that this is the average annual amount of wash-material load derived from the upper sub-catchments of the Halse Water and upper River Tone.

7.1.3 Assessing the impact of altering flow

In Reach T3 enhanced runoff flow is predicted to reduce deposition and increase erosion, while decreased runoff and flow is predicted to result in the opposite (Figure 7.12). Reach T3 can be seen to be a sediment source under all flow scenarios with the 5,000 tonnes/year wash-material load scenario. The rate of bed erosion increases as flow increases, for example, when associated with increased runoff due to climate change. However, with a reduced flow, for example, when associated with reduced runoff through land use change or altered land management, the tendency for bed erosion would be much reduced and the sediment dynamic equilibrium maintained.

With a wash-material load of 10,000 tonnes/year the sediment dynamic of this reach is predicted to be in balance with a stable bed elevation. However, with this wash-material load the reach is sensitive to altered flow, with increased flow resulting in the reach becoming a low-level sediment source and decreased flow leading to it becoming a low-level sediment sink.

With wash-material loads greater than 20,000 tonnes/year Reach T3 is a sediment sink with reduced flows acting to increase the amount of sediment deposition. Conversely, enhanced flow increases the capacity of the river to transport more sediment, reducing sediment deposition and bringing the reach closer to equilibrium.

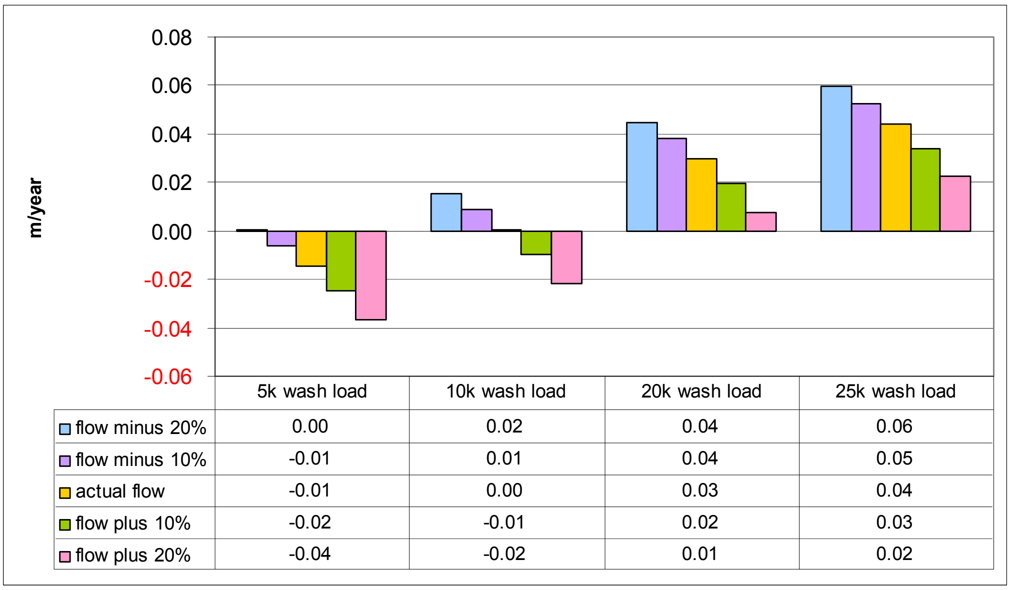


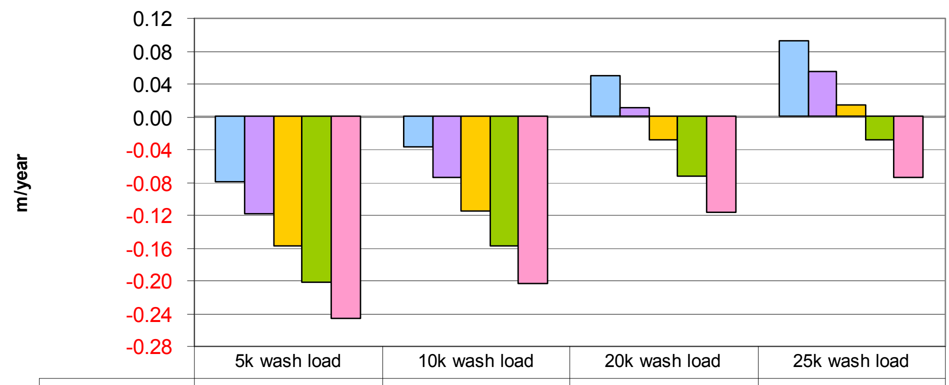
Figure 7.12 Predicted rates of bed elevation change within the River Tone Reach T3 under various wash-material load and flow scenarios

The maximum rate of bed elevation rise is 0.06 m/year when there is 25,000 tonnes/year of wash-material load and a 20% reduction in flow. The maximum rate of bed elevation lowering (0.04m/year) occurs for 5,000 tonnes/year of wash-material load and a 20% increase in flow.

The assessment indicates that any morphological response to changes in wash-material load or flow is muted in Reach T3. However, the relationship between morphology and flow in this reach, particularly at the mid-range wash-material loads (i.e. 10,000 – 15,000 tonnes/year), which appears to be a good estimate for this system, highlights the importance of aligning future flow and sediment regimes which could be altered through catchment management to avoid de-stabilising reaches that are currently morphologically balanced.

In Reach T5 increased flows, through enhanced runoff due to climatic change, are predicted to increase erosion, while decreased flows, associated with appropriate land use or land management, are predicted to result in the opposite (Figure 7.13). Reach T5 can be seen to be a sediment source for all flow scenarios with 5,000 – 10,000 tonnes/year of wash-material load, but reduced flow brings this reach closer to morphological stability. However, when wash-material loads are 20,000 tonnes/year or greater this reach is sensitive to flow changes, and the reach is predicted to be a sediment sink with reduced flows and a sediment source with increased flows.

The maximum rate of bank retreat is 0.25 m/year when enhanced sediment management is not aligned with runoff management (i.e. 5,000 tonnes/year wash-material load and a 20% increase in flow). Conversely, the maximum rate of bank advance is 0.09 m/year, and occurs when enhanced runoff management is not aligned with sediment management (i.e. 25,000 tonnes/year wash-material load and a 20% reduction in flow). This clearly demonstrates the need to devise a catchment strategy that manages both runoff and sediment to ensure the river sediment and morphological regime is optimised within and between downstream river reaches.



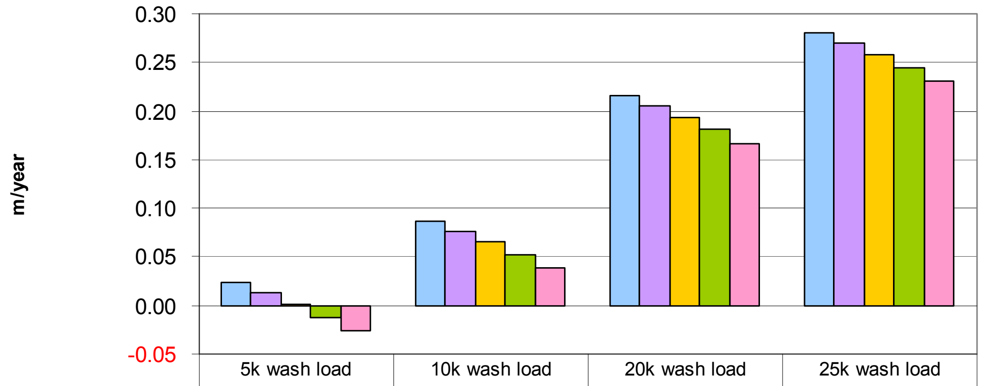
	5k wash load	10k wash load	20k wash load	25k wash load
flow minus 20%	-0.08	-0.04	0.05	0.09
flow minus 10%	-0.12	-0.07	0.01	0.06
actual flow	-0.16	-0.11	-0.03	0.02
flow plus 10%	-0.20	-0.16	-0.07	-0.03
flow plus 20%	-0.25	-0.20	-0.12	-0.07

Figure 7.13 Predicted rates of bank advance or retreat within the River Tone Reach T5 under various wash-material load and flow scenarios

Reach T7 is a sediment sink for the majority of flows under all four wash-material load scenarios (Figure 7.14), with the morphological regime linked strongly to the quantity of wash-material load. The reach becomes increasingly prone to sediment accumulation with increasing wash-material loads, rather than flow. Flow acts to dampen the response for any given wash-material load, slightly reducing sediment accumulation with increased flow as the channel has greater transport capacity or *vice versa*.

Reach T7 is predicted to be morphologically balanced only when wash-material load is 5,000 tonnes/year, becoming a mild sediment sink with reduced flow (maximum rate of bank advance = 0.02 m/year) and a mild sediment source with increased flow (maximum rate of bank retreat = 0.03 m/year).

Sediment deposition ranges from 0.04 to 0.09 m/year on each bank under a 10,000 tonnes/year wash-material load, rising up to 0.23 – 0.28 m/year on each bank under a 25,000 tonnes/year wash-material load scenario. The maximum predicted deposition rate and morphological response, which equates to approximately a 0.5m narrowing of the channel per annum, occurs when neither sediment nor rainfall runoff are managed, and are both high. However, as discussed this level of deposition is not predicted to be sustained long-term as any accreted fine sediment will eventually be re-mobilised by high flows or will slump to be re-entrained by the flow.



	5k wash load	10k wash load	20k wash load	25k wash load
flow minus 20%	0.02	0.09	0.22	0.28
flow minus 10%	0.01	0.08	0.20	0.27
actual flow	0.00	0.07	0.19	0.26
flow plus 10%	-0.01	0.05	0.18	0.24
flow plus 20%	-0.03	0.04	0.17	0.23

Figure 7.14 Predicted rates of bank advance or retreat within the River Tone Reach T7 under various wash-material load and flow scenarios

7.1.4 Assessing the impact of changing the bed-material load

When assessing morphological implications, Reaches T1 and T2 are predicted to be primarily sediment sinks for all flow scenarios (Figures 7.15 to 7.18). A bed-material load of 500 tonnes/year maintains morphological equilibrium, while a bed-material load of 1,000 tonnes/year leads to a net accumulation of approximately 500 tonnes/year of sand and gravel, resulting in the channel bed elevation rising by an average of 0.03 m/year (a reduction in average hydraulic depth by 1.5-2.0%). This is broadly consistent with field observation of active coarse-grained sediment bars in the channel at this location.

Doubling the baseline bed-material load results in a net accumulation of 1,500 tonnes/year, leading to aggradation in Reach T1 at a rate of 0.09 m/year (a reduction in average hydraulic depth by 5.8%). Under a worst case scenario, where climatic conditions and/or land use management and/or river channel management elevates the supply of coarse bed-material load to 4,000 tonnes/year, the depositional rate is predicted to reach 0.22 m/year (a reduction in average hydraulic depth by 13.2%) if all the bed-material load drops out in Reach T1, or 0.11 m/year (a reduction in average hydraulic depth by 6.1%) if excess bed-material load is distributed throughout Reaches T1 and T2. Unless offset by dredging this would likely lead to unacceptable loss of conveyance capacity and channel instability.

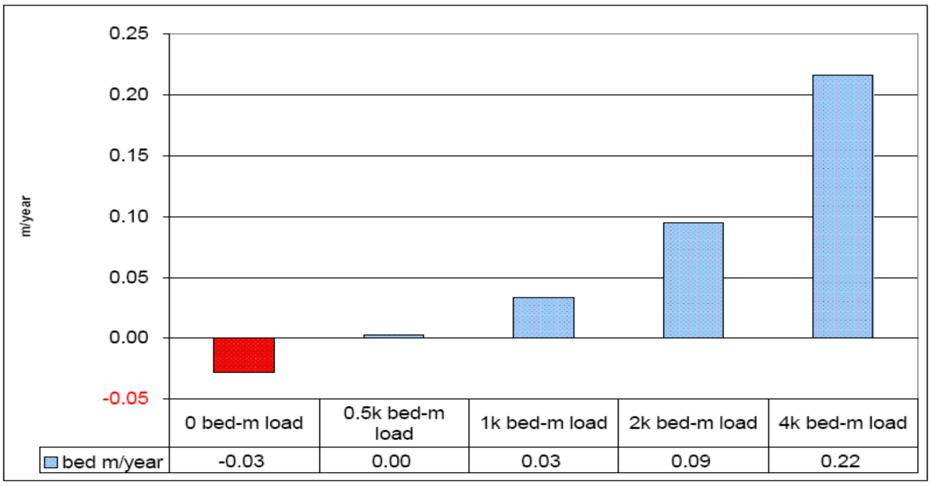


Figure 7.15 Predicted rates in bed elevation change within the River Tone Reach T1 under various bed-material load scenarios

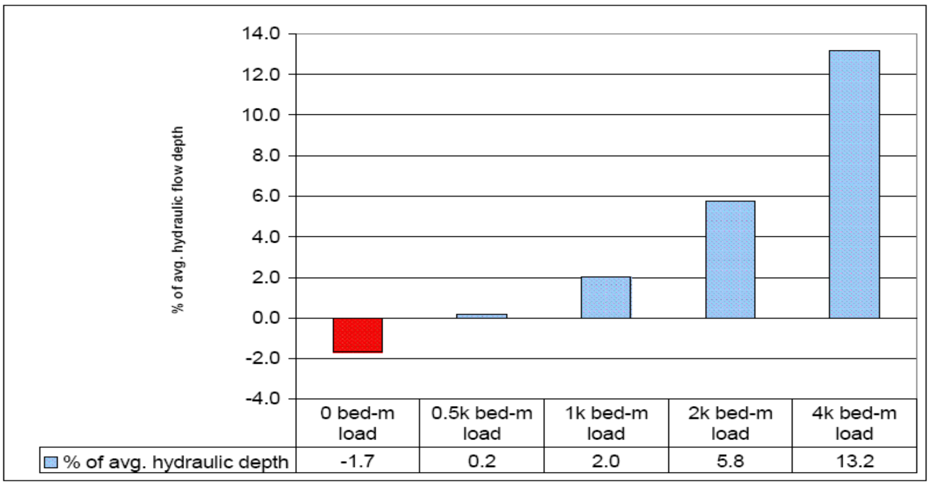


Figure 7.16 Predicted percentage change in average hydraulic depth within the River Tone Reach T1 under various bed-material load scenarios

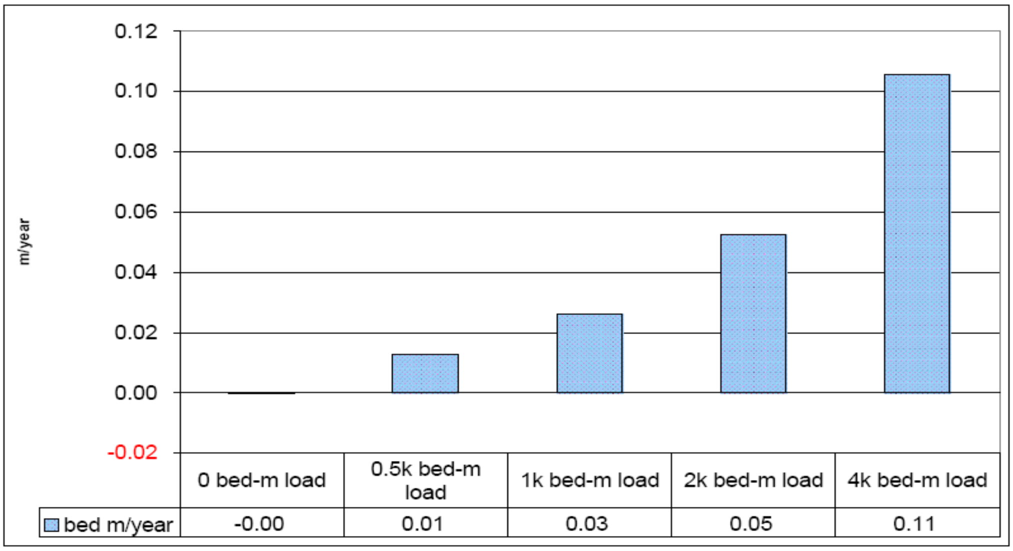


Figure 7.17 Predicted rates of bed elevation change within the River Tone Reaches T1 and T2 under various bed-material load scenarios

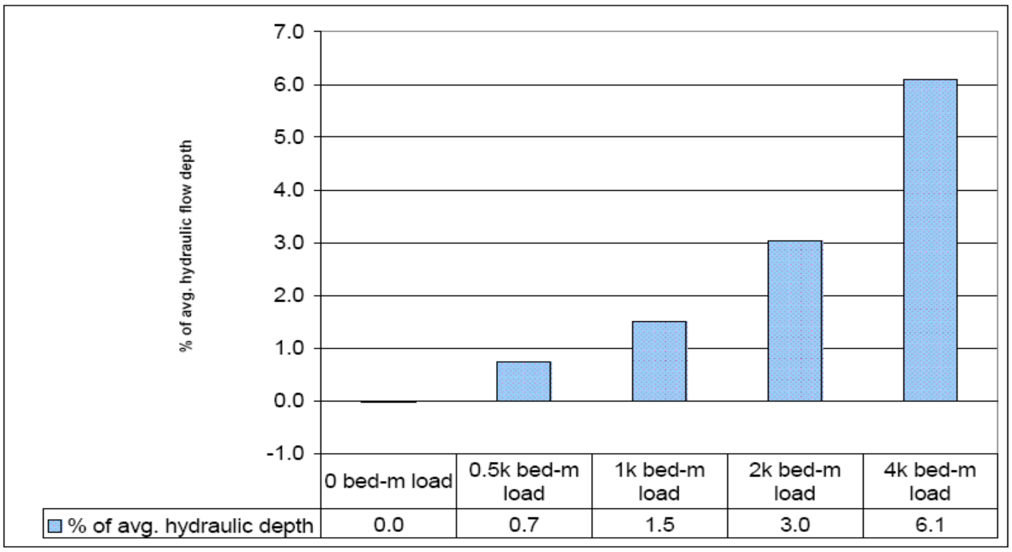


Figure 7.18 Predicted percentage change in average hydraulic depth within the River Tone Reaches T1 and T2 under various bed-material load scenarios

The sensitivity of the local sediment balance to changes in coarse sediment supply within this part of the river system is apparent when the bed-material load is set to zero, and bed scour at a rate of 0.03 m/year (an increase in average hydraulic depth by 1.7%) is then predicted for Reach T1.

Field observations suggest that Reaches T1 and T2 are in sediment dynamic equilibrium and morphologically stable, and this therefore supports the results from SIAM that the average annual bed-material load is approximately 500-1,000 tonnes/year. Similarly, SIAM outputs combined with empirical data, support the position that an average annual yield of 10,000 – 15,000 tonnes/year of wash-material load maintains dynamic equilibrium through the lower River Tone. The predicted average annual wash-material load and bed-material load entering the lower River Tone is consistent with the widely accepted view that total sediment load consists of approximately 90-95% wash-material load and 5-10% bed-material load, which again increases confidence in SIAM functionality and applicability.

7.1.5 Assessing the impact of changing bed material in Reach T7

When modelled with a fine substrate (representing deposition of material under summer flow which is tide-locked or impounded by structures), Reach T7 is predicted to be a net sediment source under low wash-material loads, which then increasingly transforms into a sediment sink for wash-material loads greater than ~5,000 tonnes/year (Figure 7.13). Sediment is predicted to accumulate on each channel bank at rates increasing from 0.07 m/year to 0.26 m/year, as wash-material loads rise from 10,000 to 25,000 tonnes/year.

When the channel substrate is coarsened (representing the system under winter flow conditions), wash-material load passes through into the tidal reach, and the sediment balance in Reach T7 becomes governed by the dynamics of bed-material load. Under this scenario sediment accumulation on the river banks (or bed) is predicted to decrease considerably, due to either the small amount of bed-material load carried in this low-energy part of the fluvial system or the highly-mobile nature of the bed-material load, with sediment accumulating at only 0.01 m/year.

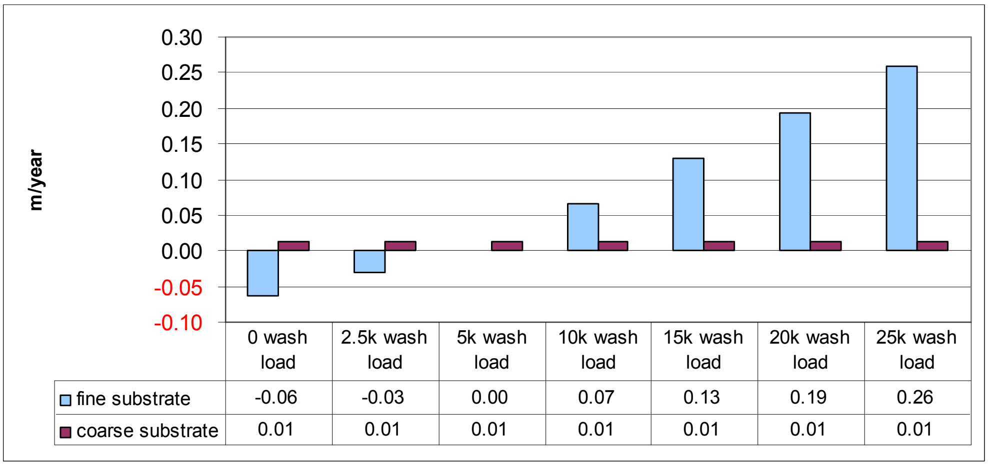


Figure 7.19 Predicted rates of bank retreat or advance within the River Tone Reach T7 under various wash-material load scenarios and altered bed material

7.1.6 Discussion

Rivers respond morphologically to changes in water and sediment supply (Schumm, 1969), and erosion, deposition and re-distribution of sediment occur naturally in all river systems. Adverse impacts associated with alterations in delivery of sediment to rivers are generally considered to be off-site, cumulative and long-term (O'Connell *et al.*, 2004). Key impacts are cited as affecting river habitat and biota (Wood and Armitage, 1999; Yarnell *et al.*, 2006), stability of structures (HR Wallingford, 2008), modifying flood inundation (Piegay and Hicks, 2005; Lane *et al.*, 2007) as well as silting reservoirs, canals and harbours (Morgan, 2006).

The results of the research presented in this thesis support the view that impacts in the sediment balances due to altered wash-material load inputs occur both off-site (delivery from headwater catchments but impacts manifest in lower River Tone, and most likely beyond in the tidal reaches) and over a long-time frame. Within the fluvial lower River Tone, morphological impacts are spatially and temporally localised, and in the long-term are predominantly self-regulating in the extent of their impact, particularly in relation to accumulation of sediment, in the majority of the fluvial system.

At certain locations or under certain circumstances, however, channel morphological change due to accumulation of sediment can result in the need for periodic and ongoing management intervention where the dynamic equilibrium end-point conflicts with river uses. For example, the largest impact of increased sedimentation is associated with deposition in front of the Taunton and Bridgwater canal entrance, which is located adjacent to Firepool Weir in Reach T3 of the lower River Tone (Figure 4.9) and is a finding supported by the work of others (e.g. Verstraeten *et al.* 2003a and b; Morgan, 2006).

Within the lower River Tone this is a localised problem, which is linked to the over-widened channel at this location which has created slack-water areas and allowed deposition of the coarser sand fraction of the wash-material load. In the long-term, left un-checked, the channel would probably reach dynamic equilibrium, with sediment completely filling up the slack-water area and allowing material to continue to pass downstream unhindered. However, this end-point is unacceptable due to the impact on navigation, which results in the need for periodic dredging to maintain a navigation route from the canal to the River Tone mid-channel. This management intervention perpetuates the sediment imbalance, leading to the resumption of sediment accumulation in this location, and ultimately to the need for ongoing periodic dredging every ten years or so. This in itself is not particularly onerous, although obviously it has an ongoing cost associated with it, but this indicates how river uses or a particular intervention can lead to an imbalance in the flow-sediment system which is at odds with natural processes.

Care must be taken when interpreting outputs from sediment modelling. Firstly, not all changes to sediment fluxes and local balances will be long-term or will de-stabilise the fluvial system. Temporary changes in rates and patterns of sedimentation occur naturally as loads fluctuate around their ‘mean’ levels, with the system maintaining a dynamic, meta-stable equilibrium in the medium-term. An example is Reach T3, where relatively large changes to wash-material loads have relatively small impacts on sediment balance and channel morphology. The model outputs suggest that small positive and negative bed elevation changes linked to annual variations in sediment load or flow will maintain equilibrium over the long-term.

Secondly, predicted sedimentation patterns would rarely continue unchanged in the longer-term. This is due to feedback loops associated with gradual evolution of channel morphology and, hence, fluvial hydraulics and sediment dynamics. An example of this is the interpretation of predicted deposition of fine sand and silt on the channel banks within the lowest reaches of the River Tone, which is predicted to occur under conditions where moderately high flow with an elevated wash-material load (i.e. summer storm event) is either tide-locked or backed-up by operation of the tidal sluice. Long-term, unhindered accumulation of sediment would lead to significant changes in channel form and capacity. However, as described in Section 4.3, the way the lowest reaches of the fluvial River Tone function determines that fine material deposits to a certain level or thickness on the banks before slumping occurs or high, spate flows re-mobilise the material *in situ*, either way re-entraining the sediment, passing it through to the tidal reaches and, over the long-term, maintaining the *status quo* in respect to the dimensions of the fluvial channel.

Thirdly, changes to sedimentation patterns are unlikely to be evenly distributed through a river reach, but instead are more likely to be associated with areas that provide suitable hydraulic conditions, and sediment will accumulate as discrete in-channel deposition features, i.e. in-channel wedges and bars. An example is seen in Reach T3 where deposition of the coarser fraction of the wash-material load is confined largely to behind Firepool Weir where the river channel is further over-widened and creates a slack-water area.

Finally, some change in sedimentation patterns is natural and in the right locations desirable. This can be seen in Reaches T3 and T7 where deposited sand and silt have formed bars/islands, which have then stabilised through deposition of plant seeds/propagules and growth of vegetation, and have increased in-channel habitat diversity at these locations. Indeed, the greatest sediment-related threats to the functioning of the River Tone system would be a protracted, major reduction in sediment supply, particularly if this is combined with an increase in discharge, which may occur due to future climatic conditions if catchment runoff is not appropriately managed. Examples can be seen within Reaches T5 and T7 of the lower River Tone where a major reduction in wash-material load combined with increased discharge results in scour and degradation which, in the long-term, could potentially threaten riverbank stability and river embankment integrity as well as other flood defence structures/assets. This could lead to a de-stabilisation of the fluvial system downstream through an increase in the supply of sediment, which would accelerate local deposition of the coarser fraction and trigger complex responses, while increasing supply of sediment to the tidal reaches.

Providing a supply of sediment that adequately maintains, or perhaps even enhances, the lowland river system as a sediment sink, which is its natural functioning state and a condition upon which flood defence assets are based, appears is a less risky strategy than dramatically reducing the supply of sediment which could turn the reach into an unnatural sediment source, which in turn could lead to acute problems.

The potential for conflict between sediment dynamics and river uses/ecosystem services is likely to alter with predicted changes in catchment water and sediment runoff due to both climate change and land/river management. For example, the need for additional or more frequent intervention could occur if the amount of wash-material load and/or bed-material load exported from the headwater catchments is decreased or increased, or changed in calibre, or if runoff/discharge increases.

The relationship between morphology and wash-material load, bed-material load and flow reinforces the importance of aligning any future flow and sediment regime which could be altered through catchment management to avoid de-stabilising reaches that are currently morphologically balanced.

7.2 Flood risk and asset management

7.2.1 Introduction

Changes to channel dimensions, geometry and roughness driven by sediment imbalances can have implications for flood elevation, inundation extent and the risk associated with events of specified return periods (Lane *et al*., 2007; Thorne *et al.*, 2010a).

Based on the outputs from Stream Power Screening, SIAM and ISIS-Sediment the Halse Water is deemed to be a sediment source and transfer system, with no significant areas of deposition. Areas of sediment accumulation are associated with off-site reaches further downstream in the lower River Tone, which is deemed to be a sediment transfer and sink system. Therefore, the flood risk assessment focuses on the lower River Tone.

The potential implications for flood risk management associated with predicted and theoretical 'worst case' morphological changes in the lower River Tone were assessed using an ISIS one-dimensional hydraulic flood model, with the modelling undertaken by Black and Veatch. The ISIS model development and construction is briefly described in Section 5.3.2, with further information on the model calibration and verification described in Black and Veatch (2005b). For the assessment presented in this thesis the river channel Manning's roughness (n) values for the River Tone were maintained at 0.04, which are the same as previous modelling studies and which were obtained through a model calibration procedure.

The primary output from the flood modelling is presented as changes in water elevation from a baseline level (mAOD) for a range of morphological change scenarios for a given annual probability event. Water elevations are provided for key locations in each model reach, and are compared against known bank and/or defence levels (mAOD). Based on these model outputs the implications for flood risk management are presented and discussed in this section in terms of:

- Changes in flood water elevation;
- Changes to timing of over-topping of banks/defence structures;
- Changes in the frequency, depth and duration of inundation; and
- Implications for operation and/or management of flood defence assets, particularly flood storage areas.

The flood model was run for a range of annual probability flood events, including: 1 in 2; 1 in 5; 1 in 10; 1 in 25; 1 in 50; and 1 in 100 years.

Based on the predicted local sediment balances from SIAM three key river reaches of the Tone (Reaches T1&T2; T3 and T7) are predicted to be sensitive to altered wash-material load supply, altered bed-material load supply or altered discharge, and have the potential to adversely affect flood risk to adjacent assets including property, infrastructure or the operation of flood storage areas. These reaches were assessed using the flood model, with the altered channel morphological scenarios modelled for each reach given below.

Reach T1 and T2 (River Tone between Bishops Hull Weir and French Weir, a semi-natural river reach upstream of Taunton and associated with Longrun flood storage area)

- Raising the river bed by 0.25m: equivalent to ~10 years of normal (1,000 tonnes/year) bed-material load evenly deposited along the whole reach, or a single year of excessive (4,000 tonnes/year) bed-material load depositing in Reach T1 only.

- Raising the river bed by 0.50m: equivalent to 5-10 years of high (2,000 tonnes/year) bed-material load evenly deposited within the reaches without sediment management (i.e. dredging).

- Raising the river bed by 1.00m: theoretical worst case scenario equivalent to 5-10 years of excessive (4,000 tonnes/year) bed-material load evenly deposited within the reaches without sediment management (i.e. dredging). This scenario is highly unlikely to occur, but is used to test the sensitivity of flood risk in relation to an excessively de-stabilised system.

Reach T3 (River Tone between French Weir and Firepool Weir, a highly engineered and constrained channel within the centre of Taunton)

- Raising the river bed by 0.25m: equivalent to ~20 years of normal (10,000-15,000 tonnes/year) wash-material load under the current flow regime, ~7 years of normal wash-material load with a 20% reduction in flow due to catchment management, or ~5 years of excessive (25,000 tonnes/year) wash-material load supply under the current flow regime.

- Raising river bed by 0.50m: equivalent to 10-15 years of normal (10,000 tonnes/year) wash-material load with a 20% reduction in flow due to catchment runoff management, or ~10 years of excessive wash-material load. This option is also included to assess the potential for an increase in bed elevation if French Weir (see Figure 4.9) was removed, which is possible under the WFD review, which would allow the downstream migration of coarser bed material to occur and deposit within Reach T3.

- Raising river bed by 1.00m: theoretical worst case scenario equivalent to ~10 years of excessive (25,000 tonnes/year) wash-material load combined with a 20% reduction in flow due to catchment management.

Reach T7 (River Tone between Ham Weir and Newbridge, a low gradient, embanked and perched river reach associated with Currymoor flood storage area)

- Narrowing river channel by 0.15m: baseline scenario which is equivalent to a single year of deposition given a normal wash-material load (10,000-15,000 tonnes/year) and current flow regime.

- Narrowing river channel by 0.30m: a single year with excessive wash-material load (20,000 tonnes/year) and increased flow due to enhanced rainfall and sediment runoff.

- Narrowing river channel by 0.50m: predicted actual worst case scenario of a single year of excessive (25,000 tonnes/year) wash-material load or 2-3 years of normal wash-material load, leading to sediment accumulation over a prolonged drought period including low winter fluvial flows.

- Narrowing river channel by 1.00m and 1.50m: theoretical scenarios which is equivalent to 5-10 years of sediment deposition under normal wash-material loads without re-entrainment of sediment (i.e. via scouring by bankfull flow or bank slumping) or sediment management (i.e. dredging).

- Narrowing river channel by 4.00m: theoretical worst case scenario which is equivalent to 8 years of sediment deposition under an excessive wash-material load without re-entrainment of sediment or dredging.

Empirical and historic management evidence, as reported in Section 4.3, does not support the view that there is a significant build-up of sediment on the channel banks along the lower reaches of the River Tone over the long-term. Therefore, these theoretical scenarios are considered to be highly unlikely to occur, and are modelled to sensitivity test flood risk response to extreme morphological change.

7.2.2 Assessing flood risk in Reaches T1 and T2

The flood model results (Table 7.1) predict that if bed elevation was to increase by 0.25 – 1.00m between Bishops Hull and French Weir this would have a noticeable impact on flood water elevation with the maximum rise in water elevation predicted to be 0.57m immediately downstream of Bishops Hull Weir based on a 1.00m increase in bed elevation for the 1 in 2 year event.

Location	Bank level	Defence level	Flood water elevation (m AOD) and Difference from baseline (m)						
			Baseline	+ 0.25m	Diff.	+ 0.50m	Diff.	+ 1.00m	Diff.
	m AOD	m AOD		m	m	m	m	m	m
			1 in 2 annual probability event						
d/s Bishops Hull weir	19.15		18.11	18.23	0.12	18.34	0.22	18.68	0.57
Halse Water confluence	17.64		17.52	17.64	0.12	17.76	0.24	17.97	0.45
Longrun Farm	16.65		16.63	16.71	0.08	16.77	0.14	16.89	0.26
Frieze Hill		17.22	16.11	16.14	0.03	16.15	0.05	16.20	0.09
u/s French weir	16.00	16.80	15.64	15.66	0.01	15.67	0.03	15.74	0.10
			1 in 5 annual probability event						
d/s Bishops Hull weir	19.15		18.50	18.60	0.10	18.69	0.19	18.96	0.45
Halse Water confluence	17.64		17.79	17.90	0.11	17.99	0.20	18.14	0.35
Longrun Farm	16.65		16.86	16.92	0.06	16.96	0.10	17.05	0.19
Frieze Hill		17.22	16.21	16.23	0.02	16.24	0.03	16.29	0.08
u/s French weir	16.00	16.80	15.88	15.89	0.02	15.91	0.04	15.98	0.11
			1 in 10 annual probability event						
d/s Bishops Hull weir	19.15		18.73	18.81	0.07	18.86	0.13	19.09	0.35
Halse Water confluence	17.64		17.95	18.03	0.08	18.11	0.15	18.24	0.29
Longrun Farm	16.65		16.98	17.03	0.05	17.07	0.09	17.16	0.18
Frieze Hill		17.22	16.27	16.29	0.02	16.31	0.03	16.36	0.09
u/s French weir	16.00	16.80	16.03	16.04	0.01	16.05	0.03	16.09	0.07
			1 in 25 annual probability event						
d/s Bishops Hull weir	19.15		18.99	19.05	0.06	19.11	0.12	19.33	0.24
Halse Water confluence	17.64		18.12	18.19	0.07	18.25	0.13	18.37	0.25
Longrun Farm	16.65		17.13	17.17	0.04	17.21	0.08	17.29	0.16
Frieze Hill		17.22	16.37	16.39	0.02	16.41	0.04	16.46	0.09
u/s French weir	16.00	16.80	16.16	16.17	0.01	16.18	0.02	16.22	0.06
			1 in 50 annual probability event						
d/s Bishops Hull weir	19.15		19.22	19.28	0.06	19.34	0.12	19.53	0.31
Halse Water confluence	17.64		18.24	18.30	0.06	18.36	0.12	18.47	0.23
Longrun Farm	16.65		17.26	17.30	0.04	17.33	0.08	17.41	0.15
Frieze Hill		17.22	16.53	16.54	0.01	16.55	0.02	16.59	0.06
u/s French weir	16.00	16.80	16.39	16.40	NC	16.40	NC	16.41	0.02
			1 in 100 annual probability event						
d/s Bishops Hull weir	19.15		19.46	19.52	0.06	19.57	0.11	19.74	0.27
Halse Water confluence	17.64		18.37	18.42	0.06	18.47	0.10	18.55	0.18
Longrun Farm	16.65		17.40	17.43	0.04	17.46	0.07	17.53	0.14
Frieze Hill		17.22	16.71	16.72	NC	16.73	0.02	16.75	0.04
u/s French weir	16.00	16.80	16.61	16.62	NC	16.62	NC	16.62	NC

NC = No change in water elevation (<0.01m which is within modelling toleamces)

Table 7.1 Flood model results for Reaches T1 and T2 in the River Tone

The changes to flood water elevation will have an impact on subsequent flood risk in terms of frequency of floodplain inundation, flood water depth and duration of the flood. However, in only seven instances does the change in bed elevation cause the river bank to inundate the floodplain (or fill up floodplain storage) when it was previously contained within bank (highlighted yellow in Table 7.1):

- Three times at the Halse Water confluence with a 0.25m, 0.50m and 1.00m rise in bed elevation under the 1 in 2 year event;

- Three times at Longrun Farm with a 0.25m, 0.50m and 1.00m rise in bed elevation under the 1 in 2 year event; and

- Downstream of Bishops Hull Weir with a 1.00m rise in bed elevation under the 1 in 25 year event

The changes in flood water elevation do cause more frequent and deeper inundation of the natural floodplain. However, critically, none of the morphological scenarios for any flood event ever causes the existing flood defences, located at Frieze Hill and upstream of French weir, to over-top. Consequently, the flood risk to property and assets is not increased, although the standards of defence are slightly lowered for extreme events (higher than the 1 in 100). The freeboard available for defences at a given event is also slightly lowered. For example, the Frieze Hill flood defences have a freeboard of 0.51m under the 1 in 100 year flood event with existing bed elevation, whilst this is slightly reduced to 0.47m under a scenario with a 1.00m rise in river bed elevation.

The flood model results also show that the differences between water elevations for the baseline scenario and different morphological scenarios also become less pronounced as flood events get larger. This is explained by the reduction in available flood area: raising the bed elevation by 0.25m, 0.50m and 1.00m reduces the maximum within-bank river channel cross-sectional area by approximately 10%, 15% and 35% respectively. However, at the 1 in 100 annual probability flood level the reduction in total flood area is only between 1% and 5%.

Probably the major flood risk management impact associated with an increase in the bed elevation in this reach is that associated with the operation of the flood storage area constructed along the right bank at Longrun Farm. The effectiveness of this flood storage would be reduced as the storage area would fill earlier due to the riverbank spillway over-topping earlier, as shown in Table 7.1, thereby reducing the amount of water storage available when needed to attenuate peak flood flow. Whereas the spillway is currently set to over-top between the 1 in 2 and 1 in 5 year event, with the modelled bed elevation changes the spillway would over-top once or more annually. Therefore, Longrun Farm should be the priority for future channel morphological or sediment monitoring.

This could also have implications for increased deposition of sediment within storage areas, as river sediment loads would be generally higher, to create the channel morphological imbalance in the first place, and may be specifically higher on the rising flood limb, which is the most common situation (see Section 6.1). Thus sediment would be likely to enter the flood storage in greater concentrations than previously experienced. Ultimately this would have flood operational implications associated with the need to either raise the riverbank spillway or remove (dredge) sediment from the river channel to maintain current operational standards, leading to conflicts with environmental legislation, as well as potentially needing to remove and dispose of sediment from the flood storage area. Removal of sediment could also be associated with contamination and licensing issues.

7.2.3 Assessing flood risk in Reach T3

For the river reach between French Weir and Firepool Weir the flood model results (Table 7.2) predict that raising the bed elevation by 0.25m to 1.00m would have a noticeable increase on flood water elevation, with a maximum water elevation increase of approximately 0.10m to 0.50m predicted for a corresponding rise of 0.25m to 1.00m in bed elevation for flood events between 1 in 2 and 1 in 25.

The raised flood water elevation levels will generally cause the standards of flood defence to be lowered throughout the reach, but the modelled channel morphological changes, for the majority of flood return periods, do not cause flow to go out of bank or over-top defences when the flow would normally be contained within bank under the baseline condition. Under certain circumstances flood water elevation is actually slightly reduced, particularly upstream of Firepool Weir where the major control on water levels is the invert elevation at the weir crest.

Location	Bank level	Defence level	Flood water elevation (m AOD) and Difference from baseline (m)						
			Baseline	+ 0.25m	Diff.	+ 0.50m	Diff.	+ 1.00m	Diff.
	m AOD	m AOD		m	m	m	m	m	m
			1 in 2 annual probability event						
d/s French weir	16.00	16.80	14.77	14.88	0.11	14.99	0.23	15.28	0.51
Third way crossing		16.80	14.53	14.62	0.10	14.73	0.20	15.02	0.50
u/s Town Bridge		15.90	14.26	14.31	0.05	14.38	0.12	14.61	0.35
Priory Bridge		16.20	14.01	14.02	0.01	14.04	0.03	14.11	0.10
u/s Firepool weir		15.00	13.91	13.91	NC	13.91	NC	13.91	NC
			1 in 5 annual probability event						
d/s French weir	16.00	16.80	15.20	15.31	0.12	15.44	0.25	15.71	0.51
Third way crossing		16.80	14.93	15.04	0.11	15.17	0.24	15.46	0.53
u/s Town Bridge		15.90	14.60	14.66	0.06	14.74	0.14	15.01	0.42
Priory Bridge		16.20	14.24	14.26	0.02	14.28	0.04	14.37	0.13
u/s Firepool weir		15.00	14.11	14.11	NC	14.11	NC	14.11	NC
			1 in 10 annual probability event						
d/s French weir	16.00	16.80	15.52	15.62	0.10	15.74	0.22	16.01	0.49
Third way crossing		16.80	15.25	15.35	0.10	15.46	0.21	15.76	0.51
u/s Town Bridge		15.90	14.87	14.94	0.07	15.03	0.16	15.33	0.46
Priory Bridge		16.20	14.45	14.47	0.02	14.50	0.05	14.59	0.14
u/s Firepool weir		15.00	14.31	14.31	NC	14.31	NC	14.31	NC
			1 in 25 annual probability event						
d/s French weir	16.00	16.80	15.95	16.04	0.10	16.14	0.20	16.42	0.47
Third way crossing		16.80	15.66	15.75	0.09	15.86	0.20	16.19	0.53
u/s Town Bridge		15.90	15.28	15.35	0.07	15.43	0.15	15.80	0.53
Priory Bridge		16.20	14.75	14.76	0.01	14.79	0.04	14.87	0.12
u/s Firepool weir		15.00	14.59	14.58	NC	14.58	-0.01	14.56	-0.02
			1 in 50 annual probability event						
d/s French weir	16.00	16.80	16.32	16.41	0.09	16.48	0.16	16.60	0.28
Third way crossing		16.80	16.04	16.14	0.11	16.23	0.19	16.38	0.34
u/s Town Bridge		15.90	15.66	15.74	0.09	15.81	0.16	16.05	0.39
Priory Bridge		16.20	14.98	15.00	0.02	15.02	0.04	15.03	0.05
u/s Firepool weir		15.00	14.79	14.79	NC	14.78	-0.01	14.70	-0.10
			1 in 100 annual probability event						
d/s French weir	16.00	16.80	16.59	16.62	0.04	16.65	0.07	16.76	0.17
Third way crossing		16.80	16.32	16.36	0.04	16.39	0.07	16.54	0.23
u/s Town Bridge		15.90	15.94	15.96	0.02	16.02	0.08	16.37	0.43
Priory Bridge		16.20	15.13	15.12	-0.01	15.15	0.02	15.29	0.16
u/s Firepool weir		15.00	14.93	14.90	-0.03	14.90	-0.03	14.94	0.10

NC = No change in water elevation (<0.01m which is within modelling toleamces)

Table 7.2 Flood model results for Reach T3 in the River Tone

In terms of flood risk to properties and assets the flood defences upstream of Town Bridge, which are set at 15.90m AOD, is the only location which just overtops in a 1 in 100 event given the current bed elevation. At this location, a rise of 0.25m and 0.50m in bed elevation will slightly reduce the 1 in 100 year standard of protection and increase flood water depths when the defence does over-top. However, it is only under an extreme scenario, when the bed elevation is raised by 1.00m, that overtopping at this location would occur in a 1 in 50 year event when it would normally be contained within bank (highlighted yellow in Table 7.2).

The increased bed elevation for the most part reduces standards or protection and available freeboard for all locations throughout Reach T3, but after Town Bridge this reduction in freeboard is most significant immediately downstream of French Weir, particularly for the 1 in 25 to 1 in 100 year events. At this location the freeboard is reduced as follows:

- ❖ From 0.85m (baseline) to 0.76m (+0.25m bed elevation), to 0.66m (+0.50m bed elevation) and to 0.36m (+1.00m bed elevation) for the 1 in 25 year event;

- ❖ From 0.48m (baseline) to 0.39m (+0.25m bed elevation), to 0.32m (+0.50m bed elevation) and to 0.20m (+1.00m bed elevation) for the 1 in 50 year event; and

- ❖ From 0.21m (baseline) to 0.18m (+0.25m bed elevation), to 0.15m (+0.50m bed elevation) and to 0.04m (+1.00m bed elevation) for the 1 in 100 year event.

It is likely that sediment deposition will not be distributed evenly through the sediment reach, and excessive sediment accumulation may be focused where local hydraulic conditions create slack-water or back-water effects (i.e. around or upstream of in-channel structures, or where the channel is further over-widened), which is not represented in SIAM. Based on the flood model results if sediment deposition was to be concentrated at French Weir or Town Bridge, this could lead to exacerbated flood operational and maintenance issues, particularly under a future scenario featuring further elevation of catchment wash-material load or the introduction of a larger calibre sediment into the system, combined with alterations to the flow regime resulting from the effects of climate and/or catchment management. These areas in Reach T3 should therefore be the priority for future channel morphological or sediment monitoring.

The flood model results also show that the differences between water elevations for the baseline scenario and different morphological scenarios also become less pronounced as flood events get larger. This is explained by the fact that the relative reduction in the available cross-sectional area for flow decreases as the magnitude of the flood increases, i.e. raising the bed elevation by 0.25m, 0.50m and 1.00m reduces the cross-sectional area of the channel by approximately 5%, 15% and 30% respectively for the 1 in 2 year event, while for the 1 in 100 year event the reduction in cross-sectional area is only 3%, 5% and 15% respectively.

7.2.4 Assessing flood risk in Reach T7

The flood model outputs associated with channel narrowing along the embanked, low gradient section of the lower River Tone upstream of the tidal limit are presented in Table 7.3. The flood model predicts that even though this reach could be prone to high levels of sediment deposition under certain sediment and hydraulic conditions (i.e. elevated wash-material load and flow backed-up) the morphological changes are predicted to have a lesser impact on flood water elevations than those seen in the upstream reaches.

The model predicts that if the quantity of sediment depositing in Reach T7 was maximised (i.e. all available wash-material load sediment drops-out) and evenly distributed along the banks this would only increase flood water elevations at the most upstream section (Ham Weir). At this location the maximum flood water elevation increase is only 0.05m in a 1 in 2 year event when the channel is narrowed by 1.50m. For all other events the water elevation at Ham Weir is only increased by 0.01m to 0.04m for channel narrowing of 0.50m to 1.50m. At the lesser channel reductions the water elevation change is less then 0.01m, which is within the error margin of the model and can therefore be discounted.

At all other locations for all flood events, when the channel is narrowed between 0.15m and 1.50m the increase in flood elevation is either less than 0.01m (and can therefore be discounted as being within model tolerances) or, at Newbridge, the water level is slightly decreased by 0.02 – 0.03m, which is accounted for by the fact that more water is spilling out onto the floodplain at the top of the reach (Ham Weir).

Location	Bank level	Flood water elevation (m AOD) and Difference from baseline (m)												
		Baseline	+ 0.15m	Diff.	+ 0.30m	Diff.	+ 0.50m	Diff.	+ 1.00m	Diff.	+ 1.50m	Diff.	+ 4.00m	Diff.
	m AOD		m	m	m	m	m	m	m	m	m	m	m	m
		1 in 2 annual probability event												
Creech St Michael		9.05	9.05	NC	9.05	NC	9.05	NC	9.05	NC	9.06	NC	9.07	0.03
Ham weir	8.40	8.45	8.45	NC	8.45	NC	8.46	0.01	8.48	0.03	8.49	0.05	8.57	0.13
u/s Currymoor	7.96	8.03	8.02	NC	8.02	NC	8.02	NC	8.02	NC	8.02	NC	8.02	NC
Newbridge	7.97	7.80	7.80	NC	7.80	NC	7.80	NC	7.78	-0.02	7.77	-0.03	7.70	-0.10
Hookbridge spillway	7.30	7.51	7.51	NC	7.51	NC	7.51	NC	7.51	NC	7.50	NC	7.48	-0.04
Within Currymoor		6.14	6.14	NC	6.14	NC	6.14	NC	6.13	NC	6.14	NC	6.13	NC
		1 in 5 annual probability event												
Creech St Michael		9.23	9.23	NC	9.24	NC	9.24	NC	9.24	NC	9.24	NC	9.26	0.02
Ham weir	8.40	8.61	8.62	NC	8.62	NC	8.63	0.01	8.64	0.03	8.65	0.04	8.72	0.11
u/s Currymoor	7.96	8.08	8.08	NC	8.08	NC	8.08	NC	8.07	NC	8.07	NC	8.06	-0.01
Newbridge	7.97	7.83	7.83	NC	7.82	NC	7.82	NC	7.81	-0.02	7.80	-0.03	7.73	-0.09
Hookbridge spillway	7.30	7.52	7.52	NC	7.52	NC	7.52	NC	7.52	NC	7.51	NC	7.49	-0.03
Within Currymoor		6.54	6.54	NC	6.54	NC	6.54	NC	6.54	NC	6.54	NC	6.55	NC
		1 in 10 annual probability event												
Creech St Michael		9.36	9.36	NC	9.36	NC	9.36	NC	9.36	NC	9.36	NC	9.37	0.01
Ham weir	8.40	8.69	8.69	NC	8.69	NC	8.70	0.01	8.71	0.02	8.72	0.04	8.79	0.10
u/s Currymoor	7.96	8.10	8.10	NC	8.10	NC	8.10	NC	8.09	NC	8.09	NC	8.08	-0.02
Newbridge	7.97	7.84	7.84	NC	7.84	NC	7.83	NC	7.82	-0.02	7.81	-0.03	7.75	-0.09
Hookbridge spillway	7.30	7.53	7.52	NC	7.52	NC	7.52	NC	7.52	NC	7.52	NC	7.49	-0.03
Within Currymoor		6.54	6.84	NC	6.83	NC	6.84	NC	6.84	NC	6.83	NC	6.85	0.01
		1 in 25 annual probability event												
Creech St Michael		9.50	9.50	NC	9.50	NC	9.50	NC	9.50	NC	9.50	NC	9.51	NC
Ham weir	8.40	8.75	8.76	NC	8.76	NC	8.77	0.01	8.78	0.02	8.79	0.04	8.85	0.10
u/s Currymoor	7.96	8.12	8.12	NC	8.12	NC	8.11	NC	8.11	NC	8.11	NC	8.10	-0.02
Newbridge	7.97	7.85	7.85	NC	7.84	NC	7.84	NC	7.83	-0.02	7.82	-0.03	7.76	-0.09
Hookbridge spillway	7.30	7.53	7.53	NC	7.53	NC	7.53	NC	7.52	NC	7.52	NC	7.50	-0.03
Within Currymoor		7.20	7.20	NC	7.20	NC	7.20	NC	7.21	NC	7.21	NC	7.21	0.01
		1 in 50 annual probability event												
Creech St Michael		9.60	9.60	NC	9.60	NC	9.60	NC	9.60	NC	9.60	NC	9.60	NC
Ham weir	8.40	8.80	8.80	NC	8.80	NC	8.81	0.01	8.82	0.02	8.83	0.04	8.89	0.10
u/s Currymoor	7.96	8.13	8.13	NC	8.13	NC	8.13	NC	8.12	NC	8.12	NC	8.11	-0.02
Newbridge	7.97	7.85	7.85	NC	7.85	NC	7.85	NC	7.84	-0.02	7.83	-0.03	7.76	-0.09
Hookbridge spillway	7.30	7.53	7.53	NC	7.53	NC	7.53	NC	7.53	NC	7.52	NC	7.53	NC
Within Currymoor		7.50	7.49	NC	7.49	NC	7.50	NC	7.50	NC	7.50	NC	7.51	0.01
		1 in 100 annual probability event												
Creech St Michael		9.67	9.67	NC	9.67	NC	9.67	NC	9.67	NC	9.67	NC	9.67	NC
Ham weir	8.40	8.83	8.83	NC	8.84	NC	8.84	0.01	8.85	0.02	8.87	0.04	8.92	0.09
u/s Currymoor	7.96	8.14	8.14	NC	8.14	NC	8.14	NC	8.13	NC	8.13	NC	8.12	-0.02
Newbridge	7.97	7.86	7.86	NC	7.86	NC	7.85	NC	7.85	NC	7.84	-0.02	7.81	-0.05
Hookbridge spillway	7.30	7.71	7.71	NC	7.71	NC	7.71	NC	7.71	NC	7.71	NC	7.72	NC
Within Currymoor		7.70	7.70	NC	7.70	NC	7.70	NC	7.71	NC	7.70	NC	7.71	0.01

NC = No change in water elevation (<0.01m which is within modelling tolearnces)

Table 7.3 Flood model results for Reach T7 in the River Tone

Sediment deposition can affect the frequency, depth and duration of flooding as well as the peak water elevation. However, the downstream reaches of the River Tone feature tidal influence, control structures and large floodplain storage areas that dissipate the effects of changes in channel morphology and capacity.

Consequently, a review of predicted flood water elevation changes at the spillway that feeds the main flood storage area at Currymooor (located at Hookbridge) and within Currymoor flood storage area itself was undertaken. The flood model predicts no measurable change in water elevation under any of the flood event scenarios when the channel is narrowed by 0.15m to 1.50m (0.5% to 5% reduction in cross-sectional area respectively). The fact that there is no measurable change in water elevation at the spillway also means that the flood model predicts that there will be no measurable change in flooding frequency or duration within Currymoor flood storage area. This is, however, contrary to local perception (see Section 4.3).

These results are to be expected given that the width of channel of the lower River Tone is approximately 30m, and distributing the deposition resulting from a net annual sediment imbalance evenly along the ~4 kilometre long reach produces a 0.5% to 5% reduction in cross-sectional flow area for siltation of 0.15m to 1.50m, respectively. This small loss of cross-sectional area, coupled with the fact that the water surface profile is also partially controlled by tidal influence or downstream control structures in this regulated system, limits the impact of sediment deposition on flood risk, especially within the floodplain storage areas.

It is possible that sediment deposition may not be distributed evenly through the sediment reach and excessive siltation may be focused where local hydraulic conditions dictate, which is not represented in SIAM. This potentially could lead to a more significant reduction in cross sectional area at some locations, although due to the functioning of the system this is considered very unlikely.

To assess the implications for flood risk a theoretical worst case scenario that reduced the channel cross section by 4.00m, which represents a 13% reduction in cross-sectional flow area, was also tested. At Ham Weir the flood water elevation is increased by a 0.09m – 0.13m for the range of flood events, and under the 1 in 2 to 1 in 10 year event this also causes an increase in water levels between 0.01m and 0.03m upstream at Creech St Michael. The increase in flood water levels across the floodplain at Ham Weir also results in reduced water levels in the channel downstream, with water elevations being reduced by 0.01m to 0.05m depending on location and flood event.

Given this large reduction in cross-sectional flow area the flood water level within Currymoor is only increased by a maximum of 0.01m for the 1 in 10 flood event and greater. If this increase in flow to Currymoor did occur it is worth noting that there would most likely be a corresponding marginal reduction in water levels and subsequent flood risk downstream in the tidal reaches, which is where the majority of investment to maintain flood banks is provided. This benefit may be in-part offset by the fact that additional amounts of sediment may enter and deposit within Currymoor, particularly if water is more likely to overflow into the storage area on the rising limb of the flood which generally carries higher concentrations of sediment. This could potentially have flood risk operational and land management implications with associated costs, for example, maintenance of pumping stations. However, the flood storage areas are large and the Environment Agency has not reported any issues associated with excessive siltation of land to-date (Jason Flagg, Environment Agency, pers. comm.). Local landowners and farmers have reported issues relating to the duration of flood water remaining within Currymoor post-flood (see Section 4.5), but this is related to the impact of standing water and rotting vegetation on soil fertility and crop production, rather than smothering of land by excessive silt.

This 4.00m cross-section reduction is, however, a theoretical worst case scenario based on an extreme morphological change, which is very unlikely to occur and if it did would only produce a marginal impact on flood risk to the downstream flood storage moor area and river reaches beyond. Therefore it is likely that regardless of the amount of wash-material load, within the realistic range that could be supplied from the upper catchment, which enters the fluvial lower River Tone there would be no significant impact on the flood storage capacity and flood risk associated with the fluvial river channel or moors flood storage areas.

7.2.5 Discussion

There is a general lack of understanding on the role sediments play in flood risk management (Thorne, 2011), but it is recognised that dysfunctional sediment dynamics can pose significant threats to people, property and infrastructure (Thorne *et al.*, 2010a).

The linkage between sediment deposition and increased flood risk has been identified by researchers in China, Belgium, the US and New Zealand (Plate, 2002; Verstraeten *et al.*, 2003a and b; Korup *et al.*, 2004; and Pinter and Heine, 2005). Research identified that enhanced sediment delivery and river bed aggradation, particularly where rivers are embanked and are disconnected from their floodplain, can have major impacts on flood risk.

Within the UK research to address the interactions between sediment delivery, river channel response and flood risk is limited. Furthermore, as identified by Newson (2002) and Bates (2011), the research thus far has been restricted to investigating small, unmodified, upland sites. As an example, Lane *et al.* (2007 and 2008) investigated the interaction between sediment delivery, morphological response and 'flood risk' on the River Wharfe in an upland environment. The results were compared to changes in flood probability due to climate change, with the findings demonstrating that 16 months of sedimentation resulted in an increase in the 2-year inundation area which was equivalent with an increase predicted for the 2050s due to climate change.

The 2010 Flood and Water Management Act defines 'flood risk' as a combination of the 'probability of occurrence' with its 'potential consequences' [on people, property and infrastructure]. Therefore, the research on the River Wharfe is not assessing flood risk rather it is purely dealing with probability of occurrence and extent of inundation, and is making no connection between altered inundation patterns to consequences for people and assets. It is likely given the location of this study that although enhanced sediment delivery has an impact on flood inundation, the impact on flood risk will be negligible. As Bates (2011) stated the sole focus on small, rural, upland catchments is therefore misplaced when considering the impact of altered morphodynamics on flooding [and flood risk] due to the low density of assets at risk in these locations. Instead, geomorphic research, as applied within this research, needs to investigate and better understand the linkages between water, sediment and flood risk within the catchment as a whole, as enshrined in flood policy and the CFMP process, where changes in upland, headwater catchments are linked to the effects in downstream lowland, urban rivers.

The implications for assessing both components of the flood risk equation become clear when reviewing the results of the flood risk assessment undertaken as part of this research. In general, predicted 'realistic' changes in river morphology, manifesting as changes in bed or bank elevations, which are brought about by changes in sediment delivery and/or altered flow (due to climate change and/or upper catchment river/land management) can lead to a noticeable impact on flood water elevations within the river channel throughout the fluvial part of the lower River Tone.

The increases in flood water elevations under these 'realistic' scenarios lead to an increase in the frequency, duration and depth of flooding in natural floodplain areas, or lower the standards of defence (i.e. reduce the freeboard at defences for different flood events) protecting property and assets. However, crucially the changes to flooding or in-channel water levels never cause defences to over-top more frequently in any event between the 1 in 2 and 1 in 100 year event, and thus flood risk in terms of property and assets remains unchanged. This indicates that catchment-wide sediment management and/or large-scale channel maintenance (i.e. dredging) will not significantly reduce fluvial flood risk and cannot, therefore, be justified on the basis of flood risk management alone.

There are implications for operation and management of off-line flood storage areas, particularly at the top of the system (e.g. Longrun Farm), where larger impacts on flood water elevation and flood frequency are predicted. In addition, under theoretical worst case scenarios, which are highly unlikely to ever occur but were modelled to test sensitivity of the system, significant changes in bed elevations or bank profiles in the fluvial river system would be needed to effect any change in flood risk to property/assets, and these are restricted both spatially and temporally to discrete locations during very high flood flow events. Furthermore, effects of changes in water level elevation is dissipated down the river system due to the influence of larger river channels, regulated flow and presence of large amounts of flood storage on the floodplain.

This focus of this research is the fluvial system but, as described in Section 6.3.2 (and see Section 7.4), under the majority of conditions when wash-material load is elevated (i.e. during the autumn and winter) the majority of this finer sediment passes through the fluvial system into the tidal reaches below. An assessment of sediment balances, morphological change and flood risk implications within the tidal reaches of the Rivers Tone and Parrett is outside the scope of this research. However, what is evident is that potentially excessive quantities of fine sand, silt and clay are being transported from the fluvial system into the tidal reaches of the Rivers Tone and Parrett. The lowest, tidal reaches of the River Parrett are predominantly the focus for dredging with eight dredging events recorded on the lower, tidal River Parrett since 1995 as opposed to one dredging event on the lower River Tone in the same timeframe (Black and Veatch, 2011). The lower, tidal reaches are also the focus of local/riparian landowner when linking the need for dredging of rivers and increased risk of flooding (see Section 4.3). Therefore, future research investigating the interactions between sediment supply, sediment dynamics, morphology and flood risk should be focused in these tidal reaches.

7.3 Sediment continuity and habitats

7.3.1 Halse Water

The Halse Water is categorised as a sediment source and transfer system, with all wash-material load entering the system passing through the channel network and entering the lower River Tone. Sediment modelling predicts erosion of bed material within the upper reaches and deposition in the lower reaches, but with bed material migrating through the channel network unhindered providing a net supply of sediment into the lower River Tone.

Field-based observations establish localised deposition of coarser bed material and finer-grained (sand) material behind small weirs, which is not picked up by SIAM because it is a reach-based model. However, field evidence suggests that sediment forms wedges behind the weirs, which eventually reduce trapping efficiency and allow bed-material load to continue to migrate downstream unhindered. This is supported by the reach-scale modelling, which averages out these small localised pockets of deposition, and predicts continuity of sediment movement from the upper reaches to the confluence of the lower River Tone.

The connectivity of sediment through the channel network of the Halse Water is supported by a review of the field-derived RHS data. Excessive deposition of fine material is not a significant issue in this semi-natural watercourse, with bed material predominantly gravel, and many reaches have dynamic morphological features such as eroding banks and in-channel sediment bars. The majority of modification is linked to the presence of culverts (rail and road), bank reinforcement and re-sectioning, and presence of bridges and small weirs.

The majority of culverts, road bridges and bank re-sectioning/reinforcement associated with these structures and the urban areas will be difficult to remove. However, under the WFD all weirs are being reviewed, and it appears that the majority of weirs through the Halse Water and small, historic structures designed to maintain water levels (for floodplain inundation) or control flow splits, which are probably not necessary anymore. Removal of these structures would enhance habitats in terms of fish passage and de-fragmenting habitats.

It is considered that the Halse Water system in terms of sediment continuity is consistent with, and appropriate for describing, the other upper catchment watercourses including the upper Tone, Hillfarrance Brook and other headwater streams.

7.3.2 Lower River Tone

The lower River is categorised as a sediment transfer and sink system. The first major weir on the system, French Weir, is a significant constraint on the downstream migration of coarse (gravel and larger) bed-material load. The sediment modelling suggests that wash-material load has no impact on the upstream reaches, with the majority of material passing over the weir. However, the upstream reaches are controlled by bed-material load, with elevated loads predicted to deposit within this reach. It appears that coarser bed-material has deposited to form a wedge behind the weir, which probably extends upstream until it intercepts the natural bed gradient, while bed-material load is predicted to drop-out as it reaches the backwater effect of the weir.

This weir interrupts migration of bed-material load causing the river to abruptly change from a gravel-dominated channel upstream of the weir to a sand-dominated channel downstream. French Weir is a historic structure constructed to maintain water levels for large mills that once operated here. However, under the WFD the role of this weir is being reviewed and it may be removed. This would re-connect bed-material migration from upstream to downstream, and would allow coarser bed-material load to move into and deposit within the downstream reach through Taunton. This would extend the coarser bed material further downstream to Firepool Weir, which would then interrupt bed-material load. This would enhance river substrate in Reach T3, but could have implications for flood risk within Reach T3 (see Section 7.2), particularly if sediment accumulation was concentrated at French Weir or Town Bridge. Probably of more concern would be the lowering of bed elevation in the upstream reach (Reach T2 and possibly T1), which could lead to de-stabilising of banks, through undercutting, or a disconnection between the river and adjacent off-line storage at Longrun Farm as the over-spill weir becomes more perched.

Currently, sediment comprising the sand fraction and smaller continues to pass over and through French Weir. Coarse sand is predicted to deposit within the reach through Taunton, and field-based observations support this prediction by identifying deposition of coarse sand immediately upstream of Firepool Weir and on the banks at Town Bridge. The sand deposition appears to have created an underwater sediment wedge within the main channel extending approximately 200m upstream of the weir, while in the over-widened section adjacent to the entrance to the Taunton and Bridgwater canal (Figure 4.9) large sediment deposition bars have formed. These deposition features have created islands that have now stabilised and currently support mature vegetation. These islands have established since the channel was modified in the 1960s as part of flood defence works, and it is likely that the channel would reach equilibrium if deposition remained un-checked.

Within this reach these depositional features provide some of the only submerged and emergent vegetative habitat within the channel, and as such could be viewed as a positive feature. However, the sediment deposition provides an ongoing maintenance issue, which requires periodic dredging of a channel to ensure access to the canal entrance is maintained. Firepool Weir is constructed to maintain water levels for navigation, and as such cannot be removed.

Finer sands, silts and clays continue downstream. Under the majority of normal to high fluvial flows, which are not tide-locked or backed-up through operation of the tidal sluice, this material will be maintained as wash-material load and exported to the tidal reaches. However, some deposition of finer sand and silt is predicted to occur both around Ham Weir and in the lowest reaches under certain hydraulic conditions, for example, when fluvial flow is backed up by tidal influence or through the operation of the tidal sluice. In the lowest reaches the majority of sediment deposition is predicted to be on the banks, which is supported by historic dredging activity which has been used to agitate sediment off the banks to be re-entrained into the main channel flow. However, there is the occasional vegetated in-channel bar and side-bar that forms in the lower fluvial reaches, which again provide some of the only in-channel habitat features in this location.

The discontinuity of coarse bed-material load movement, which is the primary driver for river morphology, within the upper reaches of the lower River Tone is supported by a review of the field-derived RHS data, which identifies that the river is categorised as predominantly unmodified in the upper reaches and severely modified downstream of French Weir (between Reach T2 and T3).

Excessive deposition of fine wash-material load is not a significant issue in the upper reaches, which are classed as semi-natural watercourse, with bed material predominantly gravel and having dynamic morphological features such as eroding banks and in-channel sediment bars. Downstream of French Weir (Reach T3 and below) the majority of modification is linked to the ubiquitous re-sectioning of the channel combined with widespread presence of embankments and structures such as bridges and weirs. Sedimentation was not highlighted as a specific issue, but this is due to the majority of the riverbed being recorded as ‘not visible’ during the survey. The fine bed material in the middle reaches is no doubt contributing to the impacted nature of the river system through a reduction in geomorphic complexity/habitat diversity, as described by Bartley and Rutherford (2005), but management of the sediment at source is unlikely to significantly affect the RHS scores given the significant levels of modification associated with flood defence. Furthermore, the deposition of material is contributing to some of the only in-channel habitat present in the lower reaches of the fluvial River Tone. The process of plant seed/propagule transport and vegetation development/stabilisation within sediment modelling is currently poorly integrated and requires further research.

The majority of structures, bank re-sectioning/reinforcement and embankments will be difficult and impractical to remove. However, under the WFD all weirs are being reviewed, and it appears that the French Weir could be removed as its original function is no longer required. Removal of this weir would enhance habitats in terms of enhanced bed material in the next reach downstream and potentially by providing additional in-channel features, but could have adverse flood risk impacts both downstream and upstream as already discussed. Migration of fish upstream will still continue to be hampered by the presence of Firepool Weir that cannot be removed (although it is fitted with a fish pass). Although a benefit for river status under the WFD, it is doubtful whether it would greatly affect RHS habitat modification score given the high level of channel modification associated with the flood defences.

7.4 Land and river quality

7.4.1 Introduction

SIAM, supported by empirical evidence, predicts a wash-material load of approximately 10,000 - 15,000 tonnes/year delivered from the upper River Tone and Halse Water sub-catchments that enters the lower River Tone. The Halse Water model predicts approximately 10% of the total wash-material load leaving the upper catchment is derived from bed material, and thus approximately 9,000 – 14,000 tonnes/year of wash-material load is derived from the upper Tone and Halse Water catchment (290 km^2). This includes contributions from arable, pasture, river banks and road verges.

7.4.2 Land quality

The major impact on land quality is through the physical loss of soil and accompanying nutrients, which results in the need for additional amount of artificial fertiliser to maintain fertility. A loss of an average 12,000 tonnes of soil per year from the catchment equates to 41 tonnes/km^2/year, which is the equivalent of 0.41 tonnes/ha/year.

Therefore, in a decade 4.1 tonnes of soil per hectare has been lost from the upper catchment. In the last 60 years, since World War II which saw the start of intensive agricultural practices, this equates to a loss of an average of 25 tonnes of soil per hectare. Using a 1.5 tonnes/m^3 average silt density conversion rate, this tonnage of soil loss equates to 16.5m^3/ha, or a loss of 1.65mm soil/ha (range 1.2 – 1.9mm based on 9,000 – 14,000 tonnes/year).

Using the data from the sediment fingerprinting (see Section 5.3.5) the average percentage contributions of each land use type in the catchment to total sediment yield can be derived. This information combined with land use percentage cover and river channel lengths of the upper Tone catchment can yield information on the total soil loss from the sediment sources of arable, pasture and river bank.

Arable land is assumed to contribute 40% of the total wash-material sediment load, which on average is 4,800 tonnes/yr. Arable covers approximately 40% of the total upper Tone catchment, which is 116 km^2. Therefore, arable land loses on average 0.41 tonnes of soil per hectare, which since World War II equates to a loss of an average of 25 tonnes of soil per hectare, which is 16.5m^3/ha or a loss of 1.65mm soil/ha.

Pasture is assumed to contribute 20% of the total wash-material sediment load, which on average is 2,400 tonnes/yr. Pasture covers approximately 55% of the total upper Tone catchment, which is 160 km^2. Therefore, pasture loses on average 15 tonnes of soil per km^2, or 0.15 tonnes of soil per hectare. Since World War II this equates to a loss of an average of 9 tonnes of soil per hectare, which is 6m^3/ha or a loss of 0.6mm soil/ha.

River banks are assumed to contribute 25% of the total wash-material sediment load, which on average is 3,000 tonnes/yr. There is approximately 100km of river channel (200km of river bank) in the upper Tone catchment upstream of Taunton (upper Tone, Halse Water, Back Stream and Hillfarrance Brook). Therefore, river banks lose on average 30 tonnes of soil per km of river channel, or 0.03 tonnes of soil per m of river channel. Since World War II this equates to a loss of an average of 1.8 tonnes of soil per m of river channel, which is 1.2m^3/m river channel or 0.6m^3/m river bank. If it assumed that on average river banks are 1.5m high, then since WWII each metre of river bank has eroded on average by 400mm.

Sediment monitoring work undertaken on behalf of the Environment Agency (Partrac, 2009a and b) suggests that the ratio of sediment delivery from the

River Tone catchment to the River Parrett catchment is 3:7. Therefore, for every 12,000 tonnes/year delivered from the upper catchment of the River Tone, it can be estimated that the upper Parrett catchment could deliver 28,000 tonnes/year, which equates to a total average soil loss of 40,000 tonnes/year. This means that since WWII approximately 2,500,000 tonnes of soil may have been eroded from the Tone and Parrett catchments, with the sediment modelling undertaken as part of this research predicting that the majority of this sediment is exported as wash-material load to the tidal reaches and downstream to Bridgwater.

7.4.3 River water quality

The erosion of soil in the upper catchment of the River Tone and delivery of sediment into the fluvial system has both direct and potentially indirect impacts on water quality.

Direct impacts are linked to the delivery of phosphate, used as an artificial soil fertiliser, into the river system through association with the sediment runoff. Phosphate was found in association with sediment deposits behind both Firepool Weir and Ham Weir (Hooper, 2012). The high levels of phosphate are the primary cause of river status failure under WFD, leading to the stretch of the River Tone above Taunton being classified as a eutrophic sensitive area. Soil degradation and erosion, which is estimated to be approximately 720,000 tonnes or 25 tonnes/ha since WWII, provides a two-fold impact on water quality. Eroded soil not only acts as the vector delivering phosphate to the watercourses, but the physical loss of soil and associated nutrients exacerbates the loss of soil health/fertility and therefore requires additional artificial fertiliser to be applied to maintain soil viability.

There is a possibility the soil erosion and sediment delivery to watercourses could also be introducing high levels of other chemicals, such as herbicides/pesticides, which could adversely affect the river biota. Suppressed ecology is another key cause for failure under WFD associated with the upper Tone and its tributaries. However, no information is available on the level of pesticides in the watercourse.

A contamination study undertaken on behalf of the Environment Agency (Partrac, 2009c and d) found high levels of heavy metals (cadmium and zinc), Polycyclic Aromatic Hydrocarbons (PAH) and Total Hydrocarbons associated with sediment at the tidal limit at Newbridge. Older/deeper deposits of sediment behind Firepool Weir were found to be associated with polychlorinated biphenyls (PCBs), although concentrations met water quality standards (Hooper, 2012). The source of recent contamination was generally not the upper, rural catchment but instead industrial sites and major roads associated with Taunton, and thus erosion from the upper catchment is not directly linked to the delivery and presence of these contaminants and water quality impact.

Nevertheless, the loss of soil from the upper catchment may have an indirect impact on water quality, particularly in the lower reaches of the River Tone downstream of Taunton. Sediment modelling has demonstrated that sediment derived from the upper catchment does have the potential to deposit in lower reaches of fluvial system under certain hydraulic conditions, building up on the banks of the lower River Tone, and certainly forms the major component of the wash-material load sediment delivered to the tidal reaches. Both scenarios, but especially the delivery of fluvially-derived sediment into the tidal reaches, may contribute to the need for additional or more frequent dredging to maintain channel capacity, which is certainly the belief of local residents (see Section 4.3), and which could therefore lead to the disturbance and mobilisation of contaminants.

Sediment monitoring on behalf of the Environment Agency (Partrac, 2009a and b) suggests that sediment delivered from the Tone and Parrett fluvial system downstream into the tidal system is approximately 200 tonnes/day, while sediment which is delivered upstream from estuarine sources at Bridgwater is approximately 1,400 tonnes/day, giving a ratio of 1:7 between fluvial and estuarine inputs.

Therefore, for every 12,000 tonnes of sediment delivered from the upper Tone each year, it can be estimated that approximately 84,000 tonnes of sediment each year are delivered from downstream estuarine sources. This means that since WWII approximately 700,000 tonnes of sediment have been delivered from the fluvial Tone compared to approximately 5,000,000 tonnes from estuarine sources. Using the sediment delivery ratio for the Tone : Parrett (3:7), suggests that since WWII approximately 2,500,000 tonnes of sediment have been delivered to the tidal reaches of the River Parrett from the upstream fluvial systems (Tone and Parrett combined), compared to approximately 17,500,000 tonnes of sediment derived from downstream estuarine sources.

As discussed in Section 7.2, the impact of sediment derived from the fluvial system on morphology and flood risk in the tidal zone of the Parrett is outside the scope of this research. Therefore, it is impossible within this research to state whether excessive sediment delivery from the upper catchments and exported from the fluvial reaches ultimately leads to the need for additional dredging (or whether this affect is over-ridden by delivery of sediment from estuarine sources). However, what is known for certain is that due to the presence of contaminants the need for dredging will need to be assessed in relation to the potential adverse impacts on estuarine sites of European importance (i.e. Special Protection Areas).

A pragmatic view would need to be taken on whether the benefits of managing soil erosion in the upper catchment for the specific benefit of reducing morphological and flood risk impact in the tidal reaches was cost-effective. However, given that there appear to be primary benefits associated with management of the upper catchment to reduce soil erosion to maintain or improve soil health/fertility, manage and reduce high levels of nutrients in the watercourses leading to excessive eutrophication, and potentially manage other chemicals such as pesticides entering the watercourses, it would seem that a reduction in sediment delivered to the fluvial River Tone and tidal reaches would be achieved as a secondary benefit.

7.5 Defining integrated catchment management

7.5.1 Drivers for catchment land and sediment management

The Foresight Flooding project (Evans *et al.*, 2004a; Evans *et al.*, 2004b; Evans *et al.*, 2008) identifies the drivers of flooding that would affect 'fluvial systems and processes', and there are obvious links to the drivers for land use management (see below):

- *Environmental regulation*: environmental regulation has shifted river management towards meeting a range of environmental objectives, and will restrict future flood management activities such as dredging, hard defences etc;

- *River morphology and sediment supply*: climate-related changes in sediment delivery processes should be given greater emphasis, particularly as research has shown that sediment delivery is strongly influenced by high-intensity, short-duration rainfall events and is independent of the level of catchment saturation. Downstream movement of sediment may reduce the conveyance of lowland channels and flood defence functions; and

- *River vegetation and conveyance*: there is a dichotomy of views regarding channel dredging with the general public perception being that flooding may occur or be exacerbated due to lack of maintenance, while the EA view is that rivers naturally over-spill onto floodplains at high flows.

The Foresight Land Use Futures: Making the most of land in the 21st Century (Foresight Land Use Futures, 2010) project identifies six major drivers of changes in land use over the next 40 years. These include in summary:

- *Demographic change*: increase in population and increasing demand on housing and infrastructure;

- *Economic growth and changing economic conditions*: future economic growth implies an increase in consumption leading to greater demands on land, influencing the amount of land used for food production and intensity with which it is farmed;

- *Climate change*: the move to a low carbon economy and society's adaptation to climate change will affect decisions about land management;

- *New technologies*: may enable society to further increase the productivity of land whilst reducing the pressure on the environment;

- *Societal preferences and attitudes*: interacting with other drivers and may result in conflicting demands; and

- *Policy and regulatory environment*: direction of future EU policy and UK governance will have a profound influence on how land is used.

These drivers will influence the amount of land under agriculture, the primary use of agricultural land, the intensity of its use, and the way the land is managed in the future. Potentially, more land could be managed more intensively to meet a growing demand for agricultural crops and products.

These drivers will, in turn, have a profound effect on the status of soil, the potential for enhanced or reduced rainfall runoff, and the vulnerability of soil to degradation, erosion and delivery to watercourses. It is possible that left unchecked soil erosion and delivery of sediment to rivers will increase, and predicted climate change is likely to exacerbate the situation due to more intensive and more frequent water runoff. The sediment modelling presented in this thesis clearly demonstrates the important inter-relationship between runoff and sediment yield, the combination of which determine any future morphological response of a river, particularly lowland rivers, to altered wash-material and bed-material loads. As demonstrated, morphological response drives subsequent impacts on river users and uses, including potentially flood risk, habitats/biodiversity and water quality, as well as the requirement for management intervention.

7.5.2 Key legislation and policies for sediment management

Results of the sediment modelling on the fluvial River Tone system suggest that excessive amounts of wash-material load delivered from the upper catchment has negligible impact on morphology in the upper channel network (Halse Water and upper River Tone), but that excessive wash-material loads pass downstream to produce some adverse impacts on channel morphology, water quality and other river functions, particularly navigation, in the lower reaches of the fluvial system. However, these impacts are spatially and temporally localised.

Impacts associated with flood risk are negligible under realistic morphological change scenarios with flood risk to people and property remaining unchanged, although there is an increase in frequency, depth and duration of natural floodplain inundation and standards of defence are generally lowered. There is potential for off-line flood storage functioning in the upper catchment at Longrun Farm within Reach T1/T2 (see Section 7.2.2) to be compromised, through earlier over-topping of spillway and/or filling with sediment, if bed elevations in this reach rise due to delivery of elevated quantities of coarse bed-material load sediment from the upstream catchment due to de-stabilisation of the channel network by inappropriate catchment management or future climate conditions.

Sediment and flood risk modelling predict no measurable change to flood risk (frequency, depth or duration) associated with Currymoor flood storage area under all but the most extreme morphological change when flood water levels are only increased by 0.01m for flood events of 1 in 10 or greater. The flood storage area could be impacted by increased quantities of sediment entering and depositing within the floodplain, but key issues appear to be related to water-logging and rotting of vegetation due to long-standing water as opposed to smothering by sediment, which is not raised as a specific issue at this location. However, further research into this topic is recommended.

Impacts associated with sedimentation, morphological change and flood risk within the tidal reaches of the River Tone and Parrett is outside the scope of this research. However, this should be the subject of further investigation as this forms the major focus of the local community post-2012 flooding. Any investigation of sources and impacts of sediment in the tidal zone should include an assessment of the potential for excessive sediment accumulation, with implications for water quality, habitats and ecology, within the European designated nature conservation sites located in the estuarine zone of the River Parrett.

Regardless of the predicted limited impacts on flood risk due to morphological change in the fluvial River Tone, there are strong reasons to manage and reduce the amount of soil erosion in the upper catchment and sediment delivery to the river channel network, which is estimated in this study to currently be on average between 10,000 – 15,000 tonnes/year.

Primary reasons for altered management of the upper catchment relate to water quality, which includes the delivery of high levels of nutrients, especially phosphate, and potentially contaminants such as herbicides and pesticides, to downstream reaches of the river system. In addition, excessive delivery and accumulation of sediment may contribute to the need for periodic dredging in the lower river reaches, particularly within the tidal zone, which could also mobilise other industrial contaminants such as heavy metals and PAHs.

Another primary reason for altered catchment management is the sustainable use of the land and protection of the soil resource to maintain soil health/fertility and agricultural viability, which also would have a knock-on effect for water quality in that it would probably also reduce the reliance on, and increased need for, the use of artificial fertilisers to maintain the productivity of the land.

Furthermore, the sediment modelling has demonstrated that although there is potential for deposition of wash-material load in the lowest reaches of the fluvial River Tone system under certain hydraulic conditions (i.e. when flow is tide-locked), in general the majority of the wash-material load passes through the fluvial system and into the tidal zone. The cumulative terrestrial inputs from the River Tone catchment, probably equates to about 700 tonnes since World War II, but this is less significant when compared to the total cumulative terrestrial input to the tidal zone from the River Parrett catchment as a whole (i.e. all fluvial rivers), which is in the order of 2.5 million tonnes. While the terrestrial input of sediment is small compared to that derived from downstream, estuarine sources it is possible that fluvial sediment could still be contributing to adverse impacts associated with morphological and flood risk change in the tidal river, and water quality/contamination of European designated nature conservation sites in the estuarine zone.

Therefore, catchment sediment management within the River Tone catchment will be strongly influenced by and primarily controlled by legislation and policy relating to sustainable use of resources and the natural environment; water quality; and soil quality.

Fluvial flood risk management is unlikely to be a primary driver for management of finer wash-material sediment delivery to the River Tone, although secondary or tertiary flood risk benefits may be realised through the implementation of appropriate catchment sediment management. However, tidal flooding may be a stronger driver in the River Tone and Parrett catchment, which may be exacerbated by fluvial sediment, and needs further investigation.

Finally, the weak association between catchment sediment delivery and predicted morphological change, and flood risk in the fluvial River Tone may not be the case for all river systems. This highlights the importance of undertaking a similar investigation for river systems on a catchment-by-catchment basis.

The UK Sustainable Development Strategy (HM Government, 2005) establishes the need to live within environmental limits, while the White Paper on the Natural Environment (HM Government, 2011) seeks to safeguard and restore the natural environment by supporting natural systems to function more effectively. This vision specifically includes: safeguarding soils and restoring nature in rivers.

The Water Framework Directive (2000/60/EC), which enshrines other nature conservation Directives, for example, the Habitats Directive, underpins the legislative framework within the UK intended to improve the chemical, morphological and ecological states of waterbodies, and to encourage sustainable river and water resource management. The WFD specified that all waterbodies must reach at least 'good' status by 2015, but recognised that for practical reasons it may take two further 6-year planning cycles for this to be achieved. A derogation is possible for waterbodies designated as being 'heavily modified' (HMWB), even cases where it is impractical to restore the HMWB to achieve 'good ecological status' due to excessive costs, technical infeasibility or because this would be against the public interest, modifications to flood defence structures, operations and maintenance are required to meet the WFD standards.

The draft European Soil Framework Directive (SFD), which is still under consultation, seeks to achieve the protection and sustainable use of soil, which is taken to be not just the prevention of impacts associated with soil erosion but recognises the intrinsic value of soil as a valuable resource.

The main mechanisms for achieving the WFD and the vision of the SFD in terms of catchment land (soil) management within the UK are the Environmental Stewardship (ES) scheme and the Catchment Sensitive

Farming (CSF) initiative, which in the south west of England is also supported by the Soils for Profit Project (S4P). The ES has a primary objective to protect natural resources (including reduction of water and sediment runoff) through monetary incentives to land owners/managers to implement appropriate land management actions. The CSF has a primary objective to reduce soil erosion and diffuse pollution through education and implementation of farming best practices to reduce both on-site and off-site impacts.

Legislation and policy relating to fluvial flood risk management, although is not a primary driver for catchment sediment management in the River Tone (which may not be the case in all rivers) does, nevertheless, necessitate flood risk management to maintain and restore natural processes, and there is a growing awareness that this should include catchment sediment management (not exacerbating or proactively reducing soil degradation, soil erosion and sediment delivery to rivers).

Even if the main focus of flood risk management in the catchment is the appropriate management of surface water runoff, which may include the increased retention of water on the land and management to reduce rainfall runoff, the sediment modelling undertaken during this research has clearly demonstrated that management of surface water cannot be undertaken in isolation from sediment management, as both are inter-related, and changes in water runoff and flow are likely to have implications for the sediment system, channel morphology and interactions with other river uses, including flood risk management to some degree at some locations.

7.5.3 Balancing management of water and sediment runoff

It is possible to conceive three main future scenarios for land use management in the upper catchment that would affect runoff, river flows, soil erosion and delivery of wash-material sediment to the river channel network, as follows:

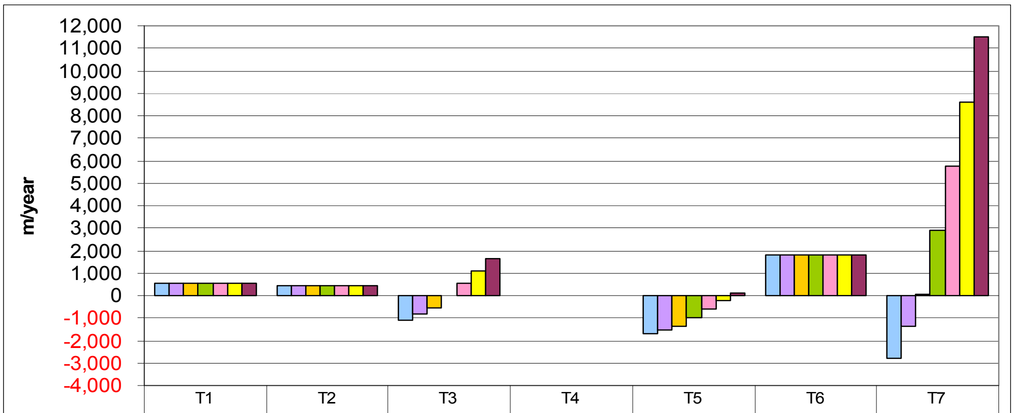
1. Implement land management to reduce soil erosion and the total amount of wash-material sediment delivered to the channel network, with the primary aim of achieving downstream water quality targets and maintaining soil condition and productivity, while mitigating the adverse impacts of climate change;

2. Implement land management to reduce the amount of runoff with a corresponding reduction in river discharges throughout the channel network, with the primary aim of achieving and sustaining downstream flood risk objectives despite the adverse impacts of climate change; and

3. Maintain or further intensify current land use management practices to increase production despite increasing runoff and river flows, which are predicted under future climate change.

Scenarios 1 and 2 are to a certain extent linked, as management to reduce sediment delivery to rivers is likely to reduce runoff, and *vice versa*. Scenario 3, as noted previously, is likely to lead to an increase in sediment delivery to rivers due to more frequent, extreme rainfall events eroding more soil.

Scenario 1 dictates a reduction in sediment delivery to the channel network. If sediment is managed in isolation from rainfall runoff and flow, the results on channel sediment dynamics is seen in Figure 7.20. Morphological implications are based on information presented in Section 7.1.



	T1	T2	T3	T4	T5	T6	T7
0 wash load	548	443	-1,103	0	-1,726	1,809	-2,808
2.5k wash load	548	443	-826	0	-1,540	1,809	-1,378
5k wash load	548	443	-548	0	-1,355	1,809	51
10k wash load	548	443	5	0	-984	1,809	2,912
15k wash load	548	443	559	0	-613	1,809	5,771
20k wash load	548	443	1,112	0	-242	1,809	8,630
25k wash load	548	443	1,666	0	129	1,809	11,500

Figure 7.20 SIAM local sediment balances (tonnes/year) for sediment reaches in the lower River Tone under different annual wash-material loads

Starting with a wash-material load of 15,000 tonnes/year, a reduction to 10,000, 5,000 and 2,500 tonnes/year are predicted to result in the following changes in river reaches sensitive to altered wash-material load:

- Reach T3 converts from a low-level sediment sink to a low-level sediment source (although remains morphologically stable throughout);

- Reach T5 becomes an increasing sediment source, with bank retreat increasing from 0.07m/year up to 0.18m/year; and

- ❖ The increased erosion at Reach T5 results in the downstream Reach T7 converting from a sediment sink (bank advance at 0.13m/year) through to maintaining morphological parity at ~5,000 tonnes/year, before converting to a sediment source at very low levels of wash-material load (bank retreat at 0.07m/year).

A low-moderate reduction in wash-material load is therefore unlikely to cause major or de-stabilising morphological shifts in the river channel downstream under the current flow regime. However, future climate change is predicted to increase river flow, which could de-stabilise the situation, for example by further increasing erosion in both Reach T5 and T7 (Table 7.5).

To maintain long-term sediment and geomorphic stability any low-moderate reduction in sediment yield should be accompanied by management of runoff which leads to a moderate reduction in flow (e.g. 10% reduction), see Table 7.4.

River Reaches	Actual flow				Flow minus 10%				Flow minus 20%			
	5k wash	10k wash	20k wash	25k wash	5k wash	10k wash	20k wash	25k wash	5k wash	10k wash	20k wash	25k wash
T1	547	547	547	547	647	647	647	647	734	734	734	734
T2	443	443	443	443	349	349	349	349	265	265	265	265
T3	-344	416	1,935	2,693	-26	734	2,253	3,011	230	990	2,509	3,267
T4	0	0	0	0	0	0	0	0	0	0	0	0
T5	-1,429	-1,130	-535	-237	-1,085	-786	-191	107	-757	-459	136	434
T6	1,809	1,809	1,809	1,809	1,393	1,393	1,393	1,393	1,032	1,032	1,032	1,032
T7	-89	2,631	8,067	10,800	418	3,137	8,573	11,300	883	3,603	9,039	11,800

Table 7.4 SIAM local sediment balance (tonnes/year) for River Tone sediment reaches with decreased flow

If a major reduction in sediment delivery was achieved, for example reducing wash-material load from 15,000 tonnes/year to 2,500 tonnes/year, then, without commensurate runoff control, Reaches T5 and T7 have the potential to increase the amount of erosion already occurring, becoming sediment source reaches. This could increase scour at the bed and bank toes to undermine banks, river embankments and flood defence structures/assets. This situation would be worsened with predicted climate change, due to increasing peak river discharges (Table 7.5).

To maintain parity with the existing morphological situation and to off-set future climate change, management of runoff to achieve a high reduction in flow (e.g. 20% or more reduction) would be required.

If management of surface water and flows are considered in isolation, as in Scenario 2, and a major (i.e. 20%) reduction in flow is achieved whilst still maintaining the current level of wash-material sediment delivery (i.e. 15,000 tonnes/year) to the watercourse (Table 7.4) then it can be seen that:

- Reach T3 will increase the amount of sediment depositing (although remaining morphological stable);

- Reach T5 will begin to reach morphological stability; and

- Reach T7 will double the amount of sediment depositing on each river bank/year, although as stated this will only be at certain times, for example, when the flow is tide-locked.

To maintain a level of parity with the current sediment and morphological regime, it is necessary to invoke some level of sediment management, but only a low-moderate level of reduction in sediment yield is necessary.

It is, therefore, essential that management to reduce wash-material sediment delivery in the upper catchment must be accompanied by appropriate management of runoff, particularly to off-set the hydrological impacts of predicted future climate change. Runoff, left un-checked, could lead to a de-stabilisation of the sediment system in the long-term as wash-material load is reduced but flows are increased.

It is, however, not as critical to manage wash-material sediment delivery when implementing management to target control of run-off to reduce flows because actions to control runoff are also likely to result in a decrease in wash-material sediment delivery to the river system.

What is of greater interest when assessing the implications of reduced flow is the predicted increase in deposition of coarser bed-material load within Reach T1 of the River Tone. The model predicts an accompanying decrease in bed-material load deposition in Reach T2, but in practice deposition is likely to be spread across both reaches. However, a shift in sedimentation could lead to an imbalance in these reaches in the long-term, which could have implications for the operation of the off-line flood storage area at Longrun Farm. These reaches are dominated by bed-material load, and therefore reductions in runoff need to be accompanied by a strategy to manage/reduce bed-material load delivered from the upper catchment, especially by avoiding or reducing de-stabilisation of channels and banks. However, management actions to reduce runoff are also likely to lead to more stable river channels and banks, with a subsequent reduction in coarse bed-material load.

Scenario 3 imagines a future where river flow is increased due to agricultural intensification coupled with increased runoff due to climate changes (Table 7.5). Under this scenario:

- ❖ Additional bed material is eroded from Reach T1 and deposited in Reach T2;
- ❖ Erosion increases in Reach T3 although the reach stays morphologically stable;
- ❖ The rate of erosion is increased in Reach T5 resulting in increased deposition of material in Reach T6; and
- ❖ In Reach T7 the rate of deposition at certain times is reduced and more of the bed-material load is exported to the tidal reaches.

River Reaches	Actual flow				Flow plus 10%				Flow plus 20%			
	5k wash	10k wash	20k wash	25k wash	5k wash	10k wash	20k wash	25k wash	5k wash	10k wash	20k wash	25k wash
T1	548	548	548	548	437	437	437	437	317	317	317	317
T2	443	443	443	443	547	547	547	547	660	660	660	660
T3	-548	5	1,112	1,666	-927	-373	733	1,288	-1,373	-819	287	842
T4	0	0	0	0	0	0	0	0	0	0	0	0
T5	-1,355	-984	-242	129	-1,728	-1,357	-615	-244	-2,117	-1,746	-1,004	-633
T6	1,809	1,809	1,809	1,809	2,294	2,294	2,294	2,294	2,842	2,842	2,842	2,842
T7	51	2,912	8,630	11,500	-524	2,337	8,055	10,900	-1,159	1,703	7,421	10,300

Table 7.5 SIAM local sediment balance (tonnes/year) for River Tone sediment reaches with increased flow

The increase in runoff and flow is unlikely to cause major sediment and geomorphic shifts downstream. However, of greater concern is that this scenario is likely to lead to greater amounts of coarser wash-material load being delivered to the river network as well as potentially leading to the instability of the upper channel network, which could lead to an increase in the amount of bed-material load supplied to the lower River Tone. This situation is likely to lead to major impacts on sediment and morphological stability in downstream river reaches, potentially leading to adverse impacts on function and operation of flood defence structures and flood storage areas.

Any predicted increase in runoff and flow should be accompanied by a strategy to manage/reduce both wash-material load and bed-material load delivered from the upper catchment.

The outputs from the sediment modelling clearly demonstrate the linkages and relationships between runoff, sediment delivery, flow, sediment balance and morphological consequences within the river network. As identified by numerous research findings (e.g. O'Connell *et al.*, 2004, Newson, 2010; Thorne *et al.* 2010b and c; Wainwright *et al.*, 2011; and Wilkinson *et al.*, 2011) this requires an integrated approach to the management and control of surface water runoff and sediment runoff at the catchment-scale.

7.5.4 Mechanisms to manage water and sediment runoff

Wood and Armitage (1999) state the most desirable way to mitigate problems associated with fine sediment problems within lowland rivers is to prevent the sediment influx, and much research has gone into assessing the effectiveness and appropriateness of various techniques to stop sediment entering rivers. Numerous studies (e.g. Barling and Moore, 1994; Bielders *et al.*, 2003; and Verstraeten *et al.*, 2006) have concluded that control of sediment runoff should, primarily, be achieved at source through alternative farming practices, which is then supported where needed by enhanced river riparian vegetation and use of buffer strips (watercourse buffers). Henshaw (2009) concluded that inappropriate land use management has the potential to alter catchment hydrology and thereby de-stabilise the channel network leading to an increase in suspended, wash-material load, sediment and bed-material load sediment. The corollary is that altered land use management could be used to reduce sediment inputs by maintaining the integrity of the channel network. Watercourse buffers alone are unlikely to lead to a major reduction in soil delivery to watercourses at the catchment scale, because although they can be highly effective at the field-scale they have a much reduced effectiveness at the catchment-scale (Verstraeten *et al.*, 2006) due sediment bypassing buffers via ditches, sewers and roads, and numerous sources in the channel network which cannot be buffered.

Within the Tone catchment this integrated approach is advocated. Reviews by Evans (1996), Godwin and Dresser (2000), and Morgan (2006) all advocate improving soil management to reduce soil erosion and delivery to rivers, particularly the very fine-grained material (i.e. fine silt and clay). Evidence suggests that the following practices can have a beneficial impact and should be implemented where practicable:

- Reducing field sizes and using judicious planting of trees and hedges to interrupt flow of water and sediment (Downs and Thorne, 1998; Evans, 2006);

- Minimising soil disturbance, appropriate timing of cultivation, and improving soil quality;

- Increasing the roughness of the soil by using mouldboard ploughing, and shallow ploughing to intercept and redistribute runoff;

- ❖ Maintaining appropriate livestock density and grazing livestock higher up field slopes to allow runoff to infiltrate into non-compacted areas lower down;

- ❖ Implementing mixed farming, improving crop rotations, maintaining a ground cover crop, and applying surface litter to protect the soil from capping; and

- ❖ Maintaining farm tracks and pathways in good condition, which could include hard-standing/paving etc.

In addition to the alterations to farming practice the use of watercourse buffers (restored riparian vegetation or buffer strips) to intercept water and sediment runoff have been widely used and studied (refer to section 2.4.2). Within the upper Tone catchment it is recommended that watercourse buffers are created, particularly along first and second order watercourses as the majority of drainage moves through these channels. Critical locations for watercourse buffers include arable land, but where land drains are present, which could include pasture, sub-surface drainage flow should be re-directed overland and through watercourse buffers (Gilvear *et al.*, 2010). Buffers should be a minimum of 5m wide, which is where the majority of sediment drop-out occurs, and support a diverse habitat of native vegetation, preferably dominated by grasses, sedges and other herbaceous plants.

Evidence, including research into the effectiveness of buffer strips in the upper Tone catchment (Owens *et al.*, 2007), suggests that buffer strips are highly effective at preventing medium-coarse silt, sand and larger grain sizes from entering the watercourse, which are the fraction of the wash-material load that has the greatest potential to affect channel morphology in downstream reaches.

Watercourse buffers are, however, less effective at preventing very fine silt and clay particles from passing through. This fine silt and clay fraction is likely to be the fraction enriched in nutrients, such as phosphate, and therefore to tackle diffuse pollution issues will also likely involve the farming community changing the way artificial fertilisers are used and/or applied to the land.

In addition to buffers situated along the top of river bank, river banks that are vulnerable to erosion or suffer from excessive poaching should be protected by fencing, and potentially re-grading, to allow vegetation to naturally re-establish to help stabilise banks. The presence of in-channel and bank-side vegetation is also an important factor in controlling fine sediment (Steiger *et al.*, 2001), and riparian vegetation is governed by channel morphology as well as presence/absence of dense shading. Therefore, in some areas of the upper catchment judicious tree removal/thinning to increase light penetration to the channel and to facilitate a diverse in-channel plant community may also be beneficial.

Drainage ditches and other small channels should be carefully managed to minimise mobilisation of fine sediment during clearance, and importantly maximise potential for sediment trapping, by carefully managing and staggering in-channel and bankside vegetation clearance. Connections between small drainage channels and the main watercourse should be designed to maximise sediment trapping, for example, creating a wide and shallow vegetated area through which flow would pass (analogous to a vegetated treatment system) which would be set back from the junction of the ditch and river, and set above the bed of the river. This is an approach advocated, although acknowledged untested, by Downs and Thorne (1998). The use of vegetated sediment traps or appropriate management of bankside and in-channel vegetation to maximise sediment trapping would also be important at road crossings or at locations where road run-off enters the watercourse, as roads are an important primary and secondary source of sediment.

It is suggested that the main mechanisms for implementing management actions to achieve a catchment vision to reduce or control water and sediment runoff within the South West are still the relevant agri-environment schemes, namely the Environmental Stewardship scheme, the Catchment Sensitive Farming initiative, and the Soils for Profit Project (which is supported by think***soils*** an Environment Agency initiative to help farmers assess soil condition), which use a combination of monetary incentives and education to change farming and land management practices. Therefore, the amount of landowners engaged with these initiatives should be maximised, with greater emphasis placed implementing actions that minimise water and sediment runoff and delivery to rivers. It has also been argued that the use of agri-environment schemes to re-connect and better manage land/habitats at the catchment scale can be enhanced by identifying farmers in priority areas and working with them on a one-to-one basis to align their needs with wider scale strategic thinking (Gilvear *et al.*, 2010).

Making Space for Nature (Lawton *et al.*, 2010) sets out a vision for restoring ecological networks based on landscape components, which include: 'core areas' (areas which contain rare or important habitats or ecosystem services), 'corridors' (habitat which allow species to migrate around the landscape and support ecosystem functions), and 'buffer zones' (habitat which protects core areas and corridors from adverse impacts). This concept is embedded within the recent White Paper for the Natural Environment (MH Government, 2011).

There is now an opportunity to designate all rivers in the UK as landscape 'core areas' and/or 'corridors' as they are important UKBAP habitats, with many also designated for wildlife under European and UK legislation, provide or support important and critical ecosystem services including water resources, flood management, recreation etc., and allow species to migrate through the landscape. If this classification occurred, all land adjacent to and, for example, within 5m of a watercourse, particularly the first and second order streams in the upper catchments, could be classed as a 'buffer zone'. These designations would instil a duty on riparian landowners to manage riparian land and the 'watercourse buffer zone' appropriately, in accordance with best practice guidelines, to minimise runoff, delivery of sediment and associated contaminants. A similar approach has recently been introduced in Denmark, where the Danish Government has prohibited the use of fertiliser within 10m of rivers and lakes as a means to reduce diffuse pollution from farming (Everett, 2012).

8 CONCLUSIONS

8.1 Key research findings and messages

The research presented within this thesis has focused on investigating linkages between sediment sources, water and sediment runoff, and downstream sediment sinks in a lowland river system to examine the role played by sediment in terms of morphology and flood risk management, while also establishing linkages to land and water quality (see Chapters 1, 2 and 3). Sediment dynamics, morphology and flood risk were investigated using a suite of data and assessment tools/models (see Chapters 5, 6 and 7), which were used to investigate various land use management and climate scenarios. The research was centred on the River Tone catchment in Somerset (see Chapter 4). This catchment has characteristics of many UK lowland rivers including size, geology, land use, morphology and physical modification, and thus research findings are broadly transferable to a wide range of UK lowland rivers.

Key research questions and objectives (Section 1.2) were established following a review of research outputs delivered by Flood Foresight (Evans *et al*., 2004a; Evans *et al*., 2008), the Flood Risk Management Research Consortium (e.g. Henshaw, 2009; Thorne *et al*., 2010b and c; Thorne *et al*., 2011) and others (e.g. Morgan, 2006; Lane and Thorne, 2007; Newson, 2010). This core scientific and catchment-management contribution of this research is to test the hypotheses (see Section 1.2) that excessive wash-material load can transition to bed-material load leading to significant effects on morphology and flood risk, which is best controlled at source. Other objectives of this research are to test and benchmark various sediment assessment tools, to aid scientists, modellers, catchment managers and other stakeholders in developing, implementing and interpreting robust sediment assessments. The key findings and messages, linked to the research questions/objectives, are provided in the following sections.

What is the role of wash-material and bed-material loads in the flow-sediment system, and how do they drive morphological response in a lowland modified river system?

How does sediment source-control and/or climate change affect the river flow-sediment system in terms of sediment continuity (sources, transfers and sinks) and subsequent channel morphology?

Headwater catchments, such as the Halse Water, are dominated by sediment supply and transfer (see Section 6.3.1). Headwaters are therefore insensitive to catchment sediment management, with alterations to the wash-material supply having little or no impact on local bed-material sediment balances, and subsequent morphology, because all available wash-material entering the river is transferred and exported to the mainstream river.

Catchment management or climate change which alters rainfall runoff can alter the magnitude of reach-scale erosion/deposition leading to an increase or decrease in the volume of exported sediment, which accords with the findings of others (i.e. Nietch *et al*. 2005; Collins and Owens, 2006). However, altered runoff does not change the pattern of sedimentation within, and between, sediment reaches in headwater systems, a finding which may be at odds with the common view (i.e. Schumm, 1969).

The middle and lower courses of rivers, such as the lower River Tone, are dominated by sediment transfer and storage (see Sections 6.3.2 and 6.4). Medium/coarse sand and larger particles are deposited, while clay, silt and fine sand fractions (representing ~90% of the total wash-material load) usually pass through to the tidal reaches. Potential impacts are therefore downstream from the source of sediment, which accords with the work of others (e.g. O'Connell *et al*. 2004), and probably the greatest potential impacts will manifest a significant distance downstream within the tidal zone.

Alterations in the quantity of wash-material load and/or volume of runoff due to upper catchment management or climate change can affect local sediment balances and channel morphology in the lower reaches, a finding which is supported by the literature (e.g. Schumm, 1969). However, deposition is both spatially and temporally localised because it is linked to back water effects and areas of slack water, which occur during in-channel and out of bank flows.

Care must be taken when interpreting predicted impacts. Not all changes to sediment fluxes and local balances will de-stabilise the fluvial system, as temporary changes in rates and patterns of sedimentation occur naturally, and predicted sedimentation patterns rarely persist unchanged in the longer-term.

Local sediment balance and consequential morphological impacts are specific to a given sediment reach (see Sections 6.3 and 7.1). The direction and scale of change depends on the sediment response in the reach immediately upstream as well as the original, causal change in rainfall runoff and/or sediment yield. This dictates that runoff and sediment dynamics must be managed in an integrated manner, aligning future flow and sediment regimes at the catchment-scale to avoid de-stabilising reaches that are currently balanced in terms of sediment and morphology.

The modelling and assessment of sediment dynamics and morphology (see Sections 6.3 and 7.1) establishes that the greatest sediment-related threats to the functioning of a lowland river, including the River Tone as well as probably many other lowland rivers in the UK, are predicted to arise from the following future scenarios (see Section 7.5.3):

- A major reduction in wash-material load combined with an increase in river discharge resulting in scour and degradation which, if protracted, could potentially threaten the stability of riverbanks and flood assets in the impact zone and de-stabilise the system downstream.

- An increase in bed-material load combined with a reduction in river discharge, resulting in deposition potentially leading to adverse impacts on the function and operation of flood defence structures and assets.

Do predicted changes in sediment dynamics, and subsequent changes in channel morphology, significantly affect inundation, flood risk or flood risk management actions?

Altered river morphology, manifesting through rising bed elevations or progressive bank accretion, can lead to a measurable impact on flood water elevations within the river channel, which will lead inevitably to some increases in the frequency, duration and depth of flooding (see Section 7.2), which accords with the work of others (e.g. Plate, 2002; Lane *et al.*, 2007).

However, as Thorne, 2011 identifies, there is a lack of understanding on the role sediments play in flood risk management and therefore, in accordance with the Flood and Water Management Act 2010, the impact of changes in sediment dynamics and morphology on people, property and other assets must be carefully considered. The importance of this is seen within the River Tone context where changes were restricted to an increase in flooding of un-developed floodplain or a lowered standard of service provided by flood defences. Yet, critically, modelled water elevation changes did not cause defences to over-top more frequently or reduce the operational effectiveness of large, lowland washlands; thus current levels of flood risk were maintained. This may be a common occurrence in lowland rivers.

Notwithstanding this, there are implications for flood risk management, operations and maintenance (see Section 7.2.5). This is particularly true where predicted increases in deposition of coarser sediment occurs at sensitive locations, for example, off-takes for flood storage areas or low spots in defences, when the operation and effectiveness of flood defence assets could be adversely affected.

The outcome of morphological and flood risk assessment of the River Tone (see Section 7.1 and 7.2) indicates that catchment-wide sediment management and/or large-scale channel maintenance (i.e. dredging) will not reduce fluvial flood risk. Therefore, these catchment and river management actions cannot be justified on the basis of flood risk management. This finding is likely to be the case for the majority of lowland rivers in the UK.

Within lowland rivers targeted channel maintenance may nevertheless be needed to periodically adjust the relative elevations of spillways, remove shoals or de-silt flood storage facilities to maintain current operational standards (see Section 7.2.5). The need for targeted maintenance must be based upon ongoing sediment monitoring in line with best practice sediment management protocols. For example, a future featuring elevated or larger calibre sediment loads is likely to lead to the need for more frequent sediment management intervention.

How does sediment management link to, and impact upon, river habitats, land quality and river water quality?

The unhindered connectivity of sediment transfer through the channel network in the upper reaches of the River Tone means excessive deposition of fine material is not a significant issue, and consequently, catchment-wide sediment management in isolation will have no direct impact on riverine habitats (see Section 7.3.1). Conversely, inappropriate runoff management could lead to increased sediment yield, via scour of bed and banks as described by Henshaw, 2009, with consequential impacts on habitats. Effort to enhance/remediate degraded river habitats should therefore be focused on rehabilitation of the river channel to de-fragment habitats and increase their resilience to changes in runoff.

Large weirs in the lowland system interrupt connectivity of bed-material load causing the river to abruptly change from a gravel-dominated to a sand-dominated channel, while medium-coarse sand deposits where back-water effects or slack-water occurs (see Section 7.3.2). Some deposition features have stabilised, now support vegetation and provide some of the only in-channel semi-natural habitat. Finer sands, silts and clays under the majority of fluvial flows are exported to the tidal reaches, although some deposition of finer sand and silt in the lowest reaches is predicted to occur when fluvial flows are backed-up due to tidal influence or the operation of in-channel structures (see Section 6.3.2). Management of elevated sediment yields at source is unlikely to significantly improve river habitat quality given the over-riding impacts of physical alteration of the channels within these highly modified reaches. Therefore, achieving habitat/ecology improvements should focus on management or removal of obstructions to biota and sediment, combined with creation, enhancement or stabilisation of in-channel features.

The major impact of elevated erosion on land quality is through the physical loss of soil and accompanying nutrients (see Section 7.4.2). Sediment modelling predicts in the order of 12,000 tonnes of soil is lost from the upper Tone annually, which up-scales to 40,000 tonnes per annum for the entire Parrett catchment (~2.5 million tonnes since World War II), with the vast majority of the sediment being exported to the tidal reaches. Soil erosion at this scale has significant impacts on water quality (see Section 7.4.3). Direct impacts include the delivery of phosphate, and potentially other chemicals, into the river system with excessive soil erosion requiring the application of additional fertiliser to maintain soil viability. Soil erosion from the upper catchment is not directly linked to the presence of industrial contaminants, however, this sediment has potential to deposit in the lower reaches and forms the major component of sediment delivered to the tidal reaches. Inappropriate sediment management may contribute to the need for more frequent channel maintenance and increased re-mobilisation of these contaminants within the Tone, as well as other urban, lowland rivers.

What are the key policies, legislation, schemes and actions to drive and deliver catchment sediment management?

The primary legislative/policy framework for catchment sediment management relates to the sustainable use of resources, protection of the natural environment, water quality and soil quality, and is encapsulated by the WFD (see Sections 7.5.1 and 7.5.2). In addition, rivers in the UK should be designated as landscape ‘corridors’ (see Section 7.5.4) in line with the White Paper for the Natural Environment (HM Government, 2011). Riparian land, particularly along first and second order streams, should then be classed as a ‘buffer zone’, instilling a duty on landowners to manage this land to minimise water and sediment runoff.

Fluvial flood risk management is very unlikely to be a primary justification for catchment sediment management (see Section 7.5.2). Tidal flooding, which may be exacerbated by delivery of fluvially-derived sediment, may be a stronger driver. Fluvial flood risk legislation/policy does, nevertheless, require the maintenance and restoration of natural processes and this includes sediment management.

An integrated catchment management approach is therefore advocated (see Section 7.5.4), employing published best practice methods (e.g. Godwin and Dresser, 2000; Morgan, 2006; Owens *et al.*, 2007), to improve land management to reduce soil erosion and delivery of fine-grained sediment to rivers, combined with use of watercourse and riparian buffers as these are effective in preventing larger grain sizes from entering the watercourse and which are the fraction of the wash-material load that has the greatest potential to affect channel morphology in downstream reaches.

Testing and benchmarking selected sediment assessment tools to compare performance against the varying data and resource input requirements.

Application of Sediment Impact Assessment Model (SIAM) in the Halse Water and lower River Tone is the first successful use of this model in the UK, and proved it to be robust in representing river sediment dynamics and allowing the rapid assessment of various management interventions (see Section 6.6). In particular, SIAM provided the ability to:

- Predict the current average annual wash-material and bed-material load by calibrating the model outputs against reliable, field-derived morphological information thereby reducing the reliance on sediment yield data that will invariably be very scarce or absent for the majority of UK rivers; and

- Establish the sensitivity of sediment reaches in terms of the response of the local sediment balance to changes in sediment load and/or runoff volume, thereby identifying those reaches most at risk from altered catchment or river management.

Compared to commonly used sediment assessment tools, SIAM outputs provide a greater level of confidence for catchment managers when making decisions on where best to commit, usually limited, resources.

Stream Power Screening (SPS) has been shown to be rapid method for assessing sediment continuity and potential imbalances through a large channel network, with outputs generally corresponding well with field-derived data, although care must be taken when selecting an appropriate reference flow in river reaches that are highly constrained (see Section 6.6). The similarity between the sedimentation predictions of SPS and the wash-material load component of SIAM, within semi-natural alluvial river reaches, suggests that SPS is able to correctly predict the transition of wash-material load to bed-material load and *vice versa*.

Sediment models are known to be subject to a wide range of uncertainties (Thorne *et al*., 2011). Model outputs can be further influenced, sometimes by orders of magnitude, depending on the choice of sediment transport function, channel roughness and wash-material load:bed-material load threshold, which must all be selected carefully on a river-by-river basis (see Section 6.6.2). Outputs from any sediment model should, generally, only be used to predict and assess the relative direction and magnitude of change to sedimentation patterns. The biggest differences between ISIS-Sediment and SIAM, see Section 6.6.2, relate to:

- Calibration/verification. SIAM, being a reduced complexity model, provided a more stable modelling platform, particularly for headwater catchments, and could be verified simply against reliable, morphological field-data.

ISIS-Sediment was unstable, highly sensitive to small input data changes, and relied heavily on sediment yield data, which is currently scarce and unreliable.

- Computing effort. Each ISIS-Sediment model run scenario took between 2-3 days computing time, compared to a few seconds to compute model outputs in SIAM. This is considered to be one of the biggest benefits of using SIAM, in that multiple model runs can be undertaken very quickly.

- Generated outputs. ISIS-Sediment generated large amounts of data, ~100GB as part of this research, compared to a few GB of data from SIAM making it easier to access, review, manipulate and share.

Establishing an appropriate level of study needed to understand the flow-sediment system and define robust sediment management in a lowland river.

Section 6.6.2 establishes the applicability of a range of sediment tools and models when assessing lowland river sediment dynamics at the catchment scale. Estimating sediment budgets based on the best available sediment monitoring data and a range of estimation techniques is useful to start to identify potential lower/upper boundaries for annual average sediment loads, which can then be used to set management scenario boundaries as part of sediment modelling.

Field observations and other empirical evidence relating to sediment dynamics, patterns and yields should always be collected, using methods prescribed in this research, to support other sediment assessment tools and models.

SPS appears to be useful in identifying river reaches that may be sensitive to altered wash-material load, which may arise, for example, from changes to catchment land use management.

SIAM is an appropriate model to investigate and assess the effect of altered catchment management and climate change on sediment dynamics in lowland rivers, especially at the river-basin scale.

ISIS-Sediment is appropriate for localised, highly-detailed sediment studies where there is a need to assess bed elevation changes over time due to discrete changes to channel maintenance/intervention or in-channel structures.

Sediment model outputs, viewed in isolation, do not provide an adequate basis from which to select appropriate river management solutions. Sediment model outputs must be converted into formats (e.g. morphology or water surface elevations) that allow river managers to compare and assess the implications of different catchment management options.

8.2 Recommendations for future research

In the short- to medium-term, future research investigating or applying sediment modelling/assessment should:

- Encompass a range of lowland river systems to allow the overall approach for assessing sediment dynamics and flood risk, as advocated in this thesis (see Section 6.6.2), to be further tested, to test the validity of the conclusions from the River Tone research, and further test SIAM appropriateness and efficacy in the UK arena.

- Encompass other ecosystem services, including protected habitats, fisheries and other protected species, water quality and water resources, to investigate their sensitivity to sediment and morpho-dynamic pressures.

- Investigate the interactions between sediment supply, sediment dynamics, morphology and flood risk in the tidal zone, including flood storage washlands, of a range of catchments as this is the area where the greatest potential sediment impacts could occur (see Section 6.3.2).

- Investigate the apparent link between SIAM and SPS to further test the hypothesis that SPS is able to correctly predict the interaction between the wash-material and bed-material loads (see Section 6.6) as this could provide a very quick and cost-efficient method for assessing sediment reaches at risk from altered catchment sediment management.

- Investigate the potential for using existing River Habitat Survey or visually-observed bed material data within SIAM (see Section 6.3.1), identifying the model output errors and whether any errors can be managed through the application of correction factors. This may provide a simpler and more cost-effective method for collecting and integrating bed material data.

In the medium- to long-term, future research investigating or applying sediment modelling/assessment (see Section 6.6.2) should:

- ❖ Integrate long-term catchment sediment yield data to allow better calibration and/or validation of sediment models. This will require a concerted programme of continuous suspended and bedload sediment monitoring for all river catchments in the UK or at the very least a number of catchments with known sediment issues.

- ❖ Investigate and integrate the process of plant seed/propagule transport and vegetation development within sediment models, or at least define appropriate protocols for interpretation of model outputs to take account of this process. This will allow sediment modelling outputs to better represent typical channel conditions and predicted future changes.

ISIS is a UK industry-standard modelling suite, and the majority of UK lowland rivers are covered by an ISIS flood model (see Section 5.2.4). Therefore, ISIS should be adapted to be able to provide both SPS and a SIAM equivalent (i.e. sediment continuity model based on a wash-material load:bed-material load threshold) as discrete modelling packages within the overall ISIS modelling suite (see Section 6.6.2). This will provide a practical and compatible modelling platform to better integrate sediment dynamics into river modelling in the UK, as well as facilitating a closer working relationship between water managers/river modellers and fluvial geomorphologists. As identified by Newson (2010b), this is critical for the future success of river modelling both within the scientific and industry communities.

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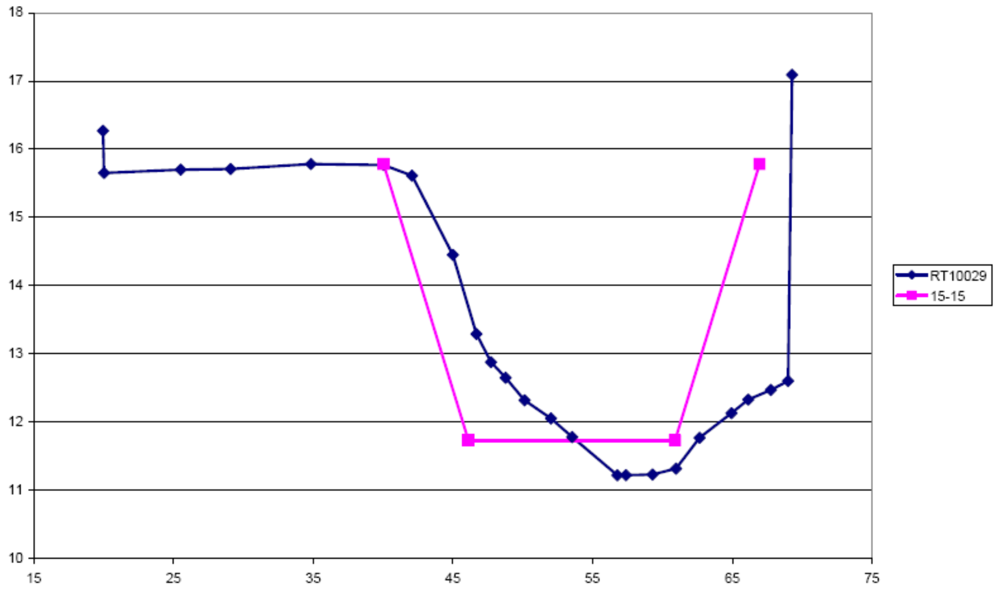
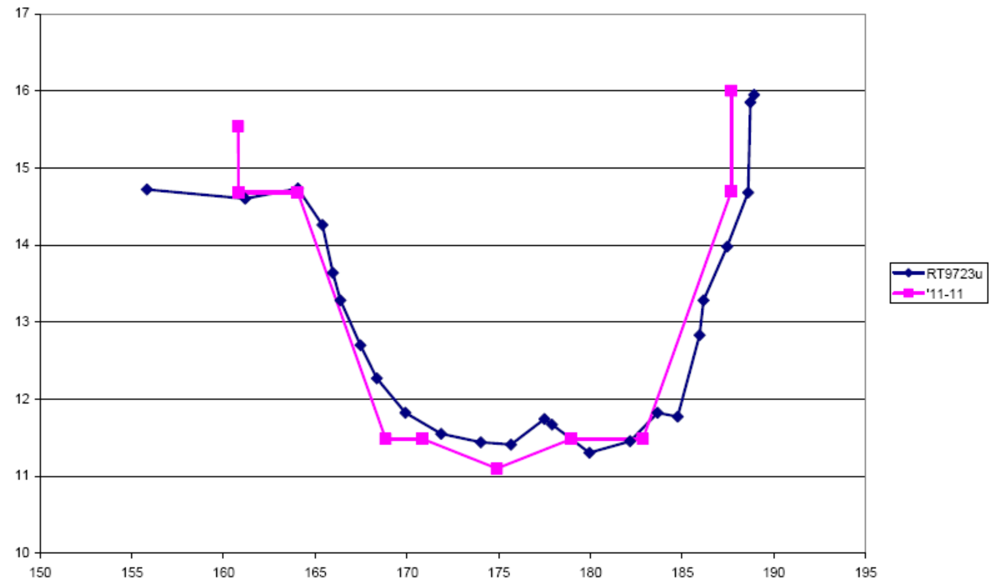
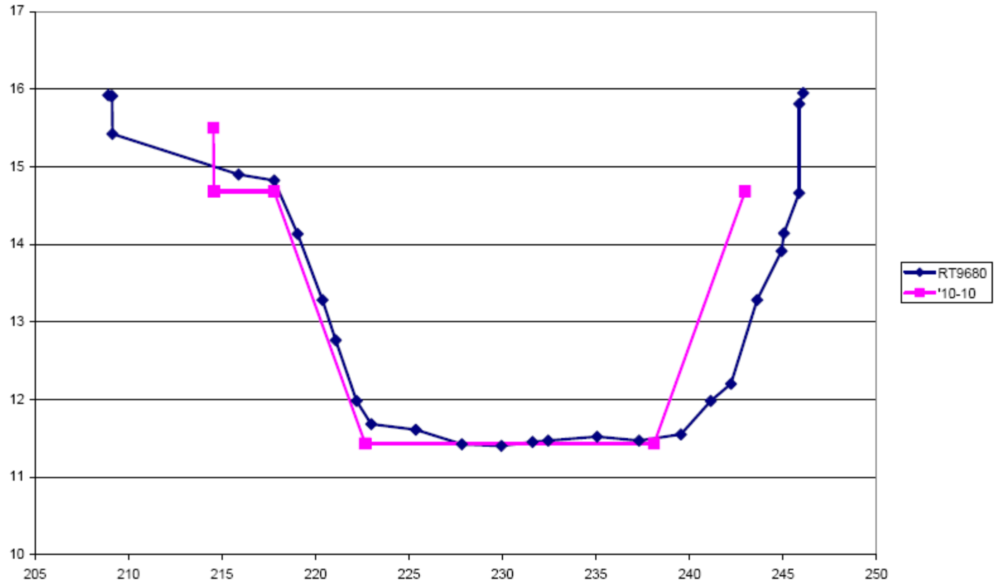
10 APPENDICES

Appendix A Channel cross-sections in River Tone Reach T3







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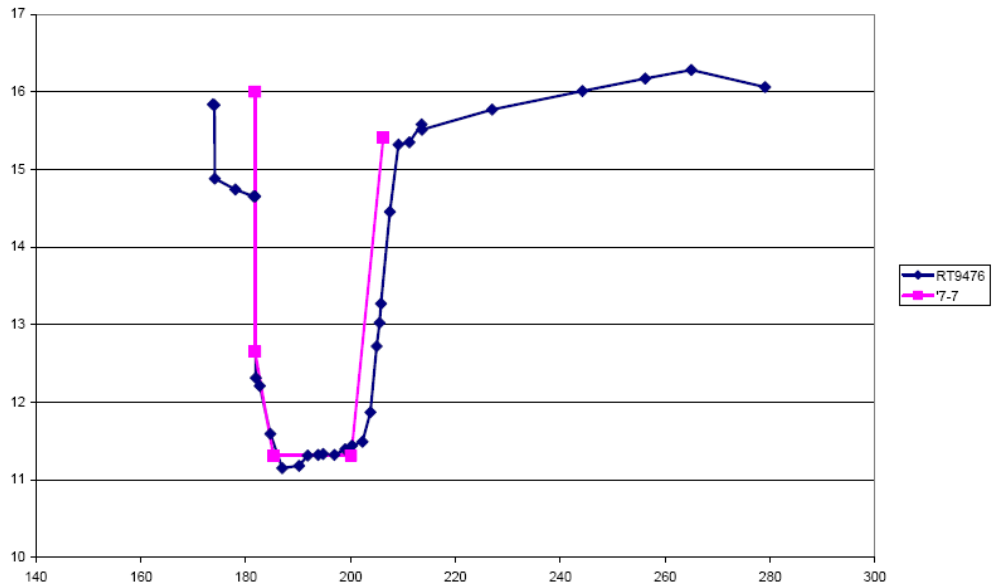

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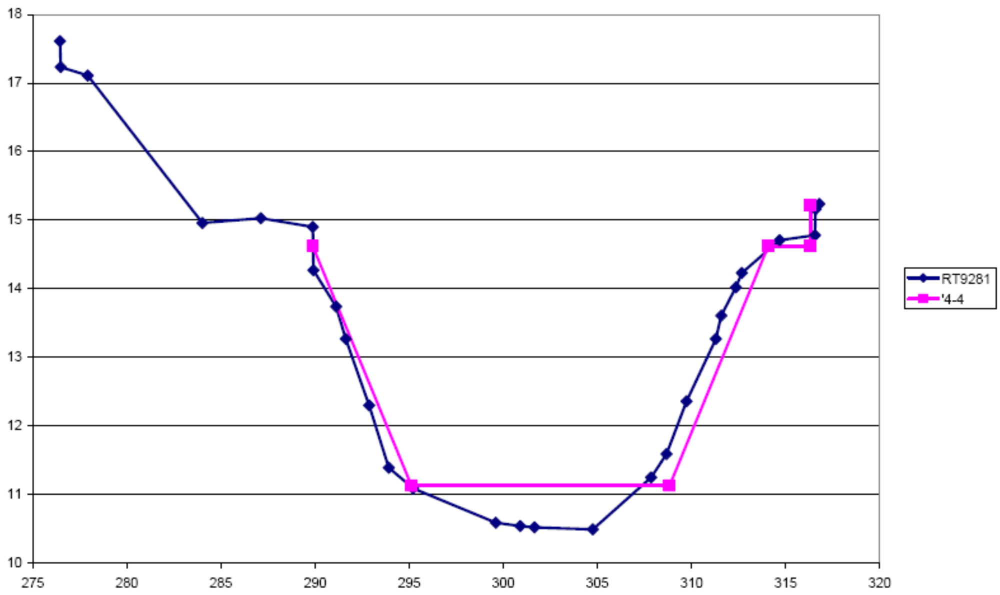
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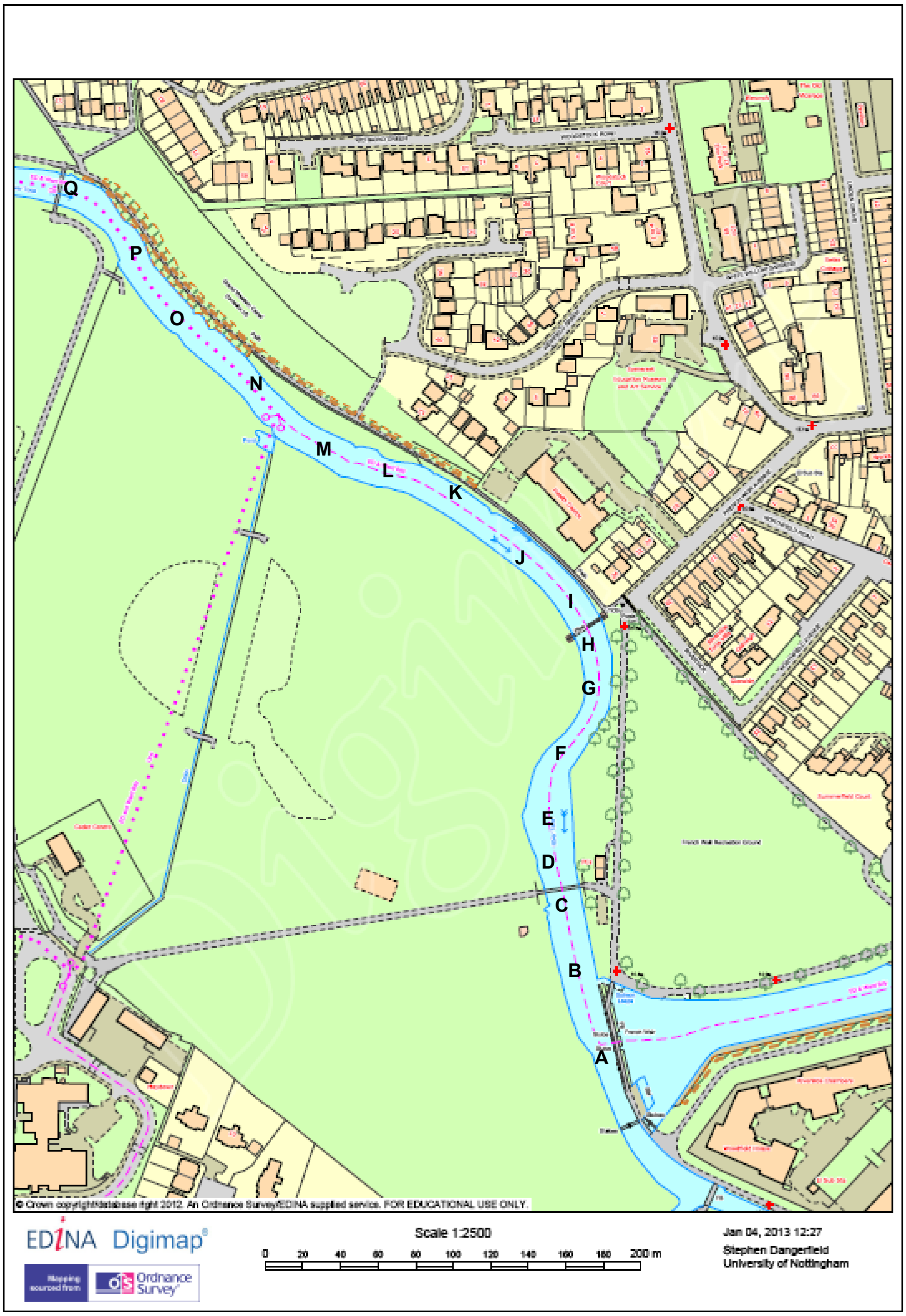
Appendix B Supplementary data from weir sediment study

French Weir



Location of bed material sampling transects upstream of French Weir

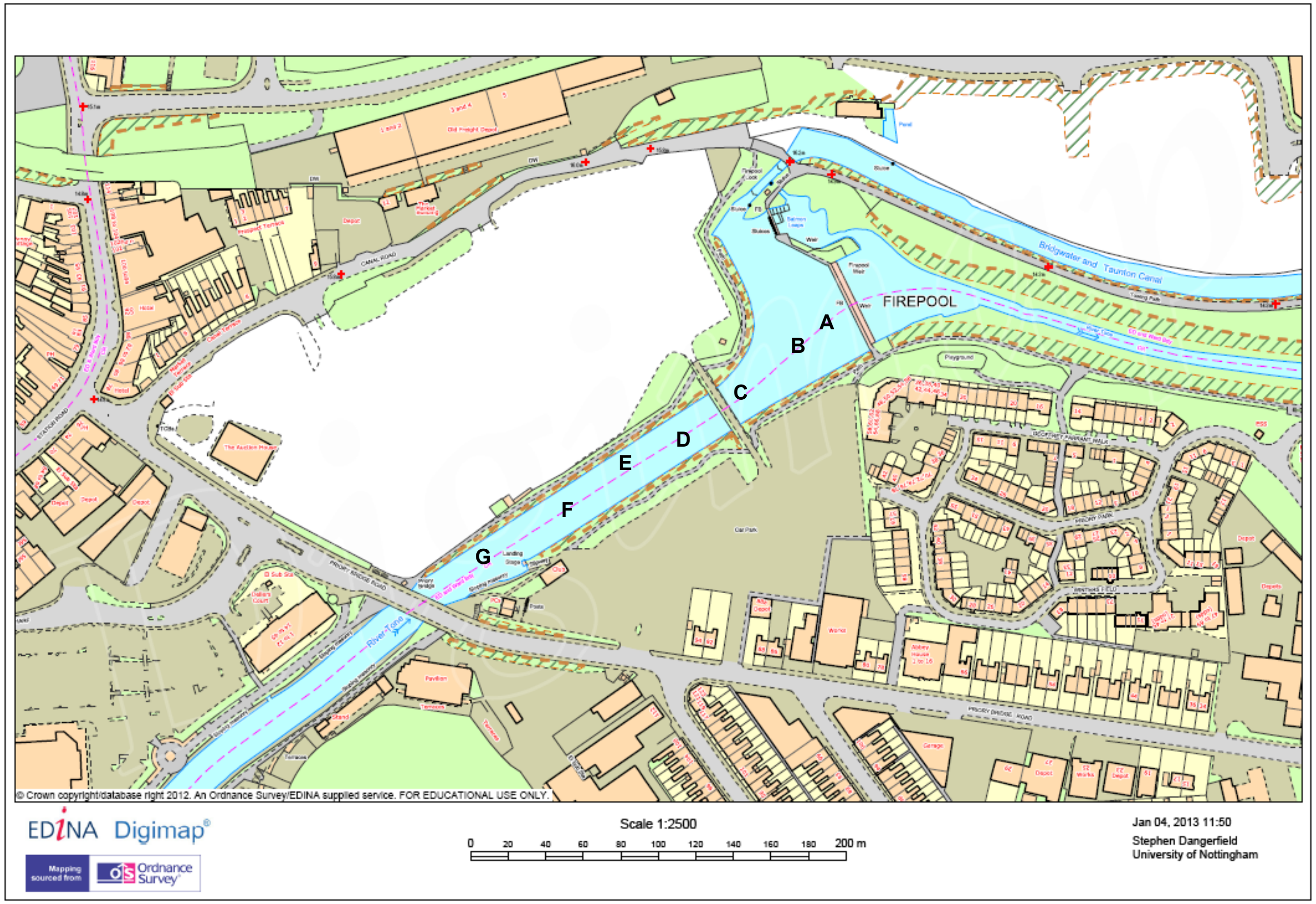
Sample	Water depth	Loose	Consolidated	Position	Loose	Consolidated
	m	m	m	LB, M, RB	Composition	Composition
A1	1.9	0.1	1.4	M	sand/gravel	cobble
A2	1.9	0.1	1.4	M	sand/gravel	cobble
A3	1.7	0.3	1.4	RB	silt	gravel
A4	1.9	0.1	1.4	M	sand/gravel	cobble
A5	1.2	0.1	2.1	M (weir)	sand/gravel	cobble
A6	1.4	0.1	1.9	M	sand/gravel	cobble
A7	1.8	0.1	1.5	M	sand/gravel	cobble
A8	2.4	0.8	0.2	RB	silt	gravel
A9	2.1	0.1	1.2	M	silt	gravel
A10	2.4	0.8	0.2	LB	clay/silt	gravel
B1	1.8	0.1	1.5	RB	sand/gravel	cobble
B2	2.1	0.1	1.2	M	sand/gravel	cobble
B3	1.4	1.0	1.0	LB	silt/sand	cobble
C1	2.1	0.1	1.2	RB	silt	cobble
C2	1.8		1.6	M		gravel/cobble
C3	1.7	0.4	1.3	LB	sand/gravel	gravel/cobble
D1	1.8		1.6	RB		cobble
D2	1.8		1.6	M		cobble
D3	1.0	0.1	2.3	LB	silt/sand/gravel	cobble
E1	1.3		2.1	RB		gravel/cobble
E2	1.2		2.2	M		cobble
E3	1.2		2.2	LB		cobble
F1	2.2	0.6	0.6	RB	silt/sand/gravel	cobble
F2	2.4	0.6	0.4	M	sand/gravel	cobble
F3	2.4	0.3	0.7	LB	sand/gravel	cobble
G1	1.5	1.0	0.9	RB	sand	cobble
G2	2.1		1.3	M		cobble
G3	2.6		0.8	LB		cobble
H1	1.5	0.1	1.8	RB	sand/gravel	cobble
H2	1.8	0.1	1.5	M	gravel	cobble
H3	2.2		1.2	LB		cobble
I1	1.4	0.1	1.9	RB	sand/gravel	cobble
I2	1.5		1.9	M		cobble
I3	2.1		1.3	LB		cobble
J1	2.1	0.1	1.2	RB	sand	cobble
J2	2.0		1.4	M		cobble
J3	2.1		1.3	LB		cobble
K1	2.1	0.1	1.2	RB	sand/gravel	cobble
K2	2.1	0.1	1.2	M	sand/gravel	cobble
K3	2.3	0.1	1.0	LB	sand/gravel	cobble
L1	1.8	0.9	0.7	RB	clay/sand	cobble
L2	2.0	0.2	1.2	M	sand/gravel	cobble
L3	2.1	0.4	0.9	LB	sand/gravel	cobble
M1	2.6	0.2	0.6	RB	silt/sand	cobble
M2	2.4	0.2	0.8	M	sand/gravel	cobble
M3	1.7	0.2	1.5	LB	silt/sand/gravel	cobble
N1	1.3		2.1	RB		cobble
N2	1.9	0.1	1.4	M	silt/sand	cobble
N3	2.0	0.1	1.3	LB	silt/sand	cobble
O1	2.2		1.2	RB		cobble
O2	1.8		1.6	M		cobble
O3	1.7	0.2	1.5	LB	sand/gravel	cobble
P1	2.5	0.2	0.7	RB	sand/gravel	cobble
P2	2.4	0.1	0.9	M	silt/sand/gravel	cobble
P3	1.9	0.3	1.2	LB	silt/sand	cobble
Q1	2.3	0.1	1.0	RB	silt/sand	cobble
Q2	2.8	0.2	0.4	M	silt	cobble
Q3	1.5		1.9	LB	sand/gravel	cobble
Total		11.0	75.0			
Average		0.2	1.3			

A - Q Downstream to upstream

RB Right bank
M Mid-channel
LB Left bank

Results from bed material sampling upstream of French Weir

Firepool Weir



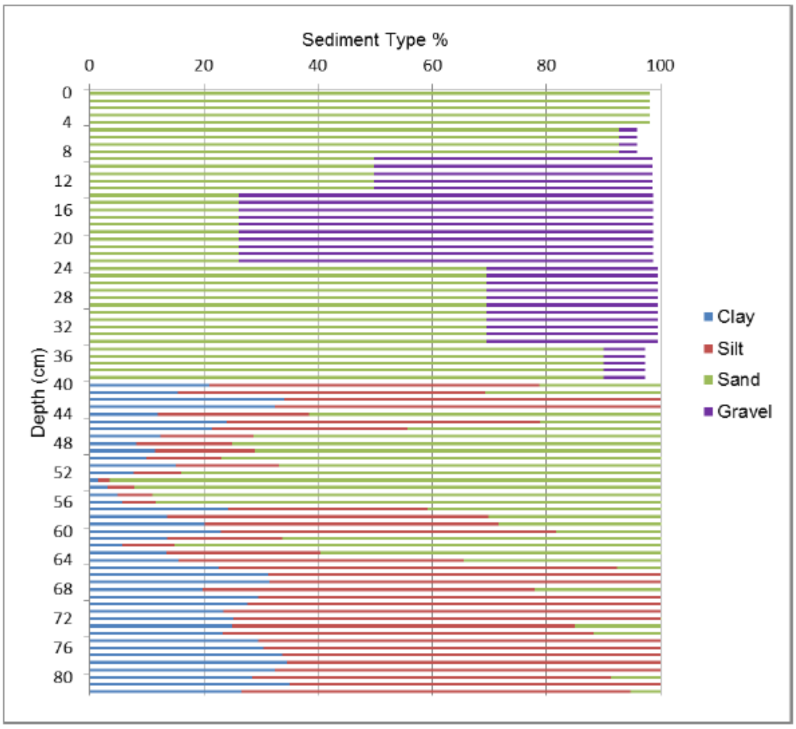
Location of bed material sampling transects upstream of Firepool Weir

Sample	Water depth	Loose	Consolidated	Position	Loose	Consolidated
	m	m	m	LB, M, RB	Composition	Composition
A1	1.3	1.3	0.8	RB	clay/silt	uk
A2	1.2	1.4	0.8	M	sand/gravel over silt/sand	uk
A3	1.0	1.4	1.0	M	sand/gravel over silt/sand	uk
A4	0.5	1.5	1.4	LB	sand/gravel over silt	uk
B1	0.5	1.5	1.4	LB	sand over silt	uk
B2	1.3	1.7	0.4	M	sand/gravel over silt/sand	uk
B3	1.7	0.6	1.1	M	sand/gravel	uk
B4	1.6	1.5	0.3	RB	clay/silt	gravel
C1	1.3	0.6	1.5	LB	silt/gravel	uk
C2	2.3	0.5	0.6	M	sand/gravel	uk
C3	2.1		1.3	RB		cobbles
D1	2.2	0.1	1.1	LB	sand/gravel	uk
D2	2.2	0.7	0.5	M	gravel over clay/sand	uk
D3	2.3	0.6	0.5	RB	silt/sand over sand/gravel	uk
E1	2.1	0.3	1.0	LB	gravel/cobble over sand/gravel	uk
E2	2.3	0.3	0.8	M	silt/sand/gravel	uk
E3	2.0	0.8	0.6	RB	silt over sand/gravel	uk
F1	0.8	0.2	2.4	LB	gravel	uk
F2	2.4	0.4	0.6	M	sand/gravel	uk
F3	1.9	0.3	1.2	RB	silt/sand	uk
G1	1.9	0.1	1.4	LB	silt/sand	gravel/cobble
G2	2.3	0.3	0.8	M	silt/sand/gravel	gravel/cobble
G3	1.8	0.5	1.1	RB	silt/sand	gravel/cobble
Total		16.6	22.6			
Average		0.7	1.0			

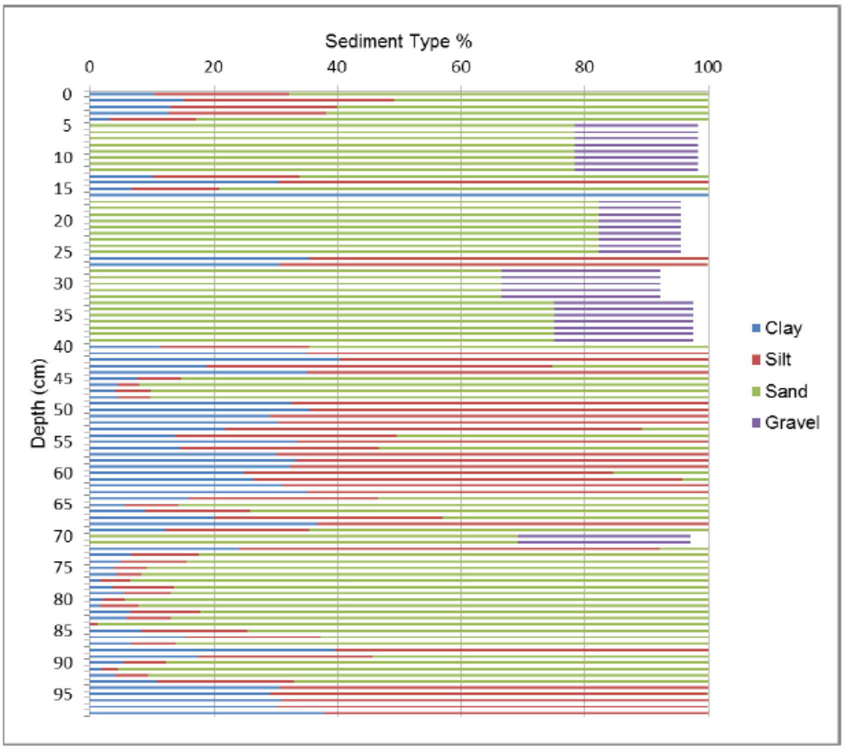
A - G Downstream to upstream

RB Right bank
M Mid-channel
LB Left bank

Results from bed material sampling upstream of Firepool Weir



Particle size distribution (for four main sediment groups) plotted against depth for a sediment core taken 3m upstream of weir crest in mid-channel (Sample No. A2) (Source: Hooper, 2012)

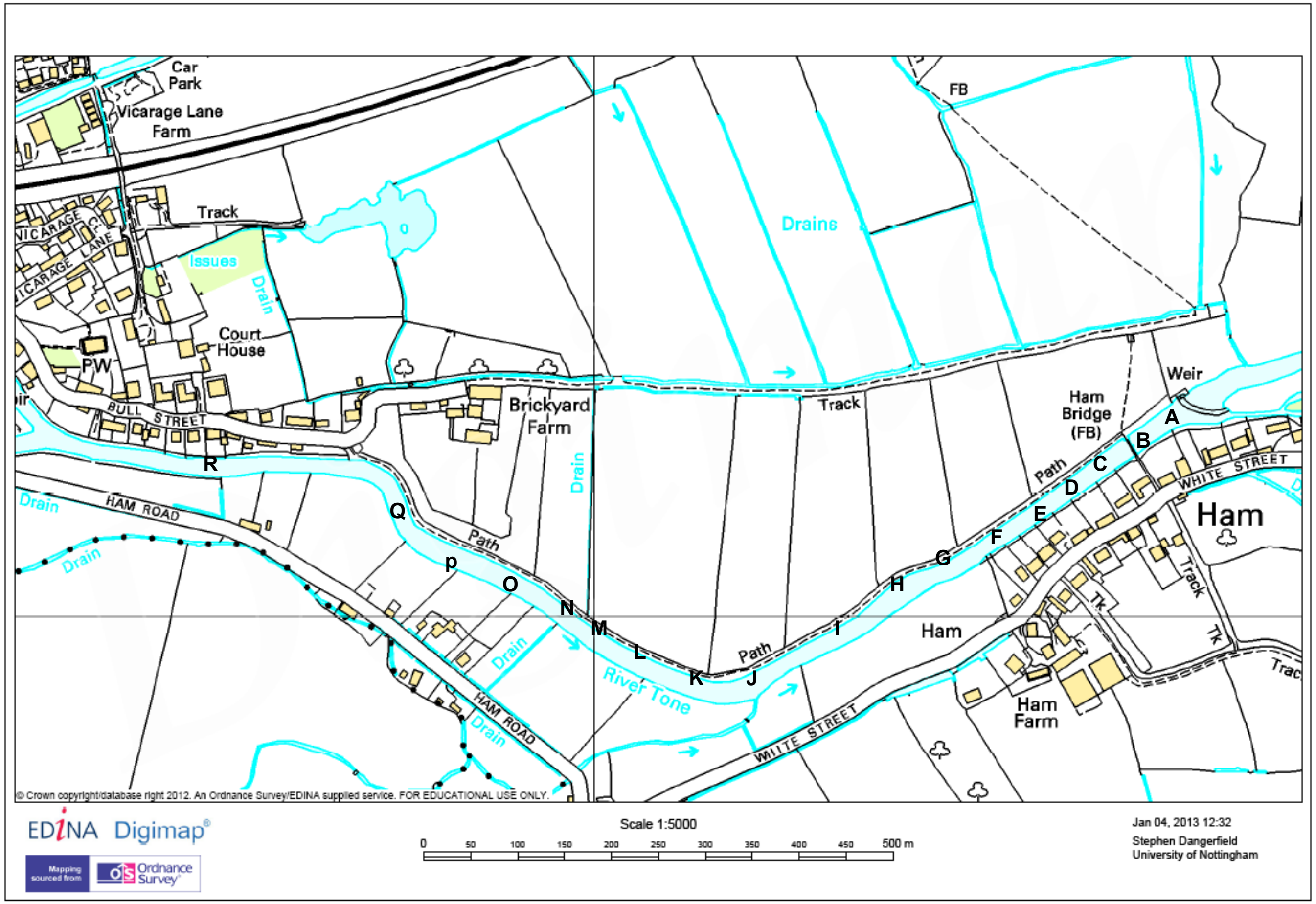


Particle size distribution (for four main sediment groups) plotted against depth for a sediment core taken 8m upstream of weir crest on left bank (Sample No. B1) (Source: Hooper, 2012)

Photographs of Firepool Weir sediment core (Sample No. A2) 0-35cm (top) and 35-85cm (bottom) showing band of sandy gravel over sand/silt/clay

Photographs of Firepool Weir sediment core (Sample No. B1) 0-50cm (top) and 50-100cm (bottom) showing band of gravely sand over a band of silt/clay over silty sand

Ham Weir



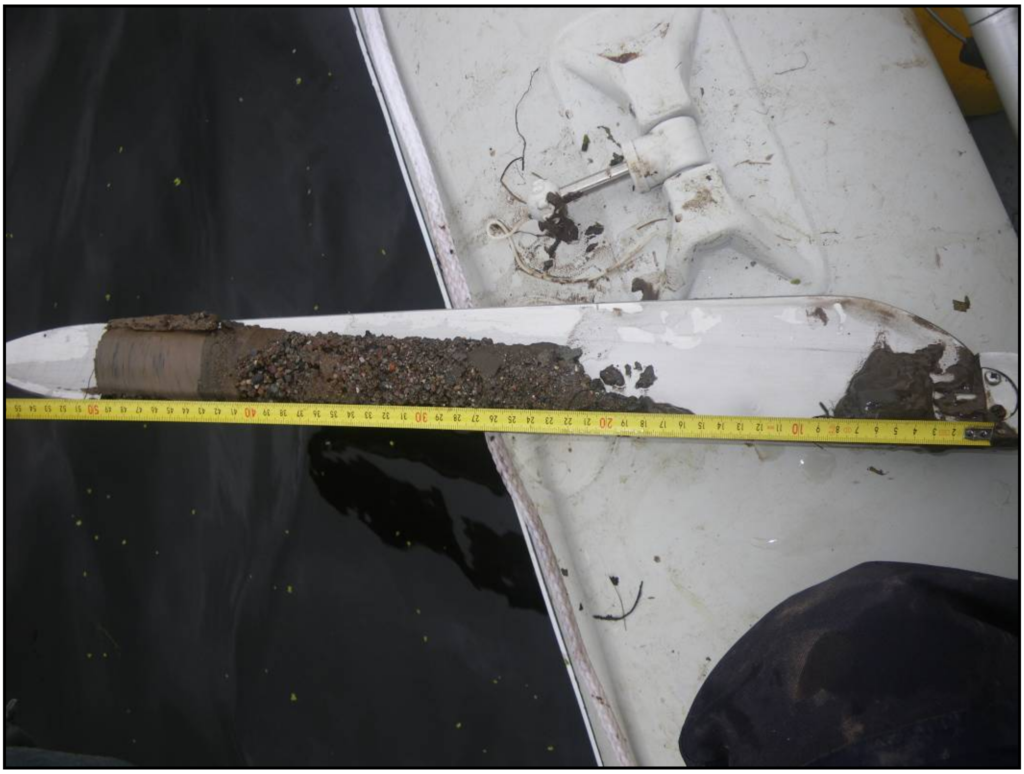
Location of bed material sampling transects upstream of Ham Weir

Sample	Water depth	Loose	Consolidated	Position	Loose	Consolidated
	m	m	m	LB, M, RB	Composition	Composition
A1	1.7	1.2	0.9	RB	clay/silt	clay
A2	1.9	1.3	0.6	M	clay/silt	clay
A3	2.1	1.3	0.4	LB	clay/silt	clay
B1	1.8	0.5	1.5	RB	gravel over clay/silt	clay
B2	2.1	0.4	1.3	M	silt/sand/gravel	clay
B3	2.3	0.2	1.3	LB	clay/silt	clay
C1	1.9	1.3	0.6	RB	sand/gravel over clay/silt	clay
C2	2.2	1.3	0.3	M	clay/silt	clay
C3	1.2	1.1	1.5	LB	gravel over silt/sand/gravel	clay
D1	2.0	1.3	0.5	RB	clay/silt	clay
D2	2.2	1.3	0.3	M	gravel over silt/sand/gravel	clay
D3	2.0	0.6	1.2	LB	gravel over silt/sand/gravel	clay
E1	2.1	1.3	0.4	RB	clay/silt	clay
E2	2.5	1.0	0.3	M	clay/silt	clay
E3	1.5	0.4	1.9	LB	gravel over silt/sand	clay
F1	2.1	1.3	0.4	RB	clay/silt	clay
F2	2.3	1.0	0.5	M	silt over silt/sand/gravel	clay
F3	1.9	0.1	1.8	LB	clay/silt	clay
G1	1.9	1.3	0.6	RB	clay/silt	clay
G2	2.1	1.3	0.4	M	silt/sand/gravel	clay
G3	2.0	1.3	0.5	LB	silt/sand/gravel	clay
H1	1.9	0.7	1.2	RB	clay/silt	clay
H2	1.4	1.0	1.4	M	silt/sand/gravel	clay
H3	1.9	1.0	0.9	LB	silt/sand/gravel	clay
I1	2.0	1.3	0.5	RB	clay/silt	clay
I2	3.2	0.3	0.3	M	silt/sand/gravel	clay
I3	2.5	0.5	0.8	LB	silt/sand/gravel	clay
J1	1.0	1.5	1.3	RB	silt/sand/gravel	clay
J2	2.2	1.3	0.3	M	clay/silt	clay
J3	2.4	1.0	0.4	LB	clay/silt	clay
K1	1.7	0.5	1.6	RB	silt/sand/gravel	clay
K2	2.0	0.9	0.9	M	clay/silt	clay
K3	1.5	1.3	1.0	LB	clay/silt	clay
L1	2.1	1.0	0.7	M	silt/sand/gravel	clay
M1	1.7	0.5	1.6	M	silt/sand/gravel	clay
N1	2.4	0.6	0.8	M	silt/sand/gravel	clay
O1	2.3	1.0	0.5	M	silt/sand/gravel	clay
P1	2.5	0.5	0.8	M	clay/silt	clay
Q1	2.6	0.5	0.7	M	clay/silt	clay
R1	1.8	1.3	0.7	M	clay/silt	clay
Total	80.9	37.5	33.6			
Average	2.0	0.9	0.8			

A - R Downstream to upstream

RB Right bank
M Mid-channel
LB Left bank

Results from bed material sampling upstream of Firepool Weir



Photographs of Ham Weir sediment core (Sample No. A3) 0-50cm (top) and 20-70cm (bottom) showing band of sandy gravel (20-40cm) over silt/clay. Note: the top 20cm of sand/silt material was lost during retrieval of corer

Appendix C Cross-section data for the Halse Water and River Tone

Halse Water

River Reach	XS Ref	Chainage	Bankfull Stage	XS Area	Bankfull Width	Wetted Perimeter	Hydraulic Depth	Bankfull Flow	Avg. Velocity	Max. Water Slope	Specific Stream Power (water)
		m	mOAD	m^2	m	m	m	m^3/sec	m/sec		W/m^2
HW 1	Tylers Bridge	0.0	66.64	3.38	6.62	7.24	0.47	3.45	1.02	0.0065	33.40
	HW-05242	213.0	65.45	2.97	4.91	5.64	0.53	3.20	1.08	0.0065	41.78
	HW-05103	351.9	64.73	3.07	5.09	5.81	0.53	3.45	1.12	0.0065	43.43
	HW-04964	490.8	63.99	3.12	5.15	5.87	0.53	3.70	1.19	0.0065	46.05
	HW-04825	629.7	63.25	3.15	5.17	5.92	0.53	4.00	1.27	0.0065	49.60
	HW-04686	768.6	62.51	3.23	5.30	6.10	0.53	4.00	1.24	0.0065	48.31
	HW-04270	1185.3	60.00	2.07	3.62	4.45	0.46	2.50	1.21	0.0065	44.19
	HW-03853	1602.0	57.99	3.41	5.15	6.52	0.52	4.50	1.32	0.0065	55.96
HW 2	HW-03740	1715.5	57.15	2.63	3.85	4.85	0.54	3.30	1.26	0.0051	42.51
	HW-03626	1829.0	56.66	3.56	5.36	6.38	0.56	4.80	1.35	0.0051	44.41
	HW-03172	2283.0	53.99	3.86	4.63	5.83	0.66	5.35	1.39	0.0051	57.34
	HW-03069	2386.5	53.21	2.72	4.15	5.04	0.54	3.48	1.28	0.0051	41.63
	HW-02758	2697.0	51.52	3.71	6.99	7.90	0.47	3.60	0.97	0.0051	25.55
	HW-02648	2807.5	51.00	3.87	6.92	7.85	0.49	3.85	1.00	0.0051	27.58
	HW-02537	2918.0	50.47	3.96	6.79	7.74	0.51	4.00	1.01	0.0051	29.22
	HW-02316	3139.0	49.41	4.14	6.52	7.53	0.55	4.40	1.06	0.0051	33.46
HW 3	HW-02206	3249.5	48.88	4.22	6.39	7.43	0.57	4.60	1.09	0.0041	29.03
	HW-01211	4244.0	43.95	3.88	5.69	6.84	0.57	4.40	1.13	0.0041	31.21
	HW-00793	4662.0	41.76	2.99	5.40	6.13	0.49	2.80	0.94	0.0041	20.93
	HW-00665	4790.0	41.14	2.06	5.75	6.34	0.33	2.50	1.21	0.0041	17.53
	HW-00281	5174.0	40.12	7.04	7.26	8.91	0.79	5.70	0.81	0.0041	31.66
	HW-00000	5455.0	39.27	3.29	3.79	5.42	0.61	3.10	0.94	0.0041	32.97
HW 4	HW-00000i1	5582.0	38.83	4.86	5.98	7.24	0.67	2.45	0.50	0.0040	15.93
	HW-00000i7	6344.0	37.01	3.28	4.95	5.79	0.57	2.65	0.81	0.0040	20.82
	HW100	6571.0	36.01	3.27	4.42	5.26	0.62	3.40	1.04	0.0040	29.90
	HW200	6671.0	35.55	3.12	4.35	5.21	0.60	3.20	1.02	0.0040	28.63
	HW300	6771.0	35.30	4.11	5.25	6.32	0.65	5.30	1.29	0.0040	39.28
	HW400	6871.0	34.74	2.73	3.95	4.88	0.56	3.75	1.37	0.0040	36.89
	HW500	6971.0	34.28	3.51	5.33	5.86	0.60	4.20	1.20	0.0040	30.62
	HW600	7071.0	33.94	4.54	6.05	6.71	0.68	6.20	1.36	0.0040	39.83
	HW700	7171.0	33.24	3.13	5.43	5.86	0.53	3.80	1.22	0.0040	27.22
	HW800	7271.0	32.89	4.01	4.82	5.73	0.70	5.70	1.42	0.0040	46.02
	HW850	7321.0	32.61	6.02	11.44	11.93	0.50	4.10	0.68	0.0040	13.94
	HW874	7345.0	32.70	7.22	10.30	11.51	0.63	5.60	0.78	0.0040	21.14
	HW893	7364.0	32.58	4.66	8.20	9.23	0.50	5.20	1.12	0.0040	24.66
HW 5	HW1106	7577.0	31.45	2.89	4.03	5.15	0.56	3.35	1.16	0.0034	27.87
	HW1222	7693.0	30.86	4.37	5.28	6.27	0.70	7.60	1.74	0.0034	48.29
	HW1325	7796.0	30.07	5.62	5.70	7.00	0.80	4.30	0.77	0.0034	25.32
	HW1418	7889.0	30.08	5.66	5.74	6.94	0.82	6.50	1.15	0.0034	37.97
	HW1507	7978.0	29.72	5.37	5.98	7.02	0.77	7.30	1.36	0.0034	40.94
	HW1560	8031.0	29.32	4.14	4.40	5.69	0.73	3.40	0.82	0.0034	25.96
	HW1633	8104.0	29.13	4.02	3.80	5.67	0.71	2.90	0.72	0.0034	25.63
	HW1671	8162.0	29.01	3.51	6.00	7.18	0.49	3.20	0.91	0.0034	17.89
HW 6	HW1783	8274.0	28.70	5.24	6.23	7.06	0.74	2.80	0.53	0.0032	13.97
	HW1829	8320.0	28.57	3.08	5.76	6.28	0.49	3.80	1.23	0.0032	20.50
	HW1875	8366.0	28.68	5.52	4.49	6.43	0.86	11.90	2.16	0.0032	82.29
	HW1909	8400.0	28.30	3.41	4.90	5.98	0.57	4.80	1.41	0.0032	30.45
	HW1959	8450.0	28.14	3.47	5.17	6.01	0.58	5.40	1.56	0.0032	32.47
	HW2009	8500.0	27.99	3.49	5.23	5.98	0.58	6.20	1.78	0.0032	36.80
	HW2109	8600.0	27.67	3.50	4.61	5.55	0.63	11.30	3.23	0.0032	76.10
	HW2149	8640.0	27.14	5.92	8.03	8.88	0.67	5.20	0.88	0.0032	20.11
	HW2345.1	8836.1	26.65	6.17	7.29	8.20	0.75	4.50	0.73	0.0032	19.19
	HW2529.11	9020.1	25.68	3.75	4.30	5.38	0.70	2.90	0.77	0.0032	20.95
	HW3023	9514.1	24.08	1.70	4.73	5.21	0.33	5.20	3.07	0.0032	34.18
	HW3177.96	9669.0	23.18	2.37	4.98	5.47	0.43	2.50	1.06	0.0032	15.59
	HW3197.18	9792.2	23.05	2.43	4.75	5.29	0.46	3.30	1.36	0.0032	21.59

River Reach	XS Ref	Chainage	Bankfull Stage	XS Area	Bankfull Width	Wetted Perimeter	Hydraulic Depth	Bankfull Flow	Avg. Velocity	Max. Water Slope	Specific Stream Power (water)
		m	mOAD	m^2	m	m	m	m^3/sec	m/sec		W/m^2
HW 7	HW3378.07U	9869.1	22.34	3.23	5.18	5.70	0.57	1.85	0.57	0.0025	8.89
	HW3423.07	9914.1	22.66	4.38	3.72	6.42	0.68	4.80	1.10	0.0025	32.16
	HW3443.07	9934.1	22.48	4.27	9.33	10.98	0.39	4.10	0.96	0.0025	10.94
	HW3469.07D	9960.1	21.94	5.92	6.92	7.88	0.75	2.60	0.44	0.0025	9.35
	HW3512.07	10003.1	22.73	9.60	6.33	8.98	1.07	8.00	0.83	0.0025	31.47
	HW3533.52	10024.5	22.33	6.06	6.43	8.38	0.72	4.80	0.79	0.0025	18.58
	HW3560.82	10051.8	21.74	4.27	5.12	5.94	0.72	2.20	0.51	0.0025	10.69
	HW3609.82	10100.8	22.44	9.90	7.26	9.07	1.09	6.25	0.63	0.0025	21.44
	HW3650.82	10141.8	21.84	5.84	5.17	6.70	0.87	3.15	0.54	0.0025	15.17
	HW3694.82	10185.8	22.01	5.41	5.09	6.39	0.85	4.20	0.78	0.0025	20.54
	HW3733.82	10224.8	21.38	2.82	4.25	4.96	0.57	1.70	0.60	0.0025	9.96
	HW3785.82	10276.8	21.82	5.44	5.43	6.59	0.83	4.20	0.77	0.0025	19.26
	HW3831.82	10322.8	21.58	4.66	5.27	6.13	0.76	3.80	0.82	0.0025	17.95
	HW3874.82	10365.8	21.82	6.67	6.04	7.26	0.92	5.20	0.78	0.0025	21.44
	HW3914.82	10405.8	21.63	6.15	5.93	7.02	0.88	5.00	0.81	0.0025	21.00
	HW3927.32	10418.3	21.57	6.07	5.81	6.88	0.88	6.70	1.10	0.0025	28.70
	HW3958.82	10449.8	21.98	11.59	7.55	9.84	1.18	6.50	0.56	0.0025	21.45
	HW3965.82	10456.8	21.96	28.84	20.49	22.30	1.29	11.00	0.38	0.0025	13.37
	HW3990.32	10481.3	21.94	25.19	17.56	18.94	1.33	11.00	0.44	0.0025	15.60
	HW4024.32	10515.3	21.97	28.77	22.19	23.36	1.23	7.50	0.26	0.0025	8.42
	HW4066.82	10557.8	21.95	28.70	18.79	20.06	1.43	11.00	0.38	0.0025	14.58
	HW4104.32	10595.3	22.00	30.28	18.97	20.31	1.49	11.00	0.36	0.0025	14.44
	HW4135.82	10626.8	21.98	31.25	19.29	20.66	1.51	11.00	0.35	0.0025	14.20
	HW4185.82	10676.8	21.96	31.80	19.27	20.69	1.54	11.00	0.35	0.0025	14.22
	HW4235.82	10726.8	21.96	33.55	18.96	21.06	1.59	11.00	0.33	0.0025	14.45
	HW4323.82	10814.8	22.11	45.97	23.75	25.75	1.79	7.50	0.16	0.0025	7.86
	HW4363.82	10854.8	22.11	47.08	23.75	25.83	1.82	7.50	0.16	0.0025	7.86
	HW4440.12	10931.1	22.00	37.87	22.35	24.16	1.57	7.00	0.18	0.0025	7.80
	HW4454.82	10945.8	22.00	33.38	21.00	24.37	1.37	7.00	0.21	0.0025	8.30
	HW4477.82	10968.8	21.39	13.46	7.19	10.44	1.29	7.50	0.56	0.0025	25.97
	HW4494.66	10985.7	20.88	6.82	9.13	9.86	0.69	4.80	0.70	0.0025	13.10
	HW4573.81	11064.8	20.55	4.81	6.57	7.72	0.62	6.50	1.35	0.0025	24.64
HW 8	HALS5_590	11132.8	20.17	3.26	4.31	5.17	0.63	2.90	0.89	0.0024	15.83
	HALS5_580	11197.8	20.02	4.99	5.46	6.42	0.78	3.40	0.68	0.0024	14.66
	HALS5_570	11273.8	20.07	4.85	7.85	8.75	0.55	3.85	0.79	0.0024	11.55
	HALS5_560	11317.8	20.07	4.85	7.85	8.75	0.55	8.90	1.84	0.0024	26.67
	HALS5_550	11358.8	19.56	6.28	6.90	8.21	0.76	3.40	0.54	0.0024	11.59
	HALS5_540	11426.8	19.32	3.97	4.72	5.80	0.69	2.90	0.73	0.0024	14.47
	HALS5_530	11484.8	19.04	4.10	4.56	5.67	0.72	2.10	0.51	0.0024	10.83
	HALS5_520	11554.8	19.22	6.41	5.91	7.03	0.91	3.10	0.48	0.0024	12.35
	HALS7_70	11554.8	19.22	6.54	5.91	7.09	0.92	6.80	1.04	0.0024	27.09
	HALS7_60	11604.8	19.00	11.82	8.87	10.13	1.17	5.00	0.42	0.0024	13.26
	HALS7_55	11695.3	19.20	12.14	7.79	10.73	1.13	8.00	0.66	0.0024	24.17
	HALS7_39	11845.8	18.14	8.86	6.01	8.83	1.00	9.30	1.05	0.0024	36.42
	HALS7_35	11874.8	18.08	11.13	8.18	9.71	1.15	9.70	0.87	0.0024	27.90
	HALS7_26	12022.8	17.78	12.72	10.91	12.39	1.03	16.90	1.33	0.0024	36.46
	HALS7_25	12119.3	16.75	6.69	8.36	9.19	0.73	5.50	0.82	0.0024	15.49
	HALS7_10	12175.8	16.54	7.20	6.98	7.93	0.91	5.10	0.71	0.0024	17.18

KEY

sediment deposition potential (<15 Wm^{-2})
sediment transfer (15-35 Wm^{-2})
sediment erosion potential (>35 Wm^{-2})

Lower River Tone

River Reach	XS Ref	Chainage	Bankfull Stage	XS Area	Bankfull Width	Wetted Perimeter	Hydraulic Depth	Bankfull Flow	Avg. Velocity	Max. Water Slope	Specific Stream Power (water)
		m	mOAD	m^2	m	m	m	m^3/sec	m/sec		W/m^2
T 1 & T 2	RT12100	0.0	17.64	41.24	20.85	22.79	1.81	69.00	1.67	0.0010	33.73
	RT11863	237.0	17.41	47.06	24.34	25.85	1.82	77.00	1.64	0.0010	32.24
	RT11622	477.0	16.91	36.73	19.18	21.71	1.69	58.00	1.58	0.0010	30.81
	RT11368	730.9	16.05	26.48	20.21	21.35	1.24	26.00	0.98	0.0010	13.11
	RT11106	992.6	16.28	47.63	24.61	27.17	1.75	50.00	1.05	0.0010	20.70
	RT11006	1093.0	16.16	47.15	20.71	23.80	1.98	48.00	1.02	0.0010	23.62
	RT10846	1253.5	15.52	38.13	17.01	19.62	1.94	18.00	0.47	0.0010	10.78
	RT10603	1496.5	15.44	18.16	17.08	18.13	1.00	26.00	1.43	0.0010	15.52
	RT10448	1650.9	15.39	44.70	20.14	22.24	2.01	36.00	0.81	0.0010	18.22
	FRWRu1	1685.6	15.39	44.79	20.30	22.39	2.00	38.00	0.85	0.0010	19.08
T 3	RT10373	1685.6	15.03	50.46	31.75	32.96	1.53	74.00	1.47	0.0012	27.24
	RT10315	1743.6	15.01	59.72	35.76	36.84	1.62	74.00	1.24	0.0012	24.18
	RT10257	1801.6	15.03	69.94	31.75	33.55	2.08	78.00	1.12	0.0012	28.71
	RT10143	1915.5	14.19	47.73	30.54	31.56	1.51	39.50	0.83	0.0012	15.11
	RT10029	2029.3	15.61	86.71	27.10	30.86	2.81	123.50	1.42	0.0012	53.26
	RT9904	2154.9	15.14	72.40	26.47	28.96	2.50	99.00	1.37	0.0012	43.70
	RT9778	2280.4	14.73	61.76	24.56	26.60	2.32	85.00	1.38	0.0012	40.45
	RT9723	2335.4	14.73	61.76	24.56	26.60	2.32	95.00	1.54	0.0012	45.21
	RT9680	2378.2	14.82	76.00	28.07	30.03	2.53	102.00	1.34	0.0012	42.46
	RT9625	2433.2	14.79	98.02	39.89	44.36	2.21	100.00	1.02	0.0012	29.30
	RT9476	2582.2	14.65	76.10	26.05	29.34	2.59	102.00	1.34	0.0012	45.76
	RT9281	2777.0	14.27	61.60	22.94	24.96	2.47	91.00	1.48	0.0012	46.36
	RT9186	2872.9	14.96	83.79	27.41	29.73	2.82	180.00	2.15	0.0012	76.74
	RT8980	3078.3	14.74	219.30	102.96	106.25	2.06	153.00	0.70	0.0012	17.37
T 4	RT8980d	3078.3	14.74	418.63	102.96	108.20	3.87	153.00	0.37	0.0016	23.76
	RT8902	3156.4	12.11	18.19	17.66	18.66	0.98	14.00	0.77	0.0016	12.67
	RT8902d1	3206.4	12.03	17.29	16.28	17.19	1.01	13.00	0.75	0.0016	12.77
	RT8787	3271.0	12.18	21.88	20.94	22.16	0.99	18.00	0.82	0.0016	13.74
	RT8787d1	3321.0	11.89	16.89	20.12	20.95	0.81	13.00	0.77	0.0016	10.33
	RT8787d2	3371.0	12.20	24.54	23.21	24.04	1.02	19.00	0.77	0.0016	13.09
	RT8787d3	3421.0	12.47	32.07	25.02	26.01	1.23	27.00	0.84	0.0016	17.25
	RT8787d4	3471.0	11.77	17.46	19.50	20.57	0.85	11.00	0.63	0.0016	9.02
	RT8533	3525.3	11.88	20.43	21.39	22.89	0.89	21.00	1.03	0.0016	15.69
	RT8533d1	3575.3	11.62	17.54	20.03	20.86	0.84	14.00	0.80	0.0016	11.17
	RT8533d2	3625.3	11.88	24.60	24.82	25.52	0.96	21.00	0.85	0.0016	13.53
	RT8533d3	3675.3	11.83	28.02	29.46	30.09	0.93	20.00	0.71	0.0016	10.85
	RT8533d4	3725.3	11.32	16.84	25.29	25.90	0.65	9.00	0.53	0.0016	5.69
	RT8299	3759.3	12.33	49.14	37.21	38.17	1.29	50.00	1.02	0.0016	21.48
	RT8299d1	3809.3	12.04	41.91	32.95	33.82	1.24	39.00	0.93	0.0016	18.92
	RT8299d2	3859.3	11.74	35.15	28.59	29.51	1.19	27.00	0.77	0.0016	15.10
	RT8299d3	3909.3	11.12	21.84	18.84	19.88	1.10	15.00	0.69	0.0016	12.73
	RT8299d4	3959.3	11.02	20.77	16.37	17.78	1.17	13.00	0.63	0.0016	12.70
	RT8062	3996.4	10.95	19.47	16.63	18.47	1.05	17.00	0.87	0.0016	16.34
	RT7787	4271.2	10.63	16.94	17.25	18.42	0.92	16.00	0.94	0.0016	14.82
	RT7587	4471.4	10.26	15.94	14.39	15.79	1.01	15.00	0.94	0.0016	16.67
	RT7321	4737.5	9.87	15.29	13.91	15.16	1.01	18.00	1.18	0.0016	20.69
	RT7146	4912.7	9.28	13.73	18.44	19.09	0.72	12.00	0.87	0.0016	10.40
	RT7022	5036.4	9.48	17.14	15.15	16.36	1.05	22.00	1.28	0.0016	23.21
	RT6816	5242.7	10.71	56.84	27.41	29.03	1.96	80.00	1.41	0.0016	46.66

River Reach	XS Ref	Chainage	Bankfull Stage	XS Area	Bankfull Width	Wetted Perimeter	Hydraulic Depth	Bankfull Flow	Avg. Velocity	Max. Water Slope	Specific Stream Power (water)
		m	mOAD	m^2	m	m	m	m^3/sec	m/sec		W/m^2
T 5	RT6816d	5242.7	10.71	64.22	27.41	29.44	2.18	90.00	1.40	0.0005	16.47
	RT6667	5391.2	10.20	52.16	20.41	23.34	2.24	55.00	1.05	0.0005	13.52
	RT6504	5554.3	9.12	37.88	16.16	19.02	1.99	29.00	0.77	0.0005	9.00
	RT6339	5719.4	9.78	60.88	28.56	32.04	1.90	49.00	0.80	0.0005	8.60
	RT6102	5956.7	10.31	88.19	26.45	29.63	2.98	108.00	1.22	0.0005	20.48
T 6	RT5897	6161.6	9.53	62.13	32.00	33.83	1.84	43.00	0.69	0.0005	6.61
	RT5558	6500.6	9.99	70.43	26.82	29.69	2.37	99.00	1.41	0.0005	18.17
	RT5360	6698.9	9.54	62.45	25.77	28.15	2.22	60.00	0.96	0.0005	11.46
	RT5021	7037.9	9.63	69.76	26.07	28.67	2.43	80.00	1.15	0.0005	15.10
	RT4678	7380.4	8.43	59.20	27.86	29.44	2.01	31.00	0.52	0.0005	5.48
	RT4483	7575.0	8.42	62.08	32.74	35.37	1.75	32.00	0.52	0.0005	4.81
	RT4320L	7738.0	8.90	44.79	20.16	21.85	2.05	23.00	0.51	0.0005	5.62
	RT4193L	7865.2	9.59	51.55	17.00	21.91	2.35	34.00	0.66	0.0005	9.84
	RT3796	8262.5	8.66	45.48	20.29	23.02	1.98	55.00	1.21	0.0005	13.34
	RT3602	8456.9	8.37	74.58	25.22	28.18	2.65	45.00	0.60	0.0005	8.78
	RT3207	8851.2	8.23	70.43	26.64	28.80	2.45	41.00	0.58	0.0005	7.57
	RT2974	9084.1	8.36	73.33	26.09	28.42	2.58	53.00	0.72	0.0005	10.00
	RT2655	9403.5	8.39	127.19	83.59	85.08	1.49	56.00	0.44	0.0005	3.30
T 7	RT2655d	9403.5	8.39	219.96	83.59	87.79	2.51	62.00	0.28	0.0002	1.43
	RT2293	9765.3	7.98	69.42	22.38	25.34	2.74	43.00	0.62	0.0002	3.71
	RT1962	10096.6	7.94	86.27	27.79	30.49	2.83	45.00	0.52	0.0002	3.13
	RT1683	10375.5	7.78	60.07	21.06	23.86	2.52	40.00	0.67	0.0002	3.67
	RT1403	10655.2	7.78	69.28	29.17	30.90	2.24	45.00	0.65	0.0002	2.98
	RT1123	10935.2	8.00	72.74	28.38	30.68	2.37	47.00	0.65	0.0002	3.20
	RT822	11236.7	7.29	60.89	29.40	30.91	1.97	21.00	0.34	0.0002	1.38
	RT521	11537.7	7.56	71.72	29.29	31.41	2.28	32.00	0.45	0.0002	2.11
	RT260	11798.3	7.11	49.01	24.69	26.31	1.86	17.00	0.35	0.0002	1.33
T 8	RT000	12058.3	7.53	40.66	15.86	18.55	2.19	22.00	0.54	0.0002	2.68
	RT0001	12258.3	7.91	62.63	23.61	25.69	2.44	29.00	0.46	0.0002	2.37
	RT0002	12458.3	8.04	82.52	29.65	31.42	2.63	36.00	0.44	0.0002	2.35
	tone40	12663.3	8.07	101.57	35.52	37.16	2.73	38.00	0.37	0.0002	2.07
	tone401	12863.3	7.85	93.23	37.86	39.28	2.37	31.00	0.33	0.0002	1.58
	tone402	13063.3	7.57	79.55	39.35	40.70	1.95	21.00	0.26	0.0002	1.03
	tone39	13248.3	7.27	62.91	28.69	30.07	2.09	21.00	0.33	0.0002	1.41
	tone391	13448.3	7.15	64.69	29.46	30.58	2.12	19.00	0.29	0.0002	1.25
	tone392	13648.3	7.02	64.82	29.47	30.60	2.12	16.00	0.25	0.0002	1.05
	tone393	13848.3	6.91	63.91	28.04	29.34	2.18	14.00	0.22	0.0002	0.96
	tone38	14078.3	7.23	76.36	30.09	31.81	2.40	19.00	0.25	0.0002	1.22

KEY

- sediment deposition potential (<15 Wm^{-2})
- sediment transfer (15-35 Wm^{-2})
- sediment erosion potential (>35 Wm^{-2})