Spatial variability of floodplain sedimentation

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Abstract

Spatial patterns of overbank deposition are highly variable. This spatial variability is the result of complex interactions of key factors that constitute the mechanisms and processes that hydraulically interact with floodplain topography during overbank inundation. Some of these key factors include flood duration, settling velocity, floodplain shear stress, suspended sediment concentration, flow depth and post-peak pond depth.

This study reviews and improves the current conceptualisation of the interactions among nine key factors known to determine spatial patterns of overbank deposition. Thus, the development of a spatially explicit numerical model of overbank deposition is an improvement on earlier models by comprehensively incorporating the nine key factors, and better representing the interactions which occur during overbank inundation and deposition.

Using this model, a sensitivity analysis was used to demonstrate that, of the nine key factors, the three most important in determining the spatial heterogeneity of overbank deposition are flood duration (e.g. days of inundation), travel time and overbank flow depth. These temporal factors determine the decrease of suspended sediment concentration as the sediment travels along the floodplain during overbank inundation.

The numerical model was used to estimate overbank deposition rates on thirteen floodplain units of the dammed and regulated Goulburn River in southeastern
Australia. The modelled estimates were then compared with field estimates based on detection of $^{137}$Cs and unsupported $^{210}$Pb.

Results of this research demonstrate the importance of adequately calculating the travel time and overbank flow depth in relation to the distance from the channel along overbank flow paths, and also will advance our understanding of overbank accretion as a process of floodplain change. Regarded as one of the most important factors determining spatial patterns of overbank deposition, this distance from the channel had not been clearly established before.
Declaration

This is to certify that:

i. the thesis comprises only my original work towards the PhD except where indicated in the Preface,

ii. due acknowledgement has been made in the text to all other material used,

iii. the thesis is fewer than 100 000 words in length, exclusive of tables, maps, bibliographies and appendices
Acknowledgments

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1 Chapter One

1.1 Introduction

1.1.1 Problem statement and aims

Overbank deposition occurs when a river overflows its banks, transporting and depositing sediment across the river floodplain. This deposition, variable over space and time, together with lateral point-bar accretion, and braid-channel accretion, is one of the three most important forms of floodplain accretion (cf. Nanson & Croke 1992). In the long term, it is from floodplain accretion processes, as well as from various types of sediment erosion, that alluvial floodplains are shaped and evolve.

Alluvial floodplains are important landforms of ecological significance; they act as a buffer between the river and the surrounding land and are sinks for river-born sediment. Additionally, the spatial distribution of the fine component of overbank deposition, influence floodplain fertility (Hirst & Ibrahim 1996).

Alluvial floodplains have been classified in terms of their specific stream power, sediment characteristics, morphology and energy levels (Church 1992; Nanson & Croke 1992). Following the classification established by Church (1992), the analyses
developed in this thesis focus on the floodplain of a river with a single channel (monochannel) which has formed, under medium-energy processes, from meandering and avulsion.

Overbank deposition along alluvial floodplains is spatially heterogeneous (Walling, He & Nicholas 1996; Middelkoop & VanDerPerk 1998; Nicholas & Walling 1998; Walling & He 1998a; Tornqvist & Bridge 2002; Amos et al. 2009; Cabezas et al. 2010) and can be the dominant accretion process on floodplains, particularly floodplains of slowly migrating rivers or of those rivers artificially constrained by ‘training’ and channelisation works (Walling & He 1998a).

It has been observed in previous studies that overbank deposition tends to decrease with distance from the channel, but the way in which this distance has actually been defined and measured has not been adequately established (Asselman & Middelkoop 1995; Walling & He 1998a; Carson 2006; Casas et al. 2006).

Spatial patterns of overbank deposition result from complex interactions between floodplain topography and overbank inundation (e.g. Lewin & Denis 1980), as well as from complex interactions among important factors that constitute the mechanisms and processes of sediment transport and deposition. These factors include distance from the river, flood duration, flood flow velocity and depth, settling velocity, suspended sediment concentration, pond depth and floodplain shear stress (Magilligan 1992b; Batalla & Sala 1994; Nicholas & Walling 1996; Nicholas & Walling 1997; Asselman 1999b; Walling & Woodward 2000; Thonon et al. 2005; Buttner et al. 2006; Carson 2006; Piégay et al. 2008). This list of variables, henceforth called ‘key factors’, show spatial and temporal variability and their comparative level of influence
on spatial patterns of overbank deposition has not been established. This research gap is addressed in this PhD thesis.

Spatial patterns of overbank deposition are additionally influenced by patterns of erosion, including floodplain scouring and sediment resuspension. As noted by Cabezas et al. (2010), our knowledge about the interactions that occur among these key factors, and additional processes of erosion during overbank inundation, needs to be improved in order to make strong predictions about spatial patterns of overbank deposition and, thus, to improve our understanding of floodplain change and evolution.

Numerical models are built with the intention of representing and simulating, as accurately as possible, real processes. These are usually based on existing theory and conceptualisations. While these key factors have been identified from previous research, existing models of overbank deposition do not incorporate all of these key factors (Nicholas & Walling 1998; cf. Siggers et al. 1999; Buttner et al. 2006; Nicholas et al. 2006) and therefore, their interactions during overbank deposition are difficult to establish. This incomplete representation suggests that the existing conceptualisation of the variables and processes that occur during overbank deposition can be improved. This conceptualisation is also an issue addressed in my research.

In addition, our current level of understanding limits our ability to predict the effects of flow regulation on floodplain change and evolution. In general, the effects of artificial reservoirs have been studied with a focus on downstream channel morphology (cf. Williams & Wolman 1985; Gordon, McMahon & Finlayson 2004). Comparatively, much less research has been carried out on the possible effects of flow regulation on floodplain processes, than on in-channel effects or on freshwater ecosystems.
However, understanding the effects of flow regulation and reduced sediment regimes on river floodplains is a very real issue, especially knowing that there are 45,000 artificial reservoirs with dam walls over 15 metres across the globe, holding back 15% of the global annual river runoff (Christer Nilsson et al. 2005).

Thus, the research aims of this investigation are: first, to improve the current conceptualisation and numerical representation (i.e. overbank deposition models) of the interactions among the key factors that influence overbank deposition. Second, to use this conceptualisation to identify the comparative level of influence that the key factors have on the spatial distribution of overbank deposition. Finally, this research will investigate the effects of a large dam, and flow regulation, on overbank deposition, by comparing floodplain deposition rates before and after construction of the dam. However, as will be explained below, it was not possible to fully achieve this third aim.

By improving the representation of the interactions among the key factors in a numerical model, it is expected that this research will contribute to improving our capacity to predict spatial patterns of overbank deposition. This, in turn, by identifying and locating sediment storages, will assist in the estimation of fluvial sediment budgets and also will help to predict potential changes in floodplain dynamics and fertility of this type of alluvial rivers. Thus, this research will contribute to better explaining and predicting floodplain change and evolution.
1.1.2 Overview of the study

This thesis involves: development of an improved conceptualisation and numerical model of floodplain deposition, identification of the most sensitive variables in this model and, also, field testing of the model results.

To address the research aims, I first sought to improve the conceptualisation of the interactions among the key factors (Chapter 4). Then, based on existing numerical models of overbank deposition, I used the improved conceptualisation to more comprehensively incorporate nine key factors (listed above) in a presumably improved model. The numerical models of Nicholas and Walling (1998) and Buttner et al. (2006) were used since, with relatively simple equations, they are capable of representing spatial patterns and amounts of overbank deposition at the event to medium time scale with reasonable accuracy (because they have been tested against measured estimates); and they complement each other in relation to the key factors that they represent. Then, a sensitivity analysis, which used the newly formulated numerical model, was carried out to establish the comparative level of influence of each key factor on the spatial heterogeneity of overbank deposition (Chapter 8). This type of analysis has not been done before and therefore required defining representative values of each key factor that were valid for the selected floodplain in order to establish a range of variability of the same key factors (Chapter 8).

Alluvial floodplains are composed of different types of floodplain geomorphic units, such as scroll bars, abandoned channels, meander cutoffs, levees, crevasse channels and splay{s. Regardless of the floodplain-unit type, the hydraulic connectivity
of floodplain units (i.e. areas reached by overbank inundation) is determined by the effect that the floodplain-unit topography and the surrounding topography, has on flood distribution. In fact, the hydraulic connectivity of a floodplain unit may change with flood magnitude, because as flood height increases and reaches the unit, both flood depth and extent usually increase. Thus, this research considers that overbank inundation and overbank deposition will show similar spatial patterns. This means that floodplain units with high susceptibility to overbank inundation are those more often flooded and are those with higher sediment accumulation and vice versa. Therefore, the hydraulic connectivity and susceptibility to overbank inundation of thirteen representative floodplain units were identified, as will be discussed in Chapter 6.

The Mid-Goulburn River floodplain in Victoria, Australia, was used as a case study to carry out this investigation and to determine spatial patterns of overbank deposition. I chose this river system because (a) the available datasets and recorded history of flooding was considered adequate to complete this study, and (b) the relative paucity of investigations that focus on the spatial distribution of floodplain deposition in regulated rivers. The field area is the floodplain of a 2-kilometre wide and 90-kilometre long reach of the Goulburn River, starting ~ 10 kilometers downstream of the dam wall of Lake Eildon.

Net overbank deposition, rates and amounts were estimated from $^{137}$Cs total inventories (Chapter 7) of core samples taken from thirteen representative floodplain geomorphic units. These geomorphic units were carefully selected using a novel approach (Chapter 6) which combined a LIDAR (Light Detection and Ranging) digital elevation model of the floodplain with historical datasets and field mapping of flood
heights. Deposition estimates obtained with the newly designed overbank deposition model were compared with the estimates of deposition from $^{137}$Cs analysis to assess model accuracy (Chapter 9). Studies on spatial patterns of overbank deposition involving $^{137}$Cs detection to estimate deposition rates and for corroboration of modelled areal overbank deposition on such relatively large area have not been carried out before. For example, Nicholas and Walling tested their overbank deposition model by comparing modelled estimates with measured areal deposition amounts using sediment traps along a 600m stretch of the River Culm in the UK; Buttner et al. (2006) compared modelled with measured deposition from sediment traps along a ~2km stretch of the middle Elbe in Germany; whereas Siggers et al. (1999) compared measured deposition rates calculated from $^{137}$Cs detection along a 300m stretch of the River Culm floodplain, studying the degree of correlation between measured deposition rates with modelled floodplain hydraulics using a two-dimensional hydraulic model.

As mentioned previously, I also sought to identify the impact that the artificial reservoir has had on overbank deposition along the floodplain. I planned to achieve this by estimating and comparing sedimentation rates over the pre- and post-Eildon periods (i.e. accretion rates before and after 1955: the year in which Lake Eildon was finished). Net overbank deposition over the pre-Eildon period were to be based on detection of the isotope (unsupported) $^{210}$Pb in floodplain sediments, and compared against net deposition over the post-Eildon period (which were calculated from $^{137}$Cs detection). However, the results obtained from this technique were not adequate to define net accumulation and deposition rates over the pre-Eildon period, given the lack of a clear decay of $^{210}$Pb (ex) activity with increasing depth. Therefore, overbank net
accumulation and deposition rates could not be compared between the two periods, and the impact of the dam on floodplain accretion rates and processes could not be established (discussed in Chapter 7).

Nevertheless, it will be shown that this thesis adequately addresses the research aims and that the results demonstrate a new way of conceptualising overbank deposition, which is an important geomorphic process shaping floodplain evolution.
Chapter Two

2.1 Literature Review

2.1.1 The study of overbank deposition rates and patterns

The following literature review focuses on overbank deposition; the factors identified from the literature that are relevant to this floodplain accretion process (nine key factors) and additional processes that may occur during overbank deposition.

2.1.1.1 Floodplain classification and the floodplain here studied

Overbank deposition is the means of transporting sediment in suspension that is carried by flows that connect the river to its floodplain. In a comprehensive classification of river floodplains based on specific stream power and sediment characteristics, Nanson and Croke (1992) defined a genetic floodplain as “the largely bedded alluvial landform adjacent to a channel, separated from the channel by banks, and built of sediment transported by the present flow-regime” (Nanson & Croke 1992,
Alluvial floodplains form over considerable periods of time and by three main processes: lateral point-bar accretion, overbank accretion (here referred to as overbank deposition) and braid-channel accretion (Nanson & Croke 1992).

Floodplains (all, the confined, unconfined and braided river floodplains) can be classified in relation to their specific stream power, sediment characteristics and energy levels, and considering additional geomorphic factors that reflect a more complete hierarchy of floodplain forms and processes (Nanson & Croke 1992). The research developed in this PhD thesis focuses on 'medium-energy, non-cohesive' floodplains (cf. Nanson & Croke 1992), which are formed from meandering-river and avulsion processes and as such, levees, scroll-bars, abandoned channels and meander cutoffs are common features found along these floodplains.

### 2.1.1.2 Floodplain geomorphic units and overbank inundation

As mentioned above, and because of their nature, meandering river floodplains are usually composed of diverse geomorphic units (Schumm & Winkley 1994; Bridge 2003). These include scroll bars, crevasse channels and splays, abandoned channels, meander cutoffs and levees (Shields & Abt 1989; Leclerc & Hickin 1997; Cazanacli & Smith 1998; Slingerland & Smith 1998). The spatial distribution of the sediment that is ultimately deposited along meandering alluvial floodplains during overbank inundation is highly influenced by floodplain topography (Asselman & Middelkoop 1995; Nicholas & Walling 1997; Walling & He 1998a). Overbank deposition also occurs in ponds that form along some areas of the floodplain during the flood recession phase (i.e. post-
peak phase) and these ponds are referred hereafter as post-peak ponds (Asselman & Middelkoop 1995; Carson 2006).

It is actually the interaction between floodplain units and the surrounding topography with the overbank flow which determines the hydraulic connectivity of meandering alluvial floodplains. This connectivity is usually complex given the topography of individual floodplain units, their distance to the channel and their relative elevation (Cabezas et al. 2010). This suggests that, regardless of their type, each of these units may have a distinctive hydraulic connectivity to the river channel during overbank inundation. In fact, the hydraulic connectivity of a floodplain unit may be conceived to be variable with flood magnitude because as overbank height increases, floodplain units are generally more easily reached by the overbank flow. Moreover, as the means of transporting suspended sediment, the spatial patterns of overbank inundation may be similar to the spatial distribution of overbank deposition; thus, this possibility is analysed in this research.

2.1.1.3 Additional processes and sediment sources

During overbank deposition, sediment is transported mainly from the river channel to the floodplain. However, depending on energy levels associated with flood magnitude, overbank flow type and behavior (Brinke et al. 1998) and also to floodplain roughness, additional processes may occur that are unevenly distributed. Floodplain scouring or sediment resuspension represent sediment redistribution processes which may either add new sediment or trigger erosion, affecting spatial patterns of overbank
deposition and complicating predictions of overbank deposition patterns. Furthermore, additional sediment sources to those of the river, such as tributary inputs or hill slope erosion, may also be affecting overbank deposition amounts, adding complexity to the spatial distribution of overbank deposition (e.g. Marutani et al. 1999). Depending on the research scope, when these processes and their location can be identified (erosion, floodplain scouring and resuspension or additional sources), these may either need to be avoided (e.g. by selecting sites in which it is believed their influence is small) or considered in the analysis. In relation to this, Grams and Schmidt (2002) state that “unmeasured sediment inputs from ungaged tributaries [may] further complicate sediment budgets [...] where tributaries that contribute insignificant streamflow may contribute disproportionally large amounts of sediment to the master streams” (Grams & Schmidt 2002, p. 338). Therefore, if establishing these additional sediment inputs is difficult, it may be better to establish amounts and spatial patterns of overbank deposition of floodplain locations which can be considered to be relatively free of these effects.

2.1.1.4 Existing models of overbank deposition

Overbank deposition models can be a useful tool to assists in quantifying and predicting sedimentation amounts along alluvial floodplains. They can be used to help estimate contaminants that are associated mostly with the fine fraction of overbank deposition, to calculate sediment budgets and to help predict the evolution of floodplains (Howard 1992; Howard 1996; Nicholas & Walling 1998; Siggers et al. 1999;
Moody & Troutman 2000; Buttner et al. 2006). They can be particularly useful for establishing deposition patterns and rates and can complement field programs designed to either directly (using sediment traps) or indirectly (e.g. via isotopic analysis) estimate sedimentation amounts at various scales and spatial resolution. Pioneering theoretical approaches are those which provided the basis for developing numerical models with relatively simple configurations: those of Bridge and Leeder (1979), James (1985) and Pizzuto (1987). Following previous research, Pizzuto (1987) calibrated and tested a diffusion, sediment transport and deposition model that seems to be consistent with field investigations carried out by other researchers. His model establishes a decrease in sediment accumulation and in its mean grain size away from the channel. This observation has also been reported by other researchers (Marriot 1992; Asselman & Middelkoop 1995). Superimposed on this tendency of decreasing deposition with distance from the channel, however, high levels of spatial and temporal variability of overbank deposition (e.g. Walling, He & Nicholas 1996; Walling & He 1998a) have been identified to also be a product of temporal variation in flood magnitude and sediment load, together with complex feedbacks between floodplain topography and sediment transport and deposition processes (Nicholas et al. 2006). These complex feedbacks are all the result of hydraulic interactions which can be present at the site, floodplain reach and catchment scale. However, the partial understanding on the interactions of these complex feedbacks (description of these discussed later in this chapter) and of their influence on spatial patterns of overbank deposition (Cabezas et al. 2010) seems to be challenging the current conceptualisation of overbank deposition and possibly the accuracy of all existing overbank deposition
models, as these could be influenced by this partial understanding (further discussed below).

Overbank deposition models incorporate hydraulic, sediment transport and deposition components (e.g. Nicholas & Walling 1998; Siggers et al. 1999; Hardy, Bates & Anderson 2000; Buttner et al. 2006; Nicholas et al. 2006). They seem to have been reasonably well calibrated using real-time measurements (i.e. sediment traps used during flood events to calculate sedimentation amounts) or/and estimations obtained mainly from isotope analysis; including detection of $^{137}$Cs and unsupported $^{210}$Pb.

At present, some models are capable of representing absolute amounts and spatial patterns of overbank deposition at the event to medium time scale, i.e. decades (cf. Nicholas & Walling 1998; Siggers et al. 1999; Buttner et al. 2006; Nicholas et al. 2006) and with reasonable accuracy, but do not incorporate all relevant key factors (described in the next section) that have already been identified for determining spatial patterns of overbank deposition (Nicholas & Walling 1998; Hardy, Bates & Anderson 2000; Buttner et al. 2006). In general, the sources of uncertainty of these models are partially related to model input parameters that prove to be difficult to measure directly during the corresponding research exercise (cf. Thonon et al. 2005). For example, with a few exceptions (e.g. Buttner et al. 2006), a common problem faced by researchers has been the lack of available and adequate datasets of the suspended-sediment model component (cf. Hardy, Bates & Anderson 2000; Walling 2004; Thonon et al. 2005). As a result, it is not yet clear what has had the most effect in limiting model accuracy: (a) insufficient field measurements of key parameters (e.g. commonly incomplete records of suspended sediment concentration), or (b) the recognised need
for model improvement (Nicholas & Walling 1998; Buttner et al. 2006; Nicholas et al. 2006). In this research, the models of Nicholas and Walling (1998) and Buttner et al. (2006) are used since they involve relatively simple equations, they complement each other in relation to the key factors that they represent, are capable of representing spatial patterns of overbank deposition at the event to medium time scale, and they can do this with reasonably accuracy.

This analysis shows that improving the current conceptualisation of overbank deposition and the representation in numerical models of the key factors influencing spatial patterns of overbank deposition are relevant research gaps. This investigation is therefore, designed to address these two.

2.1.1.5 Related processes and key factors which influence overbank deposition patterns

As mentioned above, various key factors occur during overbank deposition which are, or relate to, sediment sourcing, sediment transport, deposition and erosion (e.g. Zwolinski 1992; Basil Gomez et al. 1998; Owens, Walling & Leeks 1999). Those referred to here as key factors are flood duration, suspended sediment concentration, settling velocity, flow depth and velocity, distance to the channel, pond depth, floodplain roughness, shear stress and critical shear stress (Magilligan 1992b; Batalla & Sala 1994; Nicholas & Walling 1996; Nicholas & Walling 1997; Asselman 1999b; Walling & Woodward 2000; Thonon et al. 2005; Buttner et al. 2006; Carson 2006; Piégay et al. 2008). These key factors were indentified in the literature for having important effects on the magnitude and spatial distribution of overbank deposition.
Thus, their influence on this accretion process are the result of hydraulic interactions; which are summarised below.

### 2.1.1.6 Flow characteristics and hydraulic interactions influencing spatial patterns of overbank deposition

- The hydraulic characteristics of overbank flow, including flow type (e.g. turbulent diffusion, helicoidal currents or convective flow) (Asselman & Middelkoop 1995; Rutschmann & Hager 1996; Lecce & Pavlowsky 2004), flood duration, magnitude and frequency (Moody & Troutman 2000; Lecce & Pavlowsky 2001).
- The hydraulic connectivity between river and floodplain at specific overbank discharge levels results from the interrelationship of flood magnitude with floodplain topography. As previously mentioned, distance between floodplain units and the river channel may also be relevant (Asselman & Middelkoop 1995; Walling & He 1998a; Carson 2006; Casas et al. 2006). Therefore, the hydraulic connectivity and susceptibility to overbank inundation of floodplain units are relevant aspects of the study of overbank deposition processes.
- Vegetation type and density along floodplains influence the spatial variability of floodplain roughness and floodplain shear stress. These last are also influenced by discharge (Holden & James 1989; Jeffries, Darby & Sear 2003; Nicholas & Mitchell 2003).
- The interactions related to sediment transport and deposition:
These are interactions directly related to sediment source and availability (Lecce & Pavlowsky 2004). As previously mentioned, sediment that is subsequently transported by overbank flows may originate from the river, the local floodplain, hill slopes (gully erosion), tributaries, or from sediment resuspension (which is also affected by vegetation cover).

Additionally, sediment transport is directly influenced by linkages between suspended sediment characteristics - namely suspended sediment size distribution (Marriot 1992) and suspended sediment concentration - and by overbank flow characteristics - in most cases turbulent flow (Wyzga 1999; Gordon, McMahon & Finlayson 2004; Buttner et al. 2006; Picouet, Hingray & Olivry 2009). All the former determine the fall velocity (settling velocity) of specific sediment grain-size distributions, which is also affected by flow type (Cheng 1997; Thonon et al. 2005). Therefore, the “mixture of particle sizes found in natural streams [add complexity since this] create[s] interactions which would not occur if materials were of a uniform size” (Gordon, McMahon & Finlayson 2004, p. 190).
2.1.2 Research aim and objectives

The two research aims of this PhD project are: (a) to identify the comparative level of influence that these key factors have on the spatial distribution of overbank deposition, and (b) to improve the current conceptualisation and representation in numerical models of the interactions among key factors that influence overbank deposition.

To address these aims, the following objective will be pursued: to determine the spatial patterns of overbank deposition of the alluvial floodplain selected as a case study, being the floodplain of a flow regulated river (as will be explained in the next section).

2.1.3 Scope and research design

As mentioned above, in several studies it has been either observed or taken as a premise that distance from the river channel is an important factor that affects spatial patterns of overbank deposition. In most studies and only with a few exceptions (Cabezas et al. 2010) the way in which this distance has actually been calculated is not adequately described. This is relevant, especially since the distance travelled by the overbank flow may be different at different flood magnitudes as the latter may also
change the route that the overbank flow takes to reach a specific floodplain location while flow velocity increases. To clearly define the way in which distance from channel should be measured is also important because this will presumably determine the time that suspended sediment will travel before being deposited at that distance and floodplain location.

A well-established fact is that sediment deposited along floodplains during overbank inundation is generally composed of fine sediment in comparison to the total sediment load of river systems (cf. Walling & Bradley 1989; Owens, Walling & Leeks 1999). This fact has allowed the successful use of radionuclide analyses of floodplain sediments, such as that based on $^{137}$Cs detection (Walling & Bradley 1989; Walling & He 1994; Walling, Owens & Leeks 1998; Amos et al. 2009; Hughes et al. 2009). Detection of unsupported $^{210}$Pb has, on the other hand, the potential of providing the necessary data to estimate sediment deposition rates (Siggers et al. 1999; Piégay et al. 2008) but this radionuclide has been less widely used in floodplain environments: possibly because the various sediment redistribution processes commonly occurring in this setting may complicate these estimations (MacGregor et al. 2005), in contrast to lacustrine settings.

It has also been observed that overbank deposition is higher along areas of deeper, less mobile overbank flow: such as along billabongs and backwater areas and thus they may display higher accumulation rates (Walling & Bradley 1989). This depends, however, on the effects that the many factors and processes mentioned above may have on overbank deposition. Another element to consider when establishing overbank deposition amounts and rates is the deposition that occurs along post-peak ponds, which form along deep floodplain areas where there is a
disconnection to the main flow: this is additional deposition that occurs during the flood recession phase and which, according to Asselman and Middelkoop (1995), can be a significant contribution.

Furthermore, flow velocity and sediment size distributions influence the way in which suspended sediment might be transported during a particular flood event. This will affect how long and how far sediment in suspension is transported and ultimately deposited. This influence also defines the settling velocity of the usually mixed-grain-size sediment that is transported by floods (Gordon, McMahon & Finlayson 2004). Additionally, it has been found in previous investigations that a high percentage of fines in the suspended sediment domain will result in a tendency for the sediment to aggregate and form flocs. Flocculation has been shown to have a significant effect on settling velocities and, in turn, increases the variability of sedimentation fluxes (Nicholas & Walling 1996; Thonon et al. 2005). Therefore whenever possible, it is important to consider the effects of flocculation in the settling velocity domain.

Even though valuable advances have been made to improve our understanding of the important factors and processes occurring during overbank inundation and deposition, it is still not clear which of the key factors listed earlier in this chapter more importantly determine spatial patterns of overbank deposition. The fact that these key factors have not been comprehensively incorporated in existing models suggests that the way we conceptualise the interactions among the key factors and thus the way we represent these in numerical models of overbank deposition needs to be improved.

Since not all these key factors have been adequately represented by existing models (e.g. Nicholas & Walling 1998; Siggers et al. 1999; Buttner et al. 2006; Nicholas et al. 2006) it has not been possible to explore which of these key factors have a
stronger influence on the spatial distribution of overbank deposition. This is scrutinised in the present research through the design of a sensitivity analysis in which the relevant factors are incorporated in a novel approach. Thus, pursuing the establishment of a better conceptualisation of the factors and mechanisms that influence overbank deposition, I will explore the possibility of improving two models: that of Nicholas and Walling (1998) and that of Buttner et al. (2006). These models were chosen as, (a) with relatively simple equations, they are capable of representing spatial patterns of overbank deposition with reasonably accuracy (as have been tested against field and measured estimates) and (b) they complement each other in relation to the key factors that they represent.

In addition, our current understanding is limited in its ability to deal with what happens in the case of regulated river floodplains; what are the expected effects of flow regulation on overbank deposition processes and how are the key factors and their interactions affected. In general, the effects of artificial reservoirs have been studied with a focus on downstream channel morphology (cf. Williams & Wolman 1985; Gordon, McMahon & Finlayson 2004) and comparatively, much less research has been carried out in relation to the possible effects of flow regulation on floodplain processes than there is on in-channel effects. This stresses the need for carrying out research projects which incorporate this fluvial element: alluvial floodplains.

Moreover, it is not clear what the implications of a restricted flooding and sediment regime are for the evolution of alluvial floodplains. This aspect should be dealt with first on a case-by-case basis since the purposes for building dams and the corresponding water release policies vary (Williams & Wolman 1985). Dams are built for either one or a combination of the following purposes: hydropower generation,
irrigation and water supply, or sediment control to avoid channel aggradation (Williams & Wolman 1985). For example, dams built solely for irrigation may represent a range of scenarios. “At one extreme, virtually no water is ever released, and all irrigation diversions are made directly from the reservoir (e.g. Sandford Dam, Canadian River, Texas). Near the other extreme, practically no water is released during the winter storage period, but relatively large flows are released steadily during the irrigation season” (Williams & Wolman 1985, p. 8). As Williams and Wolman point out, because “there are large variations from one dam to the other in the magnitude and duration of flow releases” (Ibid, p. 7), “the uniqueness of release policy at each dam precludes simple generalisations about the discharge distributions except that flood peaks will be decreased”. In general, the same may also be true in relation to sediment loads downstream of dams (Ibid, p. 8) –given that they are effective sediment traps. However, flood magnitude and frequency as well as suspended sediment size distributions and concentration along floodplain reaches (and at various distances downstream dams) may vary, as well as the hydraulic connectivity of floodplain units and the spatial distribution of overbank deposition. Furthermore, the spatial distribution of overbank inundation and sediment deposition is also the result of additional water and sediment sources that may feed the floodplain; including tributary inflows and sediment inputs.

Therefore, this research is a process-based numerical approach and is composed of the following three major elements. The first focuses on trying to improve the current conceptualisation of overbank deposition, including the interactions among related processes (i.e. sediment transport and mechanisms of sediment deposition) and interactions among the key factors. The second focuses on developing a numerical
model seeking to incorporate, in a more comprehensive way, the key factors that influence overbank deposition. The third is a sensitivity analysis, which is based on the new model and is designed to elucidate the relative level of influence of the mentioned key factors on the spatial variability of overbank deposition.

A floodplain reach of the meandering Mid-Goulburn River (i.e. 2-kilometre wide and 90-kilometre long), has been selected for this research. The floodplain locations chosen for further analyses were selected considering potential sediment fluxes and sediment sources; this, with the intention of incorporating sites fed only from overbank flows and sediment from the river channel; and therefore, trying to minimise additional effects caused by sediment resuspension, floodplain scouring and other floodplain erosion processes.

Thus, in order to provide a detailed description of the methods used in this research, an overview of the methodology is given in Chapter 3. The analyses carried out to estimate overbank net deposition and rates are based on isotope detection of $^{137}$Cs and unsupported $^{210}$Pb as the time scale that these involve was considered adequate for this research: a decadal time scale and up to ~100 years from present.
3 Chapter Three

3.1 Methodology

3.1.1 Introduction

This investigation responds to an identified need for building up scientific knowledge on overbank deposition processes. As discussed in Chapter 2, it is focused on identifying the influence of key factors on the spatial distribution (patterns) of overbank deposition. The methodology of this research includes a process-based conceptual and numerical approach. It includes analysis of existing conceptual and numerical models, sediment core collection, GIS and radionuclide analyses.

In order to address the research aim of this study, this research is based on a case study. Even though it is understood that some responses are specific to the particular river system being studied, the methodology used in this study is designed to allow general conclusions to be drawn and be valid for alluvial systems in general.

As discussed in Chapter 2, a relative paucity was identified of studies that investigate regulated river systems and, specifically, on regulated alluvial floodplains.
Therefore, the floodplain that was selected is a 90-km floodplain of the ‘Mid- Goulburn River’ (cf. Erskine, Rutherfurd & Tilleard 1993; Erskine 1996), located in central Victoria, Australia. This floodplain section is almost immediately downstream of Lake Eildon (Figure 5.1 in Chapter 5), the artificial reservoir in the upper catchment.

3.1.2 Research design and description of methods

In order to address the research aim of this investigation, I will carry out the following major research tasks. Based on the current framework, the first task was to pursue the improvement of the current conceptualisations of the interactions among influential factors and relevant processes that may be present during overbank deposition (as the first hypothesis). The second was to develop a numerical model of overbank deposition which, based on the improved conceptualisation, could numerically represent these interactions. Therefore, this model will have the potential to better represent and predict spatial patterns of overbank deposition (the second hypothesis). To assess its accuracy, this new model needed to be tested using field observations. These field estimations of overbank deposition were obtained from floodplain deposits along the Mid-Goulburn River floodplain.

Finally, I sought to identify the impact of flow regulation on overbank deposition along the Mid-Goulburn River floodplain by comparing deposition rates before and after completion of Lake Eildon (third hypothesis). To do so, I decided that the approach
adopted could be based on $^{137}\text{Cs}$ and unsupported $^{210}\text{Pb}$ detection (referred to hereafter as $^{210}\text{Pb}_{(ex)}$) as concentrations of these elements can be associated with the last $\sim$60 and 100 years respectively. Knowing that flow regulation by Lake Eildon started in 1955 and that approximately in this same year $^{137}\text{Cs}$ started to fallout in the southern hemisphere (Wallbrink & Murray 1996; Leslie & Hancock 2008), I considered that detection of this radionuclide could be especially useful. Moreover, these two cosmogenic elements have been used in several studies to satisfactorily calculate sediment deposition amounts and rates in floodplain settings (Wallin & Bradley 1989; Walling & He 1994; Walling, Owens & Leeks 1998; Amos et al. 2009; Hughes et al. 2009).

The reduced overbank inundation along the Goulburn River under the currently regulated flow regime excluded the possibility of basing this research on real-time measurements, such as installing sediment traps to estimate deposition over a flood event or collecting samples to establish suspended sediment concentration.

As a means of excluding processes outside of the scope of this research, only those floodplain locations whose formative processes were believed to be dominated by overbank deposition were considered relevant for this study. Therefore, I decided to select floodplain geomorphic units that could act (or have acted in the pre-Eildon period) as good sediment storages. These include abandoned channels, meander cutoffs and floodplain swales from scroll bars (Chapter 6). To further refine the selection, I excluded abandoned channels and meander cutoffs proximal to the modern channel because of their potential of being hydraulically connected to the modern channel during high in-channel flows and not only during overbank inundation.
At that point, however, a big number of geomorphic units were still candidates for further investigation and so, in order to complete this project successfully and without exceeding allocated time and costs, the number of geomorphic units needed to be reduced in a strategic way. To achieve this, and knowing that overbank inundation is the means of sediment transport in suspension, I considered that, hypothetically, similar patterns of overbank inundation exist to those of overbank deposition. Therefore, I designed a novel method to classify floodplain units in terms of their susceptibility to being hydraulically connected to the river channel during overbank inundation. A high-resolution digital elevation model of the Mid-Goulburn River (i.e. a one-meter cell resolution LIDAR\(^1\)-based DEM with a vertical and horizontal accuracy of \(\pm 10\) cm and \(\pm 20\) cm respectively) and georeferenced data of historical flood levels provided by the Goulburn-Broken Catchment Management Authority (GBCMA) were used in this task. The method is described in Chapter 6 and consisted of determining the spatial distribution of overbank inundation of different magnitudes and on classifying potentially relevant floodplain units in terms of their susceptibility to overbank inundation. This step, in fact, defines how easily the units are inundated by overbank floods of different magnitudes and was carried out using GIS analysis.

The previous task led to a strategic selection of thirteen floodplain units, which were believed to appropriately represent the spatial variability of overbank deposition along the floodplain. These units were cored and their sediment was used for the

\(^1\) LIDAR, also known as Light Detection and Ranging, is an optical remote sensing technology able to measure the distance to the floodplain surface by illuminating the target with light, often using pulses from a laser.
estimation of overbank sediment deposition over the pre- and post-Eildon period (i.e. before and after 1955).

Flood distribution predicted by a hydraulic model of the Goulburn River floodplain was used to compare the predictions on the spatial distribution of overbank inundation obtained from the novel method mentioned above on spatial patterns of overbank inundation (Chapter 6). The hydraulic model (Water Technology 2009) was provided in 2009 by the GBCMA and includes flood flow velocities and depths in raster GIS form.

The radionuclide analyses that followed the previous task were based on combined detection of concentrations of $^{137}$Cs and $^{210}$Pb$_{(ex)}$ in sediment-core samples, with the aim of estimating overbank deposition of both the pre- and post-Eildon period (measured-estimates). The procedure developed by Walling, Quine and He (1992), which was adopted for this task, allows calculating average sediment accumulation for predefined depth intervals and including a wider selection of floodplain locations (in this case geomorphic units) for a better spatial representation. Results obtained from this step can be found in Chapter 7.

Concurrent with this analysis I identified from the literature both empirical studies and numerical models of overbank deposition and, from this, the processes and factors that can be regarded as key in determining spatial patterns of overbank deposition. These are the influential factors (listed previously in Chapter 2) and related processes which usually occur (or may occur) during overbank inundation. These processes are additional sediment sourcing to that originated from the river, sediment transport in suspension by overbank flows and the actual sediment deposition along
the floodplain (including deposition during the flood rising and the flood recession phase along post-peak ponds) (see Chapter 4). Thus, erosion producing new sediment sources, sediment resuspension and floodplain scouring are all additional processes that may occur during overbank deposition. The criteria that I established for the selection of floodplain units, however, focused on the formative processes of individual floodplain units and on the selection of sites where these additional processes were less likely to prevail. Therefore, crevasse channels and splays were not included in the analysis as I considered that erosion and resuspension along these geomorphic units are more likely to occur during overbank inundation. Levees were not included either because it is known that $^{137}$Cs and $^{210}$Pb(ex) are better absorbed by fine sediment (Walling, Quine & He 1992; Wallbrink & Murray 1996) and, even though overbank deposition can be an important geomorphic process in their development, these units may in cases be composed of coarser size fractions instead of fine ones, such as silt and clay (Cazanacli & Smith 1998). Therefore, based on their textural composition, levees were not included in the analyses developed in the next chapters.

Taking as its basis existing models, specifically those of Nicholas and Walling (1998) and Buttner et. al. (2006), I focused on improving the current understanding of the interactions among the identified key factors and on improving the representation of these interactions on these numerical models (Chapter 4). From the improved conceptualisation, I developed a new model that comprehensively incorporates both the key factors and processes mentioned above. As a result, the new model better establishes the relationship and interactions that exists among the factors listed in Chapter 2 and the related processes mentioned above: i.e. sediment transport and
deposition during overbank inundation, some of which were not fully represented in previous models.

A sensitivity analysis, using the new overbank deposition model, was the means for establishing the relative influence of the key mechanisms on the spatial variability of overbank sediment deposition. Therefore, based on its numerical components (key processes and factors) the sensitivity analysis was designed to identify the factors that exerted the greatest influence on the spatial variability of overbank deposition, addressing the main aim of this research (Chapter 9). The model was also used to provide estimates of overbank deposition (modelled estimates) of the selected floodplain units. Modelled and measured estimations were compared and the comparison was used to test and assess the model’s performance (Chapter 9).

Therefore, as can be observed, the conceptual, numerical and laboratory approaches complemented each other and were designed to address the main aim and research questions of this research.

The conceptualisation of the processes related to overbank deposition, the basis for the development of the overbank deposition model, is discussed in the next chapter and ultimately facilitated the sensitivity analysis (Chapter 8).

As mentioned in Chapter 1, concentrations of $^{210}$Pb$_{(ex)}$ that could be considered to belong to the pre-Eildon period (depth intervals with no detected $^{137}$Cs activity) did not show a clear decrease in the sediment profile (as will be shown in Chapter 7). This fact did not allow establishing overbank deposition rates over the pre-Eildon period and therefore, determining the impact of Lake Eildon on spatial patterns of overbank deposition could not be achieved as was originally planned.
4 Chapter Four

4.1 Development of an alternative overbank deposition model

4.1.1 Introduction

As mentioned in Chapter 2, two numerical models, those of Nicholas and Walling (1998) and Buttner et al. (2006), were chosen and analysed to formulate a refined numerical overbank deposition model in which the nine identified key factors were incorporated and better represented.

Pioneering work on spatial patterns of overbank deposition has shown that sediment transport and deposition can be described by dispersion and diffusion mechanisms that occur across floodplain sections (James 1985; Pizzuto 1987). Distance from the main channel has often been regarded as one of the most important influences on flood behavior and overbank deposition patterns. Previous research
additionally suggests that the effect of cross-floodplain variation (such as distance to the river channel) is more perceptible than down-valley variation of overbank deposition (Middelkoop & VanDerPerk 1998; Walling & He 1998a; Thonon et al. 2007). The increasing availability of high-resolution digital elevation models, such as those generated from LIDAR, has contributed to the development of more detailed studies focused on identifying the relevance of small-scale floodplain topography on sediment transport and deposition processes (since floodplain topography significantly influences flow hydraulics and suspended sediment transport). Recently developed overbank deposition models have been coupled with hydraulic and LIDAR DEMs. With this improved spatial representation, these models have been tested with measured estimates of overbank deposition and have been used to study spatial patterns of overbank deposition. Using these models, some authors have identified a noticeable spatial heterogeneity of overbank deposition along alluvial floodplains (Nicholas & Walling 1997; Middelkoop & VanDerPerk 1998; Nicholas & Walling 1998; Buttner et al. 2006).

These models are based on either a finite- or discrete-element approach (cf. Cabezas et al. 2010) and, as discussed in Chapter 2, they provide the basis for further research which includes the establishment of the level of influence that different key factors have on the spatial variability of overbank deposition (Cabezas et al. 2010).

Within this framework, two overbank deposition models are here considered for further analysis as these represent relatively simple approaches to predict, with reasonable accuracy, spatial patterns of overbank deposition.
The model of Nicholas and Walling (1998) establishes a relationship among sediment deposition, suspended sediment concentration, flood duration and particle settling velocity, using a finite-element approach (Equation 4.1 and Equation 4.2 below). Their model also considers the additional deposition that occurs during post-peak flooding along floodplain ponds (Equation 4.4).

On the other hand, the model of Buttner et al. (2006) (Equation 4.7 below) incorporates flow characteristics and its influence on sediment and floodplain surface, representing the relationship that the magnitude of sediment deposition has with two additional factors: floodplain shear stress and critical shear stress. To test their model, they used a discrete-element approach (Cabezas et al. 2010).

Equation 4.1 below shows the mathematical relationship between net deposition rate, flood duration (or residence time), settling velocity and suspended sediment concentration (SSC) developed by Nicholas and Walling (1998).

**Equation 4.1:**  
\[ D_r = k \cdot C \cdot V_S \]

where \( D_r \) is deposition rate, \( C \) is the depth-averaged suspended sediment concentration, \( V_S \) is the sediment particle fall velocity and \( k \) is an empirical coefficient that controls the proportion of the sediment in suspension at a node that is deposited. This empirical coefficient was used by the authors to calibrate their model using

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measured deposition amounts. The equation implies that there is no sediment erosion (Nicholas & Walling 1998).

A variation of the previous equation is suggested by these researchers (Nicholas & Walling 1998) to calculate deposition over a 'time step', in which a number of sediment size fractions may be incorporated as well as corresponding changes in settling velocity and suspended sediment concentration. The expression for that case is the following:

Equation 4.2: \[ D'_{ij} = k\Delta t \left( \sum_{j=1}^{J} V_{sj} \times SSC'_{sj} \right) \]

where \( D'_{ij} \) is the amount of deposition at node \( i \) during time step \( t \); \( \Delta t \) is the duration of the time step, \( V_{sj} \) is the fall velocity of the \( j^{th} \) size fraction, \( SSC'_{sj} \) is the sediment concentration of the \( j^{th} \) size fraction at node \( i \) during time step \( t \) and \( j \) is the number of size fractions employed in the model. The empirical coefficient \( k \) in their model controls the proportion of the sediment in suspension that will be deposited. This empirical parameter can be used to calibrate the model with the aid of measured deposition amounts (Nicholas & Walling 1998).

When the research involves establishing average sediment deposition rates over periods of time (a few years or decades), and also considering that spatial data on the variation of suspended sediment concentration along floodplains is often scarce or incomplete (as previously discussed in Chapter 2), the previous equation can be written in the form below (Equation 4.3). In this expression, a representative sediment
size fraction of the suspended sediment domain is used, together with a representative value of both, settling velocity and SSC.

**Equation 4.3:**  
\[ D_{Fd} = k \cdot \Delta T \cdot V_s \cdot SSC \]

where:

- \( Fd \) is total number of flooding days along the floodplain reach over the time period of interest (in this case the post-Eildon period), expressed in seconds;
- \( D_{Fd} \) represents the net deposition amount over the total number of flooding days for the period of time investigated, expressed in kg.m\(^{-2}\);
- \( V_s \) is settling velocity of a representative size fraction (of the suspended sediment) and over the same period of time
- \( SSC \) is suspended sediment concentration of the representative size fraction during the relevant time period (i.e. number of flooding days), expressed in kg.m\(^{-3}\) and
- \( k \) is the empirical coefficient that controls the proportion of the sediment in suspension that will be deposited. This empirical parameter should be used to calibrate the model with the aid of measured deposition amounts.

Therefore, in order to evaluate the relative importance that the previous factors may have on the spatial variability of overbank deposition, a value that represents the total number of overbank flooding days over the post-Eildon period can be used as the flood duration (\( Fd \)); details of its estimation are given in Chapter 8.

Nicholas and Walling (1998) established the additional deposition that occurs in post-peak ponds during the flood-recession phase as:
Equation 4.4: 
\[ D'_{pi} = d_{pi} \sum_{j=1}^{i} SSC_{ij}^{\text{prior}} \]

where:
- \( D'_{pi} \) is the additional deposition resulting from the settling of sediment along post-peak ponds at a time step at node \( i \);
- \( d_{pi} \) is the depth of pond water at node \( i \); and
- \( SSC_{ij}^{\text{prior}} \) is the sediment concentration of the \( j^{th} \) size fraction at node \( i \) during the time step prior to the isolation of the pond area from the main flow.

The same consideration used for the formulation of Equation 4.3 applies here, in which a representative sediment size fraction of the suspended sediment domain can be used to calculate average sediment deposition rates over periods of time and also, when trying to overcome the common difficulty imposed by an incomplete spatial representation of the variability of SSC along floodplains. Therefore, Equation 4.4 can be written as Equation 4.5.

Equation 4.5: 
\[ D_p = d_p \cdot SSC_{\text{prior}} \]

where:
- \( D_p \) is the additional deposition that results from sediment settling along pond water over the time period
- \( d_p \) is the average depth of pond water;
- \( SSC_{\text{prior}} \) is the SSC of a representative size fraction a time step prior to the isolation of the pond area from the main flow.

Thus, Equation 4.3 and Equation 4.5, which are derived from those of Nicholas and Walling’s (1998), can be used to calculate the total amount of overbank deposition along a given floodplain over the flood duration (or a time period), which incorporates the additional deposition that occurs along post-peak formed ponds. This is represented by Equation 4.6.

**Equation 4.6:**

\[
D_{\text{TOTAL}} = D_{Fd} + D_p
\]

On the other hand, Buttner et al. (2006) have suggested the following equations to calculate sediment deposition rate per unit area. They use a probability function \( P_d \) to calculate the portion of suspended sediment that does not rejoin the current and is deposited along the floodplain. They also incorporate SSC and sediment settling velocity in their equation:

**Equation 4.7:**

\[
Q_{dr} = \left[1 - (\tau / \tau_c)\right] \cdot V_s \cdot SSC
\]

where \( Q_{dr} \) represents the deposition rate per unit area, \( V_s \) is the average settling velocity, and \( SSC \) the concentration of particulate suspended matter in the overbank flow. The probability of a suspended particle being deposited and not rejoining the current is calculated as \( P_d = 1 - \xi / \tau_c \). The authors establish that critical shear stress
$\tau_c$ should be bigger than floodplain shear stress $\tau$ for sediment deposition to occur. They also establish that this probability should be zero otherwise.

In order to express $Q_{db}$ in terms of kg.m$^2$ (that is, as $Q_d$ and that way make comparable the models of Nicholas and Walling (1998) and Buttner et al. (2006), a factor of time needs to be multiplied in the previous equation; this is $Fd$.

**Equation 4.8**

$$ Q_d = \left[1 - \left(\frac{\tau}{\tau_c}\right)\right] \cdot V_s \cdot SSC \cdot Fd $$

Therefore, in Equation 4.8, $Q_d$ is net deposition over a period of time (expressed in kg.m$^2$) and $Fd$ is the total number of flooding days over that period.

Thus, the total amount of overbank deposition ($Q_{d,\,TOTAL}$) is obtained by incorporating the additional deposition in post-peak ponds (from the model of Nicholas and Walling (1998), Equation 4.5) and $Q_d$ (from the model of Buttner et al. (2006); Equation 4.8 above).

**Equation 4.9:**

$$ Q_{d,\,TOTAL} = \left[1 - \left(\frac{\tau}{\tau_c}\right)\right] \cdot (V_s \cdot SSC \cdot Fd) + \left(\frac{d_o \cdot SSC_{prior}}{\tau_c}\right) $$

As demonstrated by previous empirical work and as discussed in Chapter 2, suspended sediment tends to travel by dispersion (the spreading of mass from highly concentrated areas to less concentrated areas). It therefore can be expected that a relationship exists between suspended sediment concentration and the distance to a given floodplain location or the time traveled along the floodplain. Equation 4.9, however, does not describe this relationship, and therefore, is unable to represent the
change that suspended sediment concentration undergoes as the sediment travels across the floodplain and reaches the different floodplain units. This relationship is particularly important in the absence of empirical data on suspended sediment concentration and its spatial-temporal variation (as may often be the case).

Therefore, in the next section, I define an alternative overbank deposition model that is able to represent the variability of suspended sediment concentration in relation to travel time and flow magnitude (flow depth); that is, the time that sediment being transported by overbank flows takes to reach a floodplain unit that is susceptible to overbank flooding. The model incorporates all the factors that have been identified for their influence on spatial patterns of overbank deposition (i.e. the key factors; as discussed in Chapter 2).

### 4.1.2 Conceptual model and development of an alternative overbank deposition model

Spatial patterns of overbank deposition are related to floodplain topography and sediment transporting mechanisms (Asselman & Middelkoop 1995). Overbank deposition along the floodplain can occur during two scenarios.

The first scenario involves transport of sediment in suspension along the floodplain during the rising limb, reaching different floodplain units. Various researchers, such as Pizzuto (1987) and Asselman (1999b), have indicated that the
transport of suspended sediment in rivers is commonly a function of energy conditions and tends to occur by turbulent diffusion (or sediment dispersion). As a result, coarse sediment and sand fractions are likely to travel less distance and to be deposited near their source. Observations on sediment deposits provided by previous studies show this trend, where overbank deposition amounts tend to decrease and become finer with distance to the main channel (Pizzuto 1987; Marriot 1992; Asselman & Middelkoop 1995). Thus, higher and coarser sediment may be accumulated adjacent to the river channel. An evident example of this observation is levees, which are formed from coarser sediment that tends to travel less distance before being deposited (Asselman & Middelkoop 1995; Cazanacli & Smith 1998). Therefore, provided that neither erosion nor sediment resuspension affects the concentration of the suspended sediment that is transported from the river along the overbank flow path to a given floodplain unit, this concentration will tend to decrease with distance traveled, travel time and in response to settling velocities (Figure 4.1a and Figure 4.2). Under this consideration, a smaller proportion of the suspended sediment that left the channel reaches the different floodplain units (Figure 4.2 below).

The second scenario involves sediment deposition during the flood recession phase where ponds form once a disconnection with the main flow occurs (Nicholas & Walling 1998). In this scenario, additional deposition occurs in isolated ponds (static water). SSC and pond depth are the important variables in this scenario (Nicholas & Walling 1998). SSC in these ponds once isolation with the main flow has occurred is less than that in the water column before isolation (just before isolation) and therefore,
also less than the SSC when the flow left the channel and travelled to the floodplain unit.

These two deposition scenarios are described on Figure 4.1 a) and b).

![Figure 4.1. Representation of overbank deposition during the two scenarios described above: (a) during the flood rising phase and (b) during the flood-recession phase along ponds.](image)

As observed by Buttner et al. (2006) and Asselman and Middelkoop (1995), among others researchers, floodplain units with complex topography may tend to accumulate sediment transported in suspension along floodplain units that are low lying or which are backwater areas. These areas may include abandoned channels, meander cutoffs and floodplain swales from scroll bars and they need to be hydraulically connected to the main channel during overbank flooding (as discussed in Chapter 2).

Highly determined by the hydraulic connectivity between floodplain units and the main channel, overbank flow reaches various floodplain units following preferential flow paths (Figure 4.2). The course of these overbank flow paths depends on flow magnitude and its interaction with floodplain topography at the reach scale.
Even though the same value of SSC may be assumed as an approximation along short river reaches where there is limited data, it is more realistic to expect that this factor varies spatially along the river downstream and possibly also laterally. As mentioned above, this spatial variability is due to different river conditions (e.g. bank stability), diverse floodplain geomorphology and potential sediment sources different from those originated at the river itself. Once at the floodplain unit, overbank flow type (hydraulically smooth, transitional or rough) and flow magnitude (with corresponding flow depths) strongly determine the concentration of the sediment that has been maintained in suspension (mainly by turbulence). This concentration is also determined by the sediment size distribution of suspended sediment and by sediment transport mechanisms (‘diffusion and advective’ mechanisms, (Pizzuto 1987)). Thus, during overbank inundation coarse sediment tends to travel less distance along the
floodplain from the river channel to the floodplain geomorphic units following preferential flow paths. These are here referred to as overbank flow paths.

The grain-size distribution of suspended sediment is reflected in the fall velocity at which sediment settles over a flooding period. As discussed in the literature review of Chapter 2, overbank deposition is the result of the combined effect of the suspended sediment grain-size distribution and associated settling velocities; it is also affected by local vegetation type and density (as vegetation has an effect on floodplain roughness, floodplain-floor shear stress and flow velocity) and the average water depth along the overbank flow path that hydraulically connects the river to a given floodplain unit.

4.1.3 An alternative overbank deposition model

The overbank deposition model presented in this section is based on the development of a new relationship that establishes the decrease of suspended sediment concentration as a function of distance from channel and travel time; that is, the time it takes the overbank flow to reach a given floodplain unit that is susceptible to overbank inundation with a given flow magnitude. Flood magnitude here is represented by flow depth, $D$. There is vast evidence in the literature which establishes that discharge highly affects the grain size and concentration of the suspended sediment load. Lenzi and Marchi (2000) for example, observed coarsening of the transported material for increasing discharge during seven floods in a small,
high-gradient stream of the Italian Alps. They also found different patterns of hysteresis between suspended sediment and discharge that were related to types and locations of active sediment sources. Their data, however, as is also the case in the literature at present, does not establish the spatial distribution of these changes along different locations of the floodplain as they only monitored suspended sediment concentrations at one river station.

Within this framework, I suggest the following conceptual model. Consider a parcel of water along a river channel (i.e. a Lagrangian\(^3\) specification of flow (Figure 4.3) where \(SSC(t)\) is the suspended sediment concentration at time \(t\) after it leaves the channel. Over a small time interval \((\Delta t)\), and assuming that there is no sediment erosion, there is a change in the flux rate of the transported sediment mass within the water parcel (per unit width of flow), which is equal to the deposition rate in this same time period. Mathematically, this can be represented as:

\[
\text{Equation 4.10: } \left[ SSC(t + \Delta T) - SSC(t) \right] \cdot V \cdot D = -k \cdot V \cdot SSC(t) \cdot V \cdot \Delta t
\]

\(^3\) Lagrangian specification of the flow is a way of looking at fluid motion where the observer follows an individual fluid parcel as it moves through space and time. Plotting the position of an individual parcel through time gives the pathline of the parcel. See Middleman S 1998, *An introduction to fluid dynamics: principles of analysis and design*, Cambridge University Press, New York.
Figure 4.3. Diagram showing the elements that are to be represented by the alternative overbank deposition model. SSC(t=0) is the suspended sediment concentration that exists in the river, SSC(t+Δt) sometime after the flow has travelled along an overbank flow path and SSC(TT) is the suspended sediment concentration at the time the flow reaches the floodplain unit.

Here $k$ is a non-dimensional coefficient and $V_s$ is the settling velocity. Flow depth ($D$) is the average along the overbank flow path from the river to a given floodplain unit; overbank flow velocity ($V$) is assumed to be the same as the velocity at which suspended sediment travels along the same path and is assumed constant along the water column.

The previous expression can also be written as:

\[
\text{Equation 4.11: } \frac{SSC(t + \Delta t) - SSC(t)}{\Delta t} = -\frac{k \cdot V_s \cdot SSC(t)}{D}
\]

The left side, by definition via difference quotient, can also be expressed as:
Equation 4.12: \[ \frac{SSC(t + \Delta t) - SSC(t)}{\Delta t} = \frac{d[SSC(t)]}{dt} \]

Thus, the following is obtained from substituting Equation 4.12 into Equation 4.11:

Equation 4.13: \[ \frac{d[SSC(t)]}{dt} = -\frac{k \cdot V_s \cdot SSC(t)}{D} \]

The previous expression can be solved as an integrated rate law:

Equation 4.14: \[ SSC(t) = SSC(t = 0) \cdot e^{\left(\frac{k \cdot V_s}{D}\right)} \]

Given that the \( SSC(t = 0) \) is the suspended sediment concentration in the river (\( SSC_{River} \)) and that the travel time \( t \) to the unit is \( TT \), the suspended sediment concentration at the unit (\( SSC_{Unit} \)) can be estimated in the following way:

Equation 4.15: \[ SSC_{Unit} = SSC_{River} \cdot e^{\left(\frac{k \cdot V_s \cdot TT}{D}\right)} \]

Finally, Equation 4.16 is obtained from substituting \( SSC_{Unit} \) of Equation 4.15 into Equation 4.9 above: \[ Q_{d \ Total} = \left[1 - (\tau / \tau_c)\right] \cdot [V_s \cdot SSC_{UNIT} \cdot Fd] + (d_p \cdot SSC_{prior}) \]

Therefore, the modified overbank deposition model is:

Equation 4.16: \[ Q_{d \ Total} = \left[1 - (\tau / \tau_c)\right] \cdot \left[ V_s \cdot \{SSC_{River} \cdot e^{\left(\frac{k \cdot V_s \cdot TT}{D}\right)}\} \cdot Fd\right] + (d_p \cdot SSC_{prior}) \]
where \( Q_{d TOTAL} \) is overbank deposition accumulated over the total number of flooding days of an event or flooding period in \( \text{kg.m}^{-2} \) (and is deposition that occurs during both, the rising limb and receding phases). Here, \( k \) is a non-dimensional coefficient.

The following list summarises the nine key factors that are incorporated in this model.

\( \tau \): floodplain-floor shear stress

\( \tau_c \): critical shear stress

\( V_s \): settling velocity

\( SSC_{River} \): suspended sediment concentration at the river

\( TT \): travel time; which is defined from distance from the channel and flow velocity

\( D \): (average) overbank flow depth along a flow path

\( Fd \): total flooding days over a period

\( d_p \): average pond depth of the floodplain unit where post-peak ponds form.

\( SSC_{prior} \): the suspended sediment concentration a time step prior to the isolation of the pond area from the main overbank flow.
4.1.4 Discussion

The potential improvement of the model presented above includes an analytical solution in which the decrease of SSC with travel time and the decrease of deposition away from the channel and along overbank flow paths are presumably better represented. This contrasts with the finite-element approach in which the overbank deposition model of Nicholas and Walling (1998) is based and with the discrete-element approach of Buttner et al. (2006). The conceptual representation defines overbank flood paths as those hydraulically connecting the floodplain units, shown on Figure 4.3 above. As will be discussed later in this thesis, I chose to use the flooding threshold of each unit to identify, from GIS analysis, the corresponding overbank flow paths and to calculate approximated net overbank deposition (modelled-estimates) of each unit over relevant time periods (see Chapter 6 and 8). However, this model is not restricted to this simplification: the model presented here can be used to estimate overbank deposition that corresponds to flood scenarios of different magnitudes, provided that the corresponding overbank flow paths to the individual floodplain units are identified and the related input parameters are available or calculated accordingly.

As mentioned in Chapter 3, modeled and measured estimates of overbank deposition are in this research compared in order to assess the accuracy of the overbank deposition model formulated in this chapter; this comparison is developed and discussed in Chapter 9.
As mentioned earlier in this chapter, three main assumptions are adopted. First, that the velocity at which the sediment is transported is equal to that of the flow; second, that the main means of sediment transport along the floodplain is overbank river flow and third, that the only sediment source is that from the river channel. Thus the model is limited in its capability to provide reasonably accurate predictions in cases in which floodplain scouring or additional sediment sources different from the river are occurring.

The flooding thresholds of individual floodplain units are defined in Chapter 6, in which a methodology that was developed to classify the different floodplain units in terms of their susceptibility to overbank inundation is also described. This methodology assists in the strategic selection of floodplain units that can be used for representing the spatial variability of overbank deposition along a given floodplain. Overbank flow depths, extents and velocities were obtained from a hydraulic model of the Mid-Goulburn River floodplain that was completed by Water Technology (2009). These data were used to calculate overbank deposition amounts using the alternative overbank deposition model described in this chapter (Chapter 9).

The sensitivity analysis that is described in Chapter 9 is developed from Equation 4.16 above. As will be explained in that chapter, the values used for the sensitivity analysis of each key factor were estimated once the corresponding susceptibility to overbank inundation and the flooding thresholds of selected floodplain units were established (Chapter 6). Total number of flooding days of each floodplain unit was then calculated in relation to the pre-established flooding thresholds of these units.
Chapter 5, on the other hand, describes the floodplain section selected for this study and provides details of the geomorphology of the Mid-Goulburn River. Relevant information in relation to human activities and flow regulation practices that have taken place in the Mid-Goulburn River together with some identified impacts on the flow and sediment regimes are also discussed. Additionally, Chapter 6 provides details on the method developed for a strategic selection of the floodplain units that were used for this investigation and Chapter 7 describes the method that lead to the estimation of overbank deposition amounts of each floodplain unit from $^{137}$Cs and $^{210}$Pb$_{(ex)}$ detection (measured estimates).
5 Chapter Five

5.1 Case study: the Goulburn River floodplain

5.1.1 Study area and catchment characteristics

The Goulburn River basin has an area of 17,000 km² and is located north of the Great Dividing Ranges in south-eastern Australia (Erskine, Rutherfurd & Tilleard 1993). Its basin represents about 7% of the area of the State of Victoria and produces a mean annual discharge of ~3,040,000 ML (Ibid). The Goulburn River is the largest Victorian tributary of the Murray-Darling River system, and the reservoir in its upper catchment, Lake Eildon, is the second largest water storage in Victoria (Ibid).

The river length between Lake Eildon and the Goulburn Weir near Nagambie has been referred to by Erskine et. al. (1993) and Erskine (1996) as the Mid-Goulburn River. The Mid-Goulburn River is a regulated, meandering river with a mixed suspended load and bedload. Its main water storages are Lake Eildon, the upgrade of the original Sugarloaf Reservoir (upgraded between 1929 and 1955), and Lake Nagambie, formed by the Goulburn Weir (Pollino et al. 2004). In the middle catchment
the river mostly flows in a westward direction from Eildon. It then gradually changes to a western-northerly direction to further flow into Lake Nagambie (Figure 5.1 below). The Goulburn Weir at Nagambie is used to divert water “eastward to the Shepparton area and westward to the Waranga Reservoir” (Erskine, Rutherford & Tilleard 1993, p. 6). As a result of stream flow regulation, the average annual flow below Nagambie has decreased from 2,964,000 ML to less than half (Erskine, Rutherford & Tilleard 1993).

The Lower Goulburn River is an anabranching system (Erskine, Rutherford & Tilleard 1993). The Broken River confluence, together with that of the Murray River near Echuca, extends along this section. These rivers are used to supply water for the Goulburn Murray Irrigation District.

Even though there is no diversion of water from Lake Eildon (Erskine, Rutherford & Tilleard 1993), high flow peaks and the seasonality of stream flows have been greatly altered due to river flow regulation. Since the river is used to transfer water to the downstream irrigation district (further downstream of the selected floodplain section), the annual flow regime has actually been reversed.

The floodplain section selected for this research is a section of the Mid-Goulburn River floodplain between Lake Eildon and the Yea River confluence (Figure 5.1) and is located along the 37° S latitude and 145° E longitude bands. Starting about 10 kilometers downstream of Lake Eildon and ending at to the Yea River confluence, the selected floodplain section is approximately 92 kilometers long. The downstream end is, in river length, located about 20 kilometers downstream of Molesworth. To facilitate this analysis, I subdivided the floodplain segment into four floodplain reaches (Figure 5.1). Their lengths and slopes are shown on Table 5.1 below.
Figure 5.1. Showing the course of the Mid-Goulburn River of the study section, the floodplain and the four floodplain reaches.

Table 5.1. Length and slope of the river reaches that comprise the study area. * Value obtained using the total river length, together with the initial and the ending elevation of the stream water level.

<table>
<thead>
<tr>
<th>Reach</th>
<th>River length (Km)</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (upper section)</td>
<td>19.3</td>
<td>0.00085</td>
</tr>
<tr>
<td>2 (upper section)</td>
<td>27.4</td>
<td>0.00066</td>
</tr>
<tr>
<td>3 (lower section)</td>
<td>24.4</td>
<td>0.00047</td>
</tr>
<tr>
<td>4 (lower section)</td>
<td>20.1</td>
<td>0.00051</td>
</tr>
<tr>
<td>Total length of the river segment</td>
<td>91.2</td>
<td>((147.6 \text{ m} - 203.75\text{ m}) / 91.2\text{ m}) = 0.00062 *</td>
</tr>
</tbody>
</table>

Main river confluences along the study section of the floodplain are those of Spring, Johnson, U. T. and Snobs Creeks, as well as those of the Rubicon, Acheron and Yea Rivers. Their location along the floodplain is listed on Table 5.2. Using GIS integrating cartographic material and the LIDAR-DEM of the floodplain section, I found that the Mid-Goulburn River is also an anabranching system. The river along this
section has a rectangular drainage pattern typically found in regions that have undergone structural faulting. Judging from the Geological Maps of Victoria (Short 1977) the high-angled joining tributaries of the Goulburn River along this section tend to follow the same orientation of synclines and faults that extent outside the river valley. This is the case of the Rubicon River, which flows parallel to the Rubicon fault, and of Snobs Creek, which is aligned with the Snobs Creek Fault.

Additionally, the hills surrounding the floodplain (in places composed of sandstone, siltstone, clay stone, granite or metamorphic bodies) define floodplain constrictions; such as that confining the floodplain along 5 kilometers downstream of Molesworth (Geological map; (Short 1977)).

The main tributaries of the Goulburn River along the study section (and inclusive downstream to the Shepparton area) are all reasonably steep, have fast flowing streams in narrow valleys and are subject to floods of short duration. Flood damage along these streams is confined to narrow strips of land immediately adjacent to the channel (Parliamentary Public Works Committee 1968).

As shown on Figure 5.2 below, alternating meandering and relatively straight river reaches occur along this semi-confined floodplain section delimited by bedrock material.
Table 5.2 showing main tributaries along the Mid-Goulburn River floodplain

<table>
<thead>
<tr>
<th>Part of the floodplain</th>
<th>Main tributaries</th>
<th>Floodplain reach</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern side</td>
<td>Spring Creek</td>
<td>Reach 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Johnson Creek</td>
<td>Reach 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>U. T. Creek</td>
<td>Reach 2</td>
<td></td>
</tr>
<tr>
<td>Southern side</td>
<td>Snobs Creek</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rubicon River</td>
<td>Reach 1</td>
<td>Flows along the Goulburn River floodplain; its confluence is upstream of the Acheron Breakaway.</td>
</tr>
<tr>
<td></td>
<td>Acheron River</td>
<td>Reach 2</td>
<td>River avulsion ‘Acheron Breakaway’ occurred ~1916.</td>
</tr>
<tr>
<td></td>
<td>Yea River</td>
<td>Reach 4</td>
<td></td>
</tr>
</tbody>
</table>
Mean maximum temperatures across the Eildon area occur during January and February whereas minimum temperatures occur in July (Bureau of Meteorology Website 2012). The wet season occurs during winter and spring, being June to September the months of highest rainfall. The mean annual rainfall of the area from 1887 to 2012 is 853.5 millimetres (Bureau of Meteorology Website 2012).
5.1.2 Land Use

Land use along the floodplain section is mostly pastoral at present. Native vegetation of the Mid-Goulburn catchment used to be gum and box forest and it also included a variety of grasses. After attempts at using the land for cultivation, floodplain land was considered to be more suitable for grazing of sheep and cattle by the early settlers (Reid 1997). A big impact on the catchment and riparian zone was caused by vegetation clearing, which occurred soon after European settlement. Additional detrimental impacts along the catchment were caused by the discovery of gold in the Alexandra region (Reid 1997) after the 1860s.

The planting of willows along the river banks and floodplain took place progressively, which subsequently resulted in a riparian invasion of weeds and willows which caused bank instability and erosion. This is described in the surveys of Strom (1930-1970) in which vegetation type along the riparian corridor of the Mid-Goulburn River is shown to be composed mainly of scrub and willows. Erskine, Rutherfurd and Tilleard (1993) consider that willow invasion could have been triggered by flow regulation, together with deposition of fine material along the riparian zone. In the Strom survey series (1930-1970), erosion along the river bank and proximal areas is clearly indicated.

Between the 1850s and the 1990s, channel bank erosion and ‘channel siltation’, together with problems associated with vegetation clearance, was reported not only in this catchment but in other catchments across Australia (e.g. the Latrobe River in East
Gippsland, Victoria; (Bird et al. 1979)). This can be seen on the Strom maps (Strom 1930-1970), where the floodplain is described as being cleared of native vegetation by the mid 1930s. It was not until almost six decades later that channel erosion received appropriate attention (such as by Erskine, Rutherfurd & Tilleard 1993) and that solutions to the problem started to be developed.

At present, a high percentage of the floodplain is used for grazing and a small proportion for cultivation (including wineries and pine plantations). An even smaller proportion has actually been designated for parks and ecological reserves (1:25,000 Topographic Maps 1972 and field corroboration).

5.1.3 Geomorphology of the floodplain section

5.1.3.1 Floodplain features and geomorphic units

The one-meter resolution LIDAR-DEM allowed me to corroborate that the Mid-Goulburn River has experienced periods of active lateral migration, as described by Erskine, Rutherfurd and Tilleard (1993). This is shown by the numerous meander swales that can be found adjoining abandoned channel bends that were formed mostly in the pre-regulation period. These relict channels (abandoned and paleo channels),
were formed from meander-cutoff processes, lateral migration and river avulsions (further discussed in this chapter and in Appendix A). At present, abandoned channels comprise around 30% of the total geomorphic units found along the floodplain section of study (Figure 5.3). This was determined from a digital delineation of the geomorphic units that I carried out using the LIDAR-DEM of the floodplain section.

![Figure 5.3. An abandoned channel of the Goulburn River found along the northern part of the floodplain in Killingworth.](image)

Thus, the LIDAR-DEM allowed establishing that the Mid-Goulburn River has gradually straightened along some reaches as a result of river avulsion, meander abandonment and cutoff formation processes. This explains why the modern floodplain that adjoins the current ‘straight’ river stretches is replete with these features (abandoned channels and meander cutoffs), which have progressively been abandoned as new channel paths are formed (Figure 5.4).
Other geomorphic units distributed across the floodplain section of study include levees, chute and crevasse channels, crevasse splays and scroll bars (Figure 5.4 below).

Figure 5.4. The digital delineation of the floodplain geomorphic units from the LIDAR-DEM. Abandoned channels and meander cutoffs (both shown in yellow); scroll bars (in bright pink) and crevasse channels and splays (in light pink). The modern river is in blue. Individual flood heights at specific floodplain locations (historic data of the GBCMA) are represented by green dots and were used for an analysis that is described in Chapter 6.

In addition to the avulsions that have occurred along the Goulburn River, three large anabranches were also found along some tributaries; such as those along the Acheron and Yea Rivers (Erskine, Rutherford & Tilleard 1993). A discussion on river
pattern changes that occurred during the post-European period is developed further in this chapter.

5.1.3.2 River measurements and in-channel features

Within the study section, the river channel has a width that varies between 30 and 85 meters. In a few places, the river width is over 100 meters but in most cases it is around 40 meters. Sinuosity of the meandering reaches of the modern river varies between 1.50 and 1.87, while for the straighter segments it is between 1.10 and 1.38 (Erskine, Rutherfurd & Tilleard 1993). The alternating meandering river and ‘straight’ stretches vary in length. The meandering ones are commonly separated by fewer than 2.5 kilometres of the straight segments.

One of the three longest straight segments is located just downstream of Lake Eildon and is approximately 7 kilometers long. The second is approximately 6.7 kilometers long and is just downstream of the Acheron Breakaway, which is one of the two river anabranche formed during the post-European period (see Appendix A). The third straight segment stretches along a confined floodplain section (south of Catkin) and is ~ 4.6-Km long. On the other hand, the longest meandering segment is located within reach 3, around 5 kilometers upstream of the Yea River confluence and 3.5 kilometers downstream of Molesworth.

Common features along the Mid-Goulburn River include a variety of in-channel bars, such as mid-channel bars, channel side bars, point bars and channel-junction or
mouth bars. An example of the latter is the armoured mouth bar at the confluence of the U.T. Creek (Figure 5.5c). As such, it is composed of coarse river bed material (gravels and pebbles) that overlie finer sediment. Examples of these features are shown below on Figure 5.5, Figure 5.6 and Figure 5.7.
Figure 5.5. (a) Aerial photograph (Department of Sustainability and Environment 2005) showing three point bars located along Reach 1 near Alexandra; (b) channel junction bar (mouth bar) formed at the confluence of U.T. Creek and (c) photograph taken in 2009 of the same channel junction bar (from the northern side of the river and looking south).
Figure 5.6. (a) Mid-channel and channel side bars located near the Goulburn Highway Bridge; (b) photograph taken in 2008 of the channel side bar shown on the left-hand side of the bridge (looking upstream).
Figure 5.7. Photograph taken in 2009 of the mouth bar at the Yea River confluence

Figure 5.8. A closer look of the sediment of the same Mouth Bar.
5.1.3.3 River pattern changes during the post-European period; meander cutoff and anabranch development

In order to identify river pattern and floodplain changes along the floodplain section of study, I carried out a preliminary study, which focused on the post-European period and included the post-Eildon period. The analysis mainly consisted of identifying meander cutoffs and channel abandonment during the last 100 years. These in fact represent recent geomorphic changes along the floodplain. This analysis was carried out before the digital LIDAR-DEM was available; therefore, the only sources of information that were available were old aerial photographs and maps (most of which were georeferenced and incorporated into a GIS). More recent aerial photographs were also used. Later, I decided that the meander cutoffs that I identified as having been formed within the last 100 years (Appendix A) were not to be used for further analysis, since, due to their proximity and recent connection to the modern river channel, these were likely to act as secondary channels during overbank flooding. Nevertheless, this analysis has been included in this thesis in Appendix A.

The river pattern changes that were identified from comparison of available historical cartographic material and aerial photographs include only changes that occurred from 1864, given that the oldest cartographic material dates back to that year. It appears that all the identified cutoffs and river anabranches were formed
approximately between the 1850s and 1936. This may indicate that no significant changes in river pattern have occurred since Lake Eildon was built; suggesting that regulation also alters the river dynamics and restricts the river’s ability to laterally migrate. It is important to mention that, with the exception of the Strom maps (Parliamentary Public Works Committee 1971) and the topographic maps from the 1970s, the old cartographic material tended to describe only the main river channel path and thus, details of the past state of the Goulburn River floodplain at the time the maps were drawn are not possible to obtain. These maps, however, have proved to be useful for the identification of meander-cutoff formation before completion of Lake Eildon in 1955 as well as to identify channel anabranches that formed in the last 100 years (identified here to have done so specifically before 1936 and which are at present a part of the study section of the Goulburn River floodplain).

From this analysis, I found that in total it is possible to identify 9 channel cutoffs and 2 river avulsions, all formed prior to the operation of Lake Eildon and, specifically, between the 1850s and 1936. I also found that one of the river anabranches and a meander cutoff formed during the extreme floods that occurred in 1916 and 1917. Therefore, the approximate years in which sediment started to accumulate on these two units is known. Six of the cutoffs were formed between 1864 and 1936, two were formed between 1864 and 1874 (cutoffs 4 and 6, Appendix A) and none seems to have formed after 1936, suggesting that this can be another consequence of flow regulation.
It was noticed that the topographic maps from the 1970s lacked adequate detail in the display of some floodplain features along some floodplain sections but, in general, the cartographic materials that I used were complementary and proved to be useful (including the different aerial photographs and old maps⁴). However, the 2007 LIDAR-DEM of the Goulburn River floodplain that was later provided by the Goulburn-Broken Catchment Management Authority (GBCMA), became a key source of information that allowed me to elucidate, in a visual and analytical form, the complexity of the Goulburn River floodplain along its middle reaches.

Although river avulsions seem to be part of the natural dynamics of the Goulburn River since before European occupation, it could still be possible that some human activities along the floodplain (such as gravel extraction, extensive clearing and local

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⁴ The old maps included:
- A map from 1864 found in the Victoria Archives, comprising less than half of the ~90-km river section of study. It includes the river from the confluence of King Parrot Creek to near the confluence of Scrubby Creek. Even though this map is not very detailed (e.g. lacks of scale) the channel bends are well described and so it proved to be useful for this analysis.
- Parish maps (from the 1850s; 1877 with additions made in 1943; 1874 with additions made in 1959; 1891, 1922 -with amendments from 1964)
- Topographic maps from the 1970s and
- Maps from the 1930s produced by

The modern river course was digitalised from the 2007 Lidar-DEM and aerial photographs of the Goulburn River, i.e. the 2009 Aerial photographs of the Mid-Goulburn River (Department of Sustainability and Environment 2005, 'Aerial photographs of the Mid-Goulburn River').
erosion), could have influenced the occurrence of the avulsions that occurred during the pre-regulation period.

Meander cutoffs and river anabranches other that those that I identified might have occurred during the post-European period, but the material available limited their identification. For example, two more river anabranches could have occurred within the river segment here investigated but their approximate year of formation could not be estimated with the available maps. These are a ‘lagoon’ that seem to have formed during the river avulsion near cutoff 4 (Appendix A). Another possible river anabranch is an old channel that exists within the same river reach as the Acheron Breakaway and finally, the one named in the topographic map as “river anabranch”, located just upstream the confluence of the Yea River.

5.1.4 Anthropogenic catchment disturbances

As in most Australian rivers, several catchment disturbances took place soon after European occupation. Catchment disturbances along the Mid-Goulburn River include native vegetation clearance, mining activities (initially gold mining and later mostly sand and gravel extraction from the river bed and banks) and, more recently, river
flow regulation. This section describes some associated effects on river health from these human activities as well as some identified effects on the sediment and flood regimes caused by flow regulation of the Goulburn River.

The post-European human activities that took place along the catchment, together with some associated effects and historic accounts of overbank flooding over the last ~100 years are summarized in Table 5.3 below.
Table 5.3. Chronologic summary of catchment disturbances and big flood events (discharges are measured at Eildon). The flood classification of the Bureau of Meteorology for the gauging station at Eildon classifies big floods as those with average daily discharge $> 40,000$ ML/day

<table>
<thead>
<tr>
<th>Year/ Decade</th>
<th>Human activities/disturbances</th>
<th>Flood history and outstanding wet or dry periods</th>
<th>Major impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1870</td>
<td></td>
<td>1870: large flood, estimated at 50,000 cusecs (State Rivers and Water Supply Commission 1971)</td>
<td></td>
</tr>
<tr>
<td>1830’s And 1853</td>
<td></td>
<td>1830s and 1953: evidence of large floods (State Rivers and Water Supply Commission 1971, p. 5)</td>
<td></td>
</tr>
<tr>
<td>1850s</td>
<td>Gold mining in the upper catchment (above Lake Eildon) together with Tin mining along Home Creek</td>
<td></td>
<td>Dramatic decrease in vegetation type and cover together with an increased presence of grass and introduced species (pine, willows).</td>
</tr>
<tr>
<td>1877-81</td>
<td></td>
<td>A severe drought period (Davis, Finlayson &amp; Rutherfurd 1997)</td>
<td></td>
</tr>
<tr>
<td>By the end of that century</td>
<td>Major native vegetation clearing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1906</td>
<td>Floods, “June to September” 1906, peaking at about 34,000 cusecs (83,000 ML/day) (2003)</td>
<td></td>
<td>Possible effects on sediment fluxes linked to soil erosion and increased sediment sources due to vegetation clearing and mining</td>
</tr>
<tr>
<td>Year/ Decade</td>
<td>Human activities/disturbances</td>
<td>Flood history and outstanding wet or dry periods</td>
<td>Major impacts</td>
</tr>
<tr>
<td>-------------</td>
<td>-------------------------------</td>
<td>-----------------------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>1909</td>
<td>Floods, &quot;$180,000 had been spent on flood protection work which proved to be inadequate to cope with the 1906 and 1909 floods&quot;</td>
<td></td>
<td>Possible effects on sediment fluxes linked to soil erosion and increased sediment sources due to vegetation clearing and mining</td>
</tr>
<tr>
<td></td>
<td>Sugarloaf Reservoir was built between 1915 and 1929</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1916 to 1918</td>
<td>Construction of Sugarloaf Reservoir (1915-1927)</td>
<td>1916-18: ‘outstanding’ frequent big floods and wet years. The two biggest floods on record had average daily discharges above 110,000 ML/day. From June to October 1917 there occurred seven large floods.</td>
<td>Two river avulsions along the Mid-Goulburn River associated with the 1916 flooding. Large-flood timing was during winter and spring (June to November)</td>
</tr>
<tr>
<td>1923</td>
<td></td>
<td>A flood of 76,500 ML/day in October</td>
<td></td>
</tr>
<tr>
<td>1924</td>
<td></td>
<td>A flood of 58,300 ML/day in August</td>
<td></td>
</tr>
<tr>
<td>1928</td>
<td></td>
<td>1928: two large floods one in June the other in October with discharges around 53,433 ML/day</td>
<td>The impacts on the flood regime of Sugarloaf Reservoir were smaller</td>
</tr>
<tr>
<td>Year/Decade</td>
<td>Human activities/disturbances</td>
<td>Flood history and outstanding wet or dry periods</td>
<td>Major impacts</td>
</tr>
<tr>
<td>------------</td>
<td>------------------------------</td>
<td>-----------------------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>1927</td>
<td>Sugarloaf reservoir was completed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sep 1932, Dec 1934, August 1936</td>
<td>A major flood occurred in September 1932 with a peak (average daily) discharge of 45,100 ML/day. Later in December 1934 one of the largest recorded floods occurred (with a peak of 78,300 ML/day). Another big flood in 1936 had a peak of 46,800 ML/day.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1939</td>
<td>Bushfires in 1939</td>
<td>One of the largest floods occurred in August of the same year with a peak of 82,000 ML/day.</td>
<td>More than 50% of the catchment forest was destroyed by the fires. Heavy sediment accumulation of Sugarloaf Reservoir followed soon after (2003) for a short period.</td>
</tr>
<tr>
<td>July 1942, November 1949</td>
<td>A large flood occurred in 1942 with a peak of 71,300 ML/day; another one with a peak of 34,000 ML/day in 1949</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year/ Decade</td>
<td>Human activities/disturbances</td>
<td>Flood history and outstanding wet or dry periods</td>
<td>Major impacts</td>
</tr>
<tr>
<td>-------------</td>
<td>-----------------------------</td>
<td>-----------------------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>July 1951</td>
<td></td>
<td>The last big flood event that occurred before Lake Eildon was finished had a peak of 57,800 ML/day in July 1951.</td>
<td></td>
</tr>
<tr>
<td>1955</td>
<td>Lake Eildon was finished</td>
<td>Various moderate floods occurred between August and September that year.</td>
<td></td>
</tr>
<tr>
<td>1956</td>
<td></td>
<td>Only a moderate flood in 1964 (one-day duration) and minor flooding in 1958, 1960 and 1964 occurred within this 12-year period.</td>
<td></td>
</tr>
<tr>
<td>1970, 1975</td>
<td></td>
<td>Floods with a peak discharge of 34,800 ML/day (in 1970) and another with a peak of 44,400 ML/day in 1975</td>
<td></td>
</tr>
<tr>
<td>1976-1988</td>
<td>Revegetation works started to improve channel stability</td>
<td>A 13-year period of no flooding (not even minor or moderate ones)</td>
<td></td>
</tr>
</tbody>
</table>
5.1.4.1 Vegetation and erosion across the catchment

At present, bank erosion is considered to be low and stable across most of the Goulburn River, as it is highly influenced by the state and coverage of riparian vegetation. Therefore, this issue no longer represents a river management problem (Erskine, Rutherford & Tilleard 1993; DeRose et al. 2003).

In their catchment-scale study, DeRose et al. (2003) estimated the percentage of riparian vegetation within the study segment of the Mid-Goulburn to be between 0.41% and 0.8%. In comparison to other parts of the catchment, gully density is medium to low, although the authors established that, comparatively, most of the lower catchment has the lowest gully density.

Hill slope erosion along the sub catchment of the study section is between 0 and 0.1 t.ha\(^{-1}\) per year. It increases considerably in the river reaches near Alexandra and is slightly reduced near Yea and along some areas of the river floodplain. It was also noticed by DeRose et al. (2003) that it decreases generally with distance to the river channel.

The amount of sediment deposited along the floodplain section of study can be expected to have decreased considerably as a result of flow regulation, since much of the sediment that would otherwise be transported from the upstream reaches is now trapped by Lake
Eildon. However, to determine the magnitude of the impact that flow regulation has had on overbank deposition is complex given that sediment fluxes respond to unidentified interactions that occur among the key factors influencing overbank deposition. Therefore, these interactions and their effects on sediment fluxes need to be identified before actually being able to determine this impact.

5.1.4.2 Sediment accumulation in Lake Eildon

The former State Rivers and Water Supply Commission undertook surveys of Sugarloaf Reservoir in 1930, 1939, 1940, 1941, 1944, 1955 and 1980 (Erskine, Rutherfurd & Tilleard 1993) from which it was established that an average of 200,000 m³.yr⁻¹ of sediment had been stored in the dam. In this period (i.e. 1930 to 1980), heavy rain following the ‘Black Friday’ bushfires in the summer of 1939 increased the sediment input to the dam. The Forest Commission observed then that serious and extensive erosion was accompanied by siltation in the streams due to heavy winter rains along the Victorian highlands that had been devastated by the 1939 fires (Davis, Finlayson & Rutherfurd 1997).

Davis, Finlayson and Rutherfurd (1997) report that Lake Eildon is one of few reservoirs that have had unusually high sedimentation rates, although this is noticeable especially following the 1939 bushfires and the heavy rain that followed soon after. Therefore, they established that soon after these events sedimentation rates in the reservoir fell substantially. The “1939 survey showed a loss of 0.5% over 9 years
(sediment yield of 70 t.km\(^{-2}\).yr\(^{-1}\)), however the surveys that followed illustrated a dramatic increase in the rate of siltation. Between 1939 and 1940 the rate reached 0.4\% yr\(^{-1}\) (sediment yield of 330 t.km\(^{-2}\).yr\(^{-1}\)) before dropping back to 0.2\% yr\(^{-1}\) (sediment yield of 130 t.km\(^{-2}\).yr\(^{-1}\)) over 1940/41 and diminishing to undetectable levels thereafter” (Davis, Finlayson & Rutherfurd 1997). Additionally, Erskine, Rutherfurd and Tilleard (1993) also estimated that sediment deposition in the dam dropped to less than 50,000m\(^3\) by the mid 1990s, which represents a low sedimentation rate in comparison to that of USA reservoirs (Erskine, Rutherfurd & Tilleard 1993).

From a study completed in 2006, which included a bathymetric survey undertaken by Thiess Services in April 2003, aerial photography undertaken in July 2003 and contours produced by Hydro Tasmania (Coller K 2007, Senior Reservoir Controller of the Goulburn-Murray Water, pers. comm. 12 Aug), it was found that Lake Eildon has been reduced from its original capacity of 3,390,000 ML by 55,842 ML in the last 5 decades due to sediment accumulation in the dam, which represents a relatively small total reduction of 1.65\% of its original capacity.

### 5.1.4.3 Mining activities: gold, sand and gravel extraction

Gold mining was mainly carried out in the upper catchment (i.e. upstream of Lake Eildon) and tributaries near Alexandra during early European occupation. This includes
gold mining in Johnson, U.T., Spring, Geoffrey and Home Creeks (Erskine, Rutherfurd & Tilleard 1993). Tin mining also took place along Home Creek (Ridd R 2008, landholder, pers. comm., 4 May).

Additionally, sand and gravel extraction from the river bed and banks (Erskine, Rutherfurd & Tilleard 1993; Erskine, Tennant & Tilleard 1996) progressively became common and eventually caused bank erosion and river channel instability, (1930-1970; Strom 1941; Erskine, Tennant & Tilleard 1996). Once more serious observations of its consequences on channel stability were carried out (cf. Erskine, Rutherfurd & Tilleard 1993; Erskine, Tennant & Tilleard 1996; Rutherfurd 2000), this activity was finally banned by the early 2000s, as stated by a resident of the Goulburn River area and former river manager, (Wealands R 2007, pers. comm., 9 March) and also, field corroboration.

Erskine, Rutherfurd and Tilleard (1993) identified sediment extraction as a major management issue along the Goulburn River and its tributaries. Additionally, Rutherfurd (2000) estimated that more than 200 t.yr⁻¹ had been extracted from the Goulburn River, causing channel instability and enlargement.
5.1.5 River management and flow regulation history

5.1.5.1 Flow regulation: impacts on the natural flow and sediment regimes

Lake Eildon is the upgraded reservoir of former Sugarloaf reservoir (built between 1915 and 1927 (Erskine 1996)). It is located along the upper Goulburn River just downstream of the Goulburn and Delatite River confluence where the catchment area is 3,885 Km2 (Erskine 1996). Finished in 1955 to increase water supply for irrigation and hydropower generation (Aird & Baker 1954), Lake Eildon is at present the second-largest...
water storage in Victoria (Erskine, Rutherfurd & Tilleard 1993). With initially a full-storage capacity of 3,390,000 ML (i.e. in 1955), historical and recent surveys held by the Gulburn-Murray Water show that sediment trapped in the reservoir\(^5\) has decreased its original capacity by only 1.65% (as previously mentioned). Lake Eildon controls about 23% of the Goulburn River catchment area (Erskine, Rutherfurd & Tilleard 1993). The mean annual flow of the river at the reservoir site would be 1,630,000 ML, which is approximately half the storage volume of the dam (Ibid).

Even though Sugarloaf Reservoir changed the probability distribution of mean daily flows, in comparison to Lake Eildon, it represented a small impact on the natural seasonal flow distribution: high flows were reduced, moderate flows were increased and low flows were increased in frequency (Erskine 1996). Additionally, it increased summer flows and decreased winter flows. However, flow regulation by Lake Eildon has resulted in a higher impact on all: the seasonality, frequency and magnitude of floods. With maximum flows in summer and autumn and minimum flows in winter and spring, Lake Eildon has reversed the seasonal flow distribution and has further changed the probability distribution of mean daily flows (Erskine 1996).

Gippel and Finlayson (1993) have estimated that “the reservoir has had a major impact on the frequency of wetland inundation close to the dam, with floods that used to

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occur annually now occurring three years in ten” (p. 33). This was also corroborated during a fieldwork visit in May 2009, in which the long-term land owner (resident during 70 years) stated that his land used to be “wet sometimes more than three times a year” and that he remembers the floodplain being “so much wetter than now “[it was] quite muddy during this time of the year” (Gilmore K 2009 pers. comm., 7 May). Gilmore K also mentioned that floods from the Goulburn “used to last for a whole week” along his property, which is located ~ 20 km downstream of Lake Eildon (7 May 2009).

However, even though the “reduction in flood frequency is detectable as far downstream as Murchison, 218 km from the dam” (Gippel & Finlayson 1993, p.34). the effect on wetland flood frequency is mitigated downstream due to the influence of unregulated tributaries: where “only a minor difference is apparent 200 km downstream” (Ibid). Therefore, flow regulation by Lake Eildon has resulted in lower flow and flood peak discharges for all return periods (Erskine, Rutherfurd & Tilleard 1993 and field corroboration) and a further decrease in river sediment loads: from 12,300 m$^3$.a$^{-1}$ to 2,140 m$^3$.a$^{-1}$ (Erskine, Tennant & Tilleard 1996).

Using data of the Goulburn River gauging station at Eildon, the total number of overbank peak events are shown on Figure 5.1 and Figure 5.2 below. These are divided into two periods, the pre- and post-Eildon (i.e. before and after 1955). Whereas Sugarloaf Reservoir truncated all flows above 82,000 ML/day (Erskine, Rutherfurd & Tilleard 1993), a much more marked reduction on flood magnitude exists for the post-Eildon period (Ibid): with no flood peaks above 46,200 ML/day Figure 5.2 below.
Erskine, Rutherfurd and Tillear (1993) found that the magnitude of the flood peak reduction by flow regulation of Lake Eildon at the Eildon gauging station decreases with increasing return period and ranges from a reduction of 65% at 2 years to a reduction in magnitude of 55% at 100 years.

**Figure 5.1.** The number of floods that occurred between 1916 and 1951 with peak discharges equal to or above 15,000 ML/day: the flow discharge threshold established by the Bureau of Meteorology to identify overbank events at the Goulburn River gauging station at Eildon. According to this classification floods are small if they are between 15,000 and 26,000 ML.day\(^{-1}\); moderate if they are between 26,000 and 40,000 ML.day\(^{-1}\) and big if they are \(\geq\) 40,000.
Figure 5.2. The number of overbank events that occurred between 1954 and 2004: i.e. with peak discharges equal to or above 15,000 ML/day at Eildon gauging station (reduced to 25 events over this period). The flood classification of the Bureau of Meteorology for the gauging station at Eildon classifies big floods as those with average daily discharge $> 40,000 \text{ M.day}^{-1}$. This period has been dominated by small floods and only 3 events have been bigger than 40,000 ML.day$^{-1}$ over the post-Eildon period.

Releases from Lake Eildon are passed into a 5,200 ML pondage located below the dam. This pondage potentially reduces bank erosion and slumping downstream the reservoir, contains releases within the channel and minimises danger to those using the river (Erskine, Rutherfurd & Tilleard 1993). It has been established that Lake Eildon has a sediment-trap efficiency of about 99% (Ibid), which shows that although “some fine-grained sediment is usually transported through a storage and passed out of the valves
over the spillway […] all of the incoming sand and gravel are trapped in large dams like Eildon Reservoir. […] clearly both Sugarloaf and Eildon reservoirs have trapped most of the incoming sediment” (Ibid, p. 66).

As a result of the dramatic reduction in magnitude of all flows in comparison to the pre-Eildon period, the currently regulated flows have been found to be incompetent to mobilise the bed material at the gauging stations of the Mid-Goulburn River (Erskine, Rutherford & Tilleard 1993). This effect is noticeable in the increasing size of some point bars along the floodplain: such as the ones showed on Figure 5.10 (a) and (b). As a sign of self-adjustment, river bed armouring is often found along the Mid-Goulburn River (Erskine, Rutherford & Tilleard 1993, and field corroboration), which protects the underlying finer sediment from erosion.
Figure 5.10(a) and (b). A point bar of the Mid-Goulburn River at a location visited in 2007 between Alexandra and Molesworth in Reach 2. From comparison of the aerial photographs the land owner has (which were taken in the 1940s and in 1975), it became obvious that this point bar has increased in size.
Field visits carried out in 2009 to the Mid-Goulburn River suggest that localised channel aggradation could be occurring near some tributary confluences. Such seems to be the case along the confluence of the U.T. creek and the Yea River. The mouth bars from these tributaries have increased in size and show that the coarse fraction of the bedload supplied by the tributaries cannot be mobilised by the river, due to the reduced capacity caused by flow regulation (Figure 5.5 and Figure 5.7).

Thus, the information presented in this chapter shows that the current flow regime has altered the dynamics of the Mid-Goulburn of both vertical accretion and lateral migration processes, including the development of meander cutoffs and river avulsions. The first identifiable impacts on overbank processes are the reduced occurrence of overbank floods under the present flow regime, suggesting that floodplain health and fertility have been directly affected. Hypothetically, this change in the sediment supply may be more easily detected in reaches close to and downstream of the reservoir.

A novel approach, which was developed for the strategic selection of floodplain units along this relatively long floodplain section, is described in Chapter 6. It will be shown in that chapter that the selected floodplain units can be considered representative of the spatial distribution of overbank sedimentation. These units were subsequently sampled and their sedimentation rates estimated from radionuclide analyses (Chapter 7). These estimates are later used to compare those of the overbank deposition model developed in Chapter 4 and, that way, to assess the model accuracy (Chapter 8).
6 Chapter Six

6.1 Selection of floodplain units; development of a novel method of classification

6.1.1 Introduction

The Mid-Goulburn River floodplain is a highly diverse floodplain. Together with flood magnitude, shape, dimensions and topography of the various geomorphic units directly influence the distribution of overbank inundation and, therefore, sediment deposition. Given that floodplain topography determines the hydraulic connectivity between the modern channel and floodplain, it is important to classify the floodplain units that are distributed along the floodplain in terms of their susceptibility to overbank inundation.

During overbank inundation of meandering river floodplains, a (usually) complex hydraulic interaction among floodplain units occurs, which results in a highly variable
distribution of overbank deposition. Therefore, a spatially adequate sampling program (i.e. for the selection of sediment coring sites) is a critical task. The method developed in this chapter was used to determine the areas or geomorphic units that can be more relevant for investigations into overbank sedimentation processes on alluvial river systems. This method is especially useful when a high-resolution LIDAR DEM is available as well as substantial data on the floodplain history of flooding. This historic data need to be geospatially referenced to then generate overbank inundation surfaces which approximately represent overbank inundation of various magnitudes.

The need for this methodology became clear when, using the LIDAR DEM, I identified the highly complex topography and diverse geomorphology of the Mid-Goulburn River floodplain. This showed that the floodplain is composed of different geomorphic units, which presumably have distinctive hydraulic connectivity to the modern channel. Therefore, an adequate approach that can lead to satisfactory representing and establishing spatial patterns of overbank inundation is crucial. Thus, rather than randomly selecting coring sites or floodplain units, the method includes identifying those units that are predominantly formed by overbank deposition and, accordingly, selecting the floodplain sites that will be cored. The underlying assumption is that patterns of overbank deposition and overbank inundation are similar at equivalent flood magnitudes.

The approach starts by identifying floodplain units or locations of different susceptibility to overbank inundation (i.e. presumably high, medium and low, as described on Table 6.2 below). Thus, as a generality, floodplain units with high susceptibility of
overbank inundation may be more easily flooded (e.g. more flooding days) and vice versa. The susceptibility to overbank inundation is here considered to be an indicator of the floodplain unit potential to accumulate sediment transported by overbank flows. Therefore, the method involves distinguishing floodplain units that are more likely to be activated by overbank flows of different magnitudes (i.e. discharges).

Additionally, and as a means for corroborating the validity of the method described above, datasets of overbank flow velocity and depth of a hydraulic model developed by Water Technology (Water Technology 2009, p. 33) for the floodplain section, were used to establish overbank flooding thresholds of floodplain (geomorphic) units. Theoretically, both, the corresponding susceptibilities to overbank inundation of the floodplain units established from the method above and the flooding thresholds derived from the hydraulic model should suggest similar spatial patterns of overbank deposition (based on the assumption mentioned above). Details on the identification of these thresholds are also given in this chapter.

6.1.2 First step: classifying the geomorphic units by their susceptibility to overbank inundation
In order to differentiate the geomorphic units that are representative of spatial patterns of overbank deposition, I displayed the one-meter resolution LIDAR DEM in a GIS mostly to delineate abandoned channels, meander cutoffs and swales (as shown on Figure 6.2 below). I additionally incorporated the flood heights of historic events provided by the Goulburn-Broken Catchment Management Authority (GBCMA) into the same GIS, which had already been georeferenced by the GBCMA. Most of these data have been either collected or generated as part of previous flood studies undertaken by the GBCMA (such as the ‘Goulburn River-Eildon to Seymour, History of Flooding’) and the Victorian Flood Data Transfer Project’ (Water Technology 2009). This geospatial information includes historical flood data and statistically derived flood levels (AHD heights). Flood height data were incorporated and displayed in the GIS.

For this study, The GBCMA also shared a flood contour layer, which is a shape file composed of synthetically generated poly lines that represent an event with an ARI of 1 in 100 years under the current (regulated) flood regime. This flood contour was also incorporated into the GIS and represents a flood stage of 8.77 meters and a flood height AHD of 214.5 meters at the Goulburn River gauging station at Eildon (also referred to as station number 405203 C). Zero reading at this station corresponds to an AHD of 205.73 metres (Table 6.1below).

To proceed with the methodology, I converted the flood contour layer into a flood surface (raster), using the inverse distance weighted method with bilinear interpolation in ArcGIS. Since this flood surface represents the highest possible magnitude under the
current flood regime, I derived flood surfaces equivalent to smaller magnitudes using this surface of maximum inundation as a reference. This step allowed me to include the whole spectrum: small, medium and large magnitude flood surfaces in line with the flood classification that the Bureau of Meteorology (BOM) has established for the gauging station\(^6\) (as shown on Table 6.1 below). The classification differentiates overbank floods of major, moderate and minor magnitudes by their stage and discharge values at the gauging station (Table 6.1). Thus, the various flood surfaces that I generated were obtained by subtracting a constant from the reference maximum flood surface (see Table 6.1).

Historical data on flood height provided by the GBCMA in GIS form established that one of the largest floods on record occurred before completion of Lake Eildon in December 1934\(^7\), with an instantaneous maximum flood height of 213.62 meters AHD. The gauging station at Eildon was then ~1 kilometre downstream of the present station location. Therefore, establishing a flood height of 214.5 metres for an event with an ARI of 1 in 100 years under the current flow regime at the gauging station at Eildon is adequate.

\(^6\) The Bureau of Meteorology (BOM) has developed a flood classification for this gauging station (referred to by the Bureau as station number 588125) which is based on threshold stage levels and the corresponding discharge values for “minor”, “moderate” and “major” floods.

\(^7\) This event peaked on December 1 of 1934 with an average daily flow of 78,300 ML.day\(^{-1}\) at Eildon gauge station. Under the current flow regime, the highest magnitudes have not been bigger than 50,000 ML.day\(^{-1}\). Even though larger events have occurred, (i.e the biggest on record is that of September 1916 with a peak-average daily discharge at Eildon gauge station of 153,000 ML.day\(^{-1}\)), these occurred in the pre-Eildon period (i.e. during another flow regime).
The next step was to calculate the areas and volumes of inundation along the floodplain which result from the corresponding generated flood surfaces and the floodplain DEM. ArcMap has a function that allows displaying the calculation of “net gain” and “net loss” (inundated vs. not inundated) volumes\(^8\) on a raster. The raster in this case was the LIDAR DEM of the floodplain. The resultant volumes were visually displayed, overlaying the LIDAR DEM. This allowed the identification of inundated and not-inundated parts of the floodplain with reference to different flood magnitudes (as shown on Figure 6.5, Figure 6.6 and Figure 6.7). For this step, the raster DEM was subdivided into 4 rasters (being the same as reaches 1 to 4 of Figure 5.1 in Chapter 5). This allowed the calculations to be completed successfully with the available computational capacity.

It is important to note that the reliability of the provided flood elevation data on which the initial flood contour layer was created by the GBCMA, and subsequently the flood surfaces, varies from “poor” to “fair” and “good” (stated in the ‘metadata’), which was generated from the flood studies previously mentioned.

The resultant rasters displayed the inundated areas (“net gain”) and dry areas (“net loss”) of the various flood surfaces generated and each ‘inundated’ cell provided the volume occupied by water (Figure 6.1 below) Their display gave me insight as to the ease with which overbank events of different magnitudes may reach different geomorphic units of the floodplain (susceptibility to overbank inundation). Additionally, I calculated the flood

\(^8\) In ArcMap version 9.2 it is called ‘Cut/Fill’ and is found under the ‘3D Analyst Tool’.
heights at each cell of the LIDAR DEM using the “Minus” function together with the elevation data of the four subdivided floodplain reaches of the DEM and the nine flood surfaces shown on Table 6.1. Inundated areas were therefore identified on the GIS, as shown on Figure below.
Table 6.1. Showing the calculations undertaken to generate the different flood surfaces, these based on the reference flood surface (which was derived from the flood contour provided by the GBCMA). Flood heights are valid for station 405203C; the gauging station at Eildon.

<table>
<thead>
<tr>
<th>BOM flood classification, average daily discharge in ML.day(^{-1})</th>
<th>Flood stage (height) at 405203C (m)</th>
<th>AHD elevation value (m)</th>
<th>Subtracted constant to the initial flood surface ‘contour_5midw’ (m)</th>
<th>Calculation: zero reading of gauge + flood level at gauge (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Major:</strong> above 40,000 ML.day(^{-1})</td>
<td>8.77 (reference)</td>
<td>214.5 (reference)</td>
<td>0</td>
<td>(205.73+8.77m)</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>213.73</td>
<td>0.77</td>
<td>(205.73+8m)</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>212.73</td>
<td>1.77</td>
<td>(205.73+7m)</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>211.73</td>
<td>2.77</td>
<td>(205.73+6m)</td>
</tr>
<tr>
<td></td>
<td>5 m (equivalent to 40,000 ML.day(^{-1}))</td>
<td>210.73</td>
<td>3.77</td>
<td>(205.73+5m)</td>
</tr>
<tr>
<td><strong>Moderate:</strong> between 26,000 and 40,000 ML.day(^{-1})</td>
<td>4.5</td>
<td>210.23</td>
<td>4.27</td>
<td>(205.73+4.5m)</td>
</tr>
<tr>
<td></td>
<td>4 m (equivalent to 26,000 ML.day(^{-1}))</td>
<td>209.73</td>
<td>4.77</td>
<td>(205.73+4m)</td>
</tr>
<tr>
<td><strong>Minor:</strong> between 15,000 and 26,000 ML.day(^{-1})</td>
<td>3.5</td>
<td>209.23</td>
<td>5.27</td>
<td>(205.73+3.5m)</td>
</tr>
<tr>
<td></td>
<td>3 m (equivalent to 15,000 ML.day(^{-1}))</td>
<td>208.73</td>
<td>5.77</td>
<td>(205.73+3m)</td>
</tr>
</tbody>
</table>
Figure 6.1. LIDAR DEM overlaid by inundated (blue) and not inundated (brown) areas of the floodplain using a flood surface height of 211.73 meters at the gauging station at Eildon (see Table 6.1). This floodplain section is immediately upstream of the Yea River confluence on reach 4. Note how the Goulburn River channel shows white patches (absence of elevation data) since the LIDAR technique has the difficulty of collecting elevation information along water bodies (such as the river channel). River flow is from right to left.
6.1.2.1 Classifying the floodplain units by their susceptibility to overbank inundation

The following procedure was carried out to classify the floodplain geomorphic units in terms of their susceptibility to overbank inundation. Eighty six floodplain transects distributed along the floodplain were traced and their elevation values extracted from the LIDAR DEM. This allowed the display of the cross-valley floodplain transects (Figure 6.2) in the form of floodplain profiles (Figure 6.3). For this step I used a free, downloadable add-on function for ArcMap: the ‘Easy Profiler’. This function allows extraction of elevation values along a traced transect from a raster dataset.

Various floodplain units were considered as candidates for further sediment coring in this step and were carefully identified on the floodplain profiles (Figure 6.3). Additionally, the historic flood heights of the GBCMA were geospatially represented on the floodplain DEM (green dots on Figure 6.2 below) and, when possible, spatially represented along the floodplain profiles (red line on Figure 6.3 below). This helped me to qualitatively establish the hydraulic connectivity that exists between the floodplain units and the modern channel (i.e. their potential susceptibility to overbank inundation). This step also allowed me to select a number of possible sediment coring sites along meander cutoffs, abandoned channels and swales. It was obvious, however, that their
number needed to be reduced. Around 40 floodplain transects were analysed at this level of detail.

In order to narrow down the selection, I decided selecting units that were likely to be inundated by overbank flows and have, in relation to each other, small, medium and high hydraulic connectivity with the channel during overbank inundation, as presumably, this would represent spatial patterns of overbank inundation and deposition. I established that the floodplain units needed to be at considerable distance from the modern channel and not to be activated by high, in-channel flows. Also, as previously discussed, they needed to be away from foothills and tributary confluences in order to avoid sites of active erosion processes, sediment redistribution or localised sediment inputs different from those of the river. Therefore, the final selection of the units and coring sites was based on the analysis described above together with considerations of access to each site; that is, whether access had been permitted, as most of the floodplain land is privately owned. The floodplain units that were selected in this way and their classification in terms of their susceptibility to overbank inundation are shown on Table 6.2 below, together with the final selection of coring sites (three cores collected from each floodplain unit in most cases).

From the information gathered during the fieldwork program, I found that the floodplain coring sites have been vegetated by permanent grasses and scattered trees over the last 80 to 100 years, as the main vegetation clearance occurred before then
(Chapter 5). Most of the floodplain units that were selected have only been used for grazing during the periods of interest, with the exception of the paddock where the floodplain swales (Unit 9) are located: since around 30 years ago it was a dairy farm. Special attention was given to choose the place from where the cores were going to be collected. I decided to collect, in most cases, three cores from each floodplain unit. The ones chosen from this unit are at a considerable distance from places where major earth works took place, such as the installation of underground pipes for the dairy. This was corroborated with property maps that are possessed by the land owner, (Ridd R, pers. comm., 8 May 2008). A similar scrutiny was followed for the rest of the floodplain sites with help of the land owners. I asked them whether soil or sediment disturbance was likely to have taken place at the coring sites during the periods of interest. Therefore, from the information collected during that research stage, no anthropogenic form of soil or sediment redistribution is expected to have occurred during the last ~70 to 100 years at the coring sites.

From the previous discussion, it can be assumed that floodplain vegetation (mostly grass) partially protects the floodplain floor from erosion during small and medium overbank events and that, to a certain extent, it may encourage sediment deposition. Although changes of vegetation density probably could have occurred during the period of investigation, there is no information in sufficient detail to allow an adequate reconstruction of vegetation changes along the floodplain over the last 100
years. Thus, it is assumed here that its overall composition has been relatively constant over the two periods and that local floodplain roughness at the unit scale can also be assumed constant.

Additionally, given that the selected geomorphic units are located at sufficient distance from the modern channel and that these are not directly activated by in-channel flows, these units are not likely to be affected by lateral accretion processes. Thus, it is valid to assume that the most relevant floodplain formation process of the selected units over the period of interest is overbank accretion, considering their location (at considerable distance to the modern channel, foothills and tributary confluences), their hydraulic connectivity to the modern channel under the current flow regime and the potential absence of other geomorphic or erosive processes that could otherwise be important for their evolution.
Figure 6.2. Showing floodplain transects -including transect 86- (yellow lines); delineated geomorphic units (in light and bright pink and yellow), coring sites (green crosses) and historic flood levels (green dots). The modern channel is in bright blue.
Figure 6.3. Floodplain profile generated from Transect 86 and the three selected coring sites D, TT, E along floodplain swales: Unit 1 (see Table 6.2 and Figure 6.4). Note that the modern channel and proximal geomorphic units were identified as well as the flood level correspondent to a flood that occurred in September 1993.
Table 6.2. Classification of floodplain units by their susceptibility to overbank inundation based on the GIS analysis described above; the number and name of coring sites selected along each unit and corresponding floodplain unit type. See Figure 6.4 below for Unit location.

<table>
<thead>
<tr>
<th>Number of coring sites and names</th>
<th>Unit ID and type</th>
<th>Approximate river distance to gauging station at Eildon (Km)</th>
<th>Susceptibility to overbank inundation (GIS-derived classification)</th>
<th>Location details</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 1D,1Dbis,1E</td>
<td>Unit 12 (meander cutoff)</td>
<td>13.1 Km</td>
<td>Moderate to moderate-high</td>
<td>Reach 1, 1603 Goulburn Valley Hwy, Acheron (~Transect 15)</td>
</tr>
<tr>
<td>3 1L,1G,1I</td>
<td>Unit 13 (abandoned channel)</td>
<td>16.8 Km</td>
<td>Low-moderate to moderate</td>
<td>Reach 1, 1603 Goulburn Valley Hwy, Acheron. (Transect 14)</td>
</tr>
<tr>
<td>3 1A,1B,1C</td>
<td>Unit 11 (swales)</td>
<td>17.2</td>
<td>Low to low-moderate</td>
<td>Reach 1, 1603 Goulburn Valley Hwy, Acheron (Transect 15)</td>
</tr>
<tr>
<td>1 1F</td>
<td>Unit 10 (abandoned channel)</td>
<td>17.4 Km</td>
<td>Moderate to moderate-high</td>
<td>Reach 1, 1603 Goulburn Valley Hwy, Acheron. (Transect 15)</td>
</tr>
<tr>
<td>3 2D,2E,2F</td>
<td>Unit 9 (swales)</td>
<td>39.2</td>
<td>Moderate</td>
<td>Reach 2, 708 Whanregarwen Rd, Whanregarwen (Transect 38)</td>
</tr>
<tr>
<td>3 N,J,Q</td>
<td>Unit 8 (swales)</td>
<td>57</td>
<td>Moderate</td>
<td>Reach 3, 37 Native Dog Rd, Molesworth (Transect 61)</td>
</tr>
</tbody>
</table>

Floodplain units downstream of gauging station at Eildon and their susceptibility to overbank inundation

Units located along reaches 1 and 2
<table>
<thead>
<tr>
<th>Number of coring sites and name</th>
<th>Unit ID and type</th>
<th>Approximate river distance to gauging station at Eildon (Km)</th>
<th>Susceptibility to overbank inundation (GIS-derived classification)</th>
<th>Location details</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 QQ, BB, AA</td>
<td>Unit 7 (swales)</td>
<td>76.6</td>
<td>Low</td>
<td>Reach 4, 431 McLeish Rd (Transect 79 and supplementary Transect 14)</td>
</tr>
<tr>
<td>3 FF, GG, HH</td>
<td>Unit 6 (meander cutoff)</td>
<td>76.6</td>
<td>Moderate</td>
<td>Reach 4, 431 McLeish Rd (Transect 79 and supplementary Transect 14)</td>
</tr>
<tr>
<td>3 CC, DD, EE</td>
<td>Unit 5 (swales)</td>
<td>76.6</td>
<td>Low</td>
<td>Reach 4, 431 McLeish Rd (Transect 79 and supplementary Transect 14)</td>
</tr>
<tr>
<td>2 F, G</td>
<td>Unit 4 (meander cutoff)</td>
<td>78.2</td>
<td>Moderate</td>
<td>Reach 4, 46 Higgins Rd (Transects 80 and 82)</td>
</tr>
<tr>
<td>3 K, L, M</td>
<td>Unit 2 (swales)</td>
<td>79.2</td>
<td>Low</td>
<td>Reach 4 93 Higgins Rd Transect 81</td>
</tr>
<tr>
<td>3 A, B, UU</td>
<td>Unit 3 (meander cutoff)</td>
<td>80.1</td>
<td>High</td>
<td>Reach 4, 93 Higgins Rd (Transect 81 and supplementary Transect 15)</td>
</tr>
<tr>
<td>3 D, TT, E</td>
<td>Unit 1 (swales)</td>
<td>82</td>
<td>Moderate</td>
<td>Reach 4, Gin Gin Reserve (Transect 86)</td>
</tr>
</tbody>
</table>
Figure 6.4. Location of the thirteen selected floodplain units
6.1.3 The hydraulic model to determine overbank flooding thresholds

The hydraulic model of the floodplain section, provided by the GBCMA and completed by Water Technology (2009), was used to establish overbank flooding thresholds of the selected units (listed on Table 6.2 above) and to compare these thresholds with the classification of the method described above. This allowed me to evaluate the level of correspondence between the classification of the floodplain units in terms of their susceptibility to overbank inundation (Table 6.2 below) and the flooding thresholds established from data of the hydraulic model (Table 6.4 below). This model, available in September 2009, was developed by Water Technology, Water, Coastal and Environmental Consultants as a combined product of one- and two-dimensional modelling. The hydraulic model provides flood extents, heights and overbank flow velocities in raster form (each cell of 25 meters) and considers various flood scenarios which correspond to floods of 20,000; 30,000 40,000; 50,000 and 60,000 ML.day\(^{-1}\) at the Goulburn River gauging station at Eildon.

As a first step, the authors completed a one-dimensional hydraulic model component to simulate in-channel flows up to bankfull (equivalent to up to 15,000 ML.day\(^{-1}\) at the gauging station at Eildon) using Mike 11. Stage-discharge curves were
used for calibration of this model component (Water Technology 2009) and although the model predictions underestimated water levels at Trawool, “the hydraulic model reproduced the observed rating curve well” for flows reaching bankfull (Water Technology 2009, page 23). A two-dimensional floodplain hydraulic model (using Mike 21) was designed to provide data on overbank flood behaviour (flood extents and heights) along floodplain features of large flood events (Water Technology 2009). The calibration of the two-dimensional model was focused on the determination of Manning’s n values for the floodplain to achieve a reasonable agreement between observed and model flood levels. The authors selected the flood events of May 1974 and October 1993 as calibration events. Most of the data was concentrated on locations near Seymour and Shepparton and, as a result, the direct assessment of the two-dimensional model performance was limited to those locations (Water Technology 2009). In general, the authors determined that modelled flood levels of this component were in reasonable agreement with the observed flood levels (Water Technology 2009).

Water Technology (2009) linked the one and two-dimensional model components to establish the general flow/flood behaviour for flows up to 60,000 ML.day⁻¹, enabling the simulation of flows from below bankfull up to large floodplain inundation. It was found by the authors that “the relative frequency of this flow range decreases downstream along the Goulburn River” (Water Technology 2009, p 33). Therefore, an event with 60,000 ML.day⁻¹ is approximately a 10-year ARI event at Trawool, whereas at
Shepparton it represents a 3-4 year ARI event. Water Technology used the October 1993 event for model calibration upstream of Trawool, which corresponds to the study section of my research. The peak discharge of this event was 46,000 ML.day$^{-1}$ at Eildon$^9$. According to flood records, this flood resulted in considerable floodplain inundation and a number of flood levels have been recorded upstream of Trawool. Given the availability of observed flood levels and the peak flow in range of interest, this event was used by Water Technology for calibration of the one-two dimensional hydraulic model for the section upstream of Trawool (study section). The key input data for modelling flood behaviour was the LIDAR-DEM of the Mid-Goulburn River floodplain. Data available on flood extents and depths was used by the authors for calibration (mainly of the October 1993 flood (Water Technology 2009)). It was found that "across the reach upstream of Trawool, 22 of 30 modelled flood levels lay within +/- 200 mm of the observed flood levels. Given the uncertainty in model inflows from the tributary, this calibration outcome was considered reasonable" (Water Technology 2009, p. 35).

Therefore, their hydraulic model was based mostly on a steady state flooding scenario of flood magnitudes equivalent to 20,000; 30,000; 40,000; 50,000 and 60,000 ML.day$^{-1}$ at Eildon gauging station. Although an unsteady state scenario was also run by the consultants, the calibration data that the authors used correspond to the Shepparton

$^9$ This event had an instantaneous peak discharge of 48,400 ML and a maximum gauge height of 5.47 metres at Eildon gauge station.
and Mooroopna area only, and therefore, no velocity vectors were generated for the floodplain section of this research.

The hydraulic model of the Mid-Goulburn River floodplain developed by Water Technology assumes releases mostly from Lake Eildon and gauged tributaries. Therefore, ungauged tributary inflows represent data gaps in the modelling exercise (Water Technology 2009). This stresses the importance of the calibration step for further use of the data. Additional data of the hydraulic model includes floodplain Manning’s n in raster form for the Mid-Goulburn River floodplain, which was evaluated “through calibration of the modelled and observed flood levels, and extents” (Water Technology 2009, p. 13).

The flood magnitudes that were analysed by Water Technology (2009) for the hydraulic model are listed on Table 6.3 below.

The comparison between the classification of floodplain units in terms of their susceptibility to overbank inundation (discussed in the previous section of this chapter) and the flooding thresholds established from the hydraulic model of each floodplain unit (the flow discharge from which overbank flooding is initiated) are shown on Table 6.4 below. These latter were established using the flood extents and heights of the hydraulic model provided by the GBCMA, as exemplified on Figure 6.5, Figure 6.6 and Figure 6.7. These figures illustrate inundated areas along a floodplain section of reach 2 with flood magnitudes equivalent to 20,000; 30,000 and 60,000 ML.day$^{-1}$ respectively at the
gauging station at Eildon. The three coring sites of Unit 9 (2D,2E,2F) are also shown on these figures.

From the hydraulic model data, I established that the overbank flooding threshold of this unit is a flood equivalent to a magnitude between 20,000 and 30,000 ML.day\(^{-1}\) at Eildon gauge station (in reference to Table 6.4), which suggests that this unit is quite easily flooded.
Table 6.3. The range of flood magnitudes used by Water Technology (2009) for simulating different flood scenarios (most of them considering a steady state flow). The magnitudes refer to discharges reached at the gauging station at Eildon.

<table>
<thead>
<tr>
<th>Type of flood (magnitude ML.day$^{-1}$)</th>
<th>Peak daily flow used by Water Technology for their hydraulic model -based on the gauging station at Eildon (ML.day$^{-1}$)</th>
<th>Number of flood type included</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor (between 15,000 and 26,000)</td>
<td>20,000</td>
<td>1</td>
</tr>
<tr>
<td>Moderate (between 26,000 and 40,000)</td>
<td>30,000</td>
<td>1</td>
</tr>
<tr>
<td>Major floods (above 40,000)</td>
<td>40,000</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>46,000 (unsteady state run)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60,000</td>
<td></td>
</tr>
</tbody>
</table>

The corresponding susceptibility to overbank inundation of the thirteen floodplain units selected for this research as well as their corresponding overbank flooding thresholds are summarised on Table 6.4 below.
Figure 6.5. Inundated areas along a section of reach 2. These are reached by a flood equivalent to 20,000 ML.day$^{-1}$ at Eildon gauge station. That magnitude is considered to be the threshold of inundation of Unit 9 (the coring sites along this unit are the small yellow crosses).
Figure 6.6. The same floodplain section as Figure 6.1 with coring sites of Unit 9 (small yellow crosses) showing the areas inundated by a flood with a magnitude equivalent to 30,000 ML.day\(^{-1}\) at gauging station at Eildon. River flow is from right to left.
Figure 6.7. The same floodplain section as Figure 6.5 and Figure 6.6 with coring sites of Unit 9 showing the areas inundated by a flood with a magnitude equivalent to 60,000 ML.day$^{-1}$ at Eildon gauge station.
Table 6.4. The susceptibility to overbank inundation of each floodplain unit selected (fourth column) as well as their overbank flooding threshold (fifth column). Notable differences between the two are highlighted.

<table>
<thead>
<tr>
<th>Number of coring sites</th>
<th>Unit ID and type</th>
<th>Approximate river distance to Eildon gauge station (km)</th>
<th>Susceptibility to overbank inundation (GIS-derived classification)</th>
<th>Overbank flooding threshold of unit (ML.day(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1F</td>
<td>Unit 10 abandoned channel</td>
<td>Reach 1, 17.4 km</td>
<td>Moderate to moderate-high between 20,000 to 30,000</td>
</tr>
<tr>
<td>3</td>
<td>1L,1G,1I</td>
<td>Unit 13 abandoned channel</td>
<td>Reach 1, 16.8 km</td>
<td>Low-moderate to moderate between 20,000 and 30,000</td>
</tr>
<tr>
<td>3</td>
<td>1D,1D.Bis,1E</td>
<td>Unit 12 meander cutoff</td>
<td>Reach 1,13.1 km</td>
<td>Moderate to moderate-high between 20,000 and 30,000</td>
</tr>
<tr>
<td>3</td>
<td>1A,1B,1C</td>
<td>Unit 11 swales</td>
<td>Reach 1, 17.2 km</td>
<td>Low to low-moderate 40,000</td>
</tr>
<tr>
<td>3</td>
<td>2D,2E,2F</td>
<td>Unit 9 swales</td>
<td>Reach 2, 39.2 km</td>
<td>Moderate between 20,000 and 30,000</td>
</tr>
<tr>
<td>3</td>
<td>N,J,Q</td>
<td>Unit 8 swales</td>
<td>Reach 3, 57 km</td>
<td>Moderate 30,000</td>
</tr>
<tr>
<td>3</td>
<td>QQ, BB, AA</td>
<td>Unit 7 swales</td>
<td>Reach 4, 76.6 km</td>
<td>Low Unclear, according to the hydraulic model, this unit is partly activated. Coring site QQ does by floods that are $\geq$ 40,000; AA by floods $\geq$60,000 and BB does not for the flood range</td>
</tr>
<tr>
<td>Number of coring sites</td>
<td>Unit ID and type</td>
<td>Approximate river distance to Eildon gauge station (km)</td>
<td>Susceptibility to overbank inundation (GIS-derived classification)</td>
<td>Overbank flooding threshold of unit (ML.day(^{-1}))</td>
</tr>
<tr>
<td>------------------------</td>
<td>-----------------</td>
<td>--------------------------------------------------------</td>
<td>---------------------------------------------------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>3</td>
<td>FF, GG, HH</td>
<td>Reach 4, 76.6 km</td>
<td>Moderate</td>
<td>40,000</td>
</tr>
<tr>
<td>3</td>
<td>CC, DD, EE</td>
<td>Reach 4, 76.6 km</td>
<td>Low</td>
<td>40,000</td>
</tr>
<tr>
<td>3</td>
<td>K,L,M</td>
<td>Reach 4; 79.2 km</td>
<td>low</td>
<td>30,000</td>
</tr>
<tr>
<td>2</td>
<td>F,G</td>
<td>Reach 4, 78.2 km</td>
<td>Moderate</td>
<td>40,000</td>
</tr>
<tr>
<td>3</td>
<td>A, B, UU(^{10})</td>
<td>Reach 4, 80.1 km</td>
<td>High</td>
<td>30,000</td>
</tr>
<tr>
<td>1</td>
<td>A</td>
<td>Reach 4, 82 km</td>
<td>Moderate</td>
<td>40,000</td>
</tr>
<tr>
<td>3</td>
<td>D, TT, E</td>
<td>Reach 4, 82 km</td>
<td>Moderate</td>
<td>40,000</td>
</tr>
</tbody>
</table>

\(^{10}\) An additional core, A, was taken from the same meander cutoff, Unit 3. This core was also longer than the rest (maximum collection depth was 90 cm) which, together with core 1F (Unit 10), were to be used to calculate deposition rates over the pre-Eildon period from detection of \(^{210}\)Pb\(_{es}\) concentrations.
6.1.4 Discussion

From the comparison described in the previous section, it was noticed that the areas of inundation determined from the two different methods (historic data and flood surfaces with GIS analysis, against data of the hydraulic model) were different along some parts of the floodplain. It should be remembered here that the hydraulic model has some underlying uncertainties, and therefore, its results have a degree of inaccuracy; as well as does the method described in this chapter. Because of this, it should not be surprising to note that some discrepancies exist when comparing the results of the two methods. Nevertheless, there is good correspondence between the results of the two methods in 8 out of 12 cases (as shown on Figure 6.5 above). What this analysis suggests is that the first method can be used as a starting point when the research stage allows establishing, in a qualitative way, spatial patterns of overbank inundation along a river floodplain. This method can be used to classify floodplain units in terms of their hydraulic connectivity to overbank flows; which is reflected in their susceptibilities to overbank inundation. Additionally, this method can be useful when no hydraulic model has been developed for a given floodplain to establish (in a more quantitative way) the hydraulic connectivity of the floodplain units that compose it.

In conclusion, the method presented in this chapter can be used to qualitatively determine spatial patterns of overbank inundation or deposition when this is an important aspect for a specific research question. As it has been shown here, it also
can provide substantial insight on flood distribution, since it can help identify areas that are progressively inundated by different flood magnitudes.

This method was developed in the absence of a hydraulic model when 6 out of the 13 selected floodplain units had been cored in October 2008. Defining the susceptibility to overbank inundation of the floodplain units before the acquisition of the hydraulic model in this project meant that I could complete the fieldwork program in alignment with the designated funds for sediment dating analyses ($^{137}$Cs and $^{210}$Pb$_{ex}$) and at the established times. Details of the procedures that I followed for both the fieldwork program and laboratory analyses are provided in Chapter 7.

Both procedures described in this chapter were crucial for the analysis that unfolded from this point. Whereas the first led to an adequate selection of floodplain units, the second helped to establish overbank flooding thresholds. These thresholds were used, together with data on flow velocity of the hydraulic model, to define the values of some of the nine key factors (Chapter 8). These include unit-average values of overbank flow velocities and depths, travel time from channel to floodplain unit, post-peak pond capacity, the total number of days over the post-Eildon period in which the floodplain units were flooded, as well as identification of overbank flow paths (Chapter 8).

\footnote{The Australian Institute of Nuclear Science and Engineering awarded two grants which funded the sediment dating analyses that were based on detection of $^{137}$Cs and $^{210}$Pb$_{ex}$. The awards established that these analyses had to be completed between 2008 and 2009.}
7 Chapter Seven

7.1 Estimation of sediment deposition rates using radionuclide analysis

7.1.1 Introduction

This chapter describes the procedure that was followed for the estimation of net sediment accumulation and sedimentation rates. As previously mentioned, thirteen floodplain units were strategically selected from their potential to represent different rates of overbank deposition (Chapter 6). Three sites for core collection were selected from most of these floodplain units, with the exception of units 1F (from which only one core was collected) and F.G (with only two coring sites). As will be explained later in this chapter, these cores were used to determine deposition rates for the post-Eildon period using primarily $^{137}$Cs analysis. Additionally, two longer cores, up to 90-centimeters long, were collected from the floodplain units in the upper and downstream end of the floodplain section: cores 1F and A respectively. Core A was collected from
the same abandoned channel from which core A.B.UU was extracted. High susceptibility to overbank inundation (Chapter 6) and therefore high deposition rates were expected along the two floodplain units (those of core 1F and A). Their collection was carried out in order to estimate deposition rates over the pre-Eildon period from detection of $^{210}$Pb(ex). It was expected that, by comparing deposition amounts of the pre- and post-Eildon periods, the impact of flow regulation (of Lake Eildon) on overbank deposition along the Mid-Goulburn River floodplain could be established. Additionally, combined analyses of $^{210}$Pb(ex) and $^{137}$Cs of these longer cores was expected to reveal the downstream gradient (if any) of overbank deposition over the two periods.

$^{137}$Cs and $^{210}$Pb(ex) are fallout radionuclides that have been widely used for sediment dating in numerous soil-redistribution studies to establish either erosion or deposition patterns on different settings: forest, lakes and fluvial systems (Walling, Quine & He 1992; Wallbrink & Murray 1993; Foster et al. 1994; Wallbrink, Olley & Murray 1994; Walling & He 1994; Gale, Haworth & Pisanu 1995; Walling, Owens & Leeks 1998; Siggers et al. 1999; Carson 2006; Smith & Dragovich 2008). $^{137}$Cs is a product of anthropogenic releases to the atmosphere which resulted from nuclear bomb testing between the 1950s and the 70s (half life 30.2 years) and has been used to estimate sediment accumulation since the 1950s (Wallbrink, Olley & Murray 1994).

$^{210}$Pb(ex), on the other hand, has the potential of providing deposition amounts over longer time periods. Details on this will be discussed later in this chapter.

The Australian Institute of Nuclear Science and Engineering (AINSE) granted funding for this research, which was used for a combined detection of both radionuclides in 104 sediment samples that were extracted from the cores. This
7.1.2 Estimation of sediment deposition rates using \(^{137}\text{Cs}\) and \(^{210}\text{Pb}_{(ex)}\)

7.1.2.1 Detection of \(^{137}\text{Cs}\) concentration in sediment samples; selection of reference sites

\(^{137}\text{Cs}\) is an artificial radionuclide that was released to the atmosphere as a result of nuclear bomb testings. In the southern hemisphere, fallout of this element started around 1951, although most fallout activity occurred between 1954 and 1972 (Wallbrink & Murray 1996; Leslie & Hancock 2008) and peaked in 1963—the year of the Nuclear Test Ban Treaty (Walling & He 1992; Leslie & Hancock 2008). Fallout of this radionuclide is caused primarily by rainfall and its concentrations are affected by soil and sediment permeability (Wallbrink & Murray 1996; Smith & Dragovich 2008), as well as by microclimatic variations. It is now known that this isotope (same case for \(^{210}\text{Pb}\)) is absorbed especially by fine sediment (Walling, Quine & He 1992; Wallbrink & Murray 1996): Smith and Dragovich mention that the highest concentrations have been reported on the \(<2\mu m\) fraction (UNSCEAR 2006). Previous studies, such as those of the United Nations Scientific Committee on the Effects of Atomic Radiation, have
analysed the spatial distribution of this form of radiation on global scale (Walling, Quine & He 1992; Walling, Owens & Leeks 1998) and for different latitude bands. These have shown that the southern hemisphere has received less of this element than the northern hemisphere. An additional short-term input to the atmosphere occurred in 1986 as a result of the Chernobyl accident, and this additional input has also been used to quantify recent rates of sediment deposition (cf. Walling, Quine & Rowan 1992; Petts 1995) in floodplain settings.

In floodplain depositional environments, additional inputs, apart from those associated with atmospheric fallout, are those from sediment that has already absorbed this isotope and which is subsequently deposited along the floodplain (Walling, Quine & He 1992). Therefore, the resultant chronology of $^{137}$Cs in sediment that has been deposited along the floodplain is the product of atmospheric inputs together with that from incoming sediments that are sourced within the catchment.

However, downward migration of this radionuclide in the sediment profile has been observed and may be significant in floodplain sediments. This migration results from sediment movement triggered by biological activity: e.g. insects that live in the soil and sediment or plant and root growth (Walling, Quine & He 1992; Smith et al. 2003). Walling, Quine and He (1992) consider that this redistribution is generally more accentuated in floodplains than in continuously submerged lake sediments.

As discussed in previous chapters, the spatial distribution of overbank deposition is variable, but the study of this variability is limited by the number of samples that can be analysed with the available time and funding.
Walling, Quine and He (1992); He and Walling (1996) and Walling, Owens and Leeks (1998) have demonstrated that core samples that are bulked up can be used to estimate the average accretion rate at the point where the core was collected through the calculation of the total inventory at the site. This approach reduces the number of samples that need to be analysed, as compared with sampling to obtain the depth distribution of $^{137}$Cs concentration in the sediment profile, which requires extracting a larger number of samples from individual sediment cores. Therefore, this procedure allows inclusion of more sites along the floodplain (in this case, more floodplain units). Therefore, the total inventories of floodplain sites can be compared with values obtained from reference sites and allow the ‘excess’ of $^{137}$Cs to be calculated, which in fact is, the excess that results from sediment deposition. This method can be used to estimate either net erosion or deposition: erosive sites will have a smaller inventory than the reference inventory and depositional sites will have a larger inventory. The last step of their procedure involves estimating the average $^{137}$Cs concentration of the deposited sediment. That concentration is used to establish the value of $^{137}$Cs in excess, which is then converted to an equivalent mass or depth of sediment (Walling, Quine & He 1992). Total $^{137}$Cs inventories therefore can be used to estimate the average sedimentation rate at the coring site over the period of $^{137}$Cs availability (Walling, Quine & He 1992; Walling & He 1998b).

In this study, sediment samples of the same depth interval and floodplain unit were combined (bulked up) to estimate sedimentation rates and amounts as an average over the $^{137}$Cs period of the corresponding floodplain units. Details of the
estimations are given later in this chapter; and the procedures are similar to those described by Smith and Dragovich (2008).

As previously mentioned, it is well known that $^{137}\text{Cs}$ is better absorbed in the finer fraction of the deposited sediment. One limitation of the method mentioned above is that this approach assumes a grain size distribution of the deposited sediment that is essentially uniform across the floodplain (Walling, Quine & He 1992). This may lead to underestimations in areas where coarser sediment is deposited and to overestimations in sites where finer sediment has been deposited. These effects, therefore, will be more noticeable where grain size distribution along the floodplain is more variable (Walling, Quine & He 1992; Foster et al. 1994). In cases where there is less variability in this respect, however, this is a reasonable assumption (Walling, Quine & He 1992).

### 7.1.2.2 Considerations for reference site selection

As reference sites should reflect the total cumulative input flux of $^{137}\text{Cs}$ (Owens & Walling 1996); a direct comparison of their total inventory with local depositional or erosive sites should reflect the deposition or erosion rate at those sites. An extra analysis, however, has been established from more recent studies. Over the last two decades, the spatial variability of $^{137}\text{Cs}$ in reference sites has been analysed, and it has been observed that the distribution of $^{137}\text{Cs}$ among reference sites (reflecting the $^{137}\text{Cs}$ fallout and its spatial distribution) can be highly variable, as well as their corresponding total inventories (Foster et al. 1994; Wallbrink, Olley & Murray 1994; Southerland 1996; Wallbrink & Murray 1996; Barisic, Vertacnik & Lulic 1999; Pemmock & Appleby 2002).
Foster et al. (1994) consider that this variation can be as large as 40%. The variability of the $^{137}$Cs concentration attached to the sediment in undisturbed sites is related to soil bulk density; soil type and composition; grain size; organic matter content (Barisic, Vertacnik & Lulic 1999); the infiltration capacity of the sediment and soil; presence of macropores, cracks and stones; vegetation type and density at the site (such as presence of trees, canopy size and its distribution) and downward migration of the isotope from perturbation of the sediment by roots and organisms (Loughran et al. 1993; Loughran, Pennock & Walling 2002). Micro topography and rainfall variability of the locality are also important for the spatial distribution of $^{137}$Cs, which is reflected when comparing reference site values (Barisic, Vertacnik & Lulic 1999; Loughran, Pennock & Walling 2002). Therefore, the inherent variability of this isotope among reference sites underlines the importance of a careful selection of reference sites and becomes crucial for the successful implementation of the technique. As for reference sites, the aspects mentioned above are also potential causes of $^{137}$Cs downward migration in sites where sediment has been deposited or eroded and are thought to be more important in fluvial settings than on lacustrine environments (Walling & He 1992) but more important in forested areas (Pemmock & Appleby 2002).

In this research, I based the selection of reference sites on the 'reference site criteria' established by Pemmock and Appleby (Pemmock & Appleby 2002). In general terms, a site should be used for this purpose if it has not experienced soil loss nor sediment deposition since the period in which fallout of $^{137}$Cs began. Thus, the "inventory reflects only the atmospheric inputs of the specific radionuclide and its decay through time" (Pemmock & Appleby 2002, p. 23). Reference sites should also be
located as close as possible to the disturbed (depositional) sites that are to be sampled. Ideally, the reference site should be under continuous vegetation cover for the period since deposition of $^{137}$Cs began. Pemmock and Appleby (2002) consider that “perennial grass or low herb cover [at the site] is best” (Ibid, p. 23). For example, in forested sites, the common mix of species tends to increase the spatial variability of $^{137}$Cs in the sediment profile and the stem flow concentrates $^{137}$Cs activity around tree trunks. Within this context, “landowner contact is critical to establish the disturbance history of each site” (Ibid, p. 23).

Related research suggests that it is also important to include an adequate number of reference sites to reduce the uncertainty of reference values. The minimum number of reference sites depends on the anticipated spatial variability of this radionuclide in the locality (which can be established partly from rainfall variability) and on the spatial scale of the study. When a high variability on the spatial distribution of atmospheric input of $^{137}$Cs is expected, a more rigorous approach, such as a sampling grid program or a probability sampling strategy, may be more adequate, as suggested by Southerland (1996) and Pemmock and Appleby (2002). Thus, the specific number and location of the reference site samples depend on the complexity of the environment. Southerland (1996) suggests that a minimum of 11 independent samples is necessary when a probability-based sampling design seems more adequate, which then gives an allowable error of 10% at the 90% confidence limit.

Given the common spatial variability of $^{137}$Cs content among reference sites, it is preferable that the reference value (total inventories) is compared with existing data
from other studies: ranging from reference values established for locations near the study site to regional or global data (Pemmock & Appleby 2002).

The Mid-Goulburn River floodplain is vegetated with permanent pastures. Potential alteration of the vertical and spatial distribution of $^{137}$Cs along the sediment profile is therefore influenced by the factors discussed above. As part of this, rainfall variability in the surrounding area of the floodplain will be discussed in the next section. Description of the reference site selection is given later in this chapter.

### 7.1.2.3 Detection of $^{210}$Pb$_{(ex)}$ for floodplain sediment dating

$^{210}$Pb$_{(ex)}$ is a natural radionuclide that is a product of the $^{238}$U decay that may be used to estimate deposition rates over longer periods of time; this is, in the range of 50-150 years (Siggers et al. 1999). Similar to $^{137}$Cs, it also reaches the land surface via atmospheric fallout. This element has a half life of 22.3 years, and it has been assumed that the annual fallout is essentially constant through time (Walling & He 1994; He & Walling 1996).

Information on the depth distribution of $^{210}$Pb$_{(ex)}$ concentrations in overbank deposits can be used to date specific levels and to estimate deposition rates. Similar to the use of $^{137}$Cs for the estimation of sediment accretion rates, the excess inventory of $^{210}$Pb$_{(ex)}$ due to sediment deposition of a particular site on the floodplain can be calculated as the total inventory less that from atmospheric fallout –this latter given by the reference value from reference sites (He & Walling 1996).
Although $^{210}\text{Pb}$ (ex) measurements have been extensively used to establish lacustrine sediment chronologies, its application to floodplain sediments may introduce further complexities due to higher levels of sediment transport and redistribution common in floodplain environments. Theoretically, concentrations of $^{210}\text{Pb}$ (ex) tend to exhibit an exponential decay with increasing depth more rapidly than that exhibited by $^{137}\text{Cs}$ because of its shorter half life. Therefore, reference sites can also be used for the estimation of $^{210}\text{Pb}$ (ex) inventories using sediment samples under the same principles as for the detection of $^{137}\text{Cs}$ concentrations. Detailed information about the reference sites that were selected for this study is given later in this chapter.

### 7.1.2.4 Rainfall variability across the study area

As previously mentioned in this chapter, evaluation of rainfall variability of the locality relevant for the study area is relevant to predict the level of variability of the $^{137}\text{Cs}$ reference inventory. Based on their location and on the period of data collection, I used four rainfall stations of the Australian Bureau of Meteorology to establish rainfall variability across the study area (Figure 7.2). These are the Lake Eildon (no. 88023), Acheron (no. 88000), Alexandra Post Office (no. 88001) and Yea (no. 88067) stations. Their elevations are shown on Table 7.1 and Table 7.2 below. Since rainfall records of station 88164 (Eildon Fire Tower) do not include the whole period of interest (only the last 13 years) these were not considered in this analysis.
The averaged values of annual rainfall obtained from records of the four stations and divided in two different periods, 1931 to 2008 and 1955 to 2008 respectively, are shown on Table 7.1 and Table 7.2. The later corresponds to the pre-Eildon period. Rainfall across the study area varies from 615.6 mm (Yea station) to 876.8 mm (Lake Eildon station) over the $^{137}$Cs period, with an overall difference of annual rainfall of 261 mm over the post-Eildon period (1955-2008; Table 7.2). It is important to note that this difference seems to be closely related to the elevation at which the stations are located and provides an indication on how rainfall distribution may affect reference inventories of $^{137}$Cs. This suggests that depending on their location and elevation, it is possible that slightly larger reference inventories of $^{137}$Cs exist along the upper reach than along the downstream end of the floodplain section.

Table 7.1 Mean annual rainfall at the four stations for the period of 1931 to 2008. Note that floodplain elevation is in the order of 200 meters (AHD) along the upstream end of the floodplain section and around the 150 meters along the downstream end.

<table>
<thead>
<tr>
<th>BOM Station</th>
<th>Station elevation AHD (m)</th>
<th>Average annual rainfall (between 1931 and 2008)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Eildon (88023)</td>
<td>230</td>
<td>858.9</td>
</tr>
<tr>
<td>Alexandra Post Office (88001)</td>
<td>221</td>
<td>714.9</td>
</tr>
<tr>
<td>Yea (88067)</td>
<td>193</td>
<td>624.7</td>
</tr>
<tr>
<td>Acheron (88000)</td>
<td>180</td>
<td>772.0</td>
</tr>
</tbody>
</table>

Average annual rainfall of the locality: 742 mm
Overall difference among mean annual values: 234.2 mm
Table 7.2 Mean annual rainfall of the four stations for the post-Eildon period (1955 to 2008). Note that floodplain elevation is in the order of the 200 meters along the upstream end of the floodplain and around the 150 meters along the downstream end.

<table>
<thead>
<tr>
<th>BOM Station</th>
<th>Station elevation AHD (m)</th>
<th>Mean annual rainfall (1955-2008)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Eildon (88023)</td>
<td>230</td>
<td>876.8</td>
</tr>
<tr>
<td>Alexandra Post Office (88001)</td>
<td>221</td>
<td>711.2</td>
</tr>
<tr>
<td>Yea (88067)</td>
<td>193</td>
<td>615.6</td>
</tr>
<tr>
<td>Acheron (88000)</td>
<td>180</td>
<td>784.5</td>
</tr>
</tbody>
</table>

Average of the locality: 747 mm
Overall difference among mean annual values: 261.1 mm

The mean annual rainfall of each station over the period (1955-2008) is shown on Figure 7.1.
Figure 7.1. Annual rainfall of each station.
Figure 7.2. Map showing the floodplain section of the Mid-Goulburn River; the location of the 4 BOM rainfall stations used for assessing rainfall variability across the catchment (red dots); the location of reference sites (green stars; circled) and floodplain coring sites (yellow crosses).
7.1.2.5 Core collection and sediment sampling

During the early stage of the fieldwork program, sediment augering as well as two preliminary cores were collected from abandoned channels whose approximate year of abandonment was known. They indicated that the maximum deposition along the floodplain could be expected not to exceed 50 centimetres over the flow regulation period. Nevertheless, at each of the selected coring sites the target depth of each core was 90 centimetres. The cores were subsequently collected using metal split-tube samplers of different dimensions (Figure 7.3 below) due to their availability\(^{12}\) and were hammered into the ground, as shown on Figure 7.3. These samplers were shorter than the target depth; therefore, sequential cores were taken from the same core sampling point in order to reach that depth.

Table 7.3. Dimensions of the split-tube samplers used.

<table>
<thead>
<tr>
<th>Length of split-tube sampler (cm)</th>
<th>Radius (cm)</th>
<th>Cross section area</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. 54 cm</td>
<td>2.7</td>
<td>22.9</td>
</tr>
<tr>
<td>b. 38 cm</td>
<td>2.1</td>
<td>13.9</td>
</tr>
<tr>
<td>c. 54 cm</td>
<td>2.1</td>
<td>13.9</td>
</tr>
</tbody>
</table>

\(^{12}\) The larger split-tube sampler was damaged towards the end of the fieldwork during core collection at reference sites.
Figure 7.3. The metal split-tube sampler and the tools used for sediment coring

The cores were handled with care and stored immediately. They were placed into PVC tubes, wrapped into bubble-wrap and Gladwrap plastic (Figure 7.3 and Figure 7.4) and then sealed with Sellotape. Cores were stored horizontally in the laboratory, where they were sectioned at specific depth intervals (details below).
Figure 7.4. Storing of the sediment cores using PVC half-tubes, bubble-wrap and Gladwrap plastic.

For the estimation of deposition rates over the post-Eildon period (flow regulation), cores were sectioned into 4 depth intervals: 0-5; 5-15; 15-30 and 30-50 centimetres. Core sections of the same floodplain units were carefully combined (bulked up), following the procedure that is explained below (Figure 7.5).
The combined samples were analysed with gamma spectrometry by ANSTO in their nuclear laboratory for $^{137}$Cs and $^{210}$Pb$_{\text{ex}}$ detection. Five core samples of a sectioned core whose deposition rate was expected to be high were sent for gamma analysis. Results of these showed that concentrations of $^{137}$Cs (detection limit for gamma spectrometry of 0.01 Bq.g$^{-1}$) were only detectable in the first 40 centimetres of depth, confirming that the core sectioning did not need to be carried out for depths larger than 50 centimetres, as had been anticipated.

In order to study any possible gradient of sediment accumulation downstream, two locations were selected from the upstream and downstream end of the floodplain, as previously mentioned. These were cores 1F and A respectively (Figure 7.2 above). These 90-centimetre cores were sectioned every 6 cm and sent to the ANSTO laboratory for gamma spectrometry and to detect the same radionuclides. These
samples were assessed with the intention of calculating profile inventories of both $^{137}$Cs and $^{210}\text{Pb}_{(\text{ex})}$ and to estimate deposition rates over the pre- and post- Eildon period (i.e. before and after 1955).

A total of 104 sediment samples were sent to the ANSTO nuclear laboratory for combined $^{137}$Cs and $^{210}\text{Pb}_{(\text{ex})}$ detection. Of the total 104 samples, 35 were taken from 6 reference sites (Figure 7.2 above). Details of their selection are discussed later in this chapter.

Reference sites are those for which it can be assumed, with reasonable confidence based on the available evidence, that no sediment redistribution through erosion or deposition has occurred over the last 60 years. Corroboration involved interviewing people who have lived in the area for the last 60 years and who could nominate sites that can be used as reference sites. The samples were collected from the selected reference sites following field corroboration. One to four core sampling sites were selected at each reference site. In most cases, samples from the same reference site and from the same depth intervals: 0-5; 5-15; 15-30 and 30-50 centimetres were combined.

All cores were sectioned with a surgical blade at the desired intervals, and each core section was placed into an aluminum container for further calculation of dry bulk density. Once in those containers, the core sections were immediately weighed (fresh sample weight) for accurate calculation of dry bulk density (Equation 7.1 and Equation
7.2 below). Special care was taken in marking and cutting the cores at each interval precisely and to avoid cross contamination; therefore, hand and instrument washing was carried out before each sectioning.

In most cases, core sections were gently crumbled as much as possible using the finger tips, noting presence of twigs, roots and small soil animals. Some core sections were drier and more compact. All core sections were dried in an oscillation oven for 2.5 to 4 days at below 60°C (following ANSTO recommendations to allow full detection of the radionuclides). Once dried, each core section was reweighed (dried sample weight) in order to calculate moisture content and dry bulk density using the following expressions.

**Equation 7.1** \[ \text{Moisture Content} = \text{Fresh Sample Weight} - \text{Dried Sample Weight} \]

**Equation 7.2** \[ \text{Dry Bulk Density} = \frac{\text{DrySampleWeight}}{\text{Volume of Sample in the core}} \]

Samples to be combined were mixed in equal proportions. Each of these combined samples weighed between 60 to 70 grams. Around 2 grams of each sample (both not bulked and bulked up) were analysed for grain size distributions using a laser particle analyser (Chappell et al. 2011). More details on the calculations of grain-size distributions are given below. This analysis is relevant as it shows, as previously
discussed, that both $^{137}$Cs and $^{210}$Pb(ex) are easily absorbed by the fine fraction (silt and clay).

The 104 samples, weighing ~60 grams each, were ground to powder using a soil grinding machine, following the specified laboratory procedures of ANSTO. Once the desired texture was reached, each sample was sealed in a plastic bag, adequately labeled and sealed with additional tape to avoid losses from the pressure as they were sent to the nuclear laboratory at ANSTO in New South Wales by airmail. The analysis with gamma spectrometry took between 5 (first 30 samples) and 7 months (last 60 samples) to be completed. Delays were associated with maintenance of the gamma spectrometer at ANSTO.

The next step was to estimate the grain size distribution of each sample saved for this purpose (2 grams of each) using the laser analyser (Malvern Instruments Ltd 1999). Each sample was mixed with water in 50-milliliter cylindrical containers and placed into an ultrasonic bath for about 40 minutes to help the aggregates of the fine particles to separate. After this, the samples were gently stirred and if aggregates could be felt to the touch, the fingertips were used very gently to separate them. Small floating twigs, whenever found, were taken out from the sample solution before measurement.

The grain size analyser was used assuming a normal distribution (the default optical model). Measurement time was set to 30 seconds whereas background time was set to 20 seconds. For each sample, the measurement run cycles were 3 and the
cycle measurements 20 seconds. To clean the instrument, the laser analyser was filled with clean distilled water and emptied 4 times before each sample measurement started. Results of these measurements are provided below.

### 7.1.3 Results

#### 7.1.3.1 Dry bulk densities of the samples

Dry bulk densities of each core sample, either combined or not combined, as well as the corresponding averages, are shown on Table 7.4 below. The whole average dry bulk density among the 104 samples is 1.17 g.cm⁻³. These densities were used later in this chapter to calculate total inventories and reference inventories and to ultimately calculate overbank net accumulation and deposition rates.
Table 7.4. Depth intervals of the corresponding samples; procedure and dry bulk densities

<table>
<thead>
<tr>
<th>No. of Samples 2009</th>
<th>Sample Name</th>
<th>Depth Interval (cm)</th>
<th>Procedure</th>
<th>Dry Bulk Density (g.cm(^{-3})) (averaged by depth-interval, if applicable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Core 1</td>
<td>6-8</td>
<td>Preliminary analysis: no bulking-up procedure</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>26-28</td>
<td></td>
<td>1.47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>46-48</td>
<td></td>
<td>1.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>66-68</td>
<td></td>
<td>1.39</td>
</tr>
<tr>
<td></td>
<td></td>
<td>86-88</td>
<td></td>
<td>1.95</td>
</tr>
<tr>
<td>2</td>
<td>1L+1G+1I</td>
<td>0-5</td>
<td>combined (bulked-up) samples</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5-15</td>
<td></td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15-30</td>
<td></td>
<td>1.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30-50</td>
<td></td>
<td>1.16</td>
</tr>
<tr>
<td>3</td>
<td>1F</td>
<td>0-6</td>
<td></td>
<td>1.13</td>
</tr>
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<td></td>
<td></td>
<td>6-12</td>
<td></td>
<td>1.08</td>
</tr>
<tr>
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<td></td>
<td>12-18</td>
<td></td>
<td>1.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18-24</td>
<td></td>
<td>1.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24-30</td>
<td>no bulking-up procedure</td>
<td>1.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30-36</td>
<td></td>
<td>1.14</td>
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<td>36-42</td>
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<td>1.25</td>
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<td>48-54</td>
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<td>1.06</td>
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<td></td>
<td>54-60</td>
<td></td>
<td>1.12</td>
</tr>
<tr>
<td>No. of Samples</td>
<td>Sample Name</td>
<td>Depth Interval (cm)</td>
<td>Procedure</td>
<td>Dry Bulk Density (g.cm⁻³) (averaged by depth-interval, if applicable)</td>
</tr>
<tr>
<td>----------------</td>
<td>----------------------</td>
<td>---------------------</td>
<td>-----------------------------------</td>
<td>---------------------------------------------------------------------</td>
</tr>
<tr>
<td>20</td>
<td>1F</td>
<td>60-66</td>
<td></td>
<td>1.21</td>
</tr>
<tr>
<td>21</td>
<td></td>
<td>66-72</td>
<td></td>
<td>1.00</td>
</tr>
<tr>
<td>22</td>
<td>1D+1D.Bis+1E</td>
<td>0-5</td>
<td>combined (bulked-up) samples</td>
<td>1.00</td>
</tr>
<tr>
<td>23</td>
<td></td>
<td>5-15</td>
<td></td>
<td>1.12</td>
</tr>
<tr>
<td>24</td>
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<td>15-30</td>
<td></td>
<td>1.02</td>
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<td>25</td>
<td></td>
<td>30-50</td>
<td></td>
<td>1.13</td>
</tr>
<tr>
<td>26</td>
<td>1A+1B+1C</td>
<td>0-5</td>
<td>combined (bulked-up) samples</td>
<td>0.94</td>
</tr>
<tr>
<td>27</td>
<td></td>
<td>5-15</td>
<td></td>
<td>1.02</td>
</tr>
<tr>
<td>28</td>
<td></td>
<td>15-30</td>
<td></td>
<td>1.07</td>
</tr>
<tr>
<td>29</td>
<td></td>
<td>30-50</td>
<td></td>
<td>1.15</td>
</tr>
<tr>
<td>30</td>
<td>2D+2E+2F</td>
<td>0-5</td>
<td>combined (bulked-up) samples</td>
<td>0.99</td>
</tr>
<tr>
<td>31</td>
<td></td>
<td>5-15</td>
<td></td>
<td>1.27</td>
</tr>
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<td>32</td>
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<td>15-30</td>
<td></td>
<td>1.27</td>
</tr>
<tr>
<td>33</td>
<td></td>
<td>30-50</td>
<td></td>
<td>1.29</td>
</tr>
<tr>
<td>34</td>
<td>N+J+Q</td>
<td>0-5</td>
<td>combined (bulked-up) samples</td>
<td>0.76</td>
</tr>
<tr>
<td>35</td>
<td></td>
<td>5-15</td>
<td></td>
<td>1.08</td>
</tr>
<tr>
<td>36</td>
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<td></td>
<td>30-50</td>
<td></td>
<td>1.36</td>
</tr>
<tr>
<td>38</td>
<td>QQ+BB+AA</td>
<td>0-5</td>
<td>combined (bulked up) samples</td>
<td>0.98</td>
</tr>
<tr>
<td>39</td>
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<td>5-15</td>
<td></td>
<td>1.28</td>
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<td>1.37</td>
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<tr>
<td>41</td>
<td></td>
<td>30-50</td>
<td></td>
<td>1.49</td>
</tr>
<tr>
<td>No. of Samples 2009</td>
<td>Sample Name</td>
<td>Depth Interval (cm)</td>
<td>Procedure</td>
<td>Dry Bulk Density (g.cm⁻³) (averaged by depth-interval, if applicable)</td>
</tr>
<tr>
<td>---------------------</td>
<td>-------------</td>
<td>---------------------</td>
<td>-----------</td>
<td>---------------------------------------------------------------</td>
</tr>
<tr>
<td>42</td>
<td>FF+GG+HH</td>
<td>0-5</td>
<td>combined (bulked-up) samples</td>
<td>0.79, 1.12, 1.28, 1.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5-15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15-30</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30-50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>43</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>44</td>
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<td></td>
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<tr>
<td>45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>46</td>
<td>CC+DD+EE</td>
<td>0-5</td>
<td>combined (bulked-up) samples</td>
<td>0.93, 1.21, 1.28, 1.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5-15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15-30</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>30-50</td>
<td></td>
<td></td>
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<tr>
<td>47</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>48</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>49</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>F+G only</td>
<td>0-5</td>
<td>combined (bulked-up) samples</td>
<td>1.01, 1.12, 1.21, 1.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5-15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15-30</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30-50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
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<td>52</td>
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<td></td>
</tr>
<tr>
<td>53</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>54</td>
<td>K+L+M</td>
<td>2-5*</td>
<td>combined (bulked-up) samples</td>
<td>1.00, 1.22, 1.34, 1.43</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5-15</td>
<td></td>
<td></td>
</tr>
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<td>15-30</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30-50</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Cores from this unit were collected once the grass had been removed with a shovel. It was later learnt that this procedure was not necessary and that in fact it was better not to carry it out given the possibility that attached to the grass there could be soil that may had already absorbed $^{137}$Cs, and therefore, doing so could affect the corresponding estimations of total $^{137}$Cs inventories, as well as associated estimations of sediment accumulation. Once this realisation was made, the rest of the cores were collected without excluding the grass from the cores.
<table>
<thead>
<tr>
<th>No. of Samples 2009</th>
<th>Sample Name</th>
<th>Depth Interval (cm)</th>
<th>Procedure</th>
<th>Dry Bulk Density (g.cm⁻³) (averaged by depth-interval, if applicable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>58</td>
<td>A+B+UU</td>
<td>2-5 *</td>
<td>combined (bulked-up) samples</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5-15</td>
<td></td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15-30</td>
<td></td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30-50</td>
<td></td>
<td>0.97</td>
</tr>
<tr>
<td>59</td>
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<td>5-15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td></td>
<td>15-30</td>
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<td>61</td>
<td></td>
<td>30-50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>62</td>
<td>A</td>
<td>0-6</td>
<td>no bulking-up procedure</td>
<td>0.89</td>
</tr>
<tr>
<td>63</td>
<td></td>
<td>6-12</td>
<td></td>
<td>0.89</td>
</tr>
<tr>
<td>64</td>
<td></td>
<td>12-18</td>
<td></td>
<td>0.90</td>
</tr>
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<td>65</td>
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<td>18-24</td>
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<td>0.95</td>
</tr>
<tr>
<td>66</td>
<td></td>
<td>24-30</td>
<td></td>
<td>0.97</td>
</tr>
<tr>
<td>67</td>
<td></td>
<td>30-36</td>
<td></td>
<td>1.03</td>
</tr>
<tr>
<td>68</td>
<td></td>
<td>36-42</td>
<td></td>
<td>0.74</td>
</tr>
<tr>
<td>69</td>
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<td>42-48</td>
<td></td>
<td>0.87</td>
</tr>
<tr>
<td>70</td>
<td></td>
<td>48-54</td>
<td></td>
<td>1.27</td>
</tr>
</tbody>
</table>

*Cores from this unit were collected once the grass had been removed with a shovel. It was later learnt that this procedure was not necessary and that in fact it was better not to carry it out given the possibility that attached to the grass there could be soil that may had already absorbed \(^{137}\)Cs, and therefore, doing so could affect the corresponding estimations of total \(^{137}\)Cs inventories, as well as associated estimations of sediment accumulation. Once this realisation was made, the rest of the cores were collected without excluding the grass from the cores. Core A was collected from the same floodplain unit as Cores A, B, UU but without excluding the grass. It can be noticed that the detected concentration of \(^{137}\)Cs of the sample that corresponds to the first interval of Core A (i.e. 0-6cm) is larger (4.6 Bq.m\(^{-2}\), Table 7.10 below) than that of A.B.UU (3.5 Bq.m\(^{-2}\), same table). However, the sample of the last belongs to one centimetre less of depth (0 to 5cm).*
<table>
<thead>
<tr>
<th>No. of Samples 2009</th>
<th>Sample Name</th>
<th>Depth Interval (cm)</th>
<th>Procedure</th>
<th>Dry Bulk Density (g.cm(^{-3})) (averaged by depth-interval, if applicable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>71</td>
<td>A</td>
<td>54-60</td>
<td>no bulking-up procedure</td>
<td>1.18, 1.21, 1.14, 1.09, 1.16, 1.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60-66</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>66-72</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>72-78</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td>78-84</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>84-90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>77</td>
<td>D+TT+E</td>
<td>0-5</td>
<td>combined (bulked-up) samples</td>
<td>1.04, 1.17, 1.18, 1.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5-15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15-30</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30-50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>REFERENCE SITES</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>81</td>
<td>RS-1</td>
<td>0-5</td>
<td>Just one coring site, therefore not combined (bulked-up) samples</td>
<td>0.83, 1.51, 1.48, 1.33</td>
</tr>
<tr>
<td>82</td>
<td></td>
<td>5-15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>83</td>
<td></td>
<td>15-30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>84</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>85</td>
<td>RS-2</td>
<td>0-5</td>
<td>Just one coring site, therefore not combined (bulked-up) samples</td>
<td>1.17, 1.48, 1.58, 1.41</td>
</tr>
<tr>
<td>86</td>
<td></td>
<td>5-15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>87</td>
<td></td>
<td>15-30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>88</td>
<td></td>
<td>30-50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of Samples</td>
<td>Sample Name</td>
<td>Depth Interval (cm)</td>
<td>Procedure</td>
<td>Dry Bulk Density (g.cm(^{-3})) (averaged by depth-interval, if applicable)</td>
</tr>
<tr>
<td>---------------</td>
<td>-------------</td>
<td>---------------------</td>
<td>-----------</td>
<td>--------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>89 R1+R2</td>
<td>0-5 5-15 15-30</td>
<td>Two coring sites, therefore combined (bulked-up) samples</td>
<td>1.45 1.44 1.44</td>
<td>1.56 1.88</td>
</tr>
<tr>
<td>90</td>
<td>5-15 15-30 30-50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>91</td>
<td>R3+R4 0-5 5-15 15-30 30 to ~37</td>
<td>Two coring sites, therefore combined (bulked-up) samples</td>
<td>1.07 1.68 1.81</td>
<td>1.95</td>
</tr>
<tr>
<td>92 R3+R4 0-5 5-15 15-30 30 to ~37</td>
<td>Two coring sites, therefore combined (bulked-up) samples</td>
<td>1.14 1.30 1.30</td>
<td>1.31</td>
<td></td>
</tr>
<tr>
<td>93 R5+R6+R7 0-5 5-15 15-30 30-50</td>
<td>Three coring sites, therefore combined (bulked-up) samples</td>
<td>1.15 1.47 1.67</td>
<td>1.59</td>
<td></td>
</tr>
<tr>
<td>94</td>
<td>R8+R9 0-5 5-15 15-30 30-50</td>
<td>Two coring sites, therefore combined (bulked-up) samples</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Whole Average of Dry Bulk Densities**

| | |
| | 1.17 |
7.1.3.2 Grain size distributions of floodplain sediment samples

The determined grain size distributions by sample number (here named cumulative volume) of the corresponding sediment samples are shown on Appendix B.

The estimated clay content, in cumulative volume (i.e. % per sample volume), of each floodplain-unit sample is shown in Table 7.5 below. From these results, I found that on average the samples have a cumulative volume of 24% of sand, 56% of silts and 20% of clays. This indicates that isotopes such as $^{137}$Cs and $^{210}$Pb$_{(ex)}$ must have been absorbed by these fine sediment-size fractions, of which the samples are composed in high proportion. This fine sediment content also indicates that it is possible that suspended sediment could have travelled in aggregated form (flocs) before being deposited along the floodplain units.
Table 7.5. Cumulative volume of clay of the floodplain-unit samples.

<table>
<thead>
<tr>
<th>Floodplain-unit cores</th>
<th>Sample interval</th>
<th>Cumulative volume (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1L.1G.1I</td>
<td>Samples 0 to 5cm and 5 to 15cm; Sample 15 to 30cm and 30 to 50cm</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>1F</td>
<td>Samples:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0-6cm; 6-12cm; 12-18cm and 18-24cm</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>24-30cm; 30-36cm; 36-42cm and 42-48cm</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>48-54cm; 54-60cm; 60-66cm and 66-72cm</td>
<td>18</td>
</tr>
<tr>
<td>1D.1DBis.1E</td>
<td>Sample 0 to 5cm</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Sample 5 to 15cm</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Sample 15 to 30cm</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Sample 30 to 50cm</td>
<td>28</td>
</tr>
<tr>
<td>1A.1B.1C</td>
<td>Clay content of sample 30 to 50cm</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>the other three samples</td>
<td>18</td>
</tr>
<tr>
<td>2D.2E.2F</td>
<td>Clay content of sample 30 to 50cm</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>the other three samples of this core</td>
<td>20</td>
</tr>
<tr>
<td>N.J.Q</td>
<td>Clay content of sample 30 to 50cm</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>the other three samples of this core</td>
<td>19</td>
</tr>
<tr>
<td>QQ.BB.AA</td>
<td>Clay content of sample 0 to 5cm; the other three samples of this core (5-15cm; 15-30cm and 30-50cm)</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>29</td>
</tr>
<tr>
<td>FF.GG.HH</td>
<td>Clay content of all samples of this core</td>
<td>18</td>
</tr>
<tr>
<td>Floodplain-unit cores</td>
<td>Sample interval</td>
<td>Cumulative volume (%)</td>
</tr>
<tr>
<td>-----------------------</td>
<td>----------------------------------------------------------------------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>CC.DD.EE</td>
<td>Clay content for first 3 samples of this core (i.e. 0-5cm; 5-15cm; 15-30cm);</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>sample 30-50 cm</td>
<td>25</td>
</tr>
<tr>
<td>F.G</td>
<td>Clay content of sample 0 to 5cm;</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>the other three samples (5-15cm; 15-30cm and 30-50cm)</td>
<td>32</td>
</tr>
<tr>
<td>K.L.M</td>
<td>Clay content for samples 5-15cm and 30-50cm;</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Clay content for samples 1.5-5cm and 15-30cm</td>
<td>24</td>
</tr>
<tr>
<td>A.B.UU</td>
<td>All four samples: (i.e. 0-5cm; 5-15cm; 15-30cm and 30-50cm)</td>
<td>17</td>
</tr>
<tr>
<td>A</td>
<td>Samples within interval 0 to 24cm of depth</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Samples within interval 24 to 48cm of depth</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Samples within interval 48 to 72cm of depth</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Samples within interval 72 to 90cm of depth</td>
<td>19</td>
</tr>
<tr>
<td>D.TT.EE</td>
<td>Clay content of all samples of this core</td>
<td>19</td>
</tr>
<tr>
<td>Average of samples in</td>
<td></td>
<td>20.3</td>
</tr>
<tr>
<td>the interval of 0 to</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 cm of depth</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
7.1.3.3 Estimation of overbank deposition from detection of $^{137}$Cs and $^{210}$Pb$_{ex}$ and from reference inventories

Detected concentrations by ANSTO of $^{137}$Cs and $^{210}$Pb$_{ex}$ in the corresponding sediment samples, as well as their associated uncertainties (also estimated by ANSTO), are given in Becquerels (Bq) per kilogram\textsuperscript{13}. These are shown in Table 7.6 to Table 7.8 and in Appendix C. Samples were counted for approximately 24 hours in a gamma spectrometer and with 95\% confidence.

Sample radionuclides were counted according to the following ANSTO method:

Samples were analysed using a Compton Suppression Gamma Spectrometer, whose suppression detector system comprises an active NaI(Tl) suppression annulus, a NaI(Tl) plug detector and a reverse electrode germanium detector; all housed within an inert lead shield. “Campton suppression enables the spectrometer to detect lower levels of gamma radiation, by reduction of background levels of radiation” (Smith & Dragovich 2008, p. 194). The $^{210}$Pb activity was determined using the 46.5 keV peak, and the $^{226}$Ra activity was estimated using $^{214}$Pb and $^{214}$Bi at 351.9 keV and 609.3 keV respectively. $^{210}$Pb$_{ex}$ activity was calculated by subtracting $^{226}$Ra activity from $^{210}$Pb activity. Concentrations (in Bq.kg$^{-1}$) of $^{137}$Cs of each

\textsuperscript{13} Becquerels is the SI-derived unit of radioactivity, defined as the activity of a quantity of radioactive material in which one nucleus decays per second
sample were determined using the 662 keV peak after subtraction of the $^{214}$Bi peak interference (Zawadski A 2011, Technician at ANSTO, pers. comm. 13 Feb).

$^{137}$Cs concentrations are referred to the date of counting; quoted uncertainties are 1 second counting errors and less than values (<) are quoted with a 95% confidence interval (Table 7.6 to Table 7.10). The detector system energy calibration was carried out following procedures of the National Institute of Standards and Technology (NIST); traceable $^{154}$Eu/$^{155}$Eu/$^{125}$Sb multi-nuclide standard source and the efficiency calibration of the detector system was determined using reference materials of the International Atomic Energy Agency, including RGU-1, RGTh-1, RGK-1 and Soil-6. A prepared spiked soil standard from the Queensland University of Technology was used for $^7$Be activity determination (Zawadski A 2011, Technician at ANSTO, pers. comm. 13 Feb).

7.1.3.4 Detected concentrations of $^{210}$Pb(ex): limitations for the estimation of pre-Eildon sedimentation rates

As previously mentioned, with the intention of establishing down profile inventories that included the pre-Eildon period, Cores 1F and A (Units 10 and 3 respectively) reached depths of 72 and 90 centimetres respectively and were sectioned every 6 centimetres. Finer core sectioning was not feasible given the target depths and the available funding for gamma analysis. Reported concentrations need to be considered together with their corresponding
estimated uncertainties and thus results of detected concentrations of $^{210}$Pb$_{\text{(ex)}}$ in Core 1F clearly show that below 36 centimetres this element did not have strong detectable activity (shaded rows on Table 7.6 below). On the other hand, $^{137}$Cs concentrations were detected in the first 36 cm, which suggests that the sediment of the first 36 centimetres was deposited during the post-Eildon period.

Considering the corresponding uncertainties of each analysis, the reported concentrations by ANSTO of Pb$^{210}_{\text{(ex)}}$ in Core 1F show detectable concentrations only above 36 centimetres of depth, as shown in Table 7.6; and on Figure 7.6 and Figure 7.7 below. Since concentrations of $^{137}$Cs were also detected in this depth interval (0 to 36 centimetres), this suggests that that sediment has accumulated during the post-Eildon period (since 1955). The absence of detectable concentrations of $^{210}$Pb$_{\text{(ex)}}$ below that depth therefore did not allow establishing deposition rates of the pre-Eildon period of this core.
In Core A, both detectable and insignificant concentrations of $^{210}\text{Pb}_{(ex)}$ alternate at different depth intervals below 36 centimetres of depth (highlighted in

Figure 7.6. Depth profile of Pb210(ex) concentration in Core 1F
Figure 7.7. Depth profile of $^{137}\text{Cs}$ concentration in Core 1F
Table 7.7 and shown on Figure 7.8 and Figure 7.9 below). Moreover, the actual concentrations do not decrease with depth. Similar to Core 1F, concentrations of $^{137}$Cs were also detected in the depth interval of 0 to 36 centimetres of Core A, which also suggests that the sediment with detected $^{210}$Pb$_{ex}$ concentrations has accumulated during the post-Eildon period (since 1955) and not earlier.

Therefore, it was not possible in either case (i.e. Cores A and 1F) to establish a depth from which concentration of this element fully decays, complicating the estimation of sediment deposition rates for the pre-Eildon period. This because sediment dating calculation using this radionuclide is based on the decay of Pb$^{210}_{ex}$ activity with increasing depth in a core.

Down profile migration of this element might be causing, at least partially, these inconsistencies. Possible triggers of down profile migration have been discussed previously in this chapter.

In conclusion, given that no decay of $^{210}$Pb$_{ex}$ activity with increasing depth could be established in either of these two cores below 36 centimetres of depth, sedimentation rates for the pre-regulation period (pre-Eildon or before 1955) could not be calculated. Twenty five sediment samples had been analysed with that intention.
Table 7.6. Detected concentrations of $^{210}\text{Pb}_{(ex)}$ and uncertainties reported by ANSTO of core samples of Unit 10 (Core 1F). In order to illustrate deposition during the post-Eildon period, concentrations of $^{137}\text{Cs}$ are also shown as well as the % of clay in each sample.

<table>
<thead>
<tr>
<th>Depth Interval (cm)</th>
<th>Core 1F: $^{210}\text{Pb}_{(ex)}$ detected concentrations</th>
<th>Core 1F: $^{137}\text{Cs}$ detected concentrations</th>
<th>% of Clay in sample</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>$^{210}\text{Pb}_{(ex)}$</strong> detected Concen.</td>
<td><strong>$^{137}\text{Cs}$</strong> detected Concen.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Concentration; ANSTO (Bq.kg⁻¹)</td>
<td>Concentration; ANSTO (Bq.kg⁻¹)</td>
<td>Concentration; ANSTO (Bq.kg⁻¹)</td>
</tr>
<tr>
<td>0-6</td>
<td>30.7 ± 6.9</td>
<td>6.2 ± 1.4</td>
<td>21</td>
</tr>
<tr>
<td>6-12</td>
<td>18.1 ± 6.0</td>
<td>4.9 ± 1.2</td>
<td>18</td>
</tr>
<tr>
<td>12-18</td>
<td>26.1 ± 5.6</td>
<td>6.5 ± 1.1</td>
<td>20</td>
</tr>
<tr>
<td>18-24</td>
<td>11.3 ± 6.0</td>
<td>8.2 ± 1.4</td>
<td>18</td>
</tr>
<tr>
<td>24-30</td>
<td>7.2 ± 4.3</td>
<td>4.8 ± 0.9</td>
<td>18</td>
</tr>
<tr>
<td>30-36</td>
<td>7.5 ± 5.8</td>
<td>2.9 ± 1.0</td>
<td>18</td>
</tr>
<tr>
<td>36-42</td>
<td>not detected</td>
<td>not detected</td>
<td>-</td>
</tr>
<tr>
<td>42-48</td>
<td>not detected</td>
<td>not detected</td>
<td>-</td>
</tr>
<tr>
<td>48-54</td>
<td>2.8 ± 3.9</td>
<td>not detected</td>
<td>-</td>
</tr>
<tr>
<td>54-60</td>
<td>1.2 ± 4.4</td>
<td>not detected</td>
<td>-</td>
</tr>
<tr>
<td>60-66</td>
<td>1.0 ± 3.4</td>
<td>not detected</td>
<td>-</td>
</tr>
<tr>
<td>66-72</td>
<td>5.7 ± 5.3</td>
<td>not detected</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 7.6. Depth profile of Pb$^{210}_{(ex)}$ concentration in Core 1F
Figure 7.7. Depth profile of $^{137}$Cs concentration in Core 1F
Table 7.7. Detected concentrations of $^{210}\text{Pb}_{(\text{ex})}$ and uncertainties reported by ANSTO of core samples of Unit 3 (Core A). In order to illustrate deposition during the post-Eildon period, concentrations of $^{137}\text{Cs}$ are also shown as well as the % of clay in each sample.

<table>
<thead>
<tr>
<th>Depth interval (cm)</th>
<th>Core A: $^{210}\text{Pb}_{(\text{ex})}$ detected concentrations</th>
<th>Core A: $^{137}\text{Cs}$ detected concentrations</th>
<th>% of Clay in sample</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>* Detected $^{210}\text{Pb}_{(\text{ex})}$ concentration; (Bq.kg$^{-1}$)</td>
<td>Associated Uncertainty; (Bq.kg$^{-1}$)</td>
<td>* Detected $^{137}\text{Cs}$ concentration; (Bq.kg$^{-1}$)</td>
</tr>
<tr>
<td>0-6</td>
<td>39.4 ± 5.4</td>
<td>4.6 ± 0.5</td>
<td>14</td>
</tr>
<tr>
<td>6-12</td>
<td>32.6 ± 6.8</td>
<td>6.1 ± 0.6</td>
<td>15</td>
</tr>
<tr>
<td>12-18</td>
<td>25.6 ± 5.7</td>
<td>5.3 ± 0.6</td>
<td>15</td>
</tr>
<tr>
<td>18-24</td>
<td>17.3 ± 6.8</td>
<td>4.9 ± 0.6</td>
<td>14</td>
</tr>
<tr>
<td>24-30</td>
<td>19.5 ± 5.0</td>
<td>3.1 ± 0.4</td>
<td>18</td>
</tr>
<tr>
<td>30-36</td>
<td>6.4 ± 5.6</td>
<td>1.0 ± 0.3</td>
<td>18</td>
</tr>
<tr>
<td>36-42</td>
<td>0.3 ± 6.5</td>
<td>0.8 ± 0.3</td>
<td>18</td>
</tr>
<tr>
<td>42-48</td>
<td>9.1 ± 4.6</td>
<td>not detected</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>48-54</td>
<td>not detected</td>
<td>NA</td>
<td>0.4 ± 0.3</td>
</tr>
<tr>
<td>54-60</td>
<td>5.0 ± 5.5</td>
<td>not detected</td>
<td>&lt;0.4</td>
</tr>
<tr>
<td>60-66</td>
<td>not detected</td>
<td>NA</td>
<td>not detected</td>
</tr>
<tr>
<td>66-72</td>
<td>1.3 ± 7.3</td>
<td>not detected</td>
<td>&lt;0.7</td>
</tr>
<tr>
<td>72-78</td>
<td>17.5 ± 6.5</td>
<td>1.0 ± 0.3</td>
<td>17</td>
</tr>
<tr>
<td>78-84</td>
<td>7.5 ± 4.1</td>
<td>not detected</td>
<td>&lt;0.3</td>
</tr>
<tr>
<td>84-90</td>
<td>not detected</td>
<td>NA</td>
<td>not detected</td>
</tr>
</tbody>
</table>
Figure 7.8. Depth profile of Pb$^{210}_{(ex)}$ concentration in Core A
In most of the other cores a significant activity of Pb\textsuperscript{210}(ex) was found at the surface only, with no activity below the surface sediment (Appendix C). Only in one case the combined samples of Cores A, B, UU showed a decay profile with increasing depth: (Table 7.8 below), but concentrations of \textsuperscript{137}Cs were also found in the same sediment samples, showing that the sediment has been deposited during the post-Eildon period. This is what, in fact, should be expected given that all cores, including Cores A, B, UU, were collected from the same floodplain unit.
Table 7.8. Detected concentrations by ANSTO of $^{210}\text{Pb} (\text{ex})$ (and $^{137}\text{Cs}$ for comparison) of combined samples of Unit 3 (A.BB.U). Notice the decay profile of Pb$^{210}(\text{ex})$ in this cores.

<table>
<thead>
<tr>
<th>Depth interval (cm)</th>
<th>Combined samples A.B.UU: ANSTO reported $^{210}\text{Pb} (\text{ex})$ concentrations</th>
<th>Combined samples A.BB.UU: ANSTO reported $^{137}\text{Cs}$ concentrations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>* Detected $^{210}\text{Pb} (\text{ex})$ activity (Bq.kg$^{-1}$)</td>
<td>Associated Uncertainty (Bq.kg$^{-1}$)</td>
</tr>
<tr>
<td>0-5</td>
<td>20.9 ± 4.3</td>
<td>3.5 ± 0.5</td>
</tr>
<tr>
<td>5-15</td>
<td>25.3 ± 5.1</td>
<td>4.9 ± 0.5</td>
</tr>
<tr>
<td>15-30</td>
<td>14.2 ± 5.1</td>
<td>3.8 ± 0.6</td>
</tr>
<tr>
<td>30-50</td>
<td>3.9 ± 3.6</td>
<td>0.7 ± 0.3</td>
</tr>
</tbody>
</table>

7.1.3.5 Detected concentrations of $^{137}\text{Cs}$ in floodplain-unit cores and reference sites

The corresponding detected concentrations of $^{137}\text{Cs}$ of each unit- and reference-site sample reported by ANSTO (with exception of those of 1F and A) are shown in Table 7.9 and Table 7.10 below. Uncertainties calculated by ANSTO may seem relatively high in some cases. These depend on the counting strategy that has been standardised by the ANSTO laboratory technicians, which is mentioned above and states that the detection limit for gamma spectrometry followed by ANSTO is 0.01 Bq.g$^{-1}$. Table 7.9 and Table 7.10 show that
under their procedure there were cases in which $^{137}$Cs concentration of some samples could not be established given the detection limit and the corresponding uncertainties.

Table 7.9. Detected concentrations of $^{137}$Cs in floodplain-unit samples by ANSTO

<table>
<thead>
<tr>
<th>Floodplain-unit Sample &amp; Unit ID</th>
<th>Depth interval (cm)</th>
<th>Detected concentrations of $^{137}$Cs (Bq.kg$^{-1}$)</th>
<th>Associated uncertainties (Bq.kg$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1L.1G1I (Unit 13)</td>
<td>0-5</td>
<td>5.6 ± 0.6</td>
<td>± 0.6</td>
</tr>
<tr>
<td></td>
<td>5-15</td>
<td>3.8 ± 0.3</td>
<td>± 0.6</td>
</tr>
<tr>
<td></td>
<td>15-30</td>
<td>1.2 ± 0.3</td>
<td>± 0.3</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>not established</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>1D.1DBis.1E (Unit 12)</td>
<td>0-5</td>
<td>4.0 ± 0.9</td>
<td>± 0.9</td>
</tr>
<tr>
<td></td>
<td>5-15</td>
<td>2.2 ± 1.2</td>
<td>± 1.2</td>
</tr>
<tr>
<td></td>
<td>15-30</td>
<td>not established</td>
<td>&lt; 2.2</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>not established</td>
<td>&lt; 1.3</td>
</tr>
<tr>
<td>1A.1B.1C (Unit 11)</td>
<td>0-5</td>
<td>3.4 ± 1.3</td>
<td>± 1.3</td>
</tr>
<tr>
<td></td>
<td>5-15</td>
<td>3.9 ± 0.9</td>
<td>± 0.9</td>
</tr>
<tr>
<td></td>
<td>15-30</td>
<td>not established</td>
<td>± 0.8</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>not established</td>
<td>± 2.0</td>
</tr>
<tr>
<td>2D.2E.2F (Unit 9)</td>
<td>0-5</td>
<td>5.0 ± 1.2</td>
<td>± 1.2</td>
</tr>
<tr>
<td></td>
<td>5-15</td>
<td>not established</td>
<td>&lt; 3.5</td>
</tr>
<tr>
<td></td>
<td>15-30</td>
<td>not established</td>
<td>&lt; 1.9</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>not established</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>N.J.Q (Unit 8)</td>
<td>0-5</td>
<td>5.6 ± 0.5</td>
<td>± 0.5</td>
</tr>
<tr>
<td></td>
<td>5-15</td>
<td>3.1 ± 0.2</td>
<td>± 0.4</td>
</tr>
<tr>
<td></td>
<td>15-30</td>
<td>not established</td>
<td>&lt; 0.7</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>not established</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>QQ.BB/AA (Unit 7)</td>
<td>0-5</td>
<td>4.4 ± 0.5</td>
<td>± 0.5</td>
</tr>
<tr>
<td></td>
<td>5-15</td>
<td>1.6 ± 0.2</td>
<td>± 0.2</td>
</tr>
<tr>
<td></td>
<td>15-30</td>
<td>not established</td>
<td>&lt; 0.7</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>not established</td>
<td>&lt; 0.4</td>
</tr>
<tr>
<td>Floodplain-unit Sample</td>
<td>Depth interval (cm)</td>
<td>Detected concentrations of (^{137}\text{Cs}) (Bq.kg (^{-1}))</td>
<td>Associated uncertainties (Bq.kg (^{-1}))</td>
</tr>
<tr>
<td>------------------------</td>
<td>--------------------</td>
<td>---------------------------------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>FF.GG.HH (Unit 6)</td>
<td>0-5</td>
<td>4.7</td>
<td>± 0.5</td>
</tr>
<tr>
<td></td>
<td>5-15</td>
<td>2.7</td>
<td>± 0.5</td>
</tr>
<tr>
<td></td>
<td>15-30</td>
<td>not established</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>not established</td>
<td>&lt; 0.7</td>
</tr>
<tr>
<td>CC.DD.EE (Unit 5)</td>
<td>0-5</td>
<td>4.1</td>
<td>± 0.5</td>
</tr>
<tr>
<td></td>
<td>5-15</td>
<td>2.1</td>
<td>± 0.3</td>
</tr>
<tr>
<td></td>
<td>15-30</td>
<td>not established</td>
<td>&lt;0.9</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>not established</td>
<td>&lt; 0.9</td>
</tr>
<tr>
<td>K.L.M (Unit 2)</td>
<td>2-5</td>
<td>3.5</td>
<td>± 0.6</td>
</tr>
<tr>
<td></td>
<td>5-15</td>
<td>1.8</td>
<td>± 0.5</td>
</tr>
<tr>
<td></td>
<td>15-30</td>
<td>not established</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>not established</td>
<td>&lt; 0.6</td>
</tr>
<tr>
<td>F.G (Unit 4)</td>
<td>0-5</td>
<td>4.1</td>
<td>± 0.6</td>
</tr>
<tr>
<td></td>
<td>5-15</td>
<td>2.3</td>
<td>± 0.4</td>
</tr>
<tr>
<td></td>
<td>15-30</td>
<td>not established</td>
<td>± 1.1</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>not established</td>
<td>± 0.6</td>
</tr>
<tr>
<td>A.B.UU (Unit 3)</td>
<td>2-5</td>
<td>3.5</td>
<td>± 0.5</td>
</tr>
<tr>
<td></td>
<td>5-15</td>
<td>4.9</td>
<td>± 0.5</td>
</tr>
<tr>
<td></td>
<td>15-30</td>
<td>3.8</td>
<td>± 0.6</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>0.7</td>
<td>± 0.3</td>
</tr>
<tr>
<td>D.TT.EE (Unit 1)</td>
<td>0-5</td>
<td>5.6</td>
<td>± 0.7</td>
</tr>
<tr>
<td></td>
<td>5-15</td>
<td>1.3</td>
<td>± 0.3</td>
</tr>
<tr>
<td></td>
<td>15-30</td>
<td>1.0</td>
<td>± 0.4</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>not established</td>
<td>&lt; 0.6</td>
</tr>
<tr>
<td>A (Unit 3)</td>
<td>0-6</td>
<td>4.6</td>
<td>±0.5</td>
</tr>
<tr>
<td></td>
<td>6-12</td>
<td>6.1</td>
<td>±0.6</td>
</tr>
<tr>
<td></td>
<td>12-18</td>
<td>5.3</td>
<td>±0.6</td>
</tr>
<tr>
<td></td>
<td>18-24</td>
<td>4.9</td>
<td>±0.6</td>
</tr>
<tr>
<td></td>
<td>24-30</td>
<td>3.1</td>
<td>±0.4</td>
</tr>
<tr>
<td></td>
<td>30-36</td>
<td>1.0</td>
<td>±0.3</td>
</tr>
<tr>
<td></td>
<td>36-42</td>
<td>0.8</td>
<td>±0.3</td>
</tr>
<tr>
<td></td>
<td>42-90</td>
<td>not established</td>
<td>&lt; 0.4</td>
</tr>
<tr>
<td>Floodplain-unit Sample</td>
<td>Depth interval (cm)</td>
<td>Detected concentrations of $^{137}$Cs (Bq·kg$^{-1}$)</td>
<td>Associated uncertainties (Bq·kg$^{-1}$)</td>
</tr>
<tr>
<td>------------------------</td>
<td>-------------------</td>
<td>-------------------------------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>1F</td>
<td>0-6</td>
<td>6.2 ± 1.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6-12</td>
<td>4.9 ± 1.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12-18</td>
<td>6.5 ± 1.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18-24</td>
<td>8.2 ± 1.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>24-30</td>
<td>4.8 ± 0.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30-36</td>
<td>2.9 ± 1.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>36 to 90</td>
<td>not established</td>
<td>&lt; 0.8</td>
</tr>
</tbody>
</table>
Table 7.10. Detected concentrations of $^{137}$Cs in reference-site samples by ANSTO.

<table>
<thead>
<tr>
<th>Reference-site sample</th>
<th>Depth interval (cm)</th>
<th>Detected concentrations of $^{137}$Cs (Bq.kg$^{-1}$)</th>
<th>Associated uncertainties (Bq.kg$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS-1</td>
<td>0-5</td>
<td>5.8</td>
<td>± 0.7</td>
</tr>
<tr>
<td></td>
<td>5-15</td>
<td>1.1</td>
<td>± 0.3</td>
</tr>
<tr>
<td></td>
<td>15-30</td>
<td>not established</td>
<td>&lt; 0.4</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>not established</td>
<td>&lt; 0.7</td>
</tr>
<tr>
<td>RS-2</td>
<td>0-5</td>
<td>4.3</td>
<td>± 0.5</td>
</tr>
<tr>
<td></td>
<td>5-15</td>
<td>0.5</td>
<td>± 0.3</td>
</tr>
<tr>
<td></td>
<td>15-30</td>
<td>not established</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>not established</td>
<td>&lt; 0.6</td>
</tr>
<tr>
<td>R1,R2</td>
<td>0-5</td>
<td>3.7</td>
<td>± 0.9</td>
</tr>
<tr>
<td></td>
<td>5-15</td>
<td>1.3</td>
<td>± 0.5</td>
</tr>
<tr>
<td></td>
<td>15-30</td>
<td>not established</td>
<td>&lt; 2.1</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>not established</td>
<td>&lt; 1.6</td>
</tr>
<tr>
<td>R3,R4</td>
<td>0-5</td>
<td>8.1</td>
<td>± 1.3</td>
</tr>
<tr>
<td></td>
<td>5-15</td>
<td>not established</td>
<td>&lt; 2.0</td>
</tr>
<tr>
<td></td>
<td>15-30</td>
<td>not established</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>not established</td>
<td>&lt; 1.1</td>
</tr>
<tr>
<td>R5,R6,R7</td>
<td>0-5</td>
<td>3.1</td>
<td>± 0.3</td>
</tr>
<tr>
<td></td>
<td>5-15</td>
<td>2.3</td>
<td>± 0.4</td>
</tr>
<tr>
<td></td>
<td>15-30</td>
<td>not established</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>not established</td>
<td>&lt; 0.3</td>
</tr>
<tr>
<td>R8,R9</td>
<td>0-5</td>
<td>2.5</td>
<td>± 0.8</td>
</tr>
<tr>
<td></td>
<td>5-15</td>
<td>1.6</td>
<td>± 0.8</td>
</tr>
<tr>
<td></td>
<td>15-30</td>
<td>not established</td>
<td>&lt; 0.6</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>not established</td>
<td>&lt; 1.8</td>
</tr>
</tbody>
</table>
7.1.3.6 Calculation of total inventories

Total inventories of both the floodplain units and reference sites were calculated from the estimation of areal inventories of $^{137}$Cs of the corresponding depth interval (Equation 7.4 below). Areal inventories were obtained by multiplying the detected concentration of $^{137}$Cs provided by ANSTO by the dry weight of each sample, and this product then divided by the cross sectional area of the core. When core dimensions were different, an average of the cross sectional area was calculated (Equation 7.3). Dry weights (also averaged for the case of combined samples) were registered when the samples were dried in the circulation oven for the estimation of dry bulk densities. The total $^{137}$Cs inventory of the corresponding cores (as well as that of the reference sites), was obtained adding the areal $^{137}$Cs inventories of each interval (Equation 7.4).

\textbf{Equation 7.3:}

\[
\text{Areal } ^{137}\text{Cs Inventory Interval} = \frac{(\text{averaged } ^{137}\text{Cs Detected activity}_{\text{sample}}) \times (\text{averaged Dry weight}_{\text{sample}})}{(\text{averaged area}_{\text{sample}})}
\]

\textbf{Equation 7.4:}

\[
^{137}\text{Cs Total Inventory} = \sum ^{137}\text{Cs Areal Inventory Interval}
\]
The total standard error was calculated from estimated relative uncertainties associated with each sample, as shown by Equation 7.5 and Equation 7.6:

**Equation 7.5**  \[
\text{Total Strd Error} = \sqrt{\left(\text{rel Uncert}_{\text{samp}1}\right)^2 + \left(\text{rel Uncert}_{\text{samp}2}\right)^2 + ...}
\]

**Equation 7.6**  \[
\text{rel Uncert}_{\text{sample}} = \frac{\text{(ANSTO Sample Uncert.)} \times (^{137}\text{Cs Areal Inventory})}{\text{ANSTO }^{137}\text{Cs detected concentration}}
\]

Relative uncertainties of each sample (\(\text{rel Uncert}_{\text{sample}}\)), were obtained by dividing the uncertainties provided by ANSTO by their corresponding detected concentrations of \(^{137}\text{Cs}\) and then multiplying the obtained value by the \(^{137}\text{Cs}\) areal inventories of each interval (this last in Bq.m\(^{-2}\)).

These calculations were carried out also for reference-site samples. Table C.1 to C.6 in Appendix C show the calculations that were carried out to estimate \(^{137}\text{Cs}\) total inventories of reference sites and Table C.7 to C.17 those of the floodplain units.

The weighted average of the \(^{137}\text{Cs}\) total inventories of reference sites was used for the estimation of net sediment accumulation and sedimentation rates of each floodplain unit, as described in the next section. Table 7.11 below summarises these results, which give an indication of the spatial variability of excess of \(^{137}\text{Cs}\) among the different floodplain units, as shown in the 8th column. Overbank deposition amounts are determined from the excess inventory of \(^{137}\text{Cs}\). The abandoned channel Unit 3 from which Cores A, B and UU were
collected, together with the abandoned channel Unit 10 (Core 1F) (Figure 7.2 above), show the highest sediment accumulation. This high accumulation had been predicted from the GIS analysis that was carried out in order to identify the susceptibility to overbank inundation of the floodplain units (Chapter 6).
Table 7.11. Summary of the estimated reference inventories and floodplain-unit inventories of $^{137}$Cs, and associated uncertainties. Reported concentrations of $^{137}$Cs by ANSTO and the detailed calculations of each floodplain unit and reference site are shown on Table C.1 to C.15 in Appendix C.

<table>
<thead>
<tr>
<th>Core sample name</th>
<th>Sample type</th>
<th>Total $^{137}$Cs Inventory (Bq.kg$^{-2}$)</th>
<th>Total Uncertainty (Bq.kg$^{-2}$)</th>
<th>% of Uncertainty</th>
<th>Range; Total Inventory (Bq.kg$^{-2}$)</th>
<th>Total standard error</th>
<th>Excess of $^{137}$Cs due to deposition (Bq.kg$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS-1</td>
<td>Not combined</td>
<td>407</td>
<td>± 54</td>
<td>13</td>
<td>353 to 461</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RS-2</td>
<td>Not combined</td>
<td>326</td>
<td>± 53</td>
<td>16</td>
<td>273 to 379</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1+R2</td>
<td>combined</td>
<td>456</td>
<td>± 97</td>
<td>21</td>
<td>358 to 553</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R3+R4</td>
<td>combined</td>
<td>432</td>
<td>± 69</td>
<td>16</td>
<td>363 to 502</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R5+R6+R7</td>
<td>combined</td>
<td>477</td>
<td>± 43</td>
<td>9</td>
<td>434 to 520</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R8+R9</td>
<td>combined</td>
<td>380</td>
<td>± 127</td>
<td>33</td>
<td>254 to 507</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weighted average of reference inventories</td>
<td></td>
<td>418</td>
<td></td>
<td></td>
<td>22</td>
<td>NA</td>
<td>202</td>
</tr>
<tr>
<td>Core sample name</td>
<td>Sample type</td>
<td>Total $^{137}$Cs Inventory (Bq.kg$^{-2}$)</td>
<td>Total Uncertainty (Bq.kg$^{-2}$)</td>
<td>% of Uncertainty</td>
<td>Range; Total Inventory (Bq.kg$^{-2}$)</td>
<td>Total standard error</td>
<td>Excess of $^{137}$Cs due to deposition (Bq.kg$^{-2}$)</td>
</tr>
<tr>
<td>-----------------</td>
<td>-------------</td>
<td>------------------------------------------</td>
<td>---------------------------------</td>
<td>-----------------</td>
<td>-------------------------------------</td>
<td>---------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>FLOODPLAIN UNITS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1L.1G.1I</td>
<td>Combined</td>
<td>593</td>
<td>± 50</td>
<td>11</td>
<td>543 to 643</td>
<td>175</td>
<td></td>
</tr>
<tr>
<td>1D.1Dbis.1E</td>
<td>Combined</td>
<td>448</td>
<td>± 142</td>
<td>32</td>
<td>306 to 590</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>1A.1B.1C</td>
<td>Combined</td>
<td>577</td>
<td>± 114</td>
<td>20</td>
<td>463 to 691</td>
<td>159</td>
<td></td>
</tr>
<tr>
<td>2D.2E.2F</td>
<td>Combined</td>
<td>249</td>
<td>± 60</td>
<td>24</td>
<td>189 to 308</td>
<td>-169 (suggests erosion)</td>
<td></td>
</tr>
<tr>
<td>N.J.Q</td>
<td>Combined</td>
<td>545</td>
<td>± 47</td>
<td>9</td>
<td>498 to 592</td>
<td>127</td>
<td></td>
</tr>
<tr>
<td>QQ.BB.AA</td>
<td>Combined</td>
<td>421</td>
<td>± 35</td>
<td>8</td>
<td>386 to 457</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>FF.GG.HH</td>
<td>Combined</td>
<td>488</td>
<td>± 59</td>
<td>12</td>
<td>429 to 548</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>CC.DD.EE</td>
<td>Combined</td>
<td>445</td>
<td>± 43</td>
<td>10</td>
<td>402 to 489</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>K.L.M</td>
<td>Combined</td>
<td>326</td>
<td>± 64</td>
<td>20</td>
<td>262 to 390</td>
<td>-92 (suggests erosion)</td>
<td></td>
</tr>
<tr>
<td>F.G</td>
<td>Combined</td>
<td>465</td>
<td>± 54</td>
<td>54</td>
<td>410 to 519</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>A.B.UU</td>
<td>Combined</td>
<td>1,172</td>
<td>± 114</td>
<td>10</td>
<td>1,059 to 1,286</td>
<td>754</td>
<td></td>
</tr>
<tr>
<td>D.TT.E</td>
<td>Combined</td>
<td>620</td>
<td>± 87</td>
<td>14</td>
<td>533 to 707</td>
<td>202</td>
<td></td>
</tr>
<tr>
<td>1F.</td>
<td>Not combined</td>
<td>2,348</td>
<td>± 202</td>
<td>9</td>
<td>2,145 to 2,550</td>
<td>1,930</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Not combined</td>
<td>1,410</td>
<td>± 71</td>
<td>5</td>
<td>1,339 to 1,481</td>
<td>992</td>
<td></td>
</tr>
</tbody>
</table>
Given its half life, the concentration $^{137}$Cs is expected to decay with depth but less sharply than that of $^{210}$Pb$_{(ex)}$. Additional decreases may occur as a result of other factors, which can be associated with the effects of biological activity. Because of this, detected concentrations of $^{137}$Cs in the sediment profile can be attenuated due to downward migration of this isotope. Therefore, I estimated a concentration of $^{137}$Cs that could be considered plausible for undisturbed deposited sediment. This value was obtained from averaging those values for which high concentrations of $^{137}$Cs were detected, which mostly correspond to the shallower intervals. The values used for this step are displayed in Table 7.12 below and the estimated concentration, i.e. 4.6 Bq.kg$^{-1}$, was used in the calculation of net deposition and deposition rates.
Table 7.12. Calculation of Cs\textsuperscript{137} concentration; assumed in undisturbed deposited sediment

<table>
<thead>
<tr>
<th>Core sample interval (cm)</th>
<th>Detected concentration of Cs\textsuperscript{137} (first intervals)\textsuperscript{*} (Bq.kg\textsuperscript{-1})</th>
<th>Average of Cs\textsuperscript{137} concentration (Bq.kg\textsuperscript{-1})</th>
<th>Standard error (of estimated Cs\textsuperscript{137} concentration) (Bq.kg\textsuperscript{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.B.UU (2-5)</td>
<td>3.5</td>
<td>4.1</td>
<td>0.4</td>
</tr>
<tr>
<td>A.B.UU (5-10)</td>
<td>4.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A.B.UU (10-15)</td>
<td>3.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC.DD.EE (0-5)</td>
<td>4.1</td>
<td>4.1</td>
<td>Since only one value was used, the standard error is 0</td>
</tr>
<tr>
<td>D.TT.E (0-5)</td>
<td>5.6</td>
<td>5.6</td>
<td>0</td>
</tr>
<tr>
<td>F.G (0-5)</td>
<td>4.1</td>
<td>4.1</td>
<td>0</td>
</tr>
<tr>
<td>FF.GG.HH (0-5)</td>
<td>4.7</td>
<td>4.7</td>
<td>0</td>
</tr>
<tr>
<td>K.L.M (2-5)</td>
<td>3.5</td>
<td>3.5</td>
<td>0</td>
</tr>
<tr>
<td>QQ.BB.AA (0-5)</td>
<td>4.4</td>
<td>4.4</td>
<td>0</td>
</tr>
<tr>
<td>N.J.Q (0-5)</td>
<td>5.6</td>
<td>5.6</td>
<td>0</td>
</tr>
<tr>
<td>1A.1B.1C (0-5)</td>
<td>3.4</td>
<td>3.4</td>
<td>0</td>
</tr>
<tr>
<td>1D.1Dbis.1E (0-5)</td>
<td>5.0</td>
<td>5.0</td>
<td>0</td>
</tr>
<tr>
<td>2D.2E.2F (0-5)</td>
<td>4.0</td>
<td>4.0</td>
<td>0</td>
</tr>
<tr>
<td>1L.1G.1I (0-5)</td>
<td>5.6</td>
<td>4.7</td>
<td>0.9</td>
</tr>
</tbody>
</table>

\textsuperscript{*}These taken from values reported by ANSTO, which can be found on Table C.7 to Table C.17 in Appendix C.
<table>
<thead>
<tr>
<th>Core sample interval (cm)</th>
<th>Detected concentration of $^{137}$Cs (first intervals)* (Bq.kg$^{-1}$)</th>
<th>Average of $^{137}$Cs concentration (Bq.kg$^{-1}$)</th>
<th>Standard error (of estimated $^{137}$Cs concentration) (Bq.kg$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1F (0-6)</td>
<td>6.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1F (6-12)</td>
<td>4.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1F (12-18)</td>
<td>6.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1F (18-24)</td>
<td>8.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1F (24-30)</td>
<td>4.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A (0-6)</td>
<td>4.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A (6-12)</td>
<td>6.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A (12-18)</td>
<td>5.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A (18-24)</td>
<td>4.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A (24-30)</td>
<td>3.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average from values above of $^{137}$Cs concentration (of undisturbed, deposited sediment)</td>
<td>4.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* These taken from values reported by ANSTO, which can be found on Table C7 to Table C17 in Appendix C.
7.1.3.7 Reference inventories

The calculations that were carried out in order to estimate the corresponding total inventories of $^{137}$Cs for reference sites are shown in Tables C.1 to C.6 in Appendix C. As reported in the literature, it is not surprising to find some variability among the calculated reference inventories.

The values obtained of each reference site are summarised in Table 7.13 below, which range from 326 Bq.m$^{-2}$ (that of reference site RS-2) to 478 Bq.m$^{-2}$ (that of reference site R5.R6.R7). The weighted average of the six reference inventories is 418 Bq.m$^{-2}$ with an associated uncertainty of ±22 Bq.m$^{-2}$. This weighted average is therefore considered to be the reference value for the locality of this study and is further used to calculate sediment deposition amounts (Table 7.14). As previously mentioned in the beginning of this chapter, the causes of the variability among reference inventories include differences in vegetation type and density, rainfall variability around the locality as well as different content of fine sediment in the sediment profile.

Even though four cores were collected from the Cathkin Cemetery, only cores RS-1 and RS-2 were used for further analysis as it had initially not been established that combining samples of the same site and depth intervals was a reasonable approach to take and their uncombined samples of RS-1 and RS-2 had already been sent for gamma analysis when it was decided that this approach was adequate. Therefore, core samples
taken from the rest of the reference sites were combined, providing the opportunity of including more reference and coring sites than if this approach had not been taken.

Established in 1872 as one of the first cemeteries in the area, the Cathkin Cemetery is located along very gentle slopes with a mix of grasses and a few trees (Figure 7.10 below). People who have lived nearby for several decades were interviewed and confirmed that, apart from the graveyard, this place has not been modified over the last ~60 years and earlier (Sharwood J and Ridds R 2008, pers. comm., 18 Nov). Therefore, it can be considered that soil redistribution (erosion or deposition) is unlikely to affect the site.

Similar characteristics were found at the other reference sites. Cores from the reference site R8.R9 were also collected from a cemetery. The Old Yea Cemetery has slightly more pronounced slopes but very similar distribution and type of vegetation (Figure 7.11 below).

Cores from the reference site R5.R6.R7 were collected from the floodplain but along a grassland area that was confirmed by the landowner not to have been affected by floods over the last 60 years. The landowner stated he had lived in the same property his entire life (75 years) (Gilmore K 2009, pers. comm., 7 May). Table 7.13 gives details of the location of each reference site.
Figure 7.10. Cathkin Cemetery, showing vegetation and gentle slopes.

Figure 7.11. The Old Yea Cemetery
Table 7.13. Location of reference sites and corresponding total $^{137}$Cs reference inventories.

<table>
<thead>
<tr>
<th>Reference Site</th>
<th>Location</th>
<th>$^{137}$Cs Total Inventories (Bq.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS-1</td>
<td>Cathkin Cemetery</td>
<td>407.3</td>
</tr>
<tr>
<td>RS-2</td>
<td>Cathkin Cemetery</td>
<td>326.1</td>
</tr>
<tr>
<td>R1.R2</td>
<td>Near the Maybole Cottage, hill side; Alexandra</td>
<td>455.6</td>
</tr>
<tr>
<td>R3.R4</td>
<td>Near Alexandra</td>
<td>432.4</td>
</tr>
<tr>
<td>R5.R6.R7</td>
<td>From floodplain along unaffected area by floods</td>
<td>476.9</td>
</tr>
<tr>
<td>R8.R9</td>
<td>Old Yea Cemetery</td>
<td>380.2</td>
</tr>
<tr>
<td>Weighted average</td>
<td></td>
<td>418</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>(from Equation 7.6)</td>
<td>±22</td>
</tr>
</tbody>
</table>
Chappell et al. (2011) completed a preliminary baseline map of the $^{137}$Cs reference inventory for Australia, which includes several locations of Victoria. Their analysis incorporates data of $^{137}$Cs reference inventories from the 1990 national reconnaissance survey of soil erosion in Australia. A plot of reported $^{137}$Cs reference values and corresponding mean annual rainfall values (over the period of 1954-1990) shows that the variability of reference inventories can be of hundreds of Bq.m$^{-2}$ for approximately the same mean annual rainfall. As a result, different reference sites or localities with a particular mean annual rainfall may show a variety of reference values. In the case of localities with mean annual rainfall of ~750 mm (average of the locality of the present study Table 7.2 above), only two reference values have been reported: these being of ~1,200 Bq.m$^{-2}$ and ~600 Bq.m$^{-2}$ (equivalent to 100 and 60 m Bq.cm$^{-2}$ respectively, as shown on Figure 7.14) and both being considerably larger than that obtained in the analysis developed here. Nevertheless, the variability found among the six reference site inventories here seems to be within reasonable limits (a range of 150 Bq.m$^{-2}$; Table 7.13 above) and indicates an acceptable degree of consistency.
Figure 7.13. Locations of sites where $^{137}$Cs reference inventory data are available (in mBq.cm$^{-2}$), source: Chappell et al (2011).
Figure 7.14. Relationship between long-term (1954-1990) mean annual rainfall and $^{137}$Cs reference values separated for each state and territory in Victoria. Source: Chappell et al. (2011).

### 7.1.3.8 Calculation of net sediment deposition and sedimentation rates

Net sediment accumulation ($Net\ Acc$) was obtained using the assumed concentration of $^{137}$Cs of undisturbed deposited sediment ($_{\text{assumed}}^{137}C_s^{\text{concentration}}$) estimated to be 4.6 Bq.m$^{-2}$ (Equation 7.7):
Equation 7.7 \[ Net \ Acc = \frac{(ex^{137}Cs \ due \ deposition)}{dry \ Bulk \ Density} \times \frac{1}{(\text{assumed}^{137}Cs_{\text{concentration}})} \]

The excess of $^{137}$Cs due to deposition ($ex^{137}Cs_{\text{due \ deposition}}$) is obtained by subtracting the average weighted reference inventory from the total inventory of each of the floodplain units. The estimated net deposition of the corresponding floodplain units obtained in this manner is shown in Table 7.14 below and belongs to the period of 1955 to 2008 and 1955 to 2009; this since some samples were collected in 2008 and others in 2009. Deposition rates were calculated from divining the corresponding net deposition by the number of years of the post-Eildon period (i.e. the period of $^{137}$Cs occurrence; since 1955).
Table 7.14. Estimated net deposition and sedimentation rates for the thirteen floodplain units considering a weighted reference inventory of 418 Bq.m\(^{-2}\) and an assumed \(^{137}\)Cs concentration in undisturbed deposited sediment of 4.6 Bq.m\(^{-2}\); (s) indicates that the corresponding floodplain units are swales and (a) that they are abandoned channels (including meander cutoffs). Floodplain units with a negative net sediment accumulation (in red) are eroded. Estimates highlighted in grey are for the period of 1955 to 2008 since the corresponding cores were collected in 2008. The rest were collected in 2009.

<table>
<thead>
<tr>
<th>Floodplain unit ID and corresponding coring sites</th>
<th>Total Inventory (Bq.m(^{-2}))</th>
<th>(^{137})Cs due to deposition (Bq.m(^{-2}))</th>
<th>Uncertainty (Bq.m(^{-2}))</th>
<th>Dry bulk density (Kg.m(^{-3}))</th>
<th>Net Accumulation * over 53 yr or ** over 54 yr (mm)</th>
<th>Uncertainty (mm)</th>
<th>Dep. Rate (mm.yr(^{-1}))</th>
<th>Uncertainty (mm.yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 1 D.TT.E**(s)</td>
<td>620</td>
<td>202</td>
<td>90</td>
<td>1,150</td>
<td>38</td>
<td>_17</td>
<td>0.7</td>
<td>_0.3</td>
</tr>
<tr>
<td>Unit 2 K.L.M** (a)</td>
<td>326</td>
<td>-92</td>
<td>68</td>
<td>1,250</td>
<td>-16</td>
<td>_12</td>
<td>-0.3</td>
<td>_0.2</td>
</tr>
<tr>
<td>Unit 3 A.B.UU** (a)</td>
<td>1,172</td>
<td>754</td>
<td>116</td>
<td>880</td>
<td>186</td>
<td>_33</td>
<td>3.5</td>
<td>_0.6</td>
</tr>
<tr>
<td>Unit 3 A **(a)</td>
<td>1,410</td>
<td>992</td>
<td>74</td>
<td>1,020</td>
<td>211</td>
<td>_28</td>
<td>3.9</td>
<td>_0.5</td>
</tr>
<tr>
<td>Unit 4 F.G **(a)</td>
<td>465</td>
<td>159</td>
<td>22</td>
<td>1,110</td>
<td>31</td>
<td>_0</td>
<td>0.6</td>
<td>_0.1</td>
</tr>
<tr>
<td>Unit 5 CC.DD.EE**(s)</td>
<td>446</td>
<td>27</td>
<td>48</td>
<td>1,210</td>
<td>5</td>
<td>_9</td>
<td>0.1</td>
<td>_0.2</td>
</tr>
<tr>
<td>Unit 6 FF.GG.HH (a)**</td>
<td>488</td>
<td>70</td>
<td>63</td>
<td>1,070</td>
<td>14</td>
<td>_13</td>
<td>0.3</td>
<td>_0.2</td>
</tr>
<tr>
<td>Floodplain unit ID and corresponding coring sites</td>
<td>Total Inventory (Bq.m⁻²)</td>
<td>ε¹³⁷Cs due to deposition (Bq.m⁻²)</td>
<td>Uncertainty (Bq.m⁻²)</td>
<td>Dry bulk density (Kg.m⁻³)</td>
<td>Net Accumulation • over 53 yr or ** over 54 yr (mm)</td>
<td>Uncertainty (mm)</td>
<td>Dep. Rate (mm.yr⁻¹)</td>
<td>Uncertainty (mm.yr⁻¹)</td>
</tr>
<tr>
<td>-------------------------------------------------</td>
<td>--------------------------</td>
<td>----------------------------------</td>
<td>----------------------</td>
<td>--------------------------</td>
<td>-----------------------------------------------</td>
<td>----------------</td>
<td>------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>Unit 7 QQ.BB.AA**(s)</td>
<td>421</td>
<td>3</td>
<td>41</td>
<td>1,280</td>
<td>1</td>
<td>± 7</td>
<td>0.0</td>
<td>± 0.1</td>
</tr>
<tr>
<td>Unit 8 N.J.Q*(s)</td>
<td>545</td>
<td>127</td>
<td>52</td>
<td>1,100</td>
<td>25</td>
<td>± 10</td>
<td>0.5</td>
<td>± 0.2</td>
</tr>
<tr>
<td>Unit 9 2D.2E.2F*(s)</td>
<td>249</td>
<td>-169</td>
<td>64</td>
<td>1,210</td>
<td>-30</td>
<td>± 11</td>
<td>-0.6</td>
<td>± 0.2</td>
</tr>
<tr>
<td>Unit 10 1F*(a)</td>
<td>2,348</td>
<td>1,930</td>
<td>203</td>
<td>1,160</td>
<td>362</td>
<td>± 61</td>
<td>6.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Unit 11 1A.1B.1C*(s)</td>
<td>577</td>
<td>159</td>
<td>116</td>
<td>1,050</td>
<td>33</td>
<td>± 24</td>
<td>0.6</td>
<td>± 0.4</td>
</tr>
<tr>
<td>Unit 12 1D.1DBis.1E*(a)</td>
<td>448</td>
<td>30</td>
<td>144</td>
<td>1,070</td>
<td>6</td>
<td>± 29</td>
<td>0.1</td>
<td>± 0.5</td>
</tr>
<tr>
<td>Unit 13 1L.1G.1I*(a)</td>
<td>593</td>
<td>175</td>
<td>50</td>
<td>1,160</td>
<td>33</td>
<td>± 11</td>
<td>0.6</td>
<td>± 0.2</td>
</tr>
</tbody>
</table>
7.1.4 Discussion

As discussed in this chapter, the approach used for core collection along the selected floodplain units, as well as that adopted for sediment sampling for radionuclide analysis, was adequate and allowed the incorporation of a larger number of cores and floodplain units. This, in turn, facilitated the investigation of spatial patterns of overbank deposition since the collection of sediment cores from more than one sampling point along each of the thirteen selected floodplain units made possible to estimate the average overbank deposition of each unit.

However, these estimations could only be obtained using the detected concentrations of $^{137}$Cs, and thus, for the post-Eildon period. As discussed earlier in this chapter, sediment accumulation before that period could not be established from the detection of $^{210}$Pb\textsubscript{(ex)} in floodplain core samples. Even though cases have been reported in the literature in which deposition rates are successfully estimated using this radionuclide (Siggers et al. 1999; Piégay et al. 2008), similar problems to those reported here have also been observed by others, such as by MacGregor et al. (2005). Similar to what is observed here, they found fluctuating concentrations of $^{210}$Pb\textsubscript{(ex)} with no uniform depth decay in the $^{210}$Pb\textsubscript{(ex)} inventory.

Results in Table 7.14 suggest that two floodplain units, i.e. Units 2 and 9, have undergone erosive processes because their total inventories are smaller than the
reference inventory estimated for the locality (i.e. the weighted average reference inventory). Even though this reference value (418 Bq.m\(^{-2}\)) seems to be considerably smaller that those reported in former studies for Victorian sites with similar mean annual rainfall (Chappell et al. 2011) (refer to those circled on Figure 7.14 above, which are \(\sim 1,200\) and 600 Bq.m\(^{-2}\)), the value obtained here should not be considered erroneous. Firstly, since it has been reported that the spatial variability of reference inventories is often in the range of hundreds of Bq.m\(^{-2}\) (as it can also be seen on Figure 7.14); secondly, since rainfall variability is not the only factor that affects the variability of true reference inventories (these have been mentioned in this chapter); and thirdly since the estimated reference inventories of each of the 6 reference sites are close in value, which make the estimations consistent. Therefore, the value obtained here indeed indicates the need to incorporate more \(^{137}\)Cs reference inventory values in the baseline map of the \(^{137}\)Cs reference inventory for Australia, as stated by Chappell et al. (2011).

Thus, the values of overbank net deposition obtained for each floodplain unit seem adequate and were calculated using the estimated reference inventory obtained from the six reference sites. Results suggest that two floodplain units, K.L.M and 2D.2E.2F, have been eroded over the last 54 and 53 years.

Results also show that the average net accumulation over the same period (i.e. post-Eildon period) along 11 of the 13 units ranges from 1 millimetre (CC.DD.EE floodplain swales) to 362 millimetres (abandoned channel 1F), which reflects the spatial
variability of overbank deposition among these units (Table 7.14). It was also found that in the cases where overbank deposition was identified (i.e. 11 floodplain units out of 13) $^{137}$Cs concentrations were found within the first 30 centimetres of depth. The only two floodplain units for which $^{137}$Cs concentrations were found below this depth were unit A.B.UU, (where $^{137}$Cs was found in the depth-interval sample of 36 to 42 centimetres) and unit 1F (where $^{137}$Cs was found in the depth-interval sample of 30 to 36 centimetres). Therefore, these two abandoned channels show the highest overbank sediment accumulation, which in fact, is consistent with the analysis developed in Chapter 6 where both, the hydraulic connectivity and overbank flooding thresholds of the floodplain units, were established (Table 7.15).

However, for the case of floodplain unit 1D.1Dbis.1E, for which sediment accumulation was expected to be high (given the established hydraulic connectivity and flooding threshold), contrasts with the former as overbank net deposition was found only to be of 6 millimetres over the whole post-Eildon period (Table 7.15 below).

Considering the same analysis (that of Chapter 6), it could have been expected that unit 2D.2E.2F would have shown one of the highest levels of net sediment accumulation (previously established to have a moderate hydraulic connectivity or an overbank flooding threshold of around 20,000 ML/day), as well as for floodplain K.L.M, but instead, the opposite was found: sediment erosion. However, sediment erosion
along these two units might be linked to occurrence of high flow velocities or a reduced effectiveness of the vegetation cover to protect the floodplain floor.

Results obtained in this chapter show that the best correspondence between expected values of sediment accumulation and the analysis developed in Chapter 6 exists for those units whose hydraulic connectivity was found to be moderate and to have medium floodplain thresholds (see Table 7.15 below). This suggests that more than one factor may be influencing the spatial distribution of overbank sediment accumulation, apart from the hydraulic connectivity that the floodplain and the modern river have.

The patterns of overbank deposition shown in Table 7.14 above support the idea that the variability of overbank sedimentation, regardless of the floodplain unit type (whether abandoned channels or floodplain swales), is the result of more complex interactions that exist among key factors that influence its spatial distribution (mentioned previously in former chapters). It is known that these interactions are, at the same time, the result of hydraulic interactions that are influenced by floodplain topography. Therefore, this also shows the need for testing one of the hypotheses of this research. In the next chapter, a sensitivity analysis is developed to test the hypothesis which establishes that the key factors, known for determining the spatial distribution of overbank deposition, have different levels of influence. Hence, the sensitivity analysis
that is discussed in the next chapter is designed to provide answers in relation to their influence on this geomorphic process.
Table 7.15. Comparison between estimated net sediment accumulation with the previously established hydraulic connectivity and floodplain thresholds of each floodplain unit (the last two from the analysis described in Chapter 6). (a) refers to abandoned channels and (s) to floodplain swales. Floodplain units with negative net accumulation (in red) are eroded.

<table>
<thead>
<tr>
<th>Floodplain unit ID, and correspondent cores</th>
<th>Net Accumulation * over 53 yr; ** over 54 yr (mm)</th>
<th>Hydraulic connectivity with the modern channel (chapter 6) established from GIS analysis</th>
<th>Overbank flooding threshold established from the hydraulic model (chapter 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 1 D.TT.E**(s)</td>
<td>38</td>
<td>Moderate</td>
<td>40,000</td>
</tr>
<tr>
<td>Unit 2 K.L.M ** (a)</td>
<td>-16</td>
<td>Low</td>
<td>50,000</td>
</tr>
<tr>
<td>Unit 3 A.B.UU ** (a)</td>
<td>186</td>
<td>High</td>
<td>30,000</td>
</tr>
<tr>
<td>Unit 3 A ** (a)</td>
<td>211</td>
<td>Same as A.B.UU</td>
<td>Same as A.B.UU</td>
</tr>
<tr>
<td>Unit 4 F.G ** (a)</td>
<td>31</td>
<td>Moderate</td>
<td>40,000</td>
</tr>
<tr>
<td>Unit 5 CC.DD.EE **(s)</td>
<td>5</td>
<td>Low</td>
<td>40,000</td>
</tr>
<tr>
<td>Unit 6 FF.GG.HH **(a)</td>
<td>14</td>
<td>Moderate</td>
<td>40,000</td>
</tr>
<tr>
<td>Unit 7 QQ.BB.AA **(s)</td>
<td>1</td>
<td>Low</td>
<td>Uncertain could be between 40,000 to 60,000)</td>
</tr>
<tr>
<td>Floodplain unit ID, and correspondent cores</td>
<td>Net Accumulation * over 53 yr; ** over 54 yr (mm)</td>
<td>Hydraulic connectivity with the modern channel (chapter 6) established from GIS analysis</td>
<td>Overbank flooding threshold established from the hydraulic model (chapter 6)</td>
</tr>
<tr>
<td>-------------------------------------------</td>
<td>-----------------------------------------------</td>
<td>--------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Unit 8 N.J.Q *(s)</td>
<td>25</td>
<td>Moderate</td>
<td>30,000</td>
</tr>
<tr>
<td>Unit 9 2D.2E.2F *(s)</td>
<td>-30</td>
<td>Moderate</td>
<td>20,000</td>
</tr>
<tr>
<td>Unit 10 1F *(a)</td>
<td>362</td>
<td>Moderate to moderate-high</td>
<td>30,000</td>
</tr>
<tr>
<td>Unit 11 1A.1B.1C *(s)</td>
<td>33</td>
<td>Low to low-moderate</td>
<td>60,000 (floods need to be big to activate this unit)</td>
</tr>
<tr>
<td>Unit 12 1D.1DBis.1E *(a)</td>
<td>6</td>
<td>Moderate to moderate-high</td>
<td>between 20,000 and 30,000</td>
</tr>
<tr>
<td>Unit 13 1L.1G.1I *(a)</td>
<td>33</td>
<td>Low-moderate to moderate</td>
<td>between 20,000 and 30,000</td>
</tr>
</tbody>
</table>
8 Chapter Eight

8.1 Key factors driving overbank sediment deposition

8.1.1 Introduction

As previously discussed in Chapters 2 and 4, a number of key factors influence the spatial distribution of overbank deposition; these are flood duration, pond depth, travel time, flow depth, suspended sediment concentration, settling velocity, floodplain-floor shear stress and critical shear stress. In this chapter a full discussion is developed concerning the way a range, a representative value and increments within that range were estimated for each key factor for subsequent use in the sensitivity analysis (Chapter 9). The later is designed to identify the variability of overbank deposition resulting from changes in the values assigned to the key factors and, in that way, to determine the comparative influence of these key factors on the spatial variability of overbank deposition. Results of the sensitivity analysis are shown and
discussed in Chapter 9. The estimated values of each key factor (i.e. range, representative value and increments within the range) are summarised in Table 8.22 at the end of this chapter. The key factor values of the corresponding floodplain units obtained in this chapter are used to calculate modelled estimates (Chapter 9).

The analysis developed in this chapter considers the post-Eildon period only. Modelled estimates will be compared with measured estimates derived from $^{137}$Cs detection; both estimates represent overbank deposition over the pronounced regulated flow regime.

Measured estimates (Chapter 7) are summarised in Table 8.1, and are expressed as net accumulation, deposition rates and amounts to facilitate and illustrate the discussions that will be developed in this and the next two chapters.
Table 8.1. Summary of the estimated net accumulation at each floodplain unit, derived from $^{137}$Cs detection, as well as deposition rates and equivalent deposition amounts (refer to Chapter 7). Those marked in red indicate erosion.

<table>
<thead>
<tr>
<th>Floodplain unit ID</th>
<th>Floodplain unit name</th>
<th>Net sediment accumulation over the post-Eildon period (mm)</th>
<th>Deposition rate (mm.yr$^{-1}$)</th>
<th>Deposition amount (kg.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DOWNSTREAM SEGMENT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit 1</td>
<td>D.TT.E</td>
<td>38</td>
<td>0.7</td>
<td>45</td>
</tr>
<tr>
<td>Unit 2</td>
<td>K.L.M</td>
<td>-16</td>
<td>-0.3</td>
<td>-19</td>
</tr>
<tr>
<td>Unit 3</td>
<td>A.B.UU</td>
<td>186</td>
<td>3.5</td>
<td>218</td>
</tr>
<tr>
<td>Unit 4</td>
<td>F.G</td>
<td>31</td>
<td>0.6</td>
<td>36</td>
</tr>
<tr>
<td>Unit 5</td>
<td>CC.DD.EE</td>
<td>5</td>
<td>0.1</td>
<td>6</td>
</tr>
<tr>
<td>Unit 6</td>
<td>FF.GG.HH</td>
<td>14</td>
<td>0.3</td>
<td>17</td>
</tr>
<tr>
<td>Unit 7</td>
<td>QQ.BB.AA</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Unit 8</td>
<td>N.J.Q</td>
<td>25</td>
<td>0.5</td>
<td>29</td>
</tr>
<tr>
<td><strong>UPSTREAM SEGMENT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit 9</td>
<td>2D.2E.2F</td>
<td>-30</td>
<td>-0.6</td>
<td>-36</td>
</tr>
<tr>
<td>Unit 10</td>
<td>1F</td>
<td>362</td>
<td>6.7</td>
<td>423</td>
</tr>
<tr>
<td>Unit 11</td>
<td>1A.1B.1C</td>
<td>33</td>
<td>0.6</td>
<td>38</td>
</tr>
<tr>
<td>Unit 12</td>
<td>1D.1DBis. 1E</td>
<td>6</td>
<td>0.1</td>
<td>7</td>
</tr>
<tr>
<td>Unit 13</td>
<td>1L.1G.1I</td>
<td>33</td>
<td>0.6</td>
<td>28</td>
</tr>
</tbody>
</table>
8.1.2 Flood duration. Calculation of the total number of flooding days over the post-Eildon period

This section describes the way in which the total number of overbank inundation days of each unit (flood duration over the post-Eildon period) was defined. To do so, the selected floodplain units were grouped into those located along the upstream reach and those along the downstream reach (refer to Figure 7.2; Table 8.1 and Table 8.2). The intention of the grouping is to divide the units into those closer and further to Lake Eildon as well as to group them in relation to their tributary inflows. Five of the units are in the upstream reach and eight in the downstream reach.

Flood duration was defined for each floodplain unit with reference to its corresponding flooding threshold as established in Chapter 6, providing the total number of days that each unit has been flooded over the post-Eildon period (i.e., since 1955). Gauging stations on the Goulburn River at Eildon, Acheron River at Taggerty and Home Creek at Yarck were used for this purpose. Depending on the location of the floodplain unit that was being analysed, the records of one, two or the three gauging stations were included (summed) in order to calculate the total discharge (in ML.day⁻¹) corresponding to the river reach of that unit. Once the total discharge was calculated, this was then ordered by magnitude in descending order. Next, the flooding threshold of each unit was used to calculate the total number of overbank flooding days by counting the number of days that the corresponding flooding threshold of each unit
has been exceeded over the post-Eildon period. Results obtained in this way are shown in Table 8.2 below. Therefore, only the average daily records of the gauging station of Goulburn River at Eildon were used for units located along reach 1 ((a) in Table 8.2). Records of the previous station and those of the Acheron River at Taggerty ((b) on Table 8.2) were added to calculate the flooding days of unit 2D.2E.2F and, finally, daily records of the three stations were added to those of the floodplain units located along the downstream reach ((c) Table 8.2). The range of flooding days obtained in this way extends from 2 to 155 days, with an average of 37 days. In order to consider the hypothetical case of floodplain units that were inundated more days over the period than those selected for this research, I have increased this range to 200 days for the sensitivity analysis.
Table 8.2. Total flooding days calculated for each floodplain unit. The upstream reach includes reaches 1 and 2 and the downstream reach includes reaches 3 and 4.

<table>
<thead>
<tr>
<th>Floodplain unit cores (and Unit ID)</th>
<th>Location</th>
<th>Gauging records used</th>
<th>Unit Threshold: Derived from flow heights and extents of the Hydraulic Model (ML/day)</th>
<th>Total No. of flooding days along unit over the post-Eildon period (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1F (Unit 10)</td>
<td></td>
<td>(a)</td>
<td>Between 20,000 and 30,000; (assumed 20,000)</td>
<td>90</td>
</tr>
<tr>
<td>1A.1B.1C (Unit 11)</td>
<td></td>
<td>(a)</td>
<td>40,000</td>
<td>8</td>
</tr>
<tr>
<td>1D.1Dbis.1C (Unit 12)</td>
<td></td>
<td>(a)</td>
<td>Between 20,000 and 30,000 (assumed 30,000)</td>
<td>25</td>
</tr>
<tr>
<td>1L.1G.1I (Unit 13)</td>
<td></td>
<td>(a)</td>
<td>Between 20,000 and 30,000 (assumed 30,000)</td>
<td>25</td>
</tr>
<tr>
<td>2D.2E.2F (Unit 9)</td>
<td></td>
<td>(b)</td>
<td>20,000</td>
<td>155</td>
</tr>
<tr>
<td>N.J.Q (Unit 8)</td>
<td></td>
<td>(c)</td>
<td>30,000</td>
<td>41</td>
</tr>
<tr>
<td>QQ.BB.AA (Unit 7)</td>
<td></td>
<td>(c)</td>
<td>Unclear; between 40,000 and 60,000. Assumed threshold: 50,000</td>
<td>2 (for a threshold of 50,000ML/day)</td>
</tr>
<tr>
<td>FF.GG.HH (Unit 6)</td>
<td></td>
<td>(c)</td>
<td>40,000</td>
<td>14</td>
</tr>
<tr>
<td>CC.DD.EE (Unit 5)</td>
<td></td>
<td>(c)</td>
<td>40,000</td>
<td>14</td>
</tr>
<tr>
<td>F.G (Unit 4)</td>
<td></td>
<td>(c)</td>
<td>40,000</td>
<td>14</td>
</tr>
<tr>
<td>A.B.UU (Unit 3)</td>
<td></td>
<td>(c)</td>
<td>30,000</td>
<td>41</td>
</tr>
<tr>
<td>K.L.M (Unit 2)</td>
<td></td>
<td>(c)</td>
<td>30,000</td>
<td>41</td>
</tr>
</tbody>
</table>

Upstream reach: (includes reaches 1 and 2)

Downstream reach: (includes reaches 3 and 4)
As discussed in Chapters 2 and 4, overbank deposition occurs not only during the rising limb of the flood but also by sediment settling in post-peak ponds formed during the flood recession phase. These ponds form once an inundated area of the floodplain continues to be flooded when that area is isolated from the overbank flow after the flood peak.

The analysis developed in this chapter section was carried out to calculate the maximum size of these ponds. The first step was to generate synthetic flat water surfaces along the floodplain DEM in a GIS. Since it is assumed here that there is an absence of water movement, the synthetic flood water surfaces that were generated in the GIS had no gradient. These surfaces were subtracted one by one to the LIDAR DEM until I could identify a topographic location, here called the disconnection point of
each unit, at which the corresponding floodplain units were hydraulically disconnected from the overbank flow during the flood recession phase (Figure 8.1 and figures in Appendix D).

I established the maximum size of the ponds of each floodplain unit by using the flood surface for which I identified that the disconnection of the unit from the main flow occurred. Then, I subtracted the floodplain elevations of the LIDAR-DEM to the flood surfaces. The total volume of each pond was calculated by averaging the water depth of each raster cell showing inundation (ponds) and then multiplying the dimension of the raster cell. Ordered by size, the dimensions of the identified ponds are shown on Table 8.3. I defined whether deposition in post-peak ponds is relevant for each floodplain unit by calculating the total volume of these ponds in each unit (i.e. the total pond capacity of the units) and I also identified whether the cores were collected from a pond area.

Thus, Figure 8.1 shows a pond that can form along Unit 10 (1F), which expands almost along the entire unit and is the fourth in capacity from those of the other units (in relation to total pond volume along each unit). Flood water and maximum pond size are in light blue, floodplain swales are in orange stripes and the meander cutoffs in dotted blue. Coring sites are also shown by yellow crosses together with the Goulburn River channel by the dark blue line. White patches are areas of no data on the LIDAR DEM. Ponds of the other floodplain units are Appendix D.

From this analysis I found that post-peak ponds may form along more than half of the floodplain units selected (highlighted on Table 8.3 below), but also that post-peak
pond formation is irrelevant for some of them (the last 4 units in Table 8.3). Sediment deposition along post-peak ponds is here considered relevant for the corresponding units if the cores collected were taken from the pond area. This could not be noticed during the fieldwork program as the pond areas were dry.

It was also found that pond depth ranges from 0.12 (Unit 5) to 1.47 metres. (Unit 4) with an average of 0.8 metres. Bearing in mind that post-peak ponds of bigger depth (and also smaller) to the ones found here could exist along the floodplain, I decided to chose a range of 0 to 2 meters for this key factor (pond depth) for the sensitivity analysis (as shown on Table 8.22 at the end of this chapter).
Table 8.3. Post-peak pond depth and pond capacity (measured by maximum volume), this last in descending order. Highlighted are the units with maximum pond capacity. In most cases, cores were collected from pond areas. The unit numbers correspond to those of Table 8.1 above, which are identification numbers.

<table>
<thead>
<tr>
<th>Floodplain unit cores (and Unit ID)</th>
<th>Pond capacity (total maximum volume of pond water along unit) (m$^3$)</th>
<th>Total maximum area of pond water along unit (m$^2$)</th>
<th>Overall pond depth $d_p$ (m)</th>
<th>Relevance of pond deposition along the floodplain units in relation to pond size</th>
<th>Whether pond deposition is a relevant factor for the corresponding floodplain units. If coring sites were taken from a pond area, then pond deposition will be captured</th>
</tr>
</thead>
<tbody>
<tr>
<td>F.G. (Unit 4)</td>
<td>59,570</td>
<td>40,582</td>
<td>1.47</td>
<td>Pond deposition can be relevant: a good portion of this unit is occupied by ponds. The main one is quite large</td>
<td>The two core sites are within potential pond area.</td>
</tr>
<tr>
<td>A.B.UU (Unit 3)</td>
<td>22,258</td>
<td>17,956</td>
<td>1.24</td>
<td>Pond deposition can be relevant: almost the entire unit is occupied by a pond</td>
<td>The three core sites are within potential pond area.</td>
</tr>
<tr>
<td>K.L.M (Unit 2)</td>
<td>7,394</td>
<td>15,646</td>
<td>0.47</td>
<td>Pond deposition can be relevant: quite a few ponds can form along this unit, which are of considerable size</td>
<td>The three core sites are within potential pond area.</td>
</tr>
<tr>
<td>1F (Unit 10)</td>
<td>6,215</td>
<td>5,134</td>
<td>1.21</td>
<td>Pond deposition can be relevant: almost the entire unit is occupied by the main pond</td>
<td>Core site 1F is within potential pond area.</td>
</tr>
<tr>
<td>Floodplain unit cores (and Unit ID)</td>
<td>Pond capacity (total maximum volume of pond water along unit) (m$^3$)</td>
<td>Total maximum area of pond water along unit (m$^2$)</td>
<td>Overall pond depth $d_p$ (m)</td>
<td>Relevance of pond deposition along the floodplain units in relation to pond size</td>
<td>Whether pond deposition is a relevant factor for the corresponding floodplain units. If coring sites were taken from a pond area, then pond deposition will be captured</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>-------------------------------------------------</td>
<td>--------------------------------------------</td>
<td>----------------</td>
<td>---------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>D.TT.E (Unit 1)</td>
<td>5,872</td>
<td>13,187</td>
<td>0.44</td>
<td>Pond deposition can be relevant: two large ponds can form along this unit</td>
<td>The three core sites are within potential pond area.</td>
</tr>
<tr>
<td>1L.1G.1I (13)</td>
<td>4,499</td>
<td>8,087</td>
<td>0.56</td>
<td>Pond deposition can be relevant: two good-size ponds can form.</td>
<td>Only one of the core sites is within pond area.</td>
</tr>
<tr>
<td>FF.GG.HH (6)</td>
<td>4,161</td>
<td>6,868</td>
<td>0.61</td>
<td>Pond deposition can be relevant: a good portion of this unit can be occupied by ponds</td>
<td>The three core sites are within potential pond area.</td>
</tr>
<tr>
<td>1D.1Dbis.1E (12)</td>
<td>2,490</td>
<td>4,517</td>
<td>0.55</td>
<td>Pond deposition can be relevant: more than half of this unit can be a pond.</td>
<td>The three core sites are within potential pond area.</td>
</tr>
<tr>
<td>QQ.BB.AA (7)</td>
<td>1,665</td>
<td>7,651</td>
<td>0.22</td>
<td>Pond deposition can be relevant: a few ponds can form along this unit; some of them are not so small</td>
<td>Two of the three core sites are within potential pond area.</td>
</tr>
<tr>
<td>Floodplain unit cores (and Unit ID)</td>
<td>Pond capacity (total maximum volume of pond water along unit) $\text{m}^3$</td>
<td>Total maximum area of pond water along unit $\text{m}^2$</td>
<td>Overall pond depth $d_p$ (m)</td>
<td>Relevance of pond deposition along the floodplain units in relation to pond size</td>
<td>Whether pond deposition is a relevant factor for the corresponding floodplain units. If coring sites were taken from a pond area, then pond deposition will be captured</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>-----------------------------------------------</td>
<td>-----------------------------------------------</td>
<td>---------------------------------</td>
<td>---------------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>2D.2E.2F (Unit 9 )</td>
<td>303</td>
<td>1,095</td>
<td>0.28</td>
<td>Not very relevant: just a few small ponds may form along this unit</td>
<td>Only one of the three core sites is within pond area.</td>
</tr>
<tr>
<td>N.J.Q (Unit 8 )</td>
<td>265</td>
<td>1,314</td>
<td>0.20</td>
<td>Not very relevant: just a few small ponds may form along this unit</td>
<td>Only one of the three core sites is within pond area.</td>
</tr>
<tr>
<td>1A.1B.1C (Unit 11 )</td>
<td>94</td>
<td>710</td>
<td>0.13</td>
<td>Not very relevant: practically just one small pond can form</td>
<td>Core sites are not within pond area.</td>
</tr>
<tr>
<td>CC.DD.EE (Unit 5 )</td>
<td>33</td>
<td>275</td>
<td>0.12</td>
<td>Too few and small the ponds that can form along this unit to be of relevance</td>
<td>Core sites are not within pond area.</td>
</tr>
</tbody>
</table>
8.1.4 Travel time and flow depth from channel to floodplain unit

The LIDAR DEM of the floodplain as well as the flow depth and velocity rasters provided by Water Technology (2009) as part of the hydraulic model were incorporated into a GIS. These rasters represent five (steady state) flood scenarios which are equivalent to 20 000, 30 000, 40 000, 50 000 and 60 000 ML.day$^{-1}$ at Eildon gauging station (Chapter 6).
In order to calculate travel times, I first identified the overbank flow path to each floodplain unit by analysing the flow depth and velocity rasters associated with the unit flooding thresholds in a GIS. The flow paths were delineated after identifying the shortest and fastest path to each floodplain unit. The next step was to extract the associated flow velocity values of each raster cell along the corresponding flow paths. I then calculated the time that it would take to move across the raster cell (5 meters) and along each flow path using the corresponding velocity value of the cells. The velocity values of the raster were extracted using the command ‘extract values to points’ in ArcGIS 9.2 for each cell. Travel times estimated in this manner were summed to finally estimate the total travel time from the river channel to the corresponding floodplain unit.

Travel times calculated in this manner are shown in Figure 8.2. Since I found that some velocity values were zero along the flow paths, zero velocity values were substituted by the average velocity obtained excluding these zero velocity values. This step was undertaken in order to obtain a more accurate estimation of travel times. Travel times in Table 8.4 shown as ‘approximated’ were obtained in this manner. Results show that travel time ranges from 4.3 minutes (Unit 5) to 13.7 hours (Unit 10), with an average of 4.6 hours. From these results, I decided to adopt a range of 3.3 minutes (or 200 seconds, as shown in Table 8.22) to 13.8 hours (50 000 seconds) and to use the same travel-time average for the sensitivity analysis (as shown in Table 8.4).

Similar to the estimation of total travel times, average flow depths were calculated using each of the traced flow paths and the corresponding rasters of flow depth (Table 8.4). I found that flow depth along the paths ranges from 0.7 (Units 10, 12 and 13) to 2.6 metres (Unit 8), with an average of 1.2 metres. Just as before, with the
idea of considering hypothetical average flow depths along other flow paths of other
units not included here that could be below and above the figures estimated, I decided
to adopt a range of 0.1 to 3.0 meters for the sensitivity analysis. The average flow
depth used in the sensitivity analysis was the same as the one estimated here (Table 8.22).

The identified flow paths of the floodplain units are shown in Appendix E. That
of Unit 10 (1F) is shown in Figure 8.2 below. In relation to the flow paths to Units 10,
11, 12 and 13, all located along the upstream reach, I found a peculiarity. Even though
these units are proximal to the river channel, I found that their corresponding river
spilling point (or flood commencing point) starts more than 7 kilometres upstream,
instead of from the river nearby (Figure 8.2 and Figures E.10 to E.12 in Appendix E).
Figure 8.2. Overbank flow paths from channel to Unit 10 (1F), shown in orange. The unit is shown in purple. The flow depth and velocity rasters used correspond to a peak discharge of 20,000 ML/day (the flooding threshold of this unit). Inundated areas are shown in blue.
Table 8.4. Calculated channel-to-unit flow velocities, distances and travel times. The corresponding unit numbers are in parenthesis.

<table>
<thead>
<tr>
<th>Unit name and flooding threshold (ML/day)</th>
<th>Distance from channel along path (m)</th>
<th>Average flow depth along path (m)</th>
<th>Average flow velocity along path (m/s)</th>
<th>Total travel time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Unit 1) D.TT.E (threshold: 40,000)</td>
<td>350</td>
<td>1.8</td>
<td>0.09</td>
<td>8,986 (equivalent to 2.5 hours)</td>
</tr>
<tr>
<td>(Unit 2) K.L.M (threshold: 30,000)</td>
<td>30</td>
<td>1.5</td>
<td>0.03</td>
<td>1,036 (equivalent to 17.3 minutes)</td>
</tr>
<tr>
<td>(3) A.B.UU (threshold: 30,000)</td>
<td>340</td>
<td>1.3</td>
<td>0.08</td>
<td>5,539 (equivalent to 1.5 hours)</td>
</tr>
<tr>
<td>(4) F.G (threshold: 40,000)</td>
<td>510</td>
<td>1.0</td>
<td>0.16</td>
<td>7,764 (equivalent to 2.2 hours)</td>
</tr>
<tr>
<td>(5) CC.DD.EE (threshold: 40,000)</td>
<td>125</td>
<td>0.9</td>
<td>0.49</td>
<td>261 (equivalent to 4.3 minutes)</td>
</tr>
<tr>
<td>(6) FF.GG.HH (threshold: 40,000)</td>
<td>265</td>
<td>1.2</td>
<td>0.11</td>
<td>3,936 (equivalent to 1.1 hours)</td>
</tr>
<tr>
<td>(7) QQ.BB.AA (threshold: 50,000)</td>
<td>105</td>
<td>1.3</td>
<td>0.12</td>
<td>1,255 (equivalent to 0.3 hours)</td>
</tr>
<tr>
<td>(8) N.J.Q (threshold: 30,000)</td>
<td>295</td>
<td>2.6</td>
<td>0.27</td>
<td>2,094 (equivalent to 0.6 hours)</td>
</tr>
<tr>
<td>Floodplain unit ID, cores and flooding threshold (ML/day)</td>
<td>Distance from channel along path (m)</td>
<td>Average flow depth along path (m)</td>
<td>Average flow velocity along path (m/s)</td>
<td>Total travel time (s)</td>
</tr>
<tr>
<td>----------------------------------------------------------</td>
<td>-------------------------------------</td>
<td>----------------------------------</td>
<td>-------------------------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>(Unit 9) 2D.2E.2F (threshold: 20,000)</td>
<td>1,305</td>
<td>0.9</td>
<td>0.10</td>
<td>34,025 (equivalent to 9.5 hours)</td>
</tr>
<tr>
<td>(Unit 10) 1F (threshold: 20,000)</td>
<td>3,655</td>
<td>0.7</td>
<td>0.13</td>
<td>49,384 (equivalent to 13.7 hours)</td>
</tr>
<tr>
<td>(Unit 11) 1A.1B.1C (threshold: 40,000)</td>
<td>3,685</td>
<td>0.9</td>
<td>0.24</td>
<td>21,712 (equivalent to 6 hours)</td>
</tr>
<tr>
<td>(Unit 12) 1D.1Dbis.1E (threshold: 30,000)</td>
<td>3,490</td>
<td>0.7</td>
<td>0.14</td>
<td>45,831 (equivalent to 12.7 hours)</td>
</tr>
<tr>
<td>(Unit 13) 1L.1G.1I (threshold: 30,000)</td>
<td>3,285</td>
<td>0.7</td>
<td>0.15</td>
<td>34,463 (equivalent to 9.6 hours)</td>
</tr>
<tr>
<td>Whole Average (including, KLM and 2D2E2F)</td>
<td>1,342</td>
<td>1.2</td>
<td>0.16</td>
<td>16,637 (equivalent to 4.6 hours)</td>
</tr>
</tbody>
</table>
8.1.5 Suspended sediment concentration

Suspended sediment concentration (SSC) is another key factor that influences overbank sediment deposition (Chapter 2). In order to determine a range and a fixed value of this key factor, I first gathered the available records of the post-Eildon period on SSC and turbidity. These, from two gauging stations where suspended sediment concentrations and turbidity are also monitored: the Goulburn River at Eildon, (which is in the floodplain section) and the Goulburn River at Trawool (located ~9 kilometres downstream of the floodplain section). These data were available from two agencies: Goulburn Valley Water and the Department of Sustainability and Environment through the Victorian Water Resources Data Warehouse (2011). I found, however, that the data collected by these agencies on SSC are limited in terms of frequency and limited to establish a relationship between suspended sediment concentration and turbidity for overbank flooding. Therefore, the representative value and range of this key factor had to be determined from previous investigations, as will be discussed further in this chapter.
8.1.5.1 Data of the Goulburn River gauging station at Eildon

At the gauging station at Eildon, data mostly have been collected monthly in the best cases, and, with one exception, all readings have been collected in the absence of overbank flooding. Overbank flooding at this station occurs when discharge is above 15,000 ML\(\text{day}^{-1}\). Because of this inadequate monitoring, the correlation between SSC and river discharge (Figure 8.5) is very poor.

Figure 8.3. Records on SSC (August 1990 to April 2011) of the Goulburn River at Eildon. Most records have been recorded at low flows. Bankfull at this station occurs at a discharge of 15,000 ML/day.
Figure 8.4. Records on turbidity of the Goulburn River at Eildon gauging station. Data are from January 1975 to March 2011. Note that records at high flows (close to bankfull or higher) have not been recorded. Bankfull at this station occurs at 15,000 ML/day. The higher values on turbidity shown on the graph correspond to very low discharges. However, low turbidity values occur for the whole spectrum of discharges at which the data have been collected.

Figure 8.5. Graph showing coincident records of Turbidity and SSC of the Goulburn River gauging station at Eildon. These are from August 1990. Since the records have only been collected at low flows no relationship can be established between SSC and Turbidity for overbank events.
8.1.5.2 Data on SSC and turbidity of the Goulburn River at Trawool gauging station

Similar to the data found of the previous gauging station, only monthly records on SSC have been collected at the Goulburn River at Trawool (from April 2005 to 2011), and these were not collected during overbank flooding, which at this station is above 20,000 Ml.day$^{-1}$ (Figure 8.6).

On the other hand, daily turbidity records are available from the Goulburn River at Trawool gauging station since October 2009 (see Figure 8.7). These records coincided with three recent overbank events. One occurred in September 2010, the other in December 2010 and the third in January 2011. The first shows the hysteresis effect between average daily flows and turbidity: Figure 8.9 (a) and (b). Nevertheless, no relationship could be established from suspended sediment concentration and turbidity records of this station, given that no records on SSC were available for overbank flooding.

Therefore, due to the lack of data of coincident records of SSC and turbidity across the whole range of river discharge (i.e. most data have been recorded during in-channel flows), it was not possible to establish a mathematical relationship which corresponds to overbank flooding between SSC and turbidity of either of the two gauging stations (Figure 8.5 and Figure 8.8 respectively). Therefore, the selection of the range and fixed value of suspended sediment concentration had to be based on previous studies, as discussed below.
Figure 8.6. SSC and corresponding daily flows of the Goulburn River at Trawool. No records have been taken for high flows at this station. Bankfull at this station occurs at a discharge of ~20,000 ML/day. Data are from April 2005 to 2011.

Figure 8.7. Graph showing daily turbidity records (October 2009 to August 2011) of the Goulburn River gauging station at Trawool. Overbank occurs from discharges above 20,000 ML/day. Seven readings were collected during overbank flooding; these correspond to three independent flood events. One of them is shown on Figure 8.9 (a) and (b).
Figure 8.8. Graph showing coincident records on Turbidity and SSC since April 2005. No records on SSC exist for overbank flooding. Therefore, no relationship could be established between these two variables.
Figure 8.9. (a) Discharge at the Goulburn River at Trawool during the flood event in September 2010 and (b) the correspondent turbidity records. Note that the turbidity peak occurred one day prior to the peak discharge.
8.1.5.3 Discussion on the suspended sediment concentration value adopted for the sensitivity analysis

Sediment sources may originate from various processes. These include overland flow, erosion of gullies formed as a result of land clearing or grazing and erosion of the river banks (DeRose et al. 2003).

In a report on the Health of the River Murray and the Goulburn River by the Murray-Darling Basin Commission (2001), it is stated that the Goulburn River has a naturally low suspended load. However, records to back up this statement do not seem to exist; as daily records on SSC, either for the pre-Eildon period or even before Sugarloaf Reservoir was built (prior to 1929), do not exist. In the same report, it is also considered that the river has naturally low sediment yields and that there are no substantial risks to water quality since the river bed is armoured in the upper reaches and the river channel is generally stable.

In contrast with this scenario, which applies to the Mid-Goulburn River, in the same report it is stated that the lower Goulburn River represents a significant source of suspended sediment to the River Murray. This lower part of the river has a mean suspended sediment concentration of 36 mg.L⁻¹ which results from tributary inputs in that part of the catchment.

I considered that only an approximate value of SSC for the Mid-Goulburn River could be adopted as plausible for the system and which could be used for the sensitivity analysis developed in Chapter 9. Therefore, I used 36 mg.L⁻¹ (equivalent to 0.036 kg.m⁻³) as the fixed value to represent the SSC along the Mid-Goulburn river at times of overbank flooding and a range of 0 to 60 mg.L⁻¹ (equivalent to 0 to
0.060 kg.m\(^{-3}\); as shown in Table 8.22).

8.1.6 Suspended sediment size

As discussed earlier in this thesis (Chapter 2), the size of suspended sediment affects the settling velocity at which it is deposited along floodplains during overbank inundation. This section describes the procedure followed to establish a plausible value that can be considered as a representative size of the suspended sediment. Here, the adopted range of the suspended sediment size, which is subsequently used for the calculation of settling velocities, is also discussed.

The sediment being transported by rivers is usually composed of bedload, suspended load and wash load. Suspended load is that part of the total sediment that is transported and maintained in suspension by turbulence in flowing water (therefore during overbank floods) for considerable periods of time without contact with the stream bed. For the sake of simplicity, it is assumed here that suspended sediment moves at approximately the same velocity as the flowing water (van Rijn 1993).

Flocculation is the process by which individual particles of clay aggregate into clot-like masses and precipitate in a fluid. Relatively significant percentages of clay in the suspended sediment and water quality conditions, such as salinity and pollutants, may lead to flocculation (Xia et al. 2004). Nicholas and Walling (1996; 1997) and Thonon et al. (2005) have found considerable differences in the grain size distribution between the ‘effective’ suspended sediment (that with flocs) and the corresponding
dispersed population. The difference in sediment size distribution between the two populations is reflected in the settling velocity; which can be quite large. For this reason, it is preferable that settling velocities of the suspended sediment population are not derived from the grain size distribution of the dispersed sediment but directly from the grain size distribution of the suspended sediment population (Thonon et al. 2005).

During the course of this research, however, establishing the grain size distribution of the suspended sediment by direct sampling was not possible given that overbank inundation did not occur along the selected floodplain section during the fieldwork program (2008 and 2009). Therefore, the only alternative for establishing the suspended sediment size was to consider data that have been reported in previous studies and also to analyse the grain size distributions of the deposited sediment collected during the fieldwork program of this research (Chapter 7). A representative size of the suspended sediment is needed to calculate settling velocity associated with that size (next section).

Erskine, Tennant & Tilleard (1996) collected 'substrate' samples along different locations of the floodplain section of this study (Table 8.5 below). They did so with the purpose of investigating the impacts of sand and gravel extraction from the bed and banks on the river system. Their data show that the Mid-Goulburn River is composed of a range of fine and coarse sediment: a mixed-bed river system. I converted their substrate-size values to meters, as shown and highlighted in Table 8.5, whose average is 110 µm (Table 8.6).

On the other hand, samples collected during the fieldwork program show that the cumulative volume of the clay fraction is on average 20% of the total sample
volume (of samples in the depth interval of 0 to 50 centimetres), suggesting that flocculation might be important for the sediment transport and deposition processes during overbank inundation. Therefore and as previously mentioned, the analysis presented below includes an analysis of the grain size distributions of the floodplain deposits collected during the fieldwork program of this research.

The 10th, 25th, 50th, 75th and 90th percentiles of the grain-diameter distributions obtained from floodplain deposits collected in this study are shown in Table 8.7 below and their averages in Table 8.8. Only the grain sizes of samples in which $^{137}$Cs was detected were considered in the calculation of the different percentiles (from Table 8.7 below).
Table 8.5. Measured sediment size of the various samples collected by Erskine WD, Tennant WK and Tilleard JW (1996). All are sites within the floodplain section of the research here being developed.

<table>
<thead>
<tr>
<th>Site</th>
<th>Sediment type</th>
<th>Graphic mean size ( $\phi$ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eildon</td>
<td>bedload</td>
<td>0.45</td>
</tr>
<tr>
<td>Thornton</td>
<td>Armour layer</td>
<td>-5.47</td>
</tr>
<tr>
<td></td>
<td>substrate</td>
<td>-3.19</td>
</tr>
<tr>
<td>Breakaway Road</td>
<td>armour layer</td>
<td>-5.45 to -5.65</td>
</tr>
<tr>
<td></td>
<td>substrate</td>
<td>-3.45</td>
</tr>
<tr>
<td></td>
<td>riffle tail</td>
<td>2.23</td>
</tr>
<tr>
<td>Molesworth</td>
<td>bed material</td>
<td>1.25</td>
</tr>
<tr>
<td>Trawool</td>
<td>armour layer</td>
<td>-4.47 to -5.37</td>
</tr>
<tr>
<td></td>
<td>substrate</td>
<td>-2.53 to -3.29</td>
</tr>
<tr>
<td></td>
<td>Lee-side shadow deposit</td>
<td>-1.37</td>
</tr>
<tr>
<td></td>
<td>bedload</td>
<td>1.30</td>
</tr>
</tbody>
</table>

Table 8.6. Converted sediment size of substrate sediment from Erskine WD, Tennant WK and Tilleard JW (1996).

<table>
<thead>
<tr>
<th>Averages (Φ)</th>
<th>Conversion of Φ values to millimetres</th>
<th>Equivalent substrate diameter (in m)</th>
<th>Equivalent substrate radius (in m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conversion formulae used</td>
<td></td>
<td>D = D₀ × 2^{-Φ}</td>
</tr>
<tr>
<td></td>
<td>where: D₀ = 1mm, and D = diameter of the particle in mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Substrate values:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-3.19</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-3.45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-2.91*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average of substrate values: -3.18 Φ</td>
<td>0.11 mm</td>
<td>0.00011 m (or 110 µm)</td>
<td>0.000055 m (or 55 µm)</td>
</tr>
</tbody>
</table>

*This value is in the middle between -3.29 and -2.53 (from Table 8.5).
Table 8.7. Percentiles of particle diameter determined using the laser analyser of floodplain-sediment samples (as described in Chapter 7).  

<table>
<thead>
<tr>
<th>Floodplain Unit Sample</th>
<th>(d_{10}) (µm)</th>
<th>(d_{25}) (µm)</th>
<th>(d_{50}) (µm)</th>
<th>(d_{75}) (µm)</th>
<th>(d_{90}) (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D.TT.E (0-5cm) - Average</td>
<td>2</td>
<td>7</td>
<td>33</td>
<td>118</td>
<td>317</td>
</tr>
<tr>
<td>D.TT.E (5-15cm) - Average</td>
<td>3</td>
<td>7</td>
<td>27</td>
<td>83</td>
<td>196</td>
</tr>
<tr>
<td>D.TT.E (15-30cm) - Average</td>
<td>2</td>
<td>6</td>
<td>21</td>
<td>59</td>
<td>119</td>
</tr>
<tr>
<td>K.L.M (2-5cm) - Average</td>
<td>2</td>
<td>5</td>
<td>14</td>
<td>37</td>
<td>70</td>
</tr>
<tr>
<td>K.L.M (5-15cm) - Average</td>
<td>2</td>
<td>6</td>
<td>19</td>
<td>46</td>
<td>82</td>
</tr>
<tr>
<td>A.B.UU. (2-5cm) - Average</td>
<td>2</td>
<td>7</td>
<td>23</td>
<td>66</td>
<td>252</td>
</tr>
<tr>
<td>A.B.UU. (5-15cm) - Average</td>
<td>2</td>
<td>6</td>
<td>19</td>
<td>45</td>
<td>96</td>
</tr>
<tr>
<td>A.B.UU. (15-30cm) - Average</td>
<td>2</td>
<td>8</td>
<td>24</td>
<td>56</td>
<td>113</td>
</tr>
<tr>
<td>A.B.UU. (30-50cm) - Average</td>
<td>2</td>
<td>6</td>
<td>19</td>
<td>47</td>
<td>99</td>
</tr>
<tr>
<td>F.G (0-5cm) - Average</td>
<td>3</td>
<td>9</td>
<td>33</td>
<td>128</td>
<td>329</td>
</tr>
<tr>
<td>F.G (5-15cm) - Average</td>
<td>1</td>
<td>3</td>
<td>8</td>
<td>28</td>
<td>134</td>
</tr>
<tr>
<td>CC.DD.EE (0-5cm) - Average</td>
<td>4</td>
<td>11</td>
<td>38</td>
<td>136</td>
<td>415</td>
</tr>
<tr>
<td>CC.DD.EE (5-15cm) - Average</td>
<td>3</td>
<td>9</td>
<td>33</td>
<td>100</td>
<td>262</td>
</tr>
<tr>
<td>FF.GG.HH (0-5cm) - Average</td>
<td>4</td>
<td>13</td>
<td>55</td>
<td>191</td>
<td>444</td>
</tr>
<tr>
<td>FF.GG.HH (5-15cm) - Average</td>
<td>2</td>
<td>6</td>
<td>18</td>
<td>53</td>
<td>142</td>
</tr>
<tr>
<td>QQ.BB.AA. (0-5cm) - Average</td>
<td>3</td>
<td>9</td>
<td>29</td>
<td>88</td>
<td>245</td>
</tr>
<tr>
<td>QQ.BB.AA (5-15cm) – Average</td>
<td>2</td>
<td>4</td>
<td>9</td>
<td>24</td>
<td>57</td>
</tr>
<tr>
<td>N.J.Q (0-5cm) - Average</td>
<td>3</td>
<td>8</td>
<td>27</td>
<td>69</td>
<td>158</td>
</tr>
<tr>
<td>N.J.Q (5-15cm) - Average</td>
<td>2</td>
<td>6</td>
<td>18</td>
<td>44</td>
<td>94</td>
</tr>
<tr>
<td>2D.2E.2F (0-5cm) - Average</td>
<td>3</td>
<td>8</td>
<td>25</td>
<td>81</td>
<td>283</td>
</tr>
<tr>
<td>1A.1B.1C (0-5cm) - Average</td>
<td>3</td>
<td>7</td>
<td>21</td>
<td>62</td>
<td>194</td>
</tr>
<tr>
<td>1A.1B.1C (5-15cm) - Average</td>
<td>2</td>
<td>5</td>
<td>13</td>
<td>29</td>
<td>56</td>
</tr>
<tr>
<td>1D.1DBis.1E (0-5cm) - Average</td>
<td>2</td>
<td>5</td>
<td>12</td>
<td>30</td>
<td>73</td>
</tr>
<tr>
<td>1D.1DBis.1E (5-15cm) - Average</td>
<td>2</td>
<td>4</td>
<td>11</td>
<td>25</td>
<td>54</td>
</tr>
<tr>
<td>1F (0-6cm) - Average</td>
<td>2</td>
<td>5</td>
<td>14</td>
<td>36</td>
<td>81</td>
</tr>
<tr>
<td>1F (6-12cm) - Average</td>
<td>2</td>
<td>6</td>
<td>16</td>
<td>34</td>
<td>67</td>
</tr>
<tr>
<td>1F (12-18cm) - Average</td>
<td>2</td>
<td>5</td>
<td>13</td>
<td>28</td>
<td>51</td>
</tr>
<tr>
<td>1F (18-24cm) - Average</td>
<td>2</td>
<td>6</td>
<td>16</td>
<td>36</td>
<td>76</td>
</tr>
<tr>
<td>1F (24-30cm) – Average</td>
<td>2</td>
<td>6</td>
<td>15</td>
<td>30</td>
<td>51</td>
</tr>
<tr>
<td>1L.1G.1J (0-5cm) - Average</td>
<td>3</td>
<td>11</td>
<td>69</td>
<td>348</td>
<td>681</td>
</tr>
<tr>
<td>1L.1G.1J (5-15cm) - Average</td>
<td>3</td>
<td>7</td>
<td>39</td>
<td>292</td>
<td>500</td>
</tr>
<tr>
<td>1L.1G.1J (15-30cm) - Average</td>
<td>2</td>
<td>5</td>
<td>11</td>
<td>24</td>
<td>43</td>
</tr>
</tbody>
</table>
Table 8.8. Averaged diameter size percentiles of floodplain samples

<table>
<thead>
<tr>
<th>Percentile average diameter (μm)</th>
<th>diameter (mm)</th>
<th>diameter (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>d25’s = 7</td>
<td>0.007</td>
<td>0.000007</td>
</tr>
<tr>
<td>d50’s = 22</td>
<td>0.022</td>
<td>0.000022</td>
</tr>
<tr>
<td>d75’s = 75</td>
<td>0.075</td>
<td>0.000075</td>
</tr>
<tr>
<td>d90’s = 182</td>
<td>0.182</td>
<td>0.000182</td>
</tr>
</tbody>
</table>

Considering the Wentworth grain size classification, the overall average grain diameter of floodplain deposits (50th-percentile) is around the medium silt fraction: 0.022 mm. The 75th percentile (0.075 mm) corresponds to very fine sand and the 90th percentile (0.182 mm) to fine sand.

To overcome the impossibility of knowing, from direct measurements, the grain size distribution of the suspended sediment and keeping in mind the effect that the existence of flocs may have on the sediment fall velocity, I assumed that the average grain-diameter size of the suspended sediment could be closer to the 75th percentile of the grain diameter size of floodplain deposits: i.e. 0.075-millimeter diameter. This correlates with the measured substrate samples by Erskine WD, Tennant WK and Tilleard JW (1996). This value and those reported of the substrate by Erskine WD, Tennant WK and Tilleard JW (Ibid) are used in the parameterisation of this factor for the sensitivity analysis (selection of an assumed fixed or plausible value and a range). Moreover, it was found in Chapter 7 that 56% of the floodplain deposits are silt, 20% clay and 24% sand. This high percentage of fine sediment (76% silt and clay together) in floodplain deposits suggests that floc formation is likely to have a strong influence on the sediment transport mechanisms (including settling velocities) and that they can ultimately be influential on the amount and distribution of overbank deposition along the
floodplain. Therefore, it is valid to consider the 75th percentile of the floodplain deposits as a representative grain-diameter size of the suspended sediment (Table 8.8 above). The 50th and 90th percentiles (value range) are also used for the parameterisation of the settling velocity (Table 8.10, next section). Note that the values used correspond to grain radius instead of grain diameter, as shown by Equation 8.1.

### 8.1.7 Settling velocity

The settling velocity is the velocity at which a particle, or group of particles with the same size and contained in a viscous fluid, falls by its own weight due to gravity. The falling of the particle is reached when the frictional force combined with the buoyant force exactly balance the gravitational force, resulting in zero acceleration. The resulting settling velocity is influenced by particle size and the fluid properties as established by the Stokes' law (Equation 8.1).

**Equation 8.1**

\[
V_s = \frac{2}{9} \frac{(\rho_p - \rho_f)}{\mu} g R^2
\]

where:

- \(V_s\) is the particles' settling velocity in m.s\(^{-1}\) (vertically downwards if \(\rho_p > \rho_f\) )
\( \rho_p \) is the density of the (assumed) spherical particles, in kg.m\(^{-3}\)

\( \rho_f \) is the mass density of the fluid in kg.m\(^{-3}\) and

\( g \) is the gravitational acceleration in m.s\(^{-2}\),

\( \mu \) is the dynamic viscosity in N.s.m\(^{-2}\),

\( R \) is the radius of the sphere in meters.

This expression describes the relationship between the fluid properties and the radius of a particle (theoretically a sphere), which affects its settling velocity. The expression is valid for very low Reynolds numbers, i.e. in the range of Re < 0.1 (Gordon, McMahon & Finlayson 2004). However, according to Chang (1992) the Stokes' law can also be applicable for Reynolds numbers up to 1.0 (see Figure 8.11 below). The Reynolds number can be calculated from the particle diameter (in meters), flow velocity, \( V \) (in m.s\(^{-1}\)) and kinematic viscosity, \( \nu \) (in m\(^2\).s\(^{-1}\)); as shown on Equation 8.2.

\[
\text{Equation 8.2} \quad \text{Re} = \frac{\rho VL}{\mu} = \frac{VD}{\nu}
\]

where:

\( V \) is the mean velocity of the object relative to the fluid in m.s\(^{-1}\)

\( L \) is a characteristic linear dimension, i.e. the hydraulic diameter (D) when dealing with river systems, in meters

\( \mu \) is the dynamic viscosity of the fluid (N.s.m\(^{-2}\) or kg.(m·s\(^{-1}\))
\[ \nu \] is the kinematic viscosity \( (\nu = \mu/\rho) \); in m².s⁻¹ and 

\[ \rho \] is the density of the fluid in kg.m⁻³

As mentioned in Chapter 7, the estimated average dry bulk density of the floodplain deposits is 1,170 kg.m⁻³. However, this value was estimated from bulk samples where porosity is likely to be important among the grains. Instead, I used silica density (i.e. 2,650 kg.m⁻³) in the calculations (using Equation 8.1). I also used the corresponding values of density, dynamic viscosity and kinematic viscosity of freshwater at atmospheric pressure and at a temperature of 10°C (Table 8.9 below).

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Temperature (°C)</th>
<th>Density, ( \rho ) (Kg.m⁻³)</th>
<th>Dynamic viscosity, ( \mu ) (N.s.m⁻²)</th>
<th>Kinematic viscosity, ( \nu ) (m².s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh water</td>
<td>0</td>
<td>999.9</td>
<td>1.792 x 10⁻³</td>
<td>1.792 x 10⁻⁶</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1000.0</td>
<td>1.568 x 10⁻³</td>
<td>1.568 x 10⁻⁶</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>999.7</td>
<td>1.308 x 10⁻³</td>
<td>1.308 x 10⁻⁶</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>999.1</td>
<td>1.140 x 10⁻³</td>
<td>1.141 x 10⁻⁶</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>998.2</td>
<td>1.005 x 10⁻³</td>
<td>1.007 x 10⁻⁶</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>997.1</td>
<td>0.894 x 10⁻³</td>
<td>0.897 x 10⁻⁶</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>995.7</td>
<td>0.801 x 10⁻³</td>
<td>0.804 x 10⁻⁶</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>992.2</td>
<td>0.656 x 10⁻³</td>
<td>0.661 x 10⁻⁶</td>
</tr>
<tr>
<td>Sea water</td>
<td>0</td>
<td>1028</td>
<td>1.89 x 10⁻³</td>
<td>1.84 x 10⁻⁶</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>1024</td>
<td>1.072 x 10⁻³</td>
<td>1.047 x 10⁻⁶</td>
</tr>
</tbody>
</table>

Source: Gordon, McMahon and Finlayson (2004). *Ice at 0°C has a density of 917. b Sea water salinity varies but here it is considered that sea water has a salinity of 35%.

Using the Stokes’ law (Equation 8.1 above), the corresponding settling velocities of a particle with a radius equivalent to the 50th, 75th and 90th percentiles of
the floodplain deposits are shown in Table 8.10, as well as that of the ‘substrate’ size measured by Erskine, Tennant and Tilleard (1996).

Table 8.10. Estimations of settling velocity using a range of particle radius ($R$) on Equation 8.1 above.

<table>
<thead>
<tr>
<th>Particle size</th>
<th>Radius (m)</th>
<th>$V_s$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{50}$</td>
<td>0.000011</td>
<td>0.0003</td>
</tr>
<tr>
<td>$d_{75}$</td>
<td>0.000038</td>
<td>0.0039</td>
</tr>
<tr>
<td>$d_{90}$</td>
<td>0.000091</td>
<td>0.0228</td>
</tr>
<tr>
<td>substrate (1996)</td>
<td>0.000055</td>
<td>0.0083</td>
</tr>
</tbody>
</table>

On the other hand, Rouse’s diagram (Rouse 1937) (Figure 8.10 below) can be used as a second way to calculate settling velocities (cf. Chang 1992). Settling velocity of quartz spheres can be estimated from water temperature and sediment diameter in millimetres. The settling velocities obtained are based on the two ways of estimation for a water temperature of 10°C; the four particle diameters are shown in Table 8.11. It can be noticed that the values obtained from the two different means are similar. The fourth column of the same table shows the values that could be used for the sensitivity analysis.
Figure 8.10. Rouse’s diagram (Rouse 1937) from which settling velocities can be estimated. It relates water temperature, sediment diameter (in millimetres) and settling velocity. Source (Chang 1992).

Table 8.11. Settling velocity calculated using (a) Stokes’ law and (b) Rouse’s diagram.

<table>
<thead>
<tr>
<th>Particle diameter (mm)</th>
<th>(a) Settling velocity (Stokes’ law) (m.s⁻¹)</th>
<th>(b) settling velocity Rouse’s diagram, (m.s⁻¹)</th>
<th>Settling velocities used for sensitivity analysis (m.s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>d₅₀: 0.022</td>
<td>0.0003</td>
<td>0.00028</td>
<td>0.0003</td>
</tr>
<tr>
<td>d₇₅: 0.075</td>
<td>0.0039</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>substrate measured by Erskine, <em>et al.</em> (Gordon, McMahon &amp; Finlayson 2004): 0.11</td>
<td>0.0083</td>
<td>0.006</td>
<td>0.007</td>
</tr>
<tr>
<td>d₉₀: 0.182</td>
<td>0.0228</td>
<td>0.018</td>
<td>0.02</td>
</tr>
</tbody>
</table>

It should be acknowledged, however, that no matter which of the two methods are used (Stokes’ law or Rouse’s diagram), discrepancies may exist between the calculated settling velocities and the real values due to: sediment-shape factors that
are not taken into account; the fact that estimations assume spherical grains; possible
differences in specific gravity of the various grain size fractions (ratio of the density of
the particle fractions and the density of water) and possible differences in specific
gravity between the dispersed particles and presumably existing aggregated particles
(flocs), which could be important even if these two are considered to have the same
grain size (van Rijn 1993; Agrawal & Pottsmith 2000).

As previously mentioned, Stokes' law is considered to be applicable for the silt-
and clay-size falling in water (Chang 1992) and for Reynolds number indicating laminar
flow (i.e. Re < 0.1, (Gordon, McMahon & Finlayson 2004)) and up to Re = 1 (Chang
1992). Therefore, I determined the Reynolds number (which can be established from
Equation 8.2 above) from the corresponding settling velocities. The Reynolds numbers
corresponding to particle diameters equivalent to 50th, 75th and the 90th percentiles, as
well as to the substrate diameter estimated by Erskine, Tennant and Tilleard (2005) of
Table 8.10, are shown in Table 8.12 below.

\[
Re_{d_{50}} = \frac{V_s \cdot D_{d_{50}}}{\nu} = \frac{0.0003 \times 0.000022}{1.308 \times 10^{-6}} = 0.005;
Re_{d_{75}} = \frac{V_s \cdot D_{d_{75}}}{\nu} = \frac{0.0039 \times 0.000075}{1.308 \times 10^{-6}} = 0.22
\]

\[
Re_{\text{substrate}} = \frac{V_s \cdot D_{\text{substrate}}}{\nu} = \frac{0.0083 \times 0.00111}{1.308 \times 10^{-6}} = 0.7;
Re_{d_{90}} = \frac{V_s \cdot D_{d_{90}}}{\nu} = \frac{0.0228 \times 0.000182}{1.308 \times 10^{-6}} = 3.17
\]
Table 8.12. Calculated particle Reynolds number corresponding to the four particle sizes considered for this analysis.

<table>
<thead>
<tr>
<th>Particle diameter (m)</th>
<th>( V' )</th>
<th>Re</th>
</tr>
</thead>
<tbody>
<tr>
<td>d_{s0}: 0.000022</td>
<td>0.0003</td>
<td>0.005</td>
</tr>
<tr>
<td>d_{75}: 0.000075</td>
<td>0.004</td>
<td>0.22</td>
</tr>
<tr>
<td>substrate measured by Erskine, et al. (1996): 0.00011</td>
<td>0.007</td>
<td>0.7</td>
</tr>
<tr>
<td>d_{90}: 0.000182</td>
<td>0.02</td>
<td>3.17</td>
</tr>
</tbody>
</table>

As shown in Table 8.12, three of the Reynolds numbers obtained are < 1, which according to (Figure 8.11) are within the range of applicability of the Stokes' law (i.e. if Re \( \leq 1 \)).

Figure 8.11. Reynolds number and range of validity of Stokes' law. Source: Rouse (1937); in Chang (1992).

Therefore, from this analysis I established that an adequate range for the settling velocity of the suspended sediment should go from 0.0003 to 0.007 m.s\(^{-1}\), whose upper limit includes a sediment size equivalent to the substrate size measured...
by Erskine, Tennant and Tilleard (1996) and which is just larger than the 75th percentile of the floodplain sediment size previously established.

### 8.1.8 Floodplain floor shear stress

Shear stress is the force per unit area that causes resistance along a boundary layer. This force originates from the friction that exists between a fluid and a solid for being in contact. The distribution of velocity and shear stress around the boundary layer are influenced by both the nature of the flow, whether laminar or turbulent, and the nature of the solid, whether rough or smooth (Holden & James 1989; Gordon, McMahon & Finlayson 2004; Yang, Cao & Knight 2007). Shear stress usually increases with discharge, but it is heterogeneously distributed along a natural channel or floodplain.

Shear stress can be calculated from Equation 8.3

\[
\tau = g \rho \frac{V^2 n^2}{h^{5/3}}
\]

where \( V \) is the depth averaged velocity, \( n \) is Manning's n, \( h \) water depth, \( g \) acceleration due to gravity and \( \rho \) water density. Manning's n is a function of flow velocity \( V \), water depth \( d \) and channel slope \( s \); (Equation 8.4).
Equation 8.4

\[ n = \frac{1}{V} d^{2/3} s^{1/2} \]

Since flow velocity in the main channel is usually much higher than along the floodplain (Gordon, McMahon & Finlayson 2004) when the flow overtops the river banks, Manning’s n and shear stress along these should be evaluated separately. Manning’s n integrates the combined effects of flow resistance caused by the floodplain floor roughness, the presence of vegetation and the amount of sediment or debris carried by the flow (Gordon, McMahon & Finlayson 2004). Manning’s n varies with flow depth but typically increases as the relative roughness increases; it usually increases with turbulence and decreases as the height of protuberances, such as snags or rocks, become submerged by the flow.

Water Technology (2009) calculated Manning’s n values of the floodplain separately. They were obtained from a calibration step that incorporated modelled flood extents and water levels of observed historic floods. Water Technology (2009) also estimated shear stress of the floodplain section here investigated. According to this group, this factor was estimated from Equation 8.3 and Equation 8.4: as a function of Manning’s n, flow velocity and overbank flow height. Their estimations were provided in GIS form in addition to the hydraulic model results.

Using in a GIS the provided shear stress values of each of the floodplain units separately (i.e. associated to their corresponding unit flooding thresholds), I obtained an average shear stress value for each of the units in two ways. Firstly, averaging shear stress values of the inundated area of the corresponding unit at the flooding
threshold and secondly, averaging only the shear stress values of the unit coring locations (columns (a) and (b)). Areas free of flooding along the units were not included since they represent zero shear stress (zero depth inundation).

Shear stresses obtained in the first way (Table 8.13a below) range from 0.003 to 1.28, and the ones obtained in the second way (Table 8.13b) range from 0.00006 to 1.41 N.m\(^{-2}\). As shown, the shear stress average obtained in both cases is practically the same, i.e. 0.3 N.m\(^{-2}\). Using the data from Table 8.13 I also calculated the 50\(^{th}\) and 80\(^{th}\) percentiles for each case: (a) and (b). These are shown in Table 8.14. In both cases the 80\(^{th}\) percentile is 0.5 N.m\(^{-2}\).
Table 8.13. Averaged floodplain shear stress (a) along the unit inundated areas and (b) considering the coring sites of the floodplain units only.

<table>
<thead>
<tr>
<th>Floodplain Unit</th>
<th>(a) Average shear stress of inundated area, $\tau$ (N.m$^{-2}$)</th>
<th>(b) Average shear stress of each unit core locations, $\tau$ (N.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit D.TT.E</td>
<td>0.00336</td>
<td>0.00006</td>
</tr>
<tr>
<td>K.L.M</td>
<td>0.53897</td>
<td>1.40697</td>
</tr>
<tr>
<td>A.B.UU</td>
<td>1.28639</td>
<td>0.47322</td>
</tr>
<tr>
<td>F.G</td>
<td>0.31919</td>
<td>0.00028</td>
</tr>
<tr>
<td>CC.DD.EE</td>
<td>0.09085</td>
<td>0.09075</td>
</tr>
<tr>
<td>FF.GG.HH</td>
<td>0.09217</td>
<td>0.35738</td>
</tr>
<tr>
<td>QQ.BB.AA</td>
<td>0.46754</td>
<td>Not applicable as 2 of the 3 coring sites are not inundated at the unit flooding threshold</td>
</tr>
<tr>
<td>N.J.Q</td>
<td>0.02466</td>
<td>0.00884</td>
</tr>
<tr>
<td>2D.2E.2F</td>
<td>0.52616</td>
<td>0.78120</td>
</tr>
<tr>
<td>1A.1B.1C</td>
<td>0.35830</td>
<td>0.29254</td>
</tr>
<tr>
<td>1F</td>
<td>0.25500</td>
<td>0.00003</td>
</tr>
<tr>
<td>1D.1Dbis.1E</td>
<td>0.01045</td>
<td>0.01180</td>
</tr>
<tr>
<td>1L.1G.1I</td>
<td>0.18354</td>
<td>0.21971</td>
</tr>
<tr>
<td>Overall Average</td>
<td>0.32</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Table 8.14. (a) The calculated 50th and 80th percentile of shear stress values associated to inundated areas along the floodplain at the unit flooding thresholds; (b) same as the previous case but only using shear stress values of each unit coring sites.

<table>
<thead>
<tr>
<th>Percentiles -Inundated area</th>
<th>$\tau$ (N.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50th Percentile of the values</td>
<td>0.26 $\rightarrow$ ~ 0.3</td>
</tr>
<tr>
<td>80th Percentile of the values</td>
<td>0.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Percentiles -core location values only</th>
<th>$\tau$ (N.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The 50th Percentile of the values</td>
<td>0.16 $\rightarrow$ ~ 0.2</td>
</tr>
<tr>
<td>The 80th Percentile of the values</td>
<td>0.5</td>
</tr>
</tbody>
</table>
During the fieldwork program of this research I found that the selected geomorphic units were covered by grass, others by sparse trees and a few by denser tree cover, as shown in the figures in Appendix F, which are based on the 2005 aerial photographs of the Department of Sustainability and Environment (2005). In general, the floodplain units are mostly covered by grassland that grows over the wet season and diminishes during the dry season. During visits to the floodplain I observed scattered-to-dense tree cover distributed mostly along the banks of abandoned channels and meander cutoffs (see figures in Appendix F). However, Water Technology established a Manning’s n value equal to 0.1 for most of the floodplain section (Table 8.15), which according to other sources (those of Table 8.16) would belong to a floodplain cover dominated by heavy brush and trees, which is inadequate. Taking this into account, I decided to estimate shear stress based on my observations and in Table 8.16, which suggest that Manning's n should be around 0.03 to 0.05 for the flow paths established at each unit flooding threshold.

Table 8.15. Manning’s n values assigned by Water Technology for the different areas of the floodplain and channel.

<table>
<thead>
<tr>
<th>Description</th>
<th>Assigned Manning's n value by Water Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main channel</td>
<td>mostly 0.04</td>
</tr>
<tr>
<td>Abandoned channels and floodplain units that reconnect with the river at high flows (below overbank flooding). Note that none of them are the ones studied here.</td>
<td>mostly 0.14 and 0.18</td>
</tr>
<tr>
<td>Most of the floodplain section, including all the floodplain units selected for this study</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Table 8.16. Manning’s n values given by different sources in relation to floodplain cover

<table>
<thead>
<tr>
<th>Floodplain type of cover</th>
<th>Manning’s n value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>pasture, farmland</td>
<td>0.035</td>
<td>Website of the LMNO Engineering Research and Software Ltd (10 August 2010) and The Engineering ToolBox (10 August 2010)</td>
</tr>
<tr>
<td>light brush</td>
<td>0.050</td>
<td></td>
</tr>
<tr>
<td>heavy brush</td>
<td>0.075</td>
<td></td>
</tr>
<tr>
<td>trees</td>
<td>0.15</td>
<td></td>
</tr>
</tbody>
</table>

The calculated values of floodplain-floor shear stress that were obtained using the various values of Manning’s n on Equation 8.3 are shown in Table 8.17. The shear stress calculated for pasture and farmland is 0.037 N.m\(^{-2}\) (same table), which is just above the average obtained from the raster dataset of Water Technology (2009) (as shown on Table 8.13 above).

Considering that floodplain cover is mostly pasture and farmland along the flow paths established for each floodplain unit, I selected 0.02 as the lower limit of the shear-stress value range and 0.05 N.m\(^{-2}\) as the upper one. These were used for the sensitivity analysis, together with the average value: 0.3 N.m\(^{-2}\).

Table 8.17. Calculated values of floodplain-floor shear stress using Equation 8.3 and various values of Manning’s n.

<table>
<thead>
<tr>
<th>Manning's n</th>
<th>Water density ((\rho)) kg.m(^{-3})</th>
<th>Average flow velocity along flow path V (m/s)</th>
<th>Average flow depth along flow path h (m)</th>
<th>Floodplain floor shear stress (\tau) (N.m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.035</td>
<td>999.7</td>
<td>0.18</td>
<td>1.2</td>
<td>0.37</td>
</tr>
<tr>
<td>0.05</td>
<td>999.7</td>
<td>0.18</td>
<td>1.2</td>
<td>0.75</td>
</tr>
<tr>
<td>0.075</td>
<td>999.7</td>
<td>0.18</td>
<td>1.2</td>
<td>1.68</td>
</tr>
<tr>
<td>0.1</td>
<td>999.7</td>
<td>0.18</td>
<td>1.2</td>
<td>2.99</td>
</tr>
<tr>
<td>0.15</td>
<td>999.7</td>
<td>0.18</td>
<td>1.2</td>
<td>6.73</td>
</tr>
</tbody>
</table>
Critical shear stress is the amount of shear stress that will make a particle move when, at incipient motion, the shear force acting is balanced with the submerged weight of the particle. This concept also can be applied for a particle already in motion that is about to stop moving. The critical shear stress in the latter case represents the shear force that is also balanced with its submerged weight as the flow loses strength. Therefore, the same equation that is used for incipient motion can be applied in that case. Buttner et al. (2006) consider that for sediment deposition to occur the critical shear stress \( \tau_c \) should be higher than floodplain-floor shear stress \( \tau \), as previously mentioned in Chapter 4.

According to Gordon, McMahon and Finlayson (2004) it is accepted that "the critical shear stress required to move a particle is approximately the same as the particle’s diameter in millimetres" (Ibid, p. 193). In the case of mixed bed materials, it is also accepted that "\( \tau_c \) can be calculated based on the characteristic grain diameter rather than computing individual values of \( \tau_c \) for each size fraction. For streambeds, the median size of the bed materials is often taken as the representative diameter" (Gordon, McMahon & Finlayson 2004). For this study, the characteristic diameter of the floodplain-floor material is considered based on the previous statements (instead of that of the river bed material). As discussed earlier in this chapter, the 75th percentile of the diameter size of floodplain deposits, i.e. 0.075 millimetres of diameter, may be considered a representative size of the floodplain sediments. However, considering the
range and fixed value given to floodplain-surface shear stress (previous section), and that these should be smaller than those assigned to those of critical shear stress, I chose a range of 0.07 to 2.0 N.m\(^{-2}\) and an average of 1.0 N.m\(^{-2}\) for critical shear stress (Table 8.22). This range is close to the one adopted by Buttner et al. (that of Walling, Quine & He 1992), who chose a range of 0.1 to 1 N.m\(^{-2}\).

### 8.1.9.1 Type of flow

The Shields curve is used to identify the type of flow in the system (whether hydraulically smooth, transitional or hydraulically rough). To do so, it is necessary to obtain the Shear Reynolds number (\(\text{Re}_s\); Equation 8.5 below) and the dimensionless critical shear stress (\(\theta_c\)). These values are used to find flow characteristics using the Shields curve (Figure 8.12 below). The floodplain-floor shear stress values (\(\tau\)) from Table 8.14 above can be used to calculate the Shear Reynolds number \(\text{Re}_s\) and 'shear' velocity \(V\) (Equation 8.5 and Equation 8.6 below), which in each case is \(~0.2; 0.3\) (overall average) or \(~0.5\) N.m\(^{-2}\) respectively (Table 8.18 below).
Figure 8.12. The Shields curve relates Shear Reynolds number ($Re_*$) and Dimensionless shear stress ($\theta_c$) and defines whether the flow is hydraulically smooth, rough or transitional. 

**Equation 8.5**

$$Re_* = \frac{V_* \times k}{\nu}$$

Shear Reynolds number ($Re_*$) is a function of Shear velocity ($V_*$), roughness height ($k$) and kinematic viscosity ($\nu = \mu / \rho$) where $\mu$ is the dynamic viscosity in N.s.m$^{-2}$.

Shear velocity can be obtained from Equation 8.6 below.

**Equation 8.6**

$$V_* = \sqrt{\frac{\tau}{\rho}}$$

where $\rho$ is freshwater density (same as density of water at 10°C), and $\tau$ is the shear stress acting along the floodplain floor (in N.m$^{-2}$).

The dimensionless shear stress ($\theta_c$) can be calculated from Equation 8.7.
Equation 8.7 \[ \theta_c = \frac{\tau_c}{g \cdot k (\rho_p - \rho_f)} \]

where \( \tau_c \) is the critical shear stress.

Shear velocities were then obtained using the values of floodplain-floor shear stress \( \tau \) previously estimated (from Table 8.14 above) and are shown in Table 8.18.

Table 8.18. Estimated shear velocities of the corresponding shear stress values as shown on Table 8.14 above.

<table>
<thead>
<tr>
<th>Shear stress values, ( \tau ) (N.m(^{-2}))</th>
<th>Shear velocity, ( V ) (m.s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.014</td>
</tr>
<tr>
<td>0.3 (floodplain overall average)</td>
<td>0.017</td>
</tr>
<tr>
<td>0.5 (floodplain samples 80(^{th}) Shear percentile)</td>
<td>0.022</td>
</tr>
</tbody>
</table>

In the estimation of the Shear Reynolds number (Re. in Equation 8.6 above), \( k \) is related to the effect that the size and the way objects are spaced have on the flow around those objects. Ideally, it should be a 'representative' particle size in meters; "typically some characteristic diameter of the streambed materials such as the \( d_{50} \) or \( d_{80} \) is used as the roughness height" (Gordon, McMahon & Finlayson 2004, p. 139).

Since this analysis focuses on the floodplain, the characteristic diameter of the floodplain-floor materials should be considered instead of that of the streambed. As previously mentioned in this chapter and shown in Chapter 7, grain size distributions were studied for each sediment sample taken from the floodplain units. Possible values
of $k$, based on grain-diameter percentiles calculated from floodplain samples (Table 8.7 and Table 8.8), are shown in Table 8.19.

Table 8.19. Possible values of $Re_c$ that could be used for the estimation of Shear Reynolds number, $Re_c$.

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Average diameter ($\mu$m)</th>
<th>Diameter (mm)</th>
<th>Possible values of $k$ ; Diameter in metres</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{50}$'s</td>
<td>22</td>
<td>0.022</td>
<td>0.000022</td>
</tr>
<tr>
<td>$d_{75}$'s</td>
<td>75</td>
<td>0.075</td>
<td>0.000075</td>
</tr>
<tr>
<td>$d_{substrate}$</td>
<td>75</td>
<td>0.110</td>
<td>0.000110</td>
</tr>
<tr>
<td>$d_{90}$'s</td>
<td>182</td>
<td>0.182</td>
<td>0.000182</td>
</tr>
</tbody>
</table>

The calculated values of shear (or 'grain') Reynolds numbers from Equation 8.5 that were obtained using the various roughness heights $k$ (Table 8.19) and the shear velocities obtained (Table 8.18 above) are shown in Table 8.20. These ($Re_c$) range from 0.2 to 3, which indicates that the floodplain surface can be considered hydraulically smooth: a flow is considered hydraulically smooth if $Re_c < 5$; as stated by Gordon, McMahon and Finlayson (Gordon, McMahon & Finlayson 2004, p. 139). On the other hand, a flow is transitional if $Re_c$ is between 5 and 70 (Ibid).
Table 8.20. Calculated shear Reynolds numbers. $Re$ ranges from 0.2 to 3.1

<table>
<thead>
<tr>
<th>Options of a ‘representative’ floodplain floor size; $k$</th>
<th>$V^*$</th>
<th>$Re$</th>
</tr>
</thead>
<tbody>
<tr>
<td>For $k = d_{50}$: $2.2 \times 10^{-5}$</td>
<td>0.0224</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>0.0173</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>0.0141</td>
<td>0.2</td>
</tr>
<tr>
<td>For $k = d_{75}$: $7.5 \times 10^{-5}$</td>
<td>0.0224</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>0.0173</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>0.0141</td>
<td>0.8</td>
</tr>
<tr>
<td>For $k =$ substrate diameter: $11 \times 10^{-5}$</td>
<td>0.0224</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>0.0173</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>0.0141</td>
<td>1.2</td>
</tr>
<tr>
<td>For $k = d_{90}$: $18.2 \times 10^{-5}$</td>
<td>0.0224</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>0.0173</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>0.0141</td>
<td>2.0</td>
</tr>
</tbody>
</table>

The dimensionless shear stress ($\theta_c$) was estimated from Equation 8.7 to define the type of flow using the Shields curve (Figure 8.12 above). Using the values of $k$ and those of $\tau_c$ (mentioned above) it is found that $\theta_c$ is in all cases 0.06, as shown on Table 8.21

Table 8.21. Dimensionless shear stress $\theta_c$ calculated from critical shear stress $\tau_c$ and the group of $k$ values.

<table>
<thead>
<tr>
<th>$\tau_c$ (N.m$^{-2}$)</th>
<th>$k$ (associated diameter percentile)</th>
<th>$\theta_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.075</td>
<td>associated to $d_{75}$</td>
<td>0.000075</td>
</tr>
<tr>
<td>0.110</td>
<td>associated to $d_{\text{substrate size}}$</td>
<td>0.000110</td>
</tr>
<tr>
<td>1.0</td>
<td>NA, refer to text (from chosen range)</td>
<td>0.001000</td>
</tr>
<tr>
<td>2.0</td>
<td>NA, refer to text (from chosen range)</td>
<td>0.002000</td>
</tr>
</tbody>
</table>
Therefore, using the Shields’ curve (Figure 8.12 above) the values of $\theta$, and the value range previously mentioned of $Re$. (0.2 to 3.1 of Table 8.20), it is found that the flow may be considered mostly hydraulically smooth.

### 8.1.10 Summary of values used for sensitivity analysis

The values established from the previous discussion of each key factor include ranges, increments and fixed values (shown in Table 8.22 below). These are used in the sensitivity analysis in order to define the comparative influence of the nine key factors on the spatial variability of overbank deposition. Results of the sensitivity analysis are shown and discussed in Chapter 9.

Additionally, the overbank deposition model is tested by comparing modelled with measured estimations. Results from this step are also shown and discussed in Chapter 9.
Table 8.22. Fixed values adopted ranges and increments of each key factor used in the sensitivity analysis; refer to Equation 4.16 (the overbank deposition model).

<table>
<thead>
<tr>
<th>Key Factor name and units</th>
<th>Unit-related range</th>
<th>Adopted Range</th>
<th>Increments within range</th>
<th>Fixed value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood duration, $F_d$ : total flooding days over the post-Eildon period (s)</td>
<td>1 - 155</td>
<td>0 – 17,280,000 (equivalent to 0 –200 days)</td>
<td>86,400; equivalent to 1 day</td>
<td>3,691,800; equivalent to 37 days (calculated average among unit values)</td>
</tr>
<tr>
<td>$d_p$ : average pond depth of the floodplain units where ponds may form (m)</td>
<td>0.12 – 1.47</td>
<td>0 – 2</td>
<td>0.05</td>
<td>0.8 (calculated average among unit values)</td>
</tr>
<tr>
<td>$D$ : average overbank flow depth along flow path (m)</td>
<td>0.7 - 2.6</td>
<td>0.1 – 3.0</td>
<td>0.05</td>
<td>1.2 (calculated average among unit values)</td>
</tr>
<tr>
<td>$SSC_{river}$ : suspended sediment concentration at the river (Kg m$^{-3}$)</td>
<td>NA</td>
<td>0 – 0.06</td>
<td>0.002</td>
<td>0.036</td>
</tr>
<tr>
<td>$SSC_{prior}$ : the suspended sediment concentration a time step prior to the isolation of the pond from the overbank flow (Kg.m$^{-3}$)</td>
<td>NA</td>
<td>0 – 0.06</td>
<td>0.002</td>
<td>0.028</td>
</tr>
<tr>
<td>$V_s$ : settling velocity (m.s$^{-1}$)</td>
<td>0.0003 - 0.02</td>
<td>0 – 0.007</td>
<td>0.0003</td>
<td>0.004</td>
</tr>
<tr>
<td>Key Factor name and units</td>
<td>Unit-related range</td>
<td>Adopted Range</td>
<td>Increments within range</td>
<td>Fixed value</td>
</tr>
<tr>
<td>---------------------------</td>
<td>--------------------</td>
<td>---------------</td>
<td>-------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>$TT$ : travel time (s)</td>
<td>261 - 49,384</td>
<td>200 – 50,000</td>
<td>800</td>
<td>16,637</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(equivalent to 4.6 hours)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(calculated average among unit values)</td>
</tr>
<tr>
<td>$\tau$ : floodplain shear stress (Nm$^2$)</td>
<td>0.003 – 1.4 (Water Tech. data)</td>
<td>therefore the adopted range is: 0.02 – 0.5</td>
<td>0.01</td>
<td>0.3 (calculated average among unit values from Water Technology data)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_c$ : critical shear stress (Nm$^2$)</td>
<td>NA</td>
<td>0.7 – 2.0</td>
<td>0.05</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Non-dimensional coefficient $k=1/30$ and $k=1/50$ were explored (discussed in Chapter 9)
9 Chapter Nine

9.1 Sensitivity analysis and model testing

9.1.1 Introduction

The sensitivity analysis that is described in this chapter is designed to identify the relative importance of each key factor in determining the spatial distribution of overbank deposition. The key factor values established in Chapter 8 (see Table 8.22), including representative values (‘fixed values’), range and increments of the corresponding key factors, are used in this analysis. Using the overbank deposition model (Chapter 4), I analyse one key factor at a time by varying its value within a plausible range, while holding the values of the rest of the key factors fixed: that is, assigning their corresponding representative values. By doing so, the analysis shows the influence of each on variations in overbank deposition (Figure 9.1 below). Results obtained from the sensitivity analysis are discussed in this chapter.

Additionally, the spatial patterns of overbank deposition that can be identified from both $^{137}$Cs detection and from the model are described and compared. This
comparison is carried out in order to assess the performance of the overbank deposition model.

9.1.2 Results of the sensitivity analysis

As discussed in Chapter 8, the ‘fixed’ values of some factors were directly derived from an analysis based on the floodplain units (unit-derived), whereas the ‘fixed’ values of other key factors were established from analyses that allowed choosing them as plausible values for the river system (these being floodplain shear stress, critical shear stress, settling velocity, SSC leaving the river and SSC prior to the isolation of the main flow within post-peak ponds). In both cases, these fixed or plausible values are referred to in this chapter as ‘representative values.’ These representative values, together with their corresponding ranges (Table 8.22 in Chapter 8), were incorporated into a Matlab run which calculated deposition amounts based on the overbank deposition model (Equation 4.16 in Chapter 4). As previously mentioned, the factor being analysed varied within its plausible range at predefined increments (Table 8.22 in Chapter 8), while the values of the other factors were fixed to their corresponding representative values. The output of each run was plotted and the corresponding graphs obtained for each key factor were assigned a letter, ‘a’ to ‘i’, in Figure 9.1 below. These runs were carried out using two different values of the calibration parameter: $k = 1/30$ and $1/50$. These $k$ values were used because, on the one hand, a comparison
between modelled estimates and measured overbank deposition (discussed later in this chapter) showed that these two estimates were close using these k values, and on the other, k= 1/30 was also used by Nicholas and Walling (1998) to calibrate their overbank deposition model.

Therefore, each of these graphs shows the variability of overbank deposition (values on the Y axis) that is associated with each key factor. These are used to identify the relative importance of the nine key factors on the spatial distribution of this type of deposition. The interpretation of these graphs is discussed below.
Figure 9.1. Output plots from the sensitivity analyses carried out for each of the key factors showing the variation in the amount of simulated deposition and ordered by the level of influence of the key factor: Graphs a to i. The plots also show the model response when \( k = 1/30 \) (black triangles) and \( 1/50 \) (magenta squares).
It was found from the sensitivity analysis that the three most influential key factors are, in order of importance, the total number of flooding days (Graph a), overbank travel time (Graph b) and overbank flow depth (Graph c) (Figure 9.1). As mentioned in Chapter 4, the last two factors are calculated considering the corresponding flow path for overbank flow to reach a given unit. These three most influential factors are, in turn, highly influenced by floodplain topography and the hydraulic connectivity that results from the interaction of that particular floodplain unit and surrounding topography with flood flow magnitude and stage.

Next, and in order of importance, although less marked (Figure 9.1), is river suspended sediment concentration (SSC<sub>River</sub>, Graph d), sediment settling velocity (Graph e) and floodplain-floor shear stress (Graph f). The order of importance of SSC<sub>River</sub> reflects the influence of sediment fluxes from the upstream and local catchment. Sediment sources include those originating from the river channel and sediment inputs from creeks and tributaries that join the main stream, both of which may influence the spatial and temporal variability of suspended sediment concentration and the transport capacity of the flow.

The influence of sediment settling velocity (Graph e) is related, as previously discussed in Chapters 2 and 8, to the calibre of the suspended sediment and flow properties, including fluid density (which at the same time is partially determined by the concentration of the sediment that is transported in suspension).

These results also show that floodplain-floor shear stress (Graph f) and critical shear stress (Graph g) have a considerable influence on the spatial variability of overbank deposition but that the influence is less than that found for the key factors ranked above it.
It is also found from this sensitivity analysis that the amounts and spatial
distribution of overbank deposition are little influenced by average pond depth
(Graph h) and suspended sediment prior to the isolation from the main flow (Graph i),
as these showed little variation across their plausible value range.

The plots in Figure 9.1 also show that the magnitude of change of
sedimentation amount is different using the two values of ‘k,’ being higher when k=1/50
(pink squares) and smaller for k=1/30 (black triangles on Figure 9.1). In both cases,
however, the variability of overbank deposition obtained in each run results in the same
order of importance of the key factors. The reason for this influence is explained
below.

9.1.3 Discussion of the results of the sensitivity analysis;
implications for floodplain development and evolution

From the analysis above, a hierarchy among the key factors can be established
(summarised in Table 9.1), which is relevant for the conceptualisation of floodplain
dynamics and evolution. A significant finding is that flood duration is the most
important factor influencing the spatial heterogeneity of overbank deposition. This
means that spatial patterns of overbank deposition markedly depend on the duration of
overbank inundation that occurs under the flood and sediment regime of a particular
river and over a specific time period. However, it is actually the combination of
overbank inundation days and the amount of sediment that is transported and
ultimately settles out at the floodplain units, which defines overbank deposition. That amount is partly determined by grain size distributions and settling velocities. Additionally, the amount of sediment that ultimately reaches a given floodplain unit is highly determined by the time for the sediment to reach that unit: travel time, which is the second most important factor. This time determines the decrease of SSC as the sediment travels along the overbank flow-path network. However, it is the actual interactions of all the key factors, and the effects of those interactions, which ultimately determine the amount of sediment that settles out.

On the one hand, travel time, flow depth, suspended sediment concentration and sediment size contribute to the sediment transport process. On the other, sediment sources and fluxes interacting with overbank flow paths over the cumulative duration of overbank flooding (including those originating from the river, the floodplain or even the tributaries) are also important (see Table 9.1 below).

The hierarchy of the key factors found from the sensitivity analysis means that floodplain units with a higher cumulative duration of overbank inundation, will tend to infill faster if the sediment being transported along the overbank flow paths reaches the units in a relatively shorter time. This latter factor is influenced by the distance travelled and average flow velocity along the overbank flow paths (Chapter 8).

Moreover, even though the influence of some key factors is not so strong, there may still be cases in which the interaction with the other key factors plays an important role. For example, it was found from the sensitivity analysis that post-peak pond depth, together with SSC at those ponds, is of least importance. However, there still may be cases in which the combination of (a) the existence of deep post-peak ponds along the floodplain, (b) small travel times and (c) high concentrations of suspended sediment
will lead to large amounts of overbank deposition in those ponds. It is important to note that the sensitivity analysis did not examine interacting effects of multiple key factors.

In conclusion, the sensitivity analysis developed in this research has elucidated the most significant key factors in determining the spatial variability of overbank deposition, at least for the mid-Goulburn River. This analysis was only possible using the new overbank deposition model developed for this research. A final step, however, needs to be completed. This is to assess the accuracy of the model by comparing modelled with observed estimates (established from Cs$^{137}$ analysis) of overbank deposition. For this assessment I use k$=\frac{1}{30}$ and $\frac{1}{50}$ to illustrate that modelled estimates using k$=\frac{1}{30}$ are better predictions. This comparison is shown and discussed in the next section.
Table 9.1. Hierarchy of the key factors determining the spatial variability of overbank deposition and the additional processes and sediment inputs which can all determine overbank deposition and floodplain evolution

<table>
<thead>
<tr>
<th>Hierarchy among the key factors</th>
<th>Key factor</th>
<th>Related aspects</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flood duration, ( F_d )</td>
<td>Floodplain topography (including relative elevation in relation to the overbank flow); hydraulic connectivity, and susceptibility to overbank inundation of floodplain units</td>
</tr>
<tr>
<td>2</td>
<td>Travel time, ( T_T )</td>
<td>These three are established in relation to the distance travelled along the overbank flow paths that form during overbank inundation to reach the floodplain units.</td>
</tr>
<tr>
<td>3</td>
<td>Average flow depth, ( D )</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>River suspended sediment concentration, ( SSC_{river} )</td>
<td>SSC decreases with travel time only if no additional sources from the river exist.</td>
</tr>
<tr>
<td>5</td>
<td>Sediment settling velocity, ( V_s )</td>
<td>Depends of grain-size distributions of the suspended sediment.</td>
</tr>
<tr>
<td>6 and 7</td>
<td>Shear (( \tau )) and critical (( \tau_c )) shear stress</td>
<td>Affected by floodplain vegetation cover and type</td>
</tr>
<tr>
<td>8</td>
<td>Pond depth, ( d_p )</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Suspended sediment concentration prior to isolation to the main flow, ( SSC_{prior} )</td>
<td>Occurs during the flood-recession phase (post-peak pond deposition)</td>
</tr>
</tbody>
</table>

**Additional processes and sediment inputs to those of the river**

**Additional processes and mechanisms**
- Floodplain scouring, sediment resuspension and erosion

**Additional sources to those originating from the river**
- Lateral sediment inputs (tributaries)
- Additional sources within the catchment, such as those from hill slope erosion or from floodplain scour.
9.1.4 Measured and predicted patterns of overbank deposition: assessment of the overbank deposition model

Numerical models in hydrology and earth sciences are built with the intention of representing complex systems whose operative processes are usually not fully understood and for which the required empirical input data are “incompletely or only approximately known” (Oreskes, Shrader-Frechette & Belitz 1994). It is a common case that only limited data is collected or available to test these models. This incomplete knowledge and information about fluvial system dynamics defines rivers as open and not closed systems, as specified by Oreskes, Shrader-Frechette and Belitz (1994). According to them, another reason why natural systems in general are not closed systems is that observations and measurement of independent and dependent variables are, unavoidably, loaded with inferences and assumptions, which make these systems open. In this context, Oreskes, Shrader-Frechette and Belitz (1994) argue that only closed systems may be verifiable and validated in the most rigorous way. Therefore, our capabilities as scientists are restricted to assessing the accuracy of numerical models and their relative performance in relation to observational data, as well as in relation to other models of the same site or to our own expectations, which are usually based on theoretical preconceptions and experience.

As mentioned earlier in this thesis (Chapters 2, 3 and 6), overbank deposition may be influenced by various types of floodplain erosion and different sediment sources (i.e. sediment not originating from the river channel). To overcome the added complexity that would result from combined effects of sediment erosion and deposition
processes when trying to establish spatial patterns of overbank deposition along the selected alluvial floodplain, the approach used in this thesis focused on floodplain sites that were believed to be dominated by overbank deposition and on which additional processes and sediment sourcing could be assumed minimal. Since the overbank deposition model does not include these additional processes it should therefore be expected that the model is limited in its ability to predict accurate estimates when these additional processes are present.

As discussed in Chapter 7, post-Eildon sedimentation rates were estimated from detection of $^{137}$Cs concentration in floodplain samples from sparsely distributed and strategically selected floodplain units. Results obtained from $^{137}$Cs analysis show that sediment accumulation over the post-Eildon period (i.e. from 1955) varies from -30 to 362 millimetres of thickness among the thirteen floodplain units (see Table 7.15 in Chapter 7). In order to compare the measured estimates of net accumulation with those of the model, measured estimates are expressed in kg.m$^{-2}$ after dividing net accumulation (depth) by the average density of floodplain samples (calculated in Chapter 7; i.e. 1.17 kg.m$^{-3}$). Measured net sediment accumulation of the thirteen floodplain units range from -36 to 423 kg.m$^{-2}$, as shown on Table 9.2.

Negative figures of accumulation indicate erosion, which has been found for two floodplain units (Units 2 and 9). A comparison between modelled and measured overbank deposition amounts of the thirteen floodplain units is carried out below.

Using Equation 4.16 of Chapter 4, modelled estimates were obtained from the key factor values calculated for the floodplain units (Chapter 8) as well as with various calibration parameters. Modelled estimates obtained with both, $k = 1/30$ and $k = 1/50$, are shown in Table 9.2 and on Figure 9.2 below. Of these, those obtained with $k = 1/30$
are the best predictions. This value of k was also used by Nicholas and Walling (1998) to calibrate their overbank deposition model. Therefore, k = 1/30 was chosen as the calibration parameter for the overbank deposition. As shown on Figure 9.2 and in Table 9.2 above, the model predicts better estimates of overbank deposition amounts with the calibration parameter k = 1/30, matching the measured values acceptably well for Units 1, 3, 4, 7, 11, 12, and 13. Therefore, model predictions obtained with this k value are used in further discussions.

As mentioned earlier, the overbank deposition model being evaluated only provides estimates of overbank sediment deposition (discussed earlier in Chapter 4). Measured estimates of Units 2 and 9 (obtained from $^{137}$Cs analysis) showed that these units have been eroded over the post-Eildon period (Table 9.2). As these processes are not explicitly represented in the model, it should be expected that predicted and measured deposition amounts of these two units will differ due to this fact.

$^{137}$Cs analysis shows that the eleven depositional units have accumulated a range of 0 to 423 kg.m$^{-2}$ of overbank sediment at a maximum rate of 6.7 mm.yr$^{-1}$ (Table 9.3) over the post-Eildon period. Of these eleven units, an abandoned channel and a meander cutoff show the highest sediment accumulation (i.e. Unit 3 with 186mm and Unit 10 with 362mm over the period), while most of the other units have accreted at comparatively lower rates with a maximum of 38mm of thickness over the post-Eildon period (see Table 9.2). It can be identified that positive figures of overbank deposition calculated from $^{137}$Cs detection and those predicted by the model are within the same order of magnitude (with modelled estimates ranging from 0.05 to 320 kg.m$^{-2}$, with k = 1/30; Table 9.2).
Figure 9.2. Predicted deposition amounts using k=1/50 and 1/30 and measured estimates based on $^{137}$Cs detection (see Table 9.2). Floodplain unit numbers (Units 1 to 13) are the X axis. Measured and modelled estimates better match using k=1/30. Units 1 to 8 are from the downstream reach and Units 9 to 13 from the upstream reach. Measured estimates calculated from $^{137}$Cs detection show that net erosion has occurred at Units 2 and 9 (i.e. the negative numbers).
Table 9.2. Measured and modelled estimates using $k=1/30$ and $k=1/50$. Units shown in red represent net erosion. The closest match is obtained with $k=1/30$. The highlighted figures are the largest mismatches. As discussed earlier in this thesis, the model is limited in its ability to accurately predict deposition if erosion processes are occurring; this is the case for Units 2 and 9 (in red). The type of floodplain unit (i.e. abandoned channel, meander cutoff or floodplain swale) are summarised in Table 9.3

<table>
<thead>
<tr>
<th>Floodplain unit ID (and core names)</th>
<th>Net deposition amount $^{137}\text{Cs}$-derived (Kg.m$^{-2}$)</th>
<th>Modelled estimates using $k=1/30$; (Qd) (Kg.m$^{-2}$)</th>
<th>Modelled estimates using $k=1/50$; (Qd) (Kg.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reach 1 (UPSTREAM SEGMENT)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit 10 (1F)</td>
<td>423</td>
<td>0.1 (large underestimation)</td>
<td>3, large underestimation</td>
</tr>
<tr>
<td>Unit 11 (1A.1B.1C)</td>
<td>38</td>
<td>3.2 (underestimation)</td>
<td>11 underestimation</td>
</tr>
<tr>
<td>Unit 12 (1D.1DBis.1E)</td>
<td>7</td>
<td>0.05 (small underestimation)</td>
<td>1 underestimation</td>
</tr>
<tr>
<td>Unit 13 (1L.1G.1I)</td>
<td>10</td>
<td>0.4 (small underestimation)</td>
<td>5 underestimation</td>
</tr>
<tr>
<td>Reach 2 (UPSTREAM SEGMENT)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit 9 (2D.2E.2F)</td>
<td>-36 (erosion)</td>
<td>65</td>
<td>72</td>
</tr>
<tr>
<td>Reach 3 and 4: DOWNSTREAM SEGMENT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit 8 (N.J.Q)</td>
<td>29</td>
<td>320 (large overestimation)</td>
<td>334 (large overestimation)</td>
</tr>
<tr>
<td>Unit 7 (QQ.BB.AA)</td>
<td>1</td>
<td>15 (small overestimation)</td>
<td>16 (overestimation)</td>
</tr>
<tr>
<td>Unit 6 (FF.GG.HH)</td>
<td>17</td>
<td>78 (large overestimation)</td>
<td>93 (overestimation)</td>
</tr>
<tr>
<td>Unit 5 (CC.DD.EE)</td>
<td>6</td>
<td>117 (large overestimation)</td>
<td>119 (overestimation)</td>
</tr>
<tr>
<td>Unit 4 (F.G)</td>
<td>36</td>
<td>45 (small overestimation)</td>
<td>67 (overestimation)</td>
</tr>
<tr>
<td>Unit 3 (A.B.UU)</td>
<td>218</td>
<td>201 (small underestimation)</td>
<td>253 (overestimation)</td>
</tr>
<tr>
<td>Unit 2 (K.L.M)</td>
<td>-19 (erosion)</td>
<td>338</td>
<td>352</td>
</tr>
<tr>
<td>Unit 1</td>
<td>45</td>
<td>62 (small)</td>
<td>81 (overestimation)</td>
</tr>
</tbody>
</table>
9.1.4.1 Description of the discrepancies between modelled and measured estimates

From Figure 9.2 and Table 9.2, a range of differences between the modelled and measured estimates is found, being the largest mismatches those highlighted in grey on Table 9.2, including the estimates for Units 2, and 9 which are the two eroded units. Without considering these eroded units, Units 10 and 8 are the two with the largest discrepancies.

It had been identified in Chapter 6 (refer to Table 6.4) that Unit 10 has a high susceptibility to overbank inundation, and the measured estimate of this Unit (423 kg.m\(^{-2}\)) correlates well with this, which in fact, represents the largest value among the eleven units\(^{14}\) (Table 9.2 above). The model, however, predicts a very small deposition amount for the same Unit (0.1 kg.m\(^{-2}\)). On the other hand, the model calculates a large net deposition for Unit 8 (320 kg.m\(^{-2}\)), in contrast with the estimate derived from \(^{137}\)Cs detection (29 kg.m\(^{-2}\)). Possible explanations for these two largest mismatches, and also of the other mismatches highlighted on Table 9.2, are discussed in detail later in this section.

To proceed with this analysis, it is important to mention first that there are uncertainties in the estimation of rates and amounts derived from \(^{137}\)Cs detection. As discussed in Chapter 7, uncertainties associated to detection of this radionuclide were reported by the ANSTO laboratory with a 95% confidence, although uncertainties

\(^{14}\) Eleven units because instead of net overbank deposition, net erosion has occurred in Units 2 and 9.
associated to $^{137}$Cs detection of each sediment sample reported by this nuclear laboratory, and thus uncertainties associated with the subsequent calculation of total inventories, were relatively large. Additionally, it is also important to mention that the calculated deposition amounts obtained from $^{137}$Cs detection are an average of the actual deposition amount at the three sites sampled along the floodplain unit (as explained in Chapter 7).

The floodplain units have been divided into those of the upstream (reach 1 and 2) and those of the downstream reaches (reach 3 and 4). The two estimates of each unit (model vs. measured) have been plotted on Figure 9.3 and Figure 9.4 below respectively.

A pattern of small net overbank deposition is found from both the modelled (as mentioned earlier, using $k = 1/30$) and the measured estimates for three of the units of Reach 1 (closer to the dam), which are Units 10 to 13 (as shown in Table 9.2 above). The low deposition amounts at these units is consistent with their location, as Units 10 to 13 are closer to the reservoir (see Table 9.3 below). The large volume of Eildon Reservoir relative to inflows produces large trap efficiencies and hence low sediment concentration in reservoir outflows. However, Unit 10 is the exception to this pattern (Table 9.2 and Figure 9.2 above), which is discussed further below. With only four units where net deposition has occurred in the upstream reach, a regression analysis for these units was not attempted.

For the seven depositional units of the downstream reach (i.e. excluding eroded Unit 2), it is found that a positive and significant relationship exists between the two estimates for deposition rates at the units in the downstream reach. The regression function, shown on Figure 9.4 below, gives an $R^2$ value of 0.43 with $P = 0.11$, which is
just outside the 10% significance limit. This is an especially good fit, considering the relatively small sample size, and suggests that the model is a reasonably good predictor of overbank deposition amounts along this reach.

This analysis suggests that, overall, the model is a reasonably good predictor of deposition amounts along both reaches.

Figure 9.3. Modelled estimates of deposition amounts (using K=1/30) versus $^{137}$Cs-derived estimates of the floodplain units of the upstream reach and closer to the dam; only Unit 9 is further. Both estimates reveal small deposition amounts for these units (circled), with the exception of Units 9 (eroded unit) and 10. For Unit 10, the model predicts a low deposition amount of only 0.1 while the measured deposition amount obtained from $^{137}$Cs analysis is 423 kg.m$^{-2}$. 
Figure 9.4. Modelled calculations of deposition amounts (using k=1/30) versus $^{137}$Cs-derived estimates. Floodplain units in this plot are those of the downstream reach, for which a positive and significant relationship exists between the estimates (i.e. Units 1 to 8 on Table 9.2 above). Note that the regression function has a reasonably good fit, specially given the small sample size; where P is just outside the 10% significance limit (i.e. P=0.11).

In order to carry out a deeper analysis of the discrepancies, the calculated key factors associated with each floodplain unit, as well as the predicted and measured deposition amounts are summarised in Table 9.3 below. Additionally, this table also shows the susceptibility to overbank inundation of each floodplain unit, which was established in Chapter 6. From these data, it is important to mention that I found that the anticipated patterns of overbank deposition, which was based on the susceptibility to overbank inundation of the floodplain units, correspond to the actual net sediment accumulation found from $^{137}$Cs detection; only with the exception of two units: Units 9 and 12 (compare 9th and 11th column of Table 9.3). This correspondence, therefore,
exists for the highest accumulation rates found at Unit 3 (upstream reach) and Unit 10 (downstream reach).
Table 9.3. Summary of the calculated key factors associated with each floodplain unit. Travel times, distances from channel, average flow depth and flow velocities are those calculated in function of the corresponding overbank flow paths of the floodplain units, as described in Chapter 8. Floodplain reaches 1 to 4 are shown in Figure 7.2 (Chapter 7). The average dry bulk density of the core samples collected at each floodplain unit were used to calculate net deposition based on $^{137}$Cs detection over the post-Eildon period (see Table 7.14).

<table>
<thead>
<tr>
<th>Cores and Unit ID</th>
<th>Unit type</th>
<th>River distance to Eildon station (km)</th>
<th>Flood duration (days)</th>
<th>Travel Time (m)</th>
<th>Dist from Channel (m)</th>
<th>Av. Flow Depth (m)</th>
<th>Flow Velocity (m.s$^{-1}$)</th>
<th>Net deposition ($^{137}$Cs) (post-Eildon period) (mm)</th>
<th>Net deposit. Amount ($^{137}$Cs) (post-Eildon period) (kg.m$^{-2}$)</th>
<th>Modelled Estimate (kg.m$^{-2}$)</th>
<th>Identified Suscept. to overbank inundation - Chapt 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1D,1D.Bis,1E Unit 12</td>
<td>cutoff</td>
<td>13.1 (reach 1)</td>
<td>25</td>
<td>762 (12.7 hours)</td>
<td>3,490</td>
<td>0.7</td>
<td>0.14</td>
<td>6</td>
<td>7</td>
<td>0.05</td>
<td>small under</td>
</tr>
<tr>
<td>1L,1G,1I Unit 13</td>
<td>abandoned channel</td>
<td>16.8 (reach 1)</td>
<td>25</td>
<td>576 (9.6 hours)</td>
<td>3,285</td>
<td>0.7</td>
<td>0.15</td>
<td>33</td>
<td>10</td>
<td>0.4</td>
<td>small under</td>
</tr>
<tr>
<td>1A,1B,1C Unit 11</td>
<td>swales</td>
<td>17.2 (reach 1)</td>
<td>8</td>
<td>360 (6 hours)</td>
<td>3,685</td>
<td>0.9</td>
<td>0.24</td>
<td>33</td>
<td>38</td>
<td>3.2</td>
<td>small under.</td>
</tr>
<tr>
<td>1F Unit 10</td>
<td>abandoned channel</td>
<td>17.4 (reach 1)</td>
<td>90</td>
<td>822 (13.7 hours)</td>
<td>3,665</td>
<td>0.7</td>
<td>0.13</td>
<td>362</td>
<td>423</td>
<td>0.1</td>
<td>large under</td>
</tr>
<tr>
<td>2D,2E,2F Unit 9</td>
<td>swales</td>
<td>39.2 (reach 2)</td>
<td>155</td>
<td>570 (9.5 hours)</td>
<td>1,305</td>
<td>0.9</td>
<td>0.10</td>
<td>-30</td>
<td>-36</td>
<td>65</td>
<td>large over.</td>
</tr>
<tr>
<td>Cores and Unit ID</td>
<td>Unit type</td>
<td>Riv dist. Eildon stn. (Km)</td>
<td>Flood duration (days)</td>
<td>Travel Time (min)</td>
<td>Dist from Channel (m)</td>
<td>Av. Flow Depth (m)</td>
<td>Flow velocity</td>
<td>Net deposit. ((^{137})Cs) (post-Eildon period) (mm)</td>
<td>Net deposit. Amount ((^{137})Cs) (post-Eildon period) (kg.m(^{-2}))</td>
<td>Modelled Estimate (kg.m(^{-2}))</td>
<td>Susceptibility to overbank inundation - Chapt 6</td>
</tr>
<tr>
<td>------------------</td>
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<td>-----------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>N,J,Q Unit 8</td>
<td>(swales)</td>
<td>57 (reach 3)</td>
<td>41</td>
<td>36</td>
<td>295</td>
<td>2.6</td>
<td>0.27</td>
<td>25</td>
<td>29</td>
<td>320 large over</td>
<td>Moderate</td>
</tr>
<tr>
<td>QQ, BB, AA Unit 7</td>
<td>(swales)</td>
<td>76.6 (reach 4)</td>
<td>only 2</td>
<td>18</td>
<td>105</td>
<td>1.3</td>
<td>0.12</td>
<td>1</td>
<td>1</td>
<td>15 small over</td>
<td>Low</td>
</tr>
<tr>
<td>FF, GG, HH Unit 6</td>
<td>(swales)</td>
<td>76.6 (reach 4)</td>
<td>14</td>
<td>66</td>
<td>265</td>
<td>1.2</td>
<td>0.11</td>
<td>14</td>
<td>17</td>
<td>78 large over</td>
<td>Moderate</td>
</tr>
<tr>
<td>CC, DD, EE Unit 5</td>
<td>(swales)</td>
<td>76.6 (reach 4)</td>
<td>14</td>
<td>4.3</td>
<td>125</td>
<td>0.9</td>
<td>0.49</td>
<td>5</td>
<td>6</td>
<td>117 large over</td>
<td>Low</td>
</tr>
<tr>
<td>F,G Unit 4</td>
<td>(meander cutoff)</td>
<td>78.2 (reach 4)</td>
<td>14</td>
<td>132  (2.2 hours)</td>
<td>510</td>
<td>1.0</td>
<td>0.16</td>
<td>31</td>
<td>36</td>
<td>45 small over</td>
<td>Moderate</td>
</tr>
<tr>
<td>K,L,M Unit 2</td>
<td>(swales)</td>
<td>79.2 (reach 4)</td>
<td>41</td>
<td>17.3</td>
<td>30</td>
<td>1.5</td>
<td>0.03</td>
<td>(-16)</td>
<td>(-19)</td>
<td>338 large over</td>
<td>Low</td>
</tr>
<tr>
<td>A, B, UU Unit 3</td>
<td>(meander cutoff)</td>
<td>80.1 (reach 4)</td>
<td>41</td>
<td>90  (1.5 hours)</td>
<td>340</td>
<td>1.3</td>
<td>0.8</td>
<td>186</td>
<td>218</td>
<td>201 small under</td>
<td>High</td>
</tr>
<tr>
<td>D, TT, E Unit 1</td>
<td>(swales)</td>
<td>82 (reach 4)</td>
<td>14</td>
<td>150  (2.5 hours)</td>
<td>350</td>
<td>1.8</td>
<td>0.9</td>
<td>38</td>
<td>45</td>
<td>62 small over</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
Considering the data shown in Table 9.3, the units with the highest number of flooding days over the post-Eildon period are Units 2 (with 41 days, although it is eroded), 3 and 8 (both with 41 days), Unit 9 (with 155 days, also eroded) and Unit 10 (with 90 days). In line with the positive correlation identified from the plot above (Figure 9.4), the model estimates the largest sedimentation amounts for Units 3 and 8, which correlates well with the estimates provided from $^{137}$Cs analysis, and with the high cumulative flood duration of these units. However, the model does not predict high sediment accumulation for either Units 2, 9 and 10, which have been flooded during the larger number of flooding days.

In fact, the greatest mismatches between modelled and measured estimates occur for depositional Unit 10 and eroded Units 2 and 9. For Unit 10, the modelled deposition amount is only 0.1 kg.m$^{-2}$ while the measured deposition is 423 kg.m$^{-2}$. The possible causes of these mismatches are explained below.

It was found from the sensitivity analysis that the second most influential factor determining the spatial distribution of overbank deposition is travel time.

Travel time is particularly long for Units 10 to 13 along the upper reach (see overbank flow paths on Figure 9.6; Figure 9.7, Figure 8.2 and Figures E.10 to E.12 in Appendix E). Given the nature of the model expression, a large figure in the exponential term due to long travel times associated with these four units, the model predicts small deposition amounts. This long travel time, in fact, represents the decrease in SSC along the flow path towards the unit when travel time and distance are large (i.e. sediment exhaustion).

It might be assumed that since Unit 10 is closer to the reservoir (as are the rest of the units of the upstream reach) the river sediment load would be small due to
sediment trapping in the dam, and also, that since the river bed is armoured along reaches that are close to the dam (as mentioned in Chapter 5) the river is restricted in its capacity to recruit new sediment along the upstream reach. Thus, this unusually high accumulation rate in Unit 10 could be related to the influence of other variables that are not being considered, such as the existence of additional sources of sediment that may be reaching this unit, such as tributary inputs. Analysing in detail the digital elevation model, together with the 2005 aerial photograph of the floodplain reach where Unit 10 is located, it was found that additional sources from the closest tributary, the Rubicon River (Figure 9.5 and Figure 9.6 below), could be influencing this high accumulation. A local landholder who has lived near Unit 10 for 75 years, Gilmore K (2009, pers. comm., 7 May), stressed that, even though the duration and frequency of overbank flooding of the Goulburn River has decreased considerably following the building of Lake Eildon, flooding along his land still occurs “whenever it rains over 4 inches” but that the water “comes from the Rubicon” and not from the Goulburn.

Sediment contributions from the Rubicon River have not been modelled in this analysis as the model only predicts overbank deposition from sediment of the Goulburn River. As mentioned in Chapter 5, the Rubicon River flows parallel to the Rubicon fault and approaches the Goulburn River along the floodplain, joining it just downstream of the meander cutoff that is shown on Figure 9.5. This meander cutoff has been identified in Appendix A as Meander Cutoff 3; it was formed between 1877 and 1935, and it is likely that at present it acts as a secondary channel of the Goulburn River during high in-channel flows and overbank inundation. This meander cutoff and the four floodplain units of the upstream reach are clearly shown on Figure 9.6.
Figure 9.5. Identified meander cutoff (Cutoff 3) which was formed during the pre-Eildon period and the location of the four floodplain units of the upstream reach. The Rubicon River joins the Goulburn River just downstream of that cutoff.

When the Rubicon flows are high, it contributes to the inundation of the secondary channel that is near Unit 10. As it can be seen Figure 9.7 below, a little join between the secondary channel and Unit 10 appears to exist. These three features, the Goulburn River with inflows from the Rubicon (which joints the Goulburn as indicated on Figure 9.5 above), the secondary channel and Unit 10, are likely to be hydraulically connected during overbank flooding. Gilmore K, the landholder (pers. comm., 7 May 2009) has mentioned that overbank inundation still occurs on some areas of his land (which includes three floodplain units of this reach). This could explain the fact that only Unit 10 receives this sediment input from the Rubicon but the other three units of the upstream reach do not.

Results obtained from the sensitivity analysis indicate that SSC and its spatial and temporal variability have an important influence on overbank deposition patterns.
However, the model was not designed to incorporate these additional sources, as it only predicts sediment deposition that originated from the Goulburn River channel. Therefore, the overbank deposition model underestimates the deposition amount found from $^{137}$Cs analysis for Unit 10.

Figure 9.6. The 2005 aerial photograph showing the meander cutoff (Cutoff 3 in Figure 9.5) which is near the four units of the upstream reach (delineated in purple). Yellow crosses are cored sites. The various flow paths, corresponding to each floodplain unit, are shown by the orange line.
Figure 9.7. The LIDAR DEM showing the same floodplain reach as Figure 9.6, Meander Cutoff 3 and the four units located along the upstream reach (delineated in purple). Yellow crosses are cored sites. A small ‘path’ can be seen between the cutoff and Unit 10. The various flow paths to the corresponding floodplain units are shown by the orange lines.

The other mismatches between the modelled and measured estimates for Units 2, 5, 6, 8 and 9 are large overestimates by the model relative to those obtained from $^{137}$Cs analysis (Figure 9.2, Table 9.2 and Table 9.3 above).

$^{137}$Cs analysis shows that Unit 2 has been eroded over the post-Eildon period. It was determined in Chapter 8 that this unit has been flooded 41 days over this period; that the distance from the river and travel time are short (30 metres and 17 minutes respectively) and that the average flow depth and velocity associated with this unit are, respectively, 1.5 metres and 0.03 m.s$^{-1}$. It is difficult to draw conclusions from these data as the values associated with this unit of all the three most important key factors
suggest that this unit should have accumulated sediment, as has been predicted by the model. Sediment exhaustion is likely to occur only if sediment size and settling velocity are much larger than the values used in the model calculation, but given the short distance and travel time associated with this unit, it is hard to establish that the explanation is a notable decrease of SSC along the flow path. This probably indicates that, as previously established, the model has been designed to predict sediment deposition that occurs as a result of overbank inundation and therefore, it should not be expected that it provides adequate predictions in scenarios where erosion has dominated.

For Unit 5, a notably smaller travel time from the channel exists, of only 4.3 minutes, which, in comparison to that of the other units, determines this model prediction of deposition amounts (see Chapter 8). That is, given the nature of the model equation, a small number in the exponential term will result in a relatively large figure, in this case 117 kg.m\(^{-2}\), while the amount obtained from \(^{137}\text{Cs}\) analysis is only 6 kg.m\(^{-2}\) (Table 9.3). This unit has only been flooded for 14 days over the post-Eildon period; distance from the channel to this unit (along the overbank flow path formed at its flooding threshold) is 125 metres; the average flow depth along the overbank flow path to the unit is 0.9 metres and the average overbank flow velocity along the flow path is 0.49 m.s\(^{-1}\) (Table 9.3). This last is, in fact, the highest overbank flow velocity of all of the floodplain units. If the floodplain floor is not well protected from erosion, this high flow velocity may be causing floodplain-unit scouring and a lower deposition amount than that calculated by the model. As mentioned earlier in this chapter, floodplain scouring is a process not represented in the model and, thus, is one of the model limitations. As mentioned earlier in Chapter 8, the difficulty of adequately (i.e.
spatially and temporally) representing and incorporating floodplain-floor shear stress could cause inaccuracies in the model predictions. It is also the case that the $^{137}$Cs analyses cover a long time period during which there will have been variations in floodplain condition, while the model considers only a single condition.

Similarly, for Unit 6 the model overestimates the deposition amount by calculating 78 kg.m$^{-2}$ while the observed deposition amount (calculated from $^{137}$Cs) is 17 kg.m$^{-2}$. Distance travelled along the overbank flow path to this unit is 265 metres, the average flow depth 1.2 metres, travel time 1.1 hours and flow velocity 0.11 m.s$^{-1}$ (Table 9.3). Even though a relatively low velocity and large travel time were established for this unit, the model estimates a larger deposition amount than that established from $^{137}$Cs analysis. Floodplain scouring or sediment re-suspension is not likely to occur with this low velocity. However, sediment exhaustion could be possible if the suspended sediment being transported to this unit is primarily composed of sand fractions. If that were the case, sediment exhaustion (along the overbank flow path) could occur faster than what the model predicts since sand tends to settle out faster than finer sediment. As discussed in Chapter 8, an approximation of the approach included obtaining a representative grain size that was assumed for the suspended sediment, even though this was established from floodplain deposits. This inaccuracy could be reflected in the model prediction for this unit.

For Unit 8 the model also predicts a higher deposition amount, 320 kg.m$^{-2}$, in comparison to that established from $^{137}$Cs: 20 kg.m$^{-2}$. In this case, the comparatively long number of days in which this unit has been flooded, 41 over the post-Eildon period (Table 9.3) - most likely could explain this model overestimate. Distance travelled along the overbank flow path to this unit is 295m; the average flow depth (the third
most influential factor) 2.6m and the deepest overall; travel time 36 minutes and flow
velocity is 0.27m.s\(^{-1}\) (the second highest overall); as shown in Table 8.4 (Chapter 8). If
the floodplain floor is poorly protected from sediment resuspension or floodplain
scouring, these processes could occur, and therefore, affect the accuracy of the model
predictions as the model is not designed to represent these processes.

For Unit 9 in reach 3 of the upstream reach, the model overestimates a
deposition amount of 338 kg.m\(^{-2}\), while the measured amount indicates erosion (i.e. -36
kg.m\(^{-2}\) Table 9.2). This is in fact the second largest mismatch of the model. Flood
duration (the total number of days in which this unit has been flooded) is 155 days;
travel time 9.5 hours, distance from the channel 1,305 metres and average flow
velocity and flow depth (all these four along the flow path) are 0.11 m.s\(^{-1}\) (relatively low)
and 0.9 metres respectively (this flow depth similar to the other units of the upstream
reach). The relatively low velocity and long travel time (with the consequent decrease
of SSC along the overbank flow path) indicate that, if the floodplain floor is not well
vegetated, then net erosion may be resulting, as the measured deposition amount for
this unit shows. As discussed throughout this study, erosion processes are not
adequately represented in the overbank deposition model developed in this research
and thus the model is not likely to predict accurate estimates.
9.1.4.2 Model limitations and sources of inaccuracy

In this section, I examine the uncertainties associated with both the measured and modelled estimates, and I also discuss additional factors that are not included in the model.

Firstly, to assess the model accuracy, it is important to bear in mind that observed values of deposition, obtained from $^{137}$Cs detection, have their own uncertainties and inaccuracies. As discussed in Chapter 7, $^{137}$Cs estimates were obtained from bulked samples of the same depth intervals and, in most cases, of three different locations along the floodplain units. Therefore, they are considered to be ‘an average’ of the actual deposition that may have occurred at different locations of the floodplain units over the post-Eildon period. It was also mentioned in Chapter 7 that the associated uncertainties established by the laboratory technicians at ANSTO associated with $^{137}$Cs detection were reasonable but, nevertheless, substantial.

Secondly, model inaccuracies and uncertainties are related to various aspects; including the definition of the key factor values and unavoidable approximations that had to be made. These include the definition of half of the key factor values used in the model, which was based on analyses focused on finding plausible values, as insufficient data made it impossible to define them otherwise. As discussed in Chapter 8, this is the case for the definition of the key values of shear stress ($\tau$), critical shear stress ($\tau_c$), the SSC leaving the river and SSC prior to the disconnection from the main flow during post-peak pond formation ($SSC_{River}$ and $SSC_{prior}$, respectively). Secondly, the other half of the key factor values, including flood duration ($F_d$), pond depth ($d_p$), flow depth ($D$), settling velocity ($V_s$) and travel time ($TT$), were obtained from an
approximation as these were calculated by considering only the flooding thresholds (a

discharge threshold) of the thirteen floodplain units (Chapter 8).

Additional uncertainties and sources of inaccuracies of the modelled estimates
can be related to the calculation of the actual distance between the unit and the flow
spilling points, as well as in the definition of the flow paths. As shown Chapter 8, flow
paths were derived from flow velocity rasters of the hydraulic model (Water Technology
2009) with consideration of the flooding threshold of the units (defined in Chapter 6).
However, this approach is an approximation since, in fact, it is known that flood
magnitudes higher than those of the flooding thresholds have occurred during the post-
Eildon period along this floodplain section. This means that in those cases flow height
is above the established thresholds; that the flow paths may differ from the ones
forming at the thresholds; and that, in fact, some factors, such as travel time, flow
velocity and depth (which are calculated considering flow paths) may also, in those
cases, be different to the ones defined from the corresponding flooding thresholds of
each floodplain unit analysed here. This, therefore, shows that the model estimates of
overbank deposition amounts calculated for each unit are approximations and that
some discrepancies between model and $^{137}$Cs-derived estimates should be expected.

However, considering that overbank inundation over the post-Eildon period along the
floodplain section has been dominated by small (not by moderate or big) floods makes
the approach adopted (based on the flooding thresholds of the floodplain units), an
adequate one.

Additionally, as has been identified in the previous section, other variables that
are outside of the scope of the model seem to be influencing overbank deposition
amounts along some floodplain units, including additional sediment sources, floodplain
sediment resuspension and floodplain scouring during overbank inundation. These are likely to be the cause of the largest mismatches found between observed and modelled estimates (floodplain units 2, 5, 8 and 10). These additional processes limit the accuracy of the estimates obtained with the overbank deposition model.

Thus, considering the assumptions and inferences adopted as well as the gaps previously identified in relation to records and data needed for defining the key factor values (Chapter 8), to have found the relatively small discrepancies between the modelled estimates and those derived from $^{137}$Cs analysis is a good outcome (see Figure 9.2 and Figure 9.4 above).

Therefore, even though modelled estimates differed (to different degrees) with those obtained from $^{137}$Cs detection, the results discussed are encouraging. It was shown earlier in this chapter that the two estimates (modelled vs. measured) were similar for the units in the upstream reach and that, for those of the downstream reach, a good fit was found between these (Figure 9.3 and Figure 9.4 above). This was a relatively small sample size (seven floodplain units along this reach) and the $R^2$, with $P = 0.11$ just outside of the 10% significance limit.

Even though it could be thought that model errors and uncertainties could be overcome, to some extent, by having larger sample sizes (which means increasing the number of floodplain units and then possibly adjusting the key factor values used accordingly), this strategy was not possible given the complexity and cost of the $^{137}$Cs analyses.
9.1.5 Conclusions

As discussed above, the results obtained from both the sensitivity analysis and the assessment of the model accuracy are quite satisfactory. As shown in this chapter, the main aims of this research have been addressed by finding that a hierarchy exists among the key factors, which is based on their influence on the spatial variability of overbank deposition (Table 9.1 above). This outcome was possible from an improved conceptualisation of the interaction among the key factors on which the overbank deposition model is based (Equation 4.16 in Chapter 4). All three aspects, the conceptualisation, the model and the hierarchy of the key factors, are significant contributions that may be used in studies seeking to establish spatial patterns of overbank deposition or to further explore possible improvements in predicting spatial patterns of overbank deposition.

Moreover, the evaluation of the model accuracy developed in this chapter shows that the model can be a good predictor of the spatial distribution of overbank deposition. Considering the limitations of the model and the data gaps previously identified (such as insufficient records of SSC during overbank inundation, grain size distributions of suspended sediment, floodplain-floor shear stress and critical shear stress), as well as the assumptions and inferences adopted, it is a good outcome to have found the relatively small discrepancies between model and observed deposition amounts (the last obtained from the $^{137}$Cs analysis).

As previously mentioned, it is believed that the inaccuracies of the model estimates could have been higher if the flood history of the Mid-Goulburn River in the post-Eildon period had been dominated by moderate and large floods. Given that
mostly minor floods have occurred since completion of Lake Eildon (Chapter 5), the approach adopted, which included establishing some key factors based on the flooding thresholds of the corresponding floodplain units, is adequate.

Both the hierarchy of the key factors and the alternative overbank deposition model developed may be used to continue building up the understanding of overbank deposition and those related mechanisms, which over longer time scales may impact the evolution of alluvial floodplains.

To conclude, the relevance of the results obtained in this research is discussed in Chapter 10, and the most conclusive findings are elaborated in Chapter 11.
10 Chapter Ten

10.1 Discussion

In this chapter I discuss the results of this research in relation to existing literature, and so I identify the contributions of this work. I begin by discussing how this research has contributed to improving the conceptualisation of overbank deposition; then I discuss the results of the sensitivity analysis and the model testing; I continue with a discussion on the spatial patterns of overbank deposition along the Mid-Goulburn River and the improved understanding of overbank deposition as a process of floodplain accretion; and I finish with a discussion on improved methods for the study of spatial patterns of overbank deposition.

10.1.1 Improvement of model conceptualisation

As discussed earlier in this thesis, the components of the model developed here include nine key factors that have been identified in the literature for their importance in determining the spatial distribution of overbank deposition (Magilligan 1992b; Batalla &
Sala 1994; Nicholas & Walling 1996; Nicholas & Walling 1997; Asselman 1999b; Walling & Woodward 2000; Thonon et al. 2005; Buttner et al. 2006; Carson 2006; Piégay et al. 2008). However, there has been no comprehensive analysis of the interaction between these key factors. Thus the improved representation of the key factors and their interactions in a numerical model of overbank deposition developed in this investigation facilitated this analysis.

The numerical model here developed incorporated all the key factors that are represented in the models of Nicholas and Walling (1998) and Buttner et al. (2006). Using a finite-difference-grid approach, Nicholas and Walling (1998) focused their analysis on the influence of spatial patterns of hydraulic variables (flow depth and velocity) and sedimentological variables (including SSC, deposition amount and grain-size distributions of floodplain deposits). They did so knowing that this last (grain-size distribution), together with flow velocity (influenced by floodplain topography), strongly determines spatial patterns of overbank deposition. Their predicted deposition amounts were compared with sedimentation amounts collected from 16 sediment traps during 10 flood events, confirming that the grain-size distribution of the (‘effective’) suspended sediment is larger than that of the (‘ultimate’) sediment deposits. Their model predicted 10 out of the 16 sampling sites reasonably well, along a 600-metre floodplain stretch of the River Culm in the UK.

The model of Buttner et al. (2006) calculates the probability of suspended sediment being deposited and not rejoining the current by considering the critical shear stresses on the floodplain-floor, which are also incorporated into the model developed in my research. Additionally they established hydraulic parameters (such as flow depth
and velocity) that were calculated with their hydraulic model. As with the model of Nicholas and Walling (1998), Buttner et al. (2006) compared their modelled estimates of sediment accumulation (with measured rates from sediment traps), but only for a single flood event. Their predictions of rated deposition per unit area seem to reasonably match observed data on 5 of 10 of their sampling sites, which are distributed along a 4 km stretch of the Elbe River.

The overbank deposition model developed in Chapter 4 represents effects of overbank flow velocity and depth, independently calculated by the hydraulic model of the floodplain completed by Water Technology (2009). However, in contrast with the discrete or finite difference grid approach adopted by Nicholas and Walling (1998) and Buttner et al. (2006), the model developed here explicitly represents overbank travel time and uses ‘average’ flow velocity and depth along the overbank flow paths that hydraulically connect the floodplain units to the river channel during overbank inundation. As discussed earlier in Chapter 2, even though distance from the channel had been observed to be an important factor that could explain observed spatial patterns of overbank deposition (cf. Pizzuto 1987; Marriot 1992; Asselman & Middelkoop 1995; Walling & He 1998a; Carson 2006; Casas et al. 2006) its definition had not been adequately established in previous studies for understanding and predicting spatial patterns of overbank deposition. These overbank flow paths increase in number and complexity as flood size increases, because generally more hydraulic connections form along floodplains as flood magnitude increases until the entire floodplain is inundated. As mentioned earlier, the new model explicitly incorporates overbank travel time, which is calculated as a function of distance from channel to
floodplain units, and therefore, measured along the same overbank flow paths. Additionally, a new mathematical relation is incorporated into the model, which represents the decrease of SSC with travel distance, and with time, along the overbank flow path. Finally, the model also incorporates flood duration, settling velocity, pond depth, as well as floodplain floor and critical shear stresses.

Thus, the new relationship and the way of representing these key factors (including travel time, distance from the channel and the decrease of SSC along overbank flow paths), together with the approach developed to determine overbank flow paths, improves the current conceptualisation of the way overbank deposition occurs. Rather than being a product of cell by cell steps (such as a finite-difference-grid approach), the approach uses an explicit analytical treatment that is based on individual floodplain units including characterisation of their overbank flow path. Some conceptual implications of this approach are described in a later section of this chapter (Figure 10.4).

10.1.2 Sensitivity analysis and the relative importance of the key factors influencing overbank deposition

As observed in previous research, the spatial variability of overbank deposition (Walling & He 1998a; Cabezas et al. 2010) is the result of complex feedbacks between
floodplain topography and sediment transport and deposition processes (Walling & He 1998b; Nicholas et al. 2006; Cabezas et al. 2010). The literature review in Chapter 2 identified that the key factors influencing overbank floodplain deposition are flood duration in a determined time period (e.g. days of inundation), travel time, average overbank flow depth, river suspended sediment concentration, sediment settling velocity, floodplain-floor shear stress, critical shear stress, average pond depth and suspended sediment in post-peak ponds prior to the isolation of the main flow (see Table 9.1). Although other authors have identified these factors before, few studies have identified the relative influence of these multiple factors on deposition rates. This could be done by including all of these key factors in a single numerical model, and undertaking a sensitivity analysis to establish the relative influence of these key factors in driving the spatial distribution of overbank deposition. Buttner et al. (2006) carried out a similar analysis that was based on the ‘sediment transport component’, which represents only four key factors (i.e. floodplain floor shear stress, critical shear stress, settling velocity and SSC). Based on their model, they concluded that the most sensitive factors were settling velocity and critical shear stress.

The results of the sensitivity analysis carried out in my research indicate that flood duration is the most important factor determining the spatial distribution and variability of overbank deposition (Figure 9.1 and Table 9.1). This was obtained from the sensitivity analysis (Chapter 9) that was based on the improved overbank deposition model developed in Chapter 4 and which, by contrast to the model of Buttner et al. (2006), includes both sediment transport and deposition components (all of the nine key factors). Thus, additionally, my model explicitly represents flood
duration (i.e. the total number of days that a site or floodplain unit is inundated by overbank flows), travel time, overbank flow depth and deposition in post-peak ponds (i.e. determined by pond depth and SSC prior to the isolation from the main flow). Flood duration represents the hydraulic interaction between overbank flow and floodplain topography over time, and therefore, varies across the floodplain during any given flood. Hence, the sensitivity analysis carried out in my study found that the cumulative duration of overbank flooding (e.g. days of flooding) in which areas susceptible to overbank inundation are actually flooded over a period of time (e.g. years) most markedly determines amounts and rates of overbank deposition; as found in Chapter 9.

My research also suggests that preferential areas of deposition, which may vary even along the same floodplain unit, are determined by the spatial interconnection of the overbank flow paths, the overbank travel time for the sediment to reach a given floodplain location (the second most influential factor), the average flow depth along overbank flow paths (the third most influential factor), and by the effects that linked flow paths have on suspended sediment transport and deposition along this flow-path network. Thus, depending on the effect that the interaction between the floodplain and the overbank flow paths have on the key factors, including flow velocity and settling velocity, sediment will settle out, strongly depending on particle and flow characteristics (i.e. particle and fluid densities and particle-size distribution). On the other hand, in areas of high flow velocity, sediment resuspension or floodplain scour may be initiated (depending on floodplain vegetation cover and floodplain-floor shear stress) with the
possibility of all these occurring. The other possibility is that some of the suspended sediment can simply rejoin the river channel without being deposited.

Furthermore, it is conceptualised here that the interconnection of overbank flow paths changes with flood magnitude, as do overbank flow velocity and depth. Latter in this chapter, a further description of the increased complexity of the overbank flow–path network with increasing flood stage (Figure 10.4) is developed.

In this research not only was a hierarchy among the key factors found to be determining the spatial variability of overbank deposition, but it was also noticed that the interactions among the key factors are highly complex (Chapter 9). Therefore, even though sediment settling velocity, floodplain-floor shear stress, critical shear stress, average pond depth, and suspended sediment concentration prior to the isolation from the main flow, are comparatively less influential, they can still have an influence on this floodplain accretion process. For example, and as mentioned earlier in Chapter 9, sediment deposition in post-peak ponds may be important along floodplain units where large and deep ponds form (Asselman & Middelkoop 1995; Nicholas & Walling 1998; Carson 2006), especially if these are reached quickly by the overbank flow and the water is loaded with high concentrations of suspended sediment.
10.1.3 Discussion on model testing, model limitations and accuracy

As discussed in Chapter 9, the new overbank deposition model developed here provided adequate estimates of overbank deposition amounts as measured on the Goulburn River floodplain. The modelled estimates were acceptable considering the required assumptions and approximations. The most important of these assumptions were: only considering sediment sources originating from the Goulburn River, and to consider that erosion was not occurring at the selected floodplain units. Also, a possible source of inaccuracy is basing some key factors on the commence-to-flood thresholds, i.e. the discharge at which selected floodplain units are inundated (discussed in Chapters 8 and 9). Presumably, if the flood history of the Goulburn River along the floodplain section had been dominated by moderate or large floods instead of minor ones over the post-Eildon period (refer to Figure 5.10), then the model estimates would have been less accurate; since these floods would have been larger than the threshold of overbank inundation.

Model accuracy is limited if additional processes occur or sediment sources join the overbank flow-path network. As was discussed in Chapter 9, the model is not capable of providing accurate estimates when these additional processes are occurring. These include additional sediment inputs caused by floodplain scouring, sediment resuspension and sediment inputs from tributaries, as these affect the amount (or concentration) of suspended sediment that reaches the floodplain locations (including also sediment erosion). As discussed in Chapter 9, these factors are
possible explanations for six of the biggest mismatches found between the modelled and measured estimates. On the other hand, the other major mismatch may be caused by the representative size fraction of suspended sediment traveling along the overbank flow path. If the grain-size distribution of suspended sediment is coarser than the one considered for Unit 6 (Chapter 9), then settling velocity would be higher than that calculated, causing sediment exhaustion along the flow path at a higher rate than was estimated by the model (than if sediment was finer).

As discussed throughout this thesis, model accuracy is also affected by data quality from which the key factor values can be calculated. This quality is determined by the frequency of data collection and the adequacy of its spatial representation. For example, using the model to calculate the amount of overbank deposition of each floodplain unit, I used some key factor values that I considered plausible, such as the values of SSC; the representative grain size of the suspended sediment population and related settling velocity; floodplain-floor shear stress and critical shear stress. These values, however, lacked any spatial representation along the floodplain section, and the same values of these factors were used for the estimation of overbank deposition amounts on the corresponding floodplain units.

Therefore, the lack of adequate records of SSC along the Mid-Goulburn River increased uncertainties in this research. This poor monitoring of SSC (at a low frequency), in turn, limited analysing the way in which SSC relates to discharge during overbank inundation at different flood magnitudes (Chapter 8). Additionally, inaccuracies were possibly exacerbated by the uncertainty of the modelled floodplain-floor shear stress along the floodplain section (discussed in Chapter 8).
Additional uncertainties can also be associated with the generation of the LIDAR DEM or with data of the hydraulic model (containing raster data of overbank flow velocity and height), as well as with those generated from the estimation of flooding thresholds; the corresponding travel time and distances to each floodplain unit (see Chapter 8). All of these are possible sources of inaccuracy (see Chapters 8 and 9).

It should also be mentioned that there is uncertainty associated with the measured deposition rate as well as the modelled estimates. As shown in Chapter 7, uncertainties in the $^{137}$Cs detection from which measured estimates were calculated could be relatively large. However, estimates of overbank deposition corresponding to floodplain unit samples and reference sites, showed internal consistency, suggesting an adequate estimation.

Moreover, a regression function establishing a good fit was found using the two types of estimates, modelled and measured, with a $P = 0.11$ for the units of the downstream reach (as discussed in detail in Chapter 9). For those of Reach 1, the patterns of both estimates were similar, i.e. comparatively small deposition amounts established for three of the four floodplain units of this reach. The exception in the same reach is Unit 10, which has markedly accreted over the post-Eildon period (i.e. 362 mm). This is the highest accretion rate over that period among the floodplain units, which is believed to be caused by sediment inputs from the Rubicon River. This tributary joins the Goulburn River and its flow inundates a secondary channel which is believed to be hydraulically connected to this Unit during overbank inundation (Figure 9.7).
Nevertheless, from the results and discussion presented in Chapter 9, it was found that even though the model presented here includes a larger number of complex variables, it predicted, with reasonable accuracy, spatial patterns of overbank deposition of 7 of the 13 floodplain units analysed (see Table 9.3), which is a similar degree of accuracy as the other models (Nicholas & Walling 1998; Buttner et al. 2006).
10.1.4 Overbank deposition along the Mid-Goulburn River floodplain: analysis of spatial patterns

In order to establish spatial patterns of overbank deposition, I based the set of analyses that were developed in this study on representative floodplain units distributed along the 90-kilometer stretch of the Mid-Goulburn River floodplain and targeted for being representative of the spatial patterns and variability of overbank deposition along this floodplain. Therefore, these floodplain units (including 2 abandoned channels, 3 meander cutoffs and 8 floodplain swales) are at different distances from the reservoir and from the channel, in order to capture spatial patterns of overbank deposition both laterally, and longitudinally, over a 54-year time period of marked flow regulation. Research on spatial patterns of overbank deposition with a comprehensive methodological approach of this kind for an adequate selection of floodplain sites, and therefore, representing such a relatively large floodplain area, as has in here been described (Chapters 3 and 6) has not been reported in the literature.

$^{137}$Cs analysis shows that two floodplain swales have been eroded over the post-Eildon period: one located in Reach 2 along the upstream reach of the floodplain (Unit 9), and the other, in the downstream end (Unit 2). The other eleven units experienced net overbank deposition over the post-Eildon period, ranging from 1 to 362 millimetres over 54 years (equivalent to a range of 0 to 423 kg.m$^{-2}$ of overbank deposition amount and a maximum accretion rate of 6.7 mm.yr$^{-1}$ (Table 9.3)).
Of these floodplain units, the highest sediment accumulation has occurred on an abandoned channel and a meander cutoff (as mentioned in Chapter 9, Units 3 and Unit 10 with 186 and 362mm respectively), while most of the other units have accreted at comparatively lower rates with a maximum of 38mm over the post-Eildon period (see Table 9.3). Based on the classification of the floodplain units in terms of their susceptibility to overbank inundation it was also mentioned in Chapter 9 that the anticipated patterns of overbank deposition for the units along the upstream and downstream reaches, correspond to the actual net sediment accumulation found from $^{137}$Cs detection; only with the exception of Units 9 and 12. It was also found that of the four floodplain units that have accreted along Reach 1 (closer to Lake Eildon), three have accreted at a considerably lower rate. However, instead of this being an indication of the impact of Lake Eildon on accretion rates of overbank deposition, the analysis developed in Chapter 9 indicates that this is caused by the long travel times that the suspended sediment takes to reach these units, which results from the combination of flow velocity and the distance from the channel along overbank flow paths. Moreover, even though this long travel time and distance are also associated with Unit 10, its comparatively highest accretion rate (of all thirteen floodplain units), is the result of additional sediment inputs from the Rubicon River, as discussed in Chapter 9.

From the analysis Chapter 9 focused on modelled and observed deposition amounts and on the associated key factors to each floodplain unit, including flood duration, travel time, distance from the channel, average flow depth and average flow velocity (these two averaged along the overbank flow paths). However it is clear that,
even though the hierarchy of the key factors identifies that the two key factors that most markedly influence spatial patterns of overbank deposition are flood duration and travel time, the result of their influence and the actual complex interactions that occur among all the key factors are what ultimately determine the spatial distribution of overbank deposition. It is also clear that, additional processes, such as sediment resuspension, floodplain scouring and sediment sourcing different from the River, are important and strongly influence the spatial patterns of overbank deposition.

10.1.4.1 Analysis of spatial patterns of overbank deposition along the Mid-Goulburn River

With a similar order of magnitude than measured deposition, it was found that deposition amounts predicted by the model range from 0.05 to 320 kg.m\(^{-2}\) (Table 9.3). It can be observed from the data that the model under predicts deposition amounts for three of the four units that are closer to the dam (i.e. along Reach 1; Table 9.3). In relation to this under estimation, it should be recalled that even though for the modelling exercise the same value of SSC was used to estimate deposition amounts using the model (i.e. 0.036 kg m\(^{-3}\)), suspended sediment concentration is a key factor that is known to be spatially and temporally variable. Thus, it could be possible that in fact SSC along the reaches that are closer to the dam are lower than those further downstream, especially if sediment that would be transported from upstream is being trapped in the reservoir. However, in this scenario the model should then be showing an over estimation of overbank deposition amounts, while the opposite is the case (i.e.
the measured estimates are not as small as the model predicted). It has been identified in previous studies (Erskine, Rutherford & Tilleard 1993) and was also noticed during the field work visits to the floodplain (see Chapter 5), that the bed of the Goulburn River close to the reservoir is now strongly armoured, indicating past erosion (i.e. Reach 1). This armouring occurs mostly in the few kilometres below the dam, indicating that this is ‘clear water scour’, of the stream channel in response to the artificial flow and sediment regulation (Petts 1980). Sediment eroded from the channel could be subsequently deposited along the floodplain reach during overbank flooding. Since this phenomenon is not explicitly represented by the model its occurrence could explain the model under estimations identified for the units of Reach 1.

Comparing measured and modelled estimates, it is noticed that the opposite is occurring for the units along the downstream reach, for which the model in general over estimates deposition amounts. This could be showing that SSC may be higher along this reach than the value assumed (i.e. also 0.036 kg.m\(^{-3}\)) and which could well be the result of additional sediment inputs from tributaries.

From the general spatial patterns that the measured deposition amounts suggest, the following analysis focuses on exploring the relationship between measured deposition amounts and the two most influential factors on spatial patterns of overbank deposition: flood duration and travel time.

In order to investigate the level of correspondence between these two key factors and measured deposition amounts, two graphs were plotted (Figure 10.1 and Figure 10.2). Plotting measured deposition amounts of the thirteen floodplain units against flood duration (Figure 10.1), it is observed that measured overbank deposition
amounts follow a similar trend to that found from the sensitivity analysis for this key factor (the dashed line, with a k=1/30), which represents the simulated range of the spatial variability of overbank deposition amounts for the Mid-Goulburn River (Graph (a) in Figure 9.1). This encouraging fact reflects a good correlation with the sensitivity analysis and suggests no deposition when flood duration is zero. There is, however, an outlier that is outside this tendency, which is the eroded Unit 9, with -19 kg.m\(^{-2}\) of accumulation when the cumulative flood duration is 155 days.
Figure 10.1. Flood duration versus measured deposition amounts of the thirteen floodplain units; the blue diamonds are those along the upstream reach, and the orange circles those of the upstream reach. The dotted line represents the variability of overbank deposition established from the sensitivity analysis for flood duration in Chapter 9 (Graph(a) in Figure 9.1). The outlier of the data is Unit 9.

Similarly, plotting the measured overbank deposition amounts of the thirteen floodplain units against travel time (Figure 10.2), and then comparing the data with the expected variability of overbank deposition established from the sensitivity analysis for this key factor (dashed line, also with k=1/30), it seems that Unit 10 is an outlier. Measured deposition amounts show decreasing deposition amounts with time, i.e. a tendency to zero deposition when travel time is large. However, this is only the case for the floodplain units that are reached by overbank flooding after 100 minutes. At the same time, deposition amounts deposited over a comparatively short time (i.e. within less that 100 minutes) are also quite small. This is the case at five units of the downstream reach (Units 1, 4, 5, 6 and 7). This could be showing either the effect of additional processes (such as floodplain scouring or erosion) or the effect of other key
factors (such as flow depth, flow velocity, SSC or settling velocity) influenced by fluctuations in the sediment size distribution of suspended sediment, which at the same time is sensitive to spatial and temporal variations (related to the location and type of sediment sources).

![Graph](image)

Figure 10.2. Travel time versus measured deposition amounts of the thirteen floodplain units; the blue diamonds are those along the upstream reach, and the orange circles those of the upstream reach. The dotted line represents the variability of overbank deposition established from the sensitivity analysis for travel time in Chapter 9 (Graph(b) in Figure 9.1). The outlier of the data is Unit 10.

### 10.1.4.2 Impact of flow regulation on overbank deposition along the Mid-Goulburn River floodplain

As mentioned in the previous section, one of the objectives of this research was to identify the impacts of flow regulation (by Lake Eildon) on patterns of overbank deposition along the Mid-Goulburn River floodplain but the patterns of the $^{210}$Pb$_{(ex)}$...
concentrations in the sediment profile identified were not as expected, and therefore, this approach was unsuccessful.

The Goulburn River is located in southeast Australia, where runoff and overbank flooding would naturally occur in the spring and winter months along the floodplain. As noticed during the last fieldwork visits to the river in late 2009, the river section studied in this study (Figure 5.1) consists of discontinuous armoured river-bed reaches with similar characteristics to the ones mentioned by Warner (1987), including well sorted materials that mantle and protect the sometimes poorly sorted substratum of the bed from further transport. At least some of these armoured reaches are known to have formed in response to the sand and gravel extraction that occurred along the river banks and some tributaries until the late 1990s, protecting the river bed from further channel enlargement and incision (Erskine 1996). These reaches are distributed along the ‘Sand or Mobile Zone’ of the floodplain. This zone, as defined by Schumm (1977) (cf. Warner 1987), consists of a mixed-gravel river bed that is likely to have been mobilised frequently during the pre-Eildon period, which was dominated by more frequent flood events of also higher magnitudes. Thus, the presence of this poorly sorted armoured reach is further evidence of the change in the sediment transport capacity of the Goulburn River that has resulted from the regulated flow and flood regimes. As discussed in Chapter 5, the flood regime during the current period of marked flow regulation (post-Eildon period) has been dominated by minor flood events of very short duration.

On the one hand, it has been observed that Lake Eildon has filled with sediment at a remarkably low rate, loosing only 1.65% of its initial capacity (Davis, Finlayson &
Rutherfurd 1997). On the other, Gippel and Finlayson (1993) state that, even though the impact of flow regulation by Lake Eildon has markedly altered the flood regime with a reduction in flood frequency that is detectable 218 km downstream from the dam, the effect on wetland flood frequency is mitigated downstream due to the influence of unregulated tributaries: where “only a minor difference is apparent 200 km downstream” (Ibid). The findings of the present investigation corroborate this observation on the importance of tributary inputs on overbank processes, including flooding and sedimentation.

As mentioned in Chapter 5, Gilmore K (2009, pers. comm. May 7), a local landholder who has lived near Units 11, 12 and 13 for over 75 years (i.e. in a floodplain stretch of the upstream reach), has noticed that flood events have been reduced from 3 longer-lasting ones in a year to flooding that occurs once yearly but which is generated by flows from the Rubicon River. In relation to this it is important to mention that several tributaries join the floodplain section of the Mid-Goulburn River that has been studied here (refer to Chapter 5).

As discussed in the previous section, overbank deposition amounts established from the 13 floodplain units range from 0 to 362 kg.m\(^{-2}\). Interestingly, Nicholas and Walling (1998) reported a similar deposition range of 0 to 465 kg.m\(^{-2}\), but which accumulated over a single 2-day flood event at 16 sites distributed along a 400-metre reach of the River Culm floodplain in the UK. The Culm has a similar floodplain topography to the Goulburn River floodplain studied here but which, in contrast, is activated by ‘substantial inundation’ that occurs on average seven times a year. However, Nicholas and Walling (1998) do not explicitly provide their data on monitored
suspended sediment concentrations; showing only a contour map containing SSC in terms of a percentage of the SSC at the channel.

As discussed in Chapter 8, there is a lack of adequate data of monitored suspended sediment concentration for the Goulburn River during overbank inundation, but it is considered that its SSC is ‘naturally’ low (refer to Chapter 8). In this study, it was assumed that a plausible average value of SSC along the Mid-Goulburn River was 36 mg.L⁻¹.

The only study carried out in the past to estimate overbank deposition rates of the Goulburn River is that of Reid (1997). He investigated two billabongs: the ‘Callemondah billabongs’, which are located in the floodplain section used in this study (see Figure below). He focused on both the pre- and post-European periods. The last includes a period free of flow regulation (from ~1780s to 1915) but of marked human disturbances which triggered a variety of changes in river catchments across Australia, such as vegetation clearance (refer to Chapter 5). In this fluvial system, the post-European period also includes a period of presumably subtle regulation (by Sugarloaf Reservoir: 1915 to ~ 1955) and finally, the post-Eildon period (a period of marked flow regulation due to the upgraded Eildon Dam: 1955 to date).

As mentioned in Chapter 5, floods of larger magnitudes used to inundate the floodplain section during the pre-Eildon period, as shown by the early records on flow discharge, which include those from before 1955 of the Goulburn River gauging station at Eildon. By analysing exotic pollen and radiocarbon chronologies, Reid (1997) estimated sedimentation rates over the pre-European period, finding a rate of 10 millimetres every 60 years at one of the billabongs and another, more variable rate at
the other billabong during the same period, ranging from 10 mm every 85 years to 10 millimetres every 30 years (thus 20 millimetres every 60). He also estimated that sedimentation rates ‘increased many fold at both sites after the appearance of Pinus’, which he used as the post-European marker (thus, over the post-European period which is from the 1780s), with one of the billabongs accreting at an average rate of 10 millimetres every 5 years (i.e. 2mm. year⁻¹) and the other at a rate of 10 millimetres every 2.5 years (i.e. 4mm. year⁻¹). It is important to recall that these rates include the Post-European period, which included the period of very marked catchment disturbances mentioned in Chapter 5, and also, a more recent period of flow regulation (from 1955, the post-Eildon Period). Additionally, even though Reid’s billabongs are subject to overbank inundation and therefore have accreted by overbank deposition processes, they are located at the margins between the floodplain and the hills, which is likely to make them “less susceptible to drying because the hills which form the boundary of the floodplain provide significant surface runoff and groundwater input” (Reid 1997, p. 6).

As previously reported, the units with the highest deposition rates found in this research are Units 3 and 10, which have accreted at an average rate of 3.5 and 6.7 mm.yr⁻¹ respectively over the ~54 years analysed of the post-Eildon period (1955 to 2009). Being different units, it seems inappropriate to compare accretion rates of these billabongs analysed by Reid (1997) to those of Units 3 and 10, which of the 13 floodplain units analysed, have accreted at the highest rate over the post-Eildon period. However, the comparison could be valid if the susceptibility to overbank inundation between these two groups is similar.
To explore if that indeed was the case, I defined the flooding threshold of the two billabongs studied by Reid (1997). This was done following the same procedure described in Chapter 6. I found that the flooding threshold for both of these billabongs was ~40,000 ML.day$^{-1}$ under the current flow regime, which corresponds to a low to moderate susceptibility to overbank inundation under the current flow regime. Units 3 and 10 have both a high susceptibility to overbank inundation, but various of the units of this study have a low to moderate susceptibility (Table 9.3), and their accretion rate ranges from practically zero to 38mm accumulated over 54 years, which is equivalent to a maximum of 0.7 mm.yr$^{-1}$ over the post-Eildon period.

This indicates that accretion rates at the Callemondah billabongs (Reid 1997), actually calculated over 36 and 85 years of deposition during the post-European period (2 and 4 mm.yr$^{-1}$), are higher than the maximum accumulation rate found at the units here studied with the same low to moderate susceptibility to overbank inundation, which is a rate of 0.7 mm.yr$^{-1}$ over the 54 years (the post-Eildon period). The lower floodplain accretion rates may be showing a decreased sedimentation rate that the artificially altered flow and sediment regimes by Lake Eildon have had on overbank deposition, but on the other, these higher rates at the billabongs may also be reflecting other anthropogenic processes triggered during the Early European period across some catchments, including an increasing rate of catchment erosion. Additionally, and as Reid also mentions, these billabongs are at the margins of the floodplain and near the hills, as is clearly shown on Figure 10.3 below, which then opens the possibility of the billabongs to be accumulating sediment originated from hill erosion.
All this, therefore, complicates drawing conclusions from the rates estimated by Reid (1997) about the impact of Lake Eildon on overbank accretion along the floodplain.

Figure 10.3. The Callemondah billabongs studied by Reid (1997) are located ~ 4 km downstream of Unit 8 in reach 2 (as shown in Figure 5.2), and which is along the downstream reach of the floodplain segment here studied. They are proximal to the foothills and along the margin of the floodplain.

10.1.5 **Improved understanding of overbank deposition**

This research has improved our conceptualisation of how floodplain deposition occurs. In particular, attempting to explicitly represent sediment deposition along
overbank flow paths in the model, has demonstrated the interesting interaction between paleochannels, flood size, and overbank deposition. I discuss this interaction in a conceptual model below.

It has been discussed in this chapter and in Chapter 9 that the hydraulic interactions and the effects of the nine key factors are complex, and that these determine the spatial patterns and the variability of overbank deposition. Furthermore, this research supports the idea that these interactions increase in complexity as the flow-path network increases with flood magnitude, but then may simplify in the largest floods. Furthermore, as discussed in Chapter 9, it is possible that the linkage of overbank flow paths with inundated areas or floodplain units along a floodplain may result in an increase in overbank flow velocities, which can trigger localised sediment resuspension or erosion (represented by the asterisk * on Figure 10.4 below). Depending on the sediment grain-size distribution and the key factors associated with the floodplain unit or site, this resuspension or scouring will affect the local SSC and this suspended sediment can either represent a new source of sediment to be deposited along the floodplain reach or this sediment may rejoin the river channel.

Different levels of hydraulic connectivity and the interactions occurring along a given floodplain reach, as flood stage increases, are represented on Figure 10.4 below (letters in the text refer to this figure). On this figure, two floodplain sites have been drawn along the same floodplain units and the river, representing either a higher SSC (e.g. sites A and B) or a lower concentration (e.g. sites A\(^1\) and B\(^1\)). Thus, the sites A\(^1\) to H\(^1\) represent lower SSC than their pair (sites A to H). I have defined four ‘phases’ of interaction as flood stage increases: disconnected, partially connected, well connected,
and fully flooded. On Figure 10.4, higher SSCs are represented by the dark shaded areas while the low SSCs are in lighter gray. The Disconnected Phase occurs when a flood is just exceeding bankfull (Figure 10.4A), and only a small portion of the floodplain units have been inundated; which are usually the deepest and closest to the river channel. These units may include recently abandoned channels or meander cutoffs, some of which may act as secondary channels at low flood stages.

During the Partially Connected Phase (diagram B in Figure 10.4), an increasing number of floodplain units is flooded by overbank flow paths (OFP₁ to OFP₄ on Figure 10.4B), which transport suspended sediment across the floodplain to different locations, and at different travel times and distances from the river channel. Some channels connect all the way through back to the main channel (A → A'). Where channels do not connect through, relatively higher SSC and overbank deposition is restricted to floodplain-unit areas that are closer to the OFP connecting to the floodplain unit (e.g. C, D, E, and F).

During the Well Connected phase, a more complex overbank flow-path network hydraulically connects floodplain units and larger areas of the floodplain (now five OFP₁ to OFP₆ on Figure 10.4C). As topographic features have a reduced effect on flow velocity and suspended sediment transport, larger areas of the floodplain units have less differentiated SSC, the latter also caused by the increasing interconnectivity of floodplain units through the OFP network.

Finally, during the Fully Flooded phase, most of the floodplain area and the floodplain units that are susceptible to overbank inundation (with low, moderate or high susceptibility) have been inundated. In this phase, even less contrasting concentrations
of suspended sediment occur than in the two previous phases, as suspended sediment is transported by a less turbulent flow, with a reduced effect of the topographic features on floodplain shear stress (Figure 10.4D).

It can be observed in Figure 10.4 that the shape and topography of the floodplain units, together with their distribution across the floodplain, determine the hydraulic connectivity of the floodplain units. The cumulative duration of overbank inundation (which has also been here referred to as flood duration), is actually a way of representing this connectivity over a period of time (i.e. that of the floodplain units with the river channel). As it was elucidated in this research, flood duration is the most influencing factor determining the spatial distribution of overbank deposition. At the same time, this duration, together with the other eight key factors, determine the rate of the amount of sediment that is either maintained in suspension or deposited along the floodplain during overbank inundation. The most complex scenario occurs when additional sediment sources to those originating from the river are simultaneously occurring (the circled asterisk on Figure 10.4C), which can presumably cause sediment erosion, resuspension and/or additional sediment sourcing, but also, a combination of these three while some of the sediment is being deposited.

On Figure 10.4, the sediment input from the tributary increases the SSC downstream of the confluence (site B) and therefore, floodplain sites reached by overbank flow paths downstream of the confluence will be inundated with an increased SSC (e.g. floodplain site G on Figure 10.4B and on Figure 10.4C).
Finally, the floodplain sites that accrete the fastest are those with a high cumulative duration of overbank inundation, but also, are those reached within a reasonably small travel time. This is because sediment is progressively deposited along the overbank flow paths. Therefore, if travel time is longer along OFP₂ than along OFP₁ (even though the distance from the channel along OFP₂ is shorter), a higher SSC will reach site D than will do at site D¹. This travel time is determined by distance from the channel (measured along the overbank flow path) and by the average overbank flow velocity along the same path.
Figure 10.4. Representation of the four phases of overbank inundation and deposition: (A) the Disconnected Phase, (B) the Partially Connected, (C) the Well Connected and (D) the Fully Flooded phase. High suspended sediment concentrations are represented by the darker areas and the lower suspended sediment concentrations by the light-grey areas. The floodplain-unit areas that have not been inundated are represented by the dashed line.
Thus, from the analysis developed in Chapter 9 and in this chapter, it is possible to state that floodplain units that accrete faster are those

1. which are easily reached by overbank flows (i.e. they are lowest in elevation, but also connected to the main channel), resulting in a higher cumulative duration of overbank inundation over a period of time)

2. with an associated flow velocity that, on the one hand, is high enough to effectively transport suspended sediment to them with enough time to avoid a marked reduction of suspended sediment. Also, that overbank flow velocity is that which does not cause floodplain scouring or sediment resuspension along the floodplain unit.

A key consequence of this is that proximity to the main channel has possibly a stronger influence on rates and spatial patterns of overbank deposition when the floodplain is fully flooded (leading to higher deposition along the levees near the channel). At lower overbank flooding, floodplain sites all across the floodplain can accrete most rapidly if either of the two situations just mentioned occur (1. or 2. above), and also depending on how the sites are connected along the paleochannels or other floodplain units and their proximity to tributaries.
10.1.6 Methodological contributions

10.1.6.1 Two new methods developed to assist in determining spatial patterns of overbank deposition

From the various approaches that can be used to study spatial patterns of overbank deposition, the development of this research contributes to two approaches. The first is the novel method described in Chapter 6, which uses historical data and GIS analysis to generate inundation surfaces in order to classify floodplain units in terms of their susceptibility to overbank inundation and which (a) helps selecting floodplain sites or units with relevance to the particular study and (b) can be used to qualitatively anticipate the spatial distribution of overbank deposition without having to use a hydraulic model (demonstrated in Chapter 9) as this method can be used in the preliminary research stage. Siggers et al. (1999) investigated the degree of correlation between spatial patterns of overbank inundation and overbank deposition based on a quantitative analysis that involves using a two-dimensional hydraulic model, finding a degree of correlation between spatial patterns of these two aspects.

As discussed in Chapter 6, the method developed in Chapter 6 may be used for mapping floodplain units or sites based on approximate areas of overbank inundation, which are identified from a simpler GIS analysis that does not require hydraulic modelling. The method requires adequate records of the history of flooding, including flood elevation of past events at different floodplain locations and a high-resolution digital elevation model (such as a LIDAR DEM). From these data, flood inundation
surfaces can be generated and the susceptibility to overbank inundation of floodplain units predicted. The susceptibility to overbank inundation defined in this way can then be used to refine the selection of floodplain units with relevance to the particular study, as was the case in this research (also discussed in Chapter 6). This, in fact, can be the starting point from which to quantitatively estimate overbank deposition amounts on those floodplain units.

The second approach, which includes using the overbank deposition model developed in this research (Chapter 4), can be used to calculate overbank deposition amounts and which, as discussed above, allows explicit analytical representation of the nine key factors that influence the spatial variability of overbank deposition. The advantage of this representation into a single model is that it potentially allows scrutinising and further understanding the patterns found in response to the interactions of these key factors. For this to be achieved, however, and for the overbank deposition model to be adequately used, a crucial analysis needs to be completed beforehand; that is, to determine the overbank flow paths that hydraulically connect a floodplain location or unit to the river channel at relevant discharges using a hydraulic model.

Before choosing the floodplain sites on which to focus the research, it is advisable to carry out a preliminary analysis aimed at identifying the areas in which additional processes not being represented by the overbank deposition model may occur and, from that, judge whether these areas need to be excluded from further study. These processes include sediment sourcing (different from those originating in the river; such as tributary inputs), floodplain scouring and sediment resuspension.
10.1.6.2 Radionuclide analyses to establish spatial patterns of overbank deposition

As discussed in Chapter 2, one of the objectives of this research was to establish spatial patterns of overbank deposition along the Mid-Goulburn River floodplain. Another objective was to identify the impact of Lake Eildon on accretion rates as a result of flow regulation. To address these tasks it was planned that rates of net deposition over the post-Eildon period at the floodplain units were compared with those of an equivalent length of time for the pre-Eildon period. Combined detection of $^{210}\text{Pb}_{(ex)}$ and $^{137}\text{Cs}$ was considered adequate because: (a) it is well known that both radionuclides are attached to fine sediment (especially silt and clay); (b) they have been successfully used to determine deposition rates along floodplains over 100- to 150-year periods, and (c) it was found that the period of $^{137}\text{Cs}$ fallout coincided with the post-Eildon period (i.e. 1955 to date), which in fact, would facilitate the comparison of deposition rates before and after Lake Eildon (Chapter 7) (Walling, Quine & He 1992; Walling & He 1994; He & Walling 1996; Wallbrink & Murray 1996; Siggers et al. 1999; Piégay et al. 2008; Smith & Dragovich 2008).

As discussed in Chapter 7, for an adequate interpretation, concentrations of $^{210}\text{Pb}_{(ex)}$ should exhibit an exponential decay with depth. This decrease, in fact, occurs more rapidly than that exhibited by $^{137}\text{Cs}$, because $^{210}\text{Pb}_{(ex)}$ has a shorter half life (He & Walling 1996). However, and as shown in Table 7.6 and Table 7.7, of the two cores
used for this analysis, a clear decay of $^{210}\text{Pb}_{(\text{ex})}$ activity with increasing depth was not found.

In Core A, $^{137}\text{Cs}$ was not detected below 42 centimetres, which suggests that the pre-Eildon period in this core is from below that depth. Even though $^{210}\text{Pb}_{(\text{ex})}$ was detected below this depth, $^{210}\text{Pb}_{(\text{ex})}$ was not detected in the depth intervals of 48 to 54 centimetres and 60 to 66 centimetres, complicating the interpretation of the data.

In Core 1F (Unit 10), $^{137}\text{Cs}$ was not detected below 36 centimetres (pre-Eildon period) and $^{210}\text{Pb}_{(\text{ex})}$ was not detected in the depth intervals of 36 to 42 centimetres and 42 to 48 centimetres. Below 48 centimetres in this core, $^{210}\text{Pb}_{(\text{ex})}$ concentrations are smaller than the associated uncertainties (e.g. $1.2 \pm 4.4 \text{ Bq.kg}^{-1}$), making it difficult to interpret the data. He and Walling (1996) and Piégay et al. (2008) suggest that the technique is valid if constant sedimentation rate and minimal sediment mixing can be assumed, which seems not to be the case here. As it has been discussed by He and Walling (1996), this unclear decrease of $^{210}\text{Pb}_{(\text{ex})}$ concentration may also be showing that suspended sediment transported from the upper catchment represents a mixture of sediment that has been sourced at different locations, even during the same flood event, and that these sources may also have absorbed different concentrations of $^{210}\text{Pb}_{(\text{ex})}$. Alternatively, the lack of a decrease with depth of this radionuclide could be suggesting that there are different grain-size distributions in the sediment profile (i.e. the proportion of clay in the sediment samples). However, analysing the data, I found that this is probably not the explanation. In Core A, the percentage of clay below 42 cm (i.e. below the last interval of $^{137}\text{Cs}$ detection, which defines the pre-Eildon period), varies from 14% to 19% and in Core 1F it ranges from 11% to 17% below 36 cm (i.e.
also the last interval of $^{137}$Cs detection in this core). Even more difficult to interpret, in Core A detectable concentrations of $^{210}$Pb$_{(ex)}$ alternate in different intervals below the last detection of $^{137}$Cs, being detected in the 72 to 84 cm interval. Moreover, the lack of $^{210}$Pb$_{(ex)}$ detectable concentrations in some intervals below the last detection of $^{137}$Cs are not associated with a decrease of the percentage of clay (see Table 7.6 and Table 7.7).

Such an unclear decrease of $^{210}$Pb$_{(ex)}$ concentration with depth has also been reported in the literature (MacGregor et al. 2005). MacGregor et al. suggests that the alternating detectable concentrations of $^{210}$Pb$_{(ex)}$ at deep intervals could be showing either possible erosion events or a reduction “in the sensitivity measurement brought about by the dilution effect of rapid sediment influx” (p. 210). Considering that the highest accretion rates have been found at these two units (i.e. Cores 1F and A were collected from Units 10 and 3 respectively) the latter explanation is more plausible. Therefore, the lack of the expected decrease of $^{210}$Pb$_{(ex)}$ concentration in the sediment profile in both cores complicated establishing deposition rates with this radionuclide for the pre-Eildon period.

By contrast, the estimation of overbank deposition during the post-Eildon period was achieved using $^{137}$Cs detection in sediment samples collected from the thirteen floodplain units. As mentioned earlier in this study, these units were located at various distances from the river channel and the dam (Figure 7.2 and Table 9.3) and included three types of geomorphic units: abandoned channels, meander cutoffs and floodplain swales.
Adoption of the bulking-up procedure of Walling, Quine and He (1992) (Chapter 7), allowed me to include an adequate number of floodplain units (i.e. an adequate spatial representation) in order to establish patterns of overbank deposition along the floodplain (as discussed in Chapter 6). A similar analysis of such a large area for this purpose has not been reported before. This achievement is mainly due to (a) the method from which the floodplain units were adequately and strategically selected to allow this spatial representation (Chapter 6) and (b) to the sediment-bulking method adopted from Walling, Quine and He (1992).

Comparatively, two floodplain units have accreted at a relatively high rate; five at a moderate rate, four at a low rate and two have been eroded over the post-Eildon period.
Chapter Eleven

11.1 Conclusions

This research had the aims of (a) improving the current conceptualisation and the numerical representation in overbank deposition models of the key factors that influence the spatial variability of overbank deposition; (b) identifying the comparative level of influence that the key factors have on spatial patterns of overbank deposition; and (c) investigating the impact of a large dam on floodplain deposition rates.

An important outcome of this research was the development of the overbank deposition model presented in this work, which improves the representation of the nine key factors influencing the spatial distribution and the variability of overbank deposition and represents an explicit analytical treatment of the processes occurring during overbank inundation by incorporating the nine key factors, as these were partially represented in the models of Nicholas and Walling (1998) and (Buttner et al. 2006).

Moreover, the definition of overbank travel time (as a function of distance from the channel along overbank flow paths) and its possible effect on the reduction rate of SSC along overbank flow paths is also a crucial finding of this research, which helps to
understand spatial patterns of overbank deposition and, in turn, will also help improve our predictions of floodplain change and evolution.

The improved understanding of the way overbank deposition occurs (Chapters 9 and 10 and Figure 10.4) partly arose from an improved definition of the way the distance from the river channel to a given floodplain location should be measured, which had not previously been adequately established. This distance should be represented as the distance along the overbank flow paths that hydraulically connect the floodplain during progressive overbank inundation.

Therefore, based on the definition of distance from the channel, the overbank deposition model developed here incorporates a new term that represents the decreased rate of SSC along overbank flow paths (i.e. in relation to associated distance from channel and travel times). The actual amount of sediment that is deposited at a specific floodplain location, or a geomorphic unit, is calculated by the model from the final concentration of suspended sediment that ultimately reaches that location and which, depending on its grain-size distribution and settling velocity, settles out at a distance from the channel.

To use this alternative model, it is required that travel times, average flow velocity and depths associated to overbank flow paths are established and calculated in relation to overbank flow discharges. This may involve, as in this research, the use of a hydraulic model and a high-resolution (LIDAR-based) DEM. Clearly, the representation of floodplain topography in such high-resolution has only been possible since the advent and general availability of LIDAR imagery.
The floodplain units selected for this research needed to be representative of the spatial variability of overbank deposition along meandering river floodplains and therefore, the analyses carried out for the selection of study sites along the Mid-Goulburn River focused on a 2-km wide and 90-km long floodplain section that is also downstream of an artificial reservoir (Lake Eildon). A novel method for an adequate selection of floodplain sites was developed to adequately select representative floodplain units and which can be used in future research to classify floodplain units in terms of their susceptibility to overbank inundation. As discussed in Chapter 10, this method can be helpful in qualitatively predicting spatial patterns of overbank deposition.

An improvement in the overbank deposition model developed in this research was inclusion of the nine key factors controlling deposition. A sensitivity analysis of these variables allowed me to identify the most influential variables in the model (at least for the Mid-Goulburn River floodplain). This identifies the hierarchy that exists among the key factors for their influence on the spatial variability of overbank deposition. The relative importance of the nine key factors established that the cumulative duration of overbank inundation (e.g. total days of inundation over a period of time), and travel time are the two most influential factors on the spatial variability of overbank deposition. Whereas average overbank flow depth, river suspended sediment concentration, sediment settling velocity, and floodplain-floor shear stress, are of secondary importance. Less influential are critical shear stress, average pond depth and suspended sediment in post-peak ponds prior to the isolation from the main
flow. The last two are only relevant when post-peak ponds form during the flood-recession phase along the floodplain units selected.

This hierarchy of influence is an important finding, and stresses the importance of the cumulative duration of overbank inundation along floodplain units (or sites), which in artificially flow regulated systems can be dramatically reduced, as is the case for the Goulburn River.

Determining spatial patterns of overbank deposition along a considerably extensive floodplain stretch in comparison to previous studies (Chapter 10), in where thirteen representative floodplain units with a total of 36 floodplain sites were sampled, predictions made by the model were compared with actual historical deposition amounts estimated from $^{137}$Cs detection. This comparison demonstrated that the model was capable of predicting, with reasonable accuracy, amounts and patterns of overbank deposition of the Mid-Goulburn River floodplain. This was in spite of the model (a) incorporating a larger number of complex variables -because the key factors are spatially and temporally variable, and (b) incorporating several assumptions and approximations.

However, the model is designed to predict overbank sediment deposition only and does not include erosion processes and additional sediment sources to those originating from the river. Therefore, it is limited to providing accurate estimations if these additional processes are affecting the concentration of suspended sediment that is transported along the overbank flow path network. Additionally, the model accuracy is affected by the quality of the data from which the key factor values can be calculated,
and this quality is determined by the frequency of data collection and the adequacy of its spatial representation.

It became evident during the analysis of the modelling exercise (as discussed in Chapters 9 and 10), that sediment resuspension, floodplain scouring, and different sediment sources from those originating from the river, could be occurring to a higher degree along the floodplain than was originally anticipated. Therefore, it is recommended that in further studies, such processes should be explicitly represented in the model, as this inclusion is likely to improve our capability of more accurately predicting spatial patterns of overbank deposition.

A goal of the study was to identify the effect of a large dam on overbank deposition using $^{210}$Pb$_{(ex)}$ dating. However, this could not be achieved due to the lack of a consistent decrease in $^{210}$Pb$_{(ex)}$ concentrations with depth in the sediment profile, and in particular below the last depth interval of $^{137}$Cs detection. Thus, this question needs to be investigated further using a different dating technique. However, the study did demonstrate the importance of lateral sources of sediment from hillsides and minor tributaries on floodplain deposition below dams. It also suggested that clear water scour of the stream bed could be contributing to some deposition on the floodplain.
11.1.1 Recommendations for further study

Even though the assessment of the model accuracy suggests that the model developed here can be a fair predictor of spatial patterns of overbank deposition when erosion processes are minimal (Chapters 9), it is believed that the consistency and capabilities of the model can be evaluated more broadly if it is used for simulating a range of river conditions (which may include different temporal and spatial scales) and a variety of flooding scenarios (such as progressive inundation).

The Mid-Goulburn River floodplain has accreted at a rate that ranges from 1 to 362 mm over the 54 years of marked flow regulation by Lake Eildon (at an average rate of 1 mm yr\(^{-1}\) over the same period among the thirteen units,) which is considerably low in comparison to accretion rates of other floodplains of similar geomorphology, but which are more frequently flooded - such as the Culm River in the UK. Even though the impact of Lake Eildon on overbank net deposition could not be established from analysis of unsupported \(^{210}\)Pb\(_{\text{ex}}\), the impact of the dam on this sedimentation process could be further determined by estimating overbank accretion rates for the pre-Eildon period using other dating techniques, such as optically simulated luminescence (OSL) dating.

A clear research gap identified in this work is improved understanding of the progressive transport and deposition of sediment through floodplain units (including floodplain swales, anabranches and paleochannels) as flood stage rises. A specific
issue here is the role of tributaries in directing flow and sediment into the floodplain. Exploring this issue is key to developing more appropriate ecological models of channel-floodplain interaction. Better conceptualisation of overbank deposition will be relevant for integrated ecological and physical models of river function such as the river continuum concept (Vannote et al. 1980) and the flood pulse concept (Junk & Bayley 2008)
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Appendix A

A.1. Channel planform changes over the last 100 years: meander cutoffs and river anabranches

Meander cutoff 1

This meander cutoff (figure A1 below) was formed in 1916 as it was noted by Strom on the map of 1935 which defines that this feature was the “old …[river] course since 1916”. It is clear that this unit did not exist as it cannot be found on Thornton map of 1877.

Meander cutoff 2

The old channel bend (meander cutoff? 2) either naturally or triggered by gravel extraction, took the shape of a lagoon. This feature can be easily identified on both the topographic map of 1970s and the 2005 aerial photograph. As it is not shown on the Strom maps, this cutoff (figure A1 below) was formed sometime after the 1930s. Historical records show that extensive gravel extraction had been practiced along this part of the Goulburn River, although the specific locations are partly provided. This presumably altered the geometry and stability of the river channel bed and banks. If
gravel extraction occurred along the river reach where this feature is located, this activity may have triggered its formation.

Figure A1. Cutoffs 1, 2 and 3. The channel course depicted in the Parish maps from the 1870s (digitised in the GIS) is shown in bright blue. The old channel course on the Strom (1930s) map is in yellow and the modern channel (from the 2005 aerial photographs) is in light blue. Flow is from left to right. The marks in orange represent sites where gravel extraction from the river bed and banks used to be practiced.
Meander cutoff 3

The Parish map of Thornton from 1877 depicts the old channel bend as the active channel in that year. This feature had already formed by the time the correspondent Strom map was drawn 1935. However, unlike cutoff 1 no associated year to its formation can be found in the Strom map. Therefore it can only be established that this cutoff was formed between 1877 and 1935. This meander cutoff (figure A1 above and figure A2 below) is located about one kilometre upstream of the Acheron anabranch (also known as the ‘Acheron Breakaway’).

Figure A2. Aerial photograph of the Goulburn River reach where the Acheron Breakaway (River Anabranch 1) and two of the cutoffs are located. The old channel course depicted in the Parish maps as active is in bright blue (from the 1870s), the old channel course from the 1930s (Strom map) is in yellow and the modern channel is shown in light blue. Flow is from left to right. Perennial lagoons that exist along the floodplain are marked with the letter “L” and the red arrows were transferred from the Strom map, which represent overbank flow direction. Two
sites of intense gravel extraction used to be located within this river reach, which are marked with an orange star.

**River Anabranch 1: Acheron Breakaway**

The new avulsed channel can be found in the 1874 Parish (which was amended in 1959). The formation of this long river anabranch (figure A2 above) has been identified to be related with the floods that occurred during 1916 and 1917 (unpublished report, by Robin Stewardson of old files). Ken Gilmore, an interviewed land holder who has lived for over 75 years in his property and whose land is located near and upstream the Acheron Breakaway, confirmed that this river avulsion occurred in 1916 after the big floods that occurred in that year. It is possible that the gravel extraction works that were taking place at that time also played an important role in the occurrence of this river avulsion and act as an additional trigger (one of the sites is named on the topographic maps as “Walnut Island”). The old channel path is well delineated in the Strom map (of the 1930s) of Alexandra, in where its old two limbs are described as being part of the old channel bed that were “silted up”. Two main tributaries flow from the south hills, along the floodplain and into the Goulburn River along this river reach: the Rubicon and the Acheron Rivers (figure A2 above).
Meander Cutoff 4

This cutoff could have formed as a result of the presence of Crystal Creek\textsuperscript{15}. The current abandoned bend seems to have been connected with the “deep lagoon”, as it is clear in the Strom map. This means that river channel abandonment (avulsion) occurred first (unknown year, possibly pre- or early European occupation) leading to the current path of the river and latter, but previously to 1874, this cutoff was formed. This approximation is inferred from noticing that what it is now the abandoned bend appeared active and connected to the old river path (which is described as a “deep lagoon”) in the Parish map from that year. This is possibly the oldest, post-European cutoff that can be identified from this historical analysis.

Cutoff 5

No creeks or tributaries flow near this cutoff. This feature is not depicted either on the old map from 1864 nor the Parish from 1877 but it is identifiable in the 1936 Strom map of this river section. This suggests that this cutoff formed between 1877 and 1936 (figure A3).

\textsuperscript{15} “The main tributaries of the Goulburn River between Eildon and Shepparton are all fairly steep, quick flowing streams in narrow valleys, subject to floods of short duration. Flood damage along these streams is confined to narrow strips of land immediately adjacent to the normal channel, and is of no great magnitude” Robin Stewardson, unpublished. From a ‘Report from the Parliamentary Public Works Committee on the Goulburn Flooding Enquiry’, 1968.
Figure A3. Cutoffs 4 and 5. The old channel course depicted in the Parish maps is in bright blue (from the 1870s), the old channel course depicted on the 1930s Strom map is in yellow and the modern channel is in light blue. Flow is from left to right.

River Aanabranche 2

This anabranch could be associated with the presence of Scrubby Creek, which flows from the south side of the Black Range State Forest and used to flow into the old channel bend through a looped channel. The Parish from 1877 (amended in 1943) shows this cutoff as being the old river path but the Strom map from 1936 actually depicts and describes the abandoned bends as a “river anabranch”. Thus, this unit also was formed between 1877 and 1936.
Figure A4. River Anabranch 2, which represents the old channel course until 1936. It is located at the confluence with Scrubby Creek. The old river course shown as active in the Parish map is in bright blue. The channel course on the Strom map (1930s) is in yellow and the modern channel is in light blue. Flow is from top to bottom.

**Meander cutoff 6**

The formation of this meander cutoff could be associated to the presence of Home Creek, which seemed to have had important input flows during overbank flooding during the pre-regulation period (personal communication with a long-time resident, Rodney Ridd). This cutoff is depicted as such in the Parish map from 1877/1943 and is also described in the map from 1864, suggesting that it was formed previous to those years. Together with cutoff 4, this feature is older that the rest of the post-settlement meander cutoffs that have been identified in this analysis. However, according to the land owner, the old channel became abandoned only “100 years ago” 1906/1907. This suggests that both paths of the channel were occupied for some years (and formed a
loop) before abandonment of the old channel. However, this analysis shows that it could at present still be occupied by water during high floods.

Figure A5. Old and modern river course were digitalised and georeferenced from the Strom maps, the 1930s Parish maps and the 2005 areal photograph. The old river course shown as active in the Parish map is in bright blue. The channel course shown on the 1936 Strom map is in yellow and the modern channel is in light blue.

Meander cutoff 7

This cutoff is identifiable when the maps from 1864 and the Parish from 1891 are compared with the Parish map from 1922/1964 and the topographic map from the 1980s. This suggests that this cutoff was formed between 1891 and 1922.
Meander Cutoff 8

The correspondent Strom map from the 1930s of the reach where this meander cutoff formed was unavailable. However, this cutoff seems to have formed before cutoff 9 below as the former river meander can be observed on the Parish map of 1922 (amended in 1964). This suggests that this geomorphic unit formed between 1891 and 1922 (but later than cutoff 7).

Cutoff 9

This unit was identified after comparing the map from 1864 and the Parish of Killingworth from 1891 with the topographic map (Yea) from the 1970s. It could be suggested that this cutoff formed between 1922 and 1980. The correspondent Strom map of this reach was unavailable but it would have helped me to identify if this unit formed before the 1930s. If that is the case, then all cutoffs identified here have formed previous to the construction of the Eildon Dam.
Figure A6. Cutoff 7, 8 and 9 were identified from the 1864 map (meander bends in bright blue) and the 2009 Lidar-DEM. The modern channel is the path that contains most white spots. Flow is from right to left.
Appendix B

B.1. Grain size distributions of floodplain sediment samples and reference sites

Floodplain Units
Cumulative Volume Percent (%):

- 1A.1B.1C (0-5cm) - Average
- 1A.1B.1C (5-15cm) - Average
- 1A.1B.1C (15-30cm) - Average
- 1A.1B.1C (30-50cm) - Average

Particle Diameter (μm):
Reference sites

![Graphs showing cumulative volume percent against particle diameter for different depth intervals at two reference sites (RS-1 and RS-2). The graphs display data for average values at 0-5 cm, 5-15 cm, 15-30 cm, and 30-50 cm depths. The graphs illustrate the distribution of particle sizes with varying cumulative volume percent.]
Cumulative Volume Percent (%) vs. Particle Diameter (µm)

- R1.R2 (0-5)cm - Average
- R1.R2 (5-15)cm - Average
- R1.R2 (15-30)cm - Average
- R1.R2 (30-50)cm - Average

Cumulative Volume Percent (%) vs. Particle Diameter (mm)

- R3.R4 (0-5)cm - Average
- R3.R4 (5-15)cm - Average
- R3.R4 (15-30)cm - Average
- R3.R4 (30-50)cm - Average
Appendix C

C.1. Calculation of $^{137}\text{Cs}$ total inventories
Table C.1: Calculation of 137Cs total reference inventory from core RS-1

<table>
<thead>
<tr>
<th>Depth interval (cm)</th>
<th>137Cs detected concentration ANSTO (Bq.kg⁻¹)</th>
<th>ANSTO Uncertainty</th>
<th>Dry Weight RS-1 (kg)</th>
<th>137Cs Areal activity (depth interval) (Bq.m⁻²)</th>
<th>Relative uncertainty (interval)</th>
<th>Uncertainty (interval) (Bq.m⁻²)</th>
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<tr>
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<td>5.8</td>
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<td>NA</td>
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Table C.2: Calculation of 137Cs total reference inventory from core RS-1

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<th>Depth interval (cm)</th>
<th>137Cs detected concentration ANSTO (Bq.kg⁻¹)</th>
<th>ANSTO Uncertainty</th>
<th>Dry Weight RS-1 (kg)</th>
<th>137Cs Areal activity (depth interval) (Bq.m⁻²)</th>
<th>Relative uncertainty (interval)</th>
<th>Uncertainty (interval) (Bq.m⁻²)</th>
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Table C.3: Calculation of 137Cs total reference inventory from core R1.R2
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<th>Depth interval (cm)</th>
<th>ANSTO $^{137}$Cs detect. concentration (Bq.kg$^{-1}$)</th>
<th>ANSTO Uncert.</th>
<th>Core R1: Dry Weight (kg)</th>
<th>Core R2: Dry Weight (kg)</th>
<th>Averaged Dry Weight (kg)</th>
<th>$^{137}$Cs Areal activity (depth interval) (Bq.m$^{-2}$)</th>
<th>Relative uncertainty (interval)</th>
<th>Uncertainty (interval) (Bq.m$^{-2}$)</th>
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Table C.4. Calculation of $^{137}$Cs total reference inventory from core R3.R4

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<th>ANSTO $^{137}$Cs detect. concentration (Bq.kg$^{-1}$)</th>
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<th>Averaged Dry Weight (kg)</th>
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### Table C.5. Calculation of $^{137}$Cs total reference inventory from core R5.R6.R7

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<th>Core R5: Dry Weight (kg)</th>
<th>Core R6: Dry Weight (kg)</th>
<th>Core R7: Dry Weight (kg)</th>
<th>Averaged Dry Weight (kg)</th>
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### Table C.6. Calculation of $^{137}$Cs total reference inventory from core R8.R9

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<th>Depth interval (cm)</th>
<th>ANSTO $^{137}$Cs concentration (Bq.kg$^{-1}$)</th>
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<th>Core R8: Dry Weight (kg)</th>
<th>Core R9: Dry Weight (kg)</th>
<th>Averaged Dry Weight (kg)</th>
<th>$^{137}$Cs Areal activity (depth interval) (Bq.m$^{-2}$)</th>
<th>Relative uncertainty (interval)</th>
<th>Uncertainty (interval) (Bq.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>2.5</td>
<td>± 0.8</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>144.3</td>
<td>0.3</td>
<td>46.2</td>
</tr>
<tr>
<td>5-15</td>
<td>1.6</td>
<td>± 0.8</td>
<td>0.20</td>
<td>0.21</td>
<td>0.21</td>
<td>235.9</td>
<td>0.5</td>
<td>118.0</td>
</tr>
<tr>
<td>15-30</td>
<td>not estimated</td>
<td>&lt;0.6</td>
<td>0.33</td>
<td>0.36</td>
<td>0.35</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>30-50</td>
<td>not estimated</td>
<td>&lt;1.8</td>
<td>0.47</td>
<td>0.41</td>
<td>0.44</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Total inventory</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>380.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total uncertainty</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>126.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table C.7. Calculation of the total inventory of $^{137}$Cs of floodplain unit 1L.1G.1I

<table>
<thead>
<tr>
<th>Depth Interval (cm)</th>
<th>*$^{137}$Cs detected concentration; ANSTO (Bq.kg$^{-1}$)</th>
<th>ANSTO Uncertainty</th>
<th>Averaged Dry Weight: (among samples 1L.1G.1I) (kg)</th>
<th>$^{137}$Cs Areal activity (depth interval) (Bq.m$^{-2}$)</th>
<th>Relative uncertainty (interval)</th>
<th>Uncertainty (interval) (Bq.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>5.6</td>
<td>+ 0.6</td>
<td>0.07</td>
<td>172</td>
<td>0.11</td>
<td>19</td>
</tr>
<tr>
<td>5-15</td>
<td>3.8</td>
<td>+ 0.6</td>
<td>0.18</td>
<td>291</td>
<td>0.16</td>
<td>46</td>
</tr>
<tr>
<td>15-30</td>
<td>1.2</td>
<td>+ 0.3</td>
<td>0.25</td>
<td>130</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>30-50</td>
<td>not detected</td>
<td>&lt; 0.5</td>
<td>0.32</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Total Inventory</td>
<td></td>
<td></td>
<td></td>
<td>593</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>Total Uncertainty</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table C.8. Calculation of the total inventory of $^{137}$Cs of floodplain unit 1D.1Dbis.1E

<table>
<thead>
<tr>
<th>Depth Interval (cm)</th>
<th>*$^{137}$Cs detected concentration; ANSTO (Bq.kg$^{-1}$)</th>
<th>ANSTO Uncertainty</th>
<th>Averaged Dry Weight: (among samples 1D.1Dbis.1E) (kg)</th>
<th>$^{137}$Cs Areal activity (depth interval) (Bq.m$^{-2}$)</th>
<th>Relative uncertainty (interval)</th>
<th>Uncertainty (interval) (Bq.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>4.0</td>
<td>+0.9</td>
<td>0.07</td>
<td>200</td>
<td>0.23</td>
<td>45</td>
</tr>
<tr>
<td>5-15</td>
<td>2.2</td>
<td>+1.2</td>
<td>0.16</td>
<td>247</td>
<td>0.55</td>
<td>135</td>
</tr>
<tr>
<td>15-30</td>
<td>not estimated</td>
<td>&lt;2.2</td>
<td>0.21</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>30-50</td>
<td>not estimated</td>
<td>&lt;1.3</td>
<td>0.31</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Total Inventory</td>
<td></td>
<td></td>
<td></td>
<td>448</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Uncertainty</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>142</td>
</tr>
</tbody>
</table>
Table C.9. Calculation of the total inventory of $^{137}$Cs of floodplain unit 1A.1B.1C

<table>
<thead>
<tr>
<th>Depth Interval (cm)</th>
<th>$^{137}$Cs detected concentration; ANSTO (Bq.kg$^{-1}$)</th>
<th>ANSTO Uncertainty</th>
<th>Averaged Dry Weight: (among samples 1A.1B.1C) (kg)</th>
<th>$^{137}$Cs Areal activity (depth interval) (Bq.m$^{-2}$)</th>
<th>Relative uncertainty (interval)</th>
<th>Uncertainty (interval) (Bq.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>3.4</td>
<td>± 1.3</td>
<td>0.09</td>
<td>159</td>
<td>0.38</td>
<td>61</td>
</tr>
<tr>
<td>5-15</td>
<td>3.9</td>
<td>± 0.9</td>
<td>0.20</td>
<td>418</td>
<td>0.23</td>
<td>96</td>
</tr>
<tr>
<td>15-30</td>
<td>not estimated</td>
<td>&lt;0.8</td>
<td>0.31</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>30-50</td>
<td>not estimated</td>
<td>&lt;2.0</td>
<td>0.36 (of 9cm of sample)</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Total Inventory</td>
<td></td>
<td></td>
<td></td>
<td>577</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Uncertainty</td>
<td></td>
<td></td>
<td></td>
<td>114</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table C.10. Calculation of the total inventory of $^{137}$Cs of floodplain unit 2D.2E.2F

<table>
<thead>
<tr>
<th>Depth Interval (cm)</th>
<th>$^{137}$Cs detected concentration; ANSTO (Bq.kg$^{-1}$)</th>
<th>ANSTO Uncertainty</th>
<th>Averaged Dry Weight: (among samples 2D.2E.2F) (kg)</th>
<th>$^{137}$Cs Areal activity (depth interval) (Bq.m$^{-2}$)</th>
<th>Relative uncertainty (interval)</th>
<th>Uncertainty (interval) (Bq.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>5</td>
<td>+1.2</td>
<td>0.11</td>
<td>249</td>
<td>0.24</td>
<td>60</td>
</tr>
<tr>
<td>5-15</td>
<td>not estimated</td>
<td>&lt;3.5</td>
<td>0.29</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>15-30</td>
<td>not estimated</td>
<td>&lt;1.9</td>
<td>0.44</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>30-50</td>
<td>not estimated</td>
<td>&lt;1.0</td>
<td>0.59</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Total Inventory</td>
<td></td>
<td></td>
<td></td>
<td>249</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Uncertainty</td>
<td></td>
<td></td>
<td></td>
<td>60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table C.11. Calculation of the total inventory of $^{137}$Cs of floodplain unit N.J.Q

<table>
<thead>
<tr>
<th>Depth Interval (cm)</th>
<th>$^{137}$Cs concentration; ANSTO (Bq.kg$^{-1}$)</th>
<th>ANSTO Uncertainty</th>
<th>Averaged Dry Weight: (among samples N.J.Q) (kg)</th>
<th>$^{137}$Cs Areal activity (depth interval) (Bq.m$^{-2}$)</th>
<th>Relative uncertainty (interval)</th>
<th>Uncertainty (interval) (Bq.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>5.6</td>
<td>+ 0.5</td>
<td>0.09</td>
<td>213</td>
<td>0.09</td>
<td>19</td>
</tr>
<tr>
<td>5-15</td>
<td>3.1</td>
<td>+ 0.4</td>
<td>0.25</td>
<td>332</td>
<td>0.13</td>
<td>43</td>
</tr>
<tr>
<td>15-30</td>
<td>not estimated</td>
<td>&lt;0.7</td>
<td>0.42</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>30-50</td>
<td>not estimated</td>
<td>&lt;0.5</td>
<td>0.62</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Total Inventory</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>545</td>
</tr>
<tr>
<td>Total Uncertainty</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>47</td>
</tr>
</tbody>
</table>

Table C.12. Calculation of the total inventory of $^{137}$Cs of floodplain unit QQ.BB.AA

<table>
<thead>
<tr>
<th>Depth Interval (cm)</th>
<th>$^{137}$Cs detected concentration; ANSTO (Bq.kg$^{-1}$)</th>
<th>ANSTO Uncertainty</th>
<th>Averaged Dry Weight: (among samples QQ.BB.AA) (kg)</th>
<th>$^{137}$Cs Areal activity (depth interval) (Bq.m$^{-2}$)</th>
<th>Relative uncertainty (interval)</th>
<th>Uncertainty (interval) (Bq.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>4.4</td>
<td>+ 0.5</td>
<td>0.11</td>
<td>216</td>
<td>0.11</td>
<td>25</td>
</tr>
<tr>
<td>5-15</td>
<td>1.6</td>
<td>+ 0.2</td>
<td>0.29</td>
<td>205</td>
<td>0.13</td>
<td>26</td>
</tr>
<tr>
<td>15-30</td>
<td>not estimated</td>
<td>&lt;0.7</td>
<td>0.47</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>30-50</td>
<td>not estimated</td>
<td>&lt;0.4</td>
<td>0.68</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Total Inventory</td>
<td></td>
<td></td>
<td></td>
<td>421</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Uncertainty</td>
<td></td>
<td></td>
<td></td>
<td>35</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table C.13. Calculation of the total inventory of $^{137}$Cs of floodplain unit FF.GG.HH

<table>
<thead>
<tr>
<th>Depth Interval (cm)</th>
<th>$^{137}$Cs concentration; ANSTO (Bq.kg$^{-1}$)</th>
<th>ANSTO Uncertainty</th>
<th>Averaged Dry Weight: (among samples FF.GG.HH) (kg)</th>
<th>$^{137}$Cs Areal activity (depth interval) (Bq.m$^{-2}$)</th>
<th>Relative uncertainty (interval)</th>
<th>Uncertainty (interval) (Bq.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>4.7 + 0.5</td>
<td>0.09</td>
<td>186</td>
<td>0.11</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>5-15</td>
<td>2.7 + 0.5</td>
<td>0.26</td>
<td>303</td>
<td>0.19</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>15-30</td>
<td>not established</td>
<td>0.44</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>30-50</td>
<td>not estimated</td>
<td>0.46</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Total Inventory</td>
<td></td>
<td></td>
<td>488</td>
<td></td>
<td>59</td>
<td></td>
</tr>
</tbody>
</table>

### Table C.14. Calculation of the total inventory of $^{137}$Cs of floodplain unit CC.DD.EE

<table>
<thead>
<tr>
<th>Depth Interval (cm)</th>
<th>$^{137}$Cs detected concentration; ANSTO (Bq.kg$^{-1}$)</th>
<th>ANSTO Uncertainty</th>
<th>Averaged Dry Weight: (among samples CC.DD.EE) (kg)</th>
<th>$^{137}$Cs Areal activity (depth interval) (Bq.m$^{-2}$)</th>
<th>Relative uncertainty (interval)</th>
<th>Uncertainty (interval) (Bq.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>4.1 + 0.5</td>
<td>0.11</td>
<td>191</td>
<td>0.12</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>5-15</td>
<td>2.1 + 0.3</td>
<td>0.28</td>
<td>254</td>
<td>0.14</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>15-30</td>
<td>not estimated</td>
<td>0.44</td>
<td>0</td>
<td>NA</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>30-50</td>
<td>not estimated</td>
<td>0.65</td>
<td>0</td>
<td>NA</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total Inventory</td>
<td></td>
<td></td>
<td>445</td>
<td></td>
<td>43</td>
<td></td>
</tr>
</tbody>
</table>

Total Uncertainty
Table C.15. Calculation of the total inventory of $^{137}$Cs of floodplain unit K.L.M

<table>
<thead>
<tr>
<th>Depth Interval (cm)</th>
<th>*$^{137}$Cs concentration; ANSTO (Bq.kg$^{-1}$)</th>
<th>ANSTO Uncertainty</th>
<th>Averaged Dry Weight: (among samples K.L.M) (kg)</th>
<th>$^{137}$Cs Areal activity (depth interval) (Bq.m$^{-2}$)</th>
<th>Relative uncertainty (interval)</th>
<th>Uncertainty (interval) (Bq.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-5</td>
<td>3.5 ± 0.6</td>
<td></td>
<td>0.07</td>
<td>105</td>
<td>0.17</td>
<td>18</td>
</tr>
<tr>
<td>5-15</td>
<td>1.8 ± 0.5</td>
<td></td>
<td>0.28</td>
<td>220</td>
<td>0.28</td>
<td>61</td>
</tr>
<tr>
<td>15-30</td>
<td>not established</td>
<td>&lt; 0.5</td>
<td>0.46</td>
<td>0</td>
<td>NA</td>
<td>-</td>
</tr>
<tr>
<td>30-50</td>
<td>not established</td>
<td>&lt; 0.6</td>
<td>0.66</td>
<td>0</td>
<td>NA</td>
<td>-</td>
</tr>
<tr>
<td>Total Inventory</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>326</td>
</tr>
<tr>
<td>Total Uncertainty</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>64</td>
</tr>
</tbody>
</table>

Table C.16. Calculation of the total inventory of $^{137}$Cs of floodplain unit F.G

<table>
<thead>
<tr>
<th>0Depth Interval (cm)</th>
<th>*$^{137}$Cs detected concentration; ANSTO (Bq.kg$^{-1}$)</th>
<th>ANSTO Uncertainty</th>
<th>Averaged Dry Weight: (among samples F.G) (kg)</th>
<th>$^{137}$Cs Areal activity (depth interval) (Bq.m$^{-2}$)</th>
<th>Relative uncertainty (interval)</th>
<th>Uncertainty (interval) (Bq.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>4.1 ± 0.6</td>
<td></td>
<td>0.12</td>
<td>207</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-15</td>
<td>2.3 ± 0.4</td>
<td></td>
<td>0.26</td>
<td>258</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-30</td>
<td>not established</td>
<td>&lt; 1.1</td>
<td>0.42</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30-50</td>
<td>not established</td>
<td>&lt; 0.6</td>
<td>0.51</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Inventory</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>465</td>
</tr>
<tr>
<td>Total Uncertainty</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>54</td>
</tr>
</tbody>
</table>
Table C.17. Calculation of the total inventory of $^{137}$Cs of floodplain unit A.B.UU

<table>
<thead>
<tr>
<th>Depth Interval (cm)</th>
<th>*$^{137}$Cs detected concentration; ANSTO (Bq.kg$^{-1}$)</th>
<th>ANSTO Uncertainty</th>
<th>Averaged Dry Weight: (among samples A.B.UU) (kg)</th>
<th>$^{137}$Cs Areal activity (depth interval) (Bq.m$^{-2}$)</th>
<th>Relative uncertainty (interval)</th>
<th>Uncertainty (interval) (Bq.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-5</td>
<td>3.5 + 0.5</td>
<td></td>
<td>0.03</td>
<td>53</td>
<td>0.1</td>
<td>8</td>
</tr>
<tr>
<td>5-15</td>
<td>4.9 + 0.5</td>
<td></td>
<td>0.20</td>
<td>435</td>
<td>0.1</td>
<td>44</td>
</tr>
<tr>
<td>15-30</td>
<td>3.8 + 0.6</td>
<td></td>
<td>0.33</td>
<td>549</td>
<td>0.2</td>
<td>87</td>
</tr>
<tr>
<td>30-50</td>
<td>0.7 + 0.3</td>
<td></td>
<td>0.44</td>
<td>136</td>
<td>0.4</td>
<td>58</td>
</tr>
<tr>
<td>Total Inventory</td>
<td></td>
<td></td>
<td></td>
<td>1,172</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Uncertainty</td>
<td></td>
<td></td>
<td></td>
<td>114</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table C.18. Calculation of the total inventory of $^{137}$Cs of floodplain unit D.TT.E

<table>
<thead>
<tr>
<th>Depth Interval (cm)</th>
<th>*$^{137}$Cs detected concentration; ANSTO (Bq.kg$^{-1}$)</th>
<th>ANSTO Uncertainty</th>
<th>Averaged Dry Weight: (among samples D.TT.E) (kg)</th>
<th>$^{137}$Cs Areal activity (depth interval) (Bq.m$^{-2}$)</th>
<th>Relative uncertainty (interval)</th>
<th>Uncertainty (interval) (Bq.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>5.6 + 0.7</td>
<td></td>
<td>0.12</td>
<td>292</td>
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Appendix D

D.1. Post-peak ponds along the floodplain units

Figure D.1. Ponds that can form along Unit 1 (D.TT.E) once the flood recedes to 155.5 meters (above sea level) along the reach.
Figure D.2. Ponds that can form along Unit 2 (K.L.M) once the flood recedes to 157.5 meters (above sea level) along the reach.
Figure D.3. The pond water that can form along Unit 3 (A.B.UU) once the flood recedes to 157 meters (above sea level) along the reach.
Figure D.4. Ponds that can form along Unit 4 (F.G) once the flood recedes to 158.3 meters (above sea level) along the reach.
Figure D.5. Ponds that form along Unit 5 (CC.DD.EE) once the flood recedes to 159 meters (above sea level) along the reach.
Figure D.6. Pond that can form along Unit 6 (FF.GG.HH) once the flood recedes to 158 meters (above sea level) along the reach.

Two ponds form at a flood height of 158 meters during the receding phase, at which the disconnection point exists. One is along the upstream limb of the Unit and the smaller one located along its centre and upstream limb.
Figure D.7. Ponds that can form along Unit 7 (QQ.BB.AA) once the flood recedes to 159.3 meters (above sea level) along the reach.
Figure D.8. Small ponds form along Unit 8 (N.J.Q) once the flood recedes to 168.2 (above sea level) meters along the reach
Figure D.9. Small ponds form along Unit 9 (2D.2E.2F) once the flood recedes to 177.8 meters (above sea level) along the reach.
Figure D.10. A small pond can form along Unit 11 (1A.1B.1C) once the flood recedes to 195.5 meters (above sea level) along the reach. At higher flood elevation, flood water would flow out of the Unit straight to the river channel downstream through the meander cutoff that encloses the Unit.

The pond that form along Unit 10 (1F) is shown in Chapter 8.
Figure D.11. Maximum size of ponds along Unit 12 (1D.1DBis.1E) and Unit 13 (1L.1G.1I.) Both are formed once the flood recedes to 195 meters (above sea level) along the reach.
Appendix E

E.1. Overbank flow paths forming during overbank inundation

Figure E.1. Overbank flow path from channel to Unit 1 (D.T.T.E); in orange. The Unit is shown in purple. The flow depth and velocity rasters used correspond to a peak flow discharge of 40,000 ML/day (Flooding threshold). Inundated areas are shown in blue.
Figure E.2. Overbank flow path from channel to Unit 2 (K.L.M); in orange. The Unit is shown in purple. The flow depth and velocity rasters used correspond to a peak flow discharge of 30,000 ML/day (Flooding threshold). Inundated areas are shown in blue.
Figure E.3. Overbank flow path from channel to Unit 3 (A.B.UU); in orange. The Unit is shown in purple. The flow depth and velocity rasters used correspond to a peak flow discharge of 30,000 ML/day (Flooding threshold). Inundated areas are shown in blue.
Figure E.4. Overbank flow path from channel to Unit 4 (F.G); in orange. The Unit is shown in purple. The flow depth and velocity rasters used correspond to a peak flow discharge of 40,000 ML/day (Flooding threshold). Inundated areas are shown in blue.
Figure E.5. Overbank flow path from channel to Unit 5 (CC.DD.EE); in orange. The Unit is shown in purple. The flow depth and velocity rasters used correspond to a peak flow discharge of 40,000 ML/day (Flooding threshold). Inundated areas are shown in blue.
Figure E.6. Overbank flow path from channel to Unit 6 (FF.GG.HH); in orange. The Unit is shown in purple. The flow depth and velocity rasters used correspond to a peak flow discharge of 40,000 ML/day ( Flooding threshold). Inundated areas are shown in blue.
Figure E.7. Overbank flow path from channel to Unit 7 (QQ.BB.AA); in orange. The Unit is shown in purple. The flow depth and velocity rasters used correspond to a peak flow discharge of 50,000 ML/day (Flooding threshold). Inundated areas are shown in blue.
Figure E.8. Overbank flow path from channel to Unit 8 (N.J.Q); in orange. The Unit is shown in purple. The flow depth and velocity rasters used correspond to a peak flow discharge of 30,000 ML/day (Flooding threshold). Inundated areas are shown in blue.
Figure E.9. Overbank flow path from channel to Unit 9 (2D.2E.2F); in orange. The Unit is shown in purple. The flow depth and velocity rasters used correspond to a peak flow discharge of 20,000 ML/day (Flooding threshold). Inundated areas are shown in blue.
Figure E.10. Overbank flow path from channel to Unit 11 (1A.1B.1C) in orange. The Unit is shown in purple. The flow depth and velocity rasters used correspond to a peak discharge of 40,000 ML/day (Flooding threshold). Inundated areas are shown in blue.
Figure E.11. Overbank flow path from channel to Unit 12 (1D.1Dbis.1E); in orange. The Unit is shown in purple. The flow depth and velocity rasters used correspond to a peak discharge of 30,000 ML/day (flooding threshold). Inundated areas are shown in blue.
Figure E.12. Overbank flow path from channel to Unit 13 (1L.1G.1I); in orange. The Unit is shown in purple. The flow depth and velocity rasters used correspond to a peak discharge of 30,000 ML/day (flooding threshold). Inundated areas are shown in blue.
Appendix F

F.1. Floodplain vegetation

Figure F.1. Sparse tree and grassland cover the four floodplain units of the upstream end of the floodplain; Unit 10 (core 1F), Unit 11 (cores 1A.1B.1C), Unit 12 (cores 1D.1Dbis.1E) and Unit 13 (cores 1L.1G.1I). The overbank flow path at their corresponding unit-flooding threshold is shown by the green line.
Figure F.2. Dense tree cover is found along Unit 8 (cores N.J.Q) delimited in red. The overbank flow path at the unit-flooding threshold is shown by the green line.
Figure F.3. Grassland and sparse trees are found along Unit 9 (cores 2D.2E.2F) delimited in red. The overbank flow path at the unit-flooding threshold is shown by the green line.
Figure F.4. Vegetation cover along five floodplain units (delimited in red) of the downstream end of the floodplain. These are, from left to right, Unit 2 (cores K.L.M); Unit 3 (cores A.B.UU); Unit 4 (cores F.G), Unit 7 (cores QQ.BB.AA), Unit 5 (cores CC.DD.EE) and Unit 6 (cores FFGG.HH). The overbank flow path at their unit-flooding threshold is shown by the green line.
Figure E 12. Vegetation cover along Unit 1 (cores D.TT.EE). This floodplain unit (delimited in red) is located at the furthest end downstream of the floodplain section. The overbank flow path at the Unit flooding threshold is shown by the green line.
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