The Persistence of Oxbow Lakes as Aquatic Habitats: an Assessment of Rates of Change and Patterns of Alluviation

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Abstract

Oxbow lakes are of high ecological importance due to the number and the diversity of habitats they provide. They are created after the abandonment of meanders and subsequent sediment infilling leads to their progressive terrestrialisation, taking from a few months up to several centuries. Nonetheless, little is known about oxbow lake terrestrialisation processes, sediment composition, or why such a disparity exists in lakes' longevity.

To understand the controls on oxbow lakes alluviation, field observations, remotely sensed data and GIS analyses were combined. Sediment transfers in oxbow lakes were documented by topographic and sampling surveys of sites in France and Wales. Aerial photographs and maps were used to date cutoff events, analyse oxbow lakes geometry, and understand the controls on oxbow lake terrestrialisation for eight rivers of different characteristics.

Findings from this study illustrate that the specific mechanism by which an oxbow lake is formed is critical to its persistence as a lake and to the sedimentary processes experienced. Chute cutoff oxbow lakes filled in 10 times faster than neck cutoffs and showed significantly different sediment deposits. Results also highlighted that oxbow lakes are not only fine-grained sediment stores, as often referred to, but can be significant bed material sinks since a site on the Ain River sequestered up to 34% of the bed material supply. However, the volume of sediment mobilised in the main channel during cutoff appeared to be larger than the bed-load stored in the former channel within the first decade after abandonment (40%). Sedimentary evidence showed that the terrestrialisation of oxbow lakes is driven by several processes: a flow separation zone at the entrance of the channel creating a sediment plug, sediment sorting by flow gradients and decantation in ponded areas. These results have important implications for the management of meandering rivers by providing a comprehensive analysis of depositional processes which also helps to predict oxbow lake longevity.

Acknowledgements

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Chapter 1

Introduction

Oxbow lakes are widespread features of freely meandering rivers across the planet which form as a result of the abandonment of a meander bend by cutoff. Former meanders are then isolated by progressive sediment aggradation at each end creating the oxbow lake's open-water area. Their natural evolution leads to their progressive infilling with sediment and complete terrestrialisation. Oxbow lakes have important roles on floodplain corridors such as sinks for sediment and sediment-adsorbed contaminants as well as aquatic habitat for a number of species. This thesis provides a comprehensive study of oxbow lakes' sedimentation, longevity and dynamics. The findings presented regarding the controls and processes of oxbow lake sedimentation are essential steps to understand floodplain architecture and meandering river dynamics. At last, these water bodies are of high ecological importance for the diversity of habitats they offer; therefore it is key to understand the controls on oxbow lake longevity.

1.1 Sediment transfers

Understanding channel dynamics, sediment transfers and depositional processes are key questions in fluvial geomorphology because they have important implications for floodplain habitats, the management of lands and pollution, and the general understanding of floodplain architecture. Sediment transported through a catchment has a tendency to exhibit a downstream increase in volume (Trimble 1997), in overall floodplain storage (Dietrich and Dunne 1978) and reduced sediment size (e.g. Ashworth and Ferguson 1989). Nevertheless there are exceptions, for instance Meade and Parker (1985) showed that sediment volume can decrease downstream during low flow periods on the Mississippi River (USA). A simplistic scheme for sediment transfers was advanced by Schumm (1977) and consisted of splitting a catchment in three subdivisions including an upper area where sediment was produced, a middle area where sediment was transferred and a lower area where sediment was deposited. This idealized system stresses that channel reaches may be dominated by a process, but it is not completely realistic as sediment is eroded, transported and deposited throughout the entire channel length. Sediment eroded from the drainage basin is transferred by rivers either as dissolved load (transported in solution), wash load (finer than bed-load and moving readily in suspension) or bed-material load (material found in large quantities in the bed) (Knighton 1998). Numerous field studies have shown that sediment eroded from the bank and the floodplain is largely remobilized (e.g. Trimble 1976, 1981, Aalto et al. 2008). For meandering rivers, the focus of this study, point bar deposits and meander curvature have a strong effect on currents and trigger channel migration by bank erosion (e.g. Leopold and Wolman 1960, Dietrich and Smith 1983). The progressive migration of meanders by bank erosion and point bar growth creates cross sections of scroll-shaped ridges and swales following the curve of channel (Allen 1965). Channel migration is one of the dominant processes for sediment transfers of meandering rivers with additional influence from the effect of floods and runoff, which shave the existing floodplain. Finally, meanders can also cut-off leading to the transfer of large volumes of sediment up to five orders of magnitude larger than erosion by lateral channel migration (Zinger et al. 2011). The open water areas of the cut-off channels form oxbow lakes and constitute long term records of the river loads (e.g. Allen 1965, Erskine et al. 1982; Glinska-Lewczuk 2005). Former channel processes and the sedimentation of oxbow lakes will be the focus of this study.

1.2 Meander cutoff

1.2.1 Why do meandering rivers cut-off?

Meander cutoff is a process occurring naturally on freely meandering rivers and can be defined as the shortening of a meander bend to the profit of a new path. The primary triggers of cutoffs are flood events (Johnson and Paynter 1967; Micheli and Larsen 2011) but these events are not necessarily of high magnitude (Fig. 1.1). For several cases, cutoffs were observed to occur after the repetition of moderate floods (Hooke 1995; Gay et al. 1998; Hooke 2004). Tal and Paola (2010) suggest that the incision of a new channel through floodplain sediment requires a flow at high erosion capacity; this is generated by the higher slope gradient of the shorter cut-off route. For this reason, cutoffs are more likely to occur on the most sinuous bends of a river (Allen 1965; Micheli and Larsen 2011). Overbank flow can also trigger cutoff without a direct increase in discharge. Smith and Pearce (2002) described a cutoff caused by overbank flow due to ice-jam on the Milk River (Montana, USA; and Alberta, Canada) but this is a far less common cause. Vegetation removal increases the vulnerability of the floodplain and enhance the risk of cutoff (Tal and Paola 2010; Micheli and Larsen 2011) because grass, plants and small trees play an important role in maintaining the banks by providing flow resistance and limiting erosion (e.g., Shields and Gray 1992; Millar and Quick 1993; McKenney et al. 1995; Prosser and Dietrich 1995; Abernethy and Rutherfurd 2001; Bennett et al. 2002; Jarvela 2002; Samani and Kouwen 2002; Gray and Barker 2004; Pollen et al. 2004; Corenblit et al. 2007; Eaton and Giles 2009; Langendoen et al. 2009; Pollen-Bankhead and Simon 2010).

Figure 1.1: Satellite composite image of the confluence of the Mamore River and the Isiboro River in Bolivia.
This extremely active stretch of meandering rivers expresses an impressively large number of cutoffs of various shapes and sizes. UTM coordinates: 15°13’35.30’’S, 64°55’59.16’’W.

Cutoffs may function as a control on the floodplain dynamics of meandering rivers. Leopold and Wolman (1960) stated that cutoffs have the role of adjusting the river by providing a limit to the amplitude of meanders since the new channel is often a lot shorter than the abandoned meander bend. The question of the role of cutoff in meandering river dynamics was developed later by Stolum (1996) in a numerical modelling study. Stolum (1996) suggests that meandering rivers follow a self-organisation process controlled by cutoffs. A river evolving with symmetrical meanders (Fig. 1.2: "ordered state", Stolum, 1996) is likely to migrate increasingly towards various directions with sharp bends (Fig. 1.2: "chaotic state", Stolum, 1996) when cutoffs induce strong axial asymmetry intensified by the meandering process. Oppositely, Stolum (1996) explains that cutoff might also correct asymmetry by abandoning meanders. In the investigation of the causes of multiple cutoffs on the Bollin River, UK, Hooke (2004) suggested that long-term channel patterns matches with the hypothesis of Stolum (1996) since the author observed that river sinuosity had reached a critical value before an avalanche of cutoffs occured, resembling the chaotic state described by Stolum (1996). This is also suggested by Gautier et al. (2007), who could not demonstrate a clear relationship between flood occurrence and cutoff events. As a result, meander cutoff may generally be an inherent and inevitable process of natural meandering rivers.

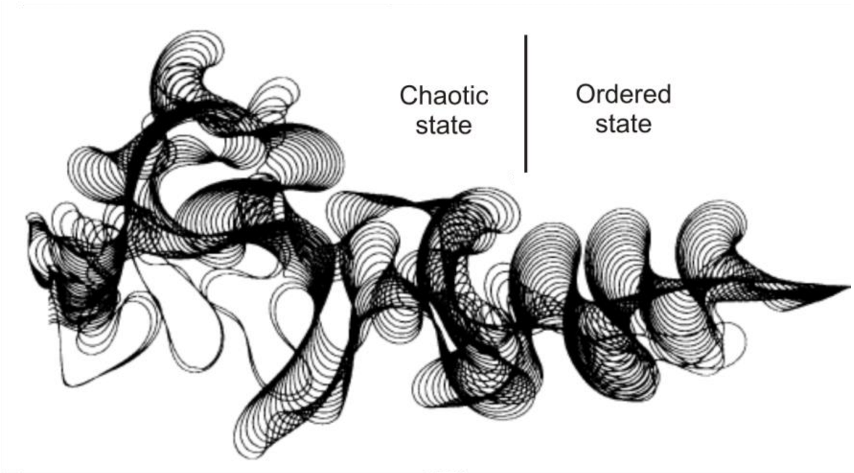

Figure 1.2: Evolution of the river simulated by Stolum (1996).
The simulation started with a nearly straight line and evolves to both chaotic (on the left) and ordered state (on the right). The transition between the two states was initiated by a cutoff cluster. "The ordered state in the right part of the figure has reached a mature stage in which the train of bends is still highly symmetrical around the original axis, while at the same time each bend is growing into an asymmetrical shape" (Stolum, 1996, p1711).

1.2.2 The significance of cutoffs for meandering rivers

The effect of cutoffs for meandering rivers is three-fold: geometric since they reduce meander amplitude, dynamic since they generate sediment transfers and structural since their sediment infilling builds the floodplain architecture. Camporeale et al.

(2008) suggested the first two factors using model simulations. Their analyses highlighted that the geometrical role relates to the elimination of older reaches from the active river, while the dynamic role is explained by the disturbance of the channel by cutoff events. Cutoffs change river geometry by removing meanders which decreases sinuosity, reorganises bend shape (Stolum 1996) and maintains its amplitude (Sun et al. 1996; Camporeale et al. 2008). The dynamic function of cutoffs lies on the fact that, while eroding a new channel, they transfer large volumes of sediment that can be equivalent to 60 years of erosion by channel migration (Zinger et al. 2011). Cutoff events bypass river segments which limits the spatial evolution of meanders and leaves water bodies that progressively store sediment. Both water body and stored sediment modify the architecture of the floodplain, with geomorphic consequences observed to persist for over a decade after the event (Hooke 1995).

1.2.3 Cutoff mechanisms

Several different types of natural channel bifurcation were reported by previous literature in fluvial geomorphology. The term oxbow lake is often used in to describe the result of various types of channel shortening. Channel shortening takes place either on single meander bends such as neck and chute cutoffs (Fisk 1947; Allen 1965), or on longer segments including notably multiple loop cutoffs (e.g., Allen 1965; Lewis and Lewin 1983) or avulsions (e.g., Slingerland and Smith 1998). However, this thesis will only focus on the mechanism of single bend cutoff given that it is by definition the only process that produces oxbow lakes.

1.2.3.1 Neck cutoff

Neck cutoff occurs when two meander bends migrate into one another and trigger channel shift (Fig. 1.3). This process is generally associated with well-developed meanders that are cut-off when two opposite bends erode the floodplain toward each other until they eventually migrate into one another (Fisk 1947; Allen 1965; Gagliano and Howard 1984). The typical conditions favourable to neck cutoffs are low gradient river reaches. Lewis and Lewin (1983) investigated the role of gradient in driving neck cutoff in Wales and Borderland, they measured a slope between 0.8 ‰ and 2.5 ‰ associated with the studied neck cutoffs. Low slope favours meander migration and imposes an important slope difference between the river and the former meander when cutoff occurs (Gagliano and Howard 1984). Slope difference could be of importance in the longevity of oxbow lakes and will be discussed in Chapter 2 using a large dataset of oxbow lake dimensions from various rivers of the world. Gagliano and Howard (1984) investigated neck cutoff formation using 26 former channels located along the Lower Mississippi River, USA. They detailed further the description of neck cutoff mechanism by suggesting two natural ways of formation: firstly by excessive growth of a whole meander loop as mentioned above, when both meander arms migrate into one another; and secondly by the migration of one meander bend into the other, possibly due to an important difference in bed material resistance of the two opposite meander sections. Regardless of their mode of formation, neck cutoffs lead to major shortening of the local channel length because an entire loop is removed.

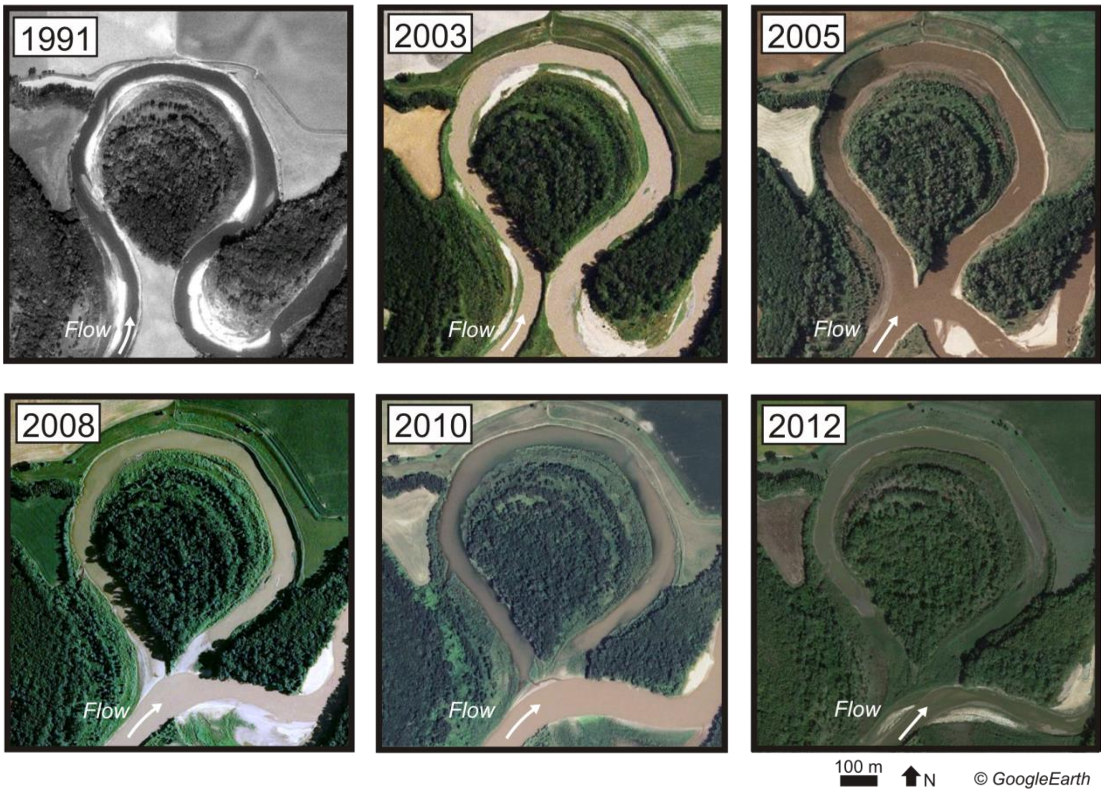

Figure 1.3: Aerial photographs showing the initiation of a neck cutoff.
The site is located on the Smoky Hill River (Kansas and Colorado, USA) and cut-off between 2003 and 2005, when the two meander arms migrated into one another. Sediment was already deposited at the ends of the former channel and isolated an oxbow lake in 2008. Vegetation developed on the new deposit around 2010. UTM coordinates: 38°58’30.62’’N, 96°56’56.83’’W.

1.2.3.2 Chute cutoff

Chute cutoff is created by the incision of a new channel across the point bar area of a meander (Fisk 1947; Allen 1965; Johnson and Paynter 1967; Gagliano and Howard 1984; Constantine et al. 2010a) (Fig. 1.4). Fisk (1947) observed that the new channel often develops as an extension of the upper arm of the cut-off meander. This cutoff process is associated with steeper slope than neck cutoff as it was observed to occur on channel slopes of up to 9.5 ‰ according to observations by Lewis and Lewin (1983). The high slope is likely to provide the energy to incise the floodplain area. The angle of bifurcation between the new channel and the upper part of the former channel (or "diversion angle") is generally lower than for neck cutoffs (Fisk 1947; Bridge 1985; Constantine et al. 2010a). Several studies (Fisk 1947; Lindner 1953; Gagliano and Howard 1984; Shields and Abt 1989; Piegay et al. 2002; Constantine et al. 2010a) suggest that this angle affects the diverted flow and sediment infilling occurring shortly after cutoff within the former channel (see 3.2).

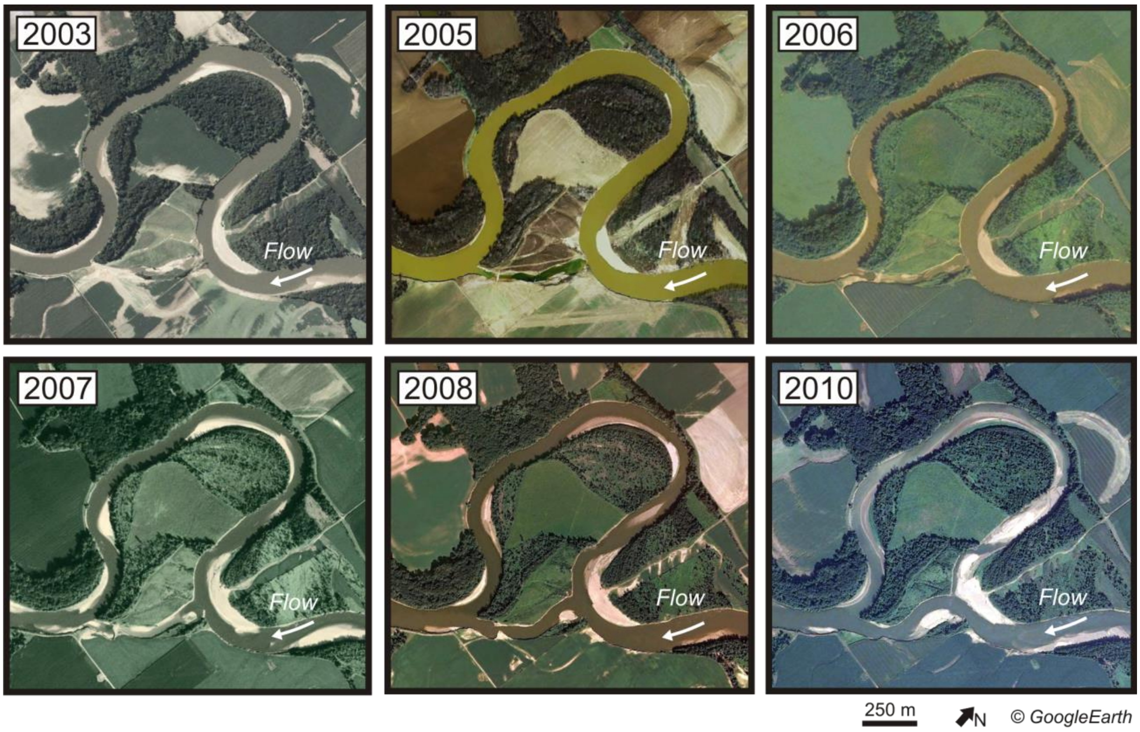

Figure 1.4: Aerial photographs showing the initiation of a chute cutoff on the White River (Indiana, USA).
Between 2003 and 2008, a narrow chute channel enlarges progressively across the floodplain by what appears to be the enlargement of a swale. Around 2008 the new channel conveys a significant part of the discharge and becomes the main conveyor in 2010. The chute cutoff can be dated here between 2008 and 2010. UTM coordinates: 38°50'36.05''N, 87°10'22.73''W.

Chute cutoffs take place either by enlargement of a swale (Fisk 1947; Grenfell et al. 2012), by headcut extension (Gay et al. 1998) or by extension of an embayment (Constantine et al. 2010b). Chute cutoff by enlargement of swale takes place when overbank flow is great enough to flood the extended rills ("swales") which are created by meander migration (Hickin and Nanson 1975). The water is then channelised in one or several channels and significant erosion of the banks can occur, leading to progressive enlargement of the swales (Fig. 1.5). Finally, enlargement can reach the point when one of the swales becomes the principal conveyor of the river discharge (Fisk 1947; Grenfell et al. 2012). According to Grenfell (2012) this mechanism of chute cutoff might be caused by a change in sediment load or inflow energy.

Figure 1.5: Photo illustrating a series of inundated swales from an Amazonian floodplain. The swales can channelise water and potentially lead to chute cutoff (Constantine et al. 2010b).

In contrast, cutoff by headcut extension requires the presence of a natural dam located upstream of the meander (Constantine et al. 2010b) (Fig. 1.6). A natural dam, made for example of woody debris, can easily divert the river flow to the point bar and force overbank flows if the channel is narrow enough (Keller and Swanson 1979). Following the highest slope gradient, the water flowing overbank plunges downstream which can result in bank incision. The created headcut incision, located on the downstream half of the bend, can propagate upward until it reaches the upstream side of the bend and forms a chute (Constantine et al. 2010b). Gay et al. (1998) studied the evolution of headcut caused by ice-jam along the Powder River (Montana, USA). Because the river is quite narrow, jammed ice has the same effect as wood to divert flow and this can also lead to cutoff. The study shows that headcut propagation rate seems to depend on overbank flow and on whether or not the bank is frozen. Thompson (2003) reported a slightly different case of headcut extension observed on the Blackledge River in

Connecticut (USA). The study shows that the relocation of the river increased significantly sediment accumulation of a point bar. This led to a superelevation of water opposite the point bar that facilitated overbank flow, progressively caused headcut incision, and formed a cutoff.

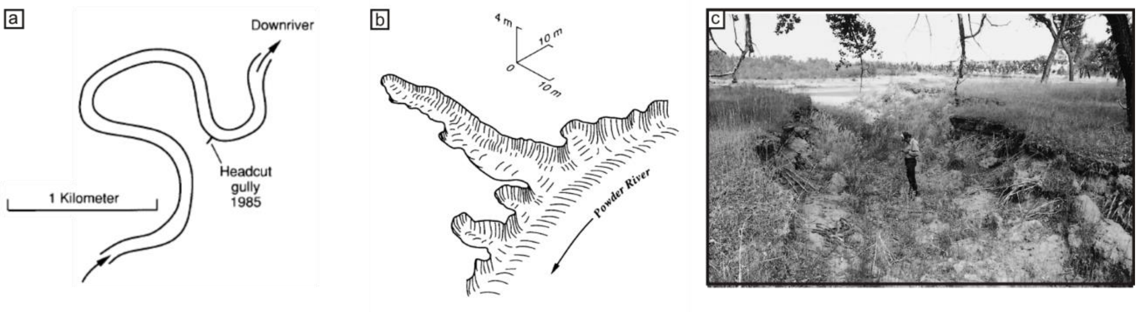

Figure 1.6: Illustration of a headcut that lead to chute cutoff on the Powder River (Montana, USA) in 1985.
(a) Schematic representation of the meander bend where the headcut occurred.
(b) Isometric drawing of headcut gully.
(c) Photograph of the headcut gully in 1986 with the Powder River at the back. John Moody is standing in the middle of the photo for scale (after Gay et al. 1998).

Constantine et al. (2010b) described a mechanism of chute cutoff by embayment extension (Fig. 1.7). It is initiated by the erosion of the outer bank of the upstream reach of the meander. Erosion is at first rather local but after successive floods the eroded zone enlarges to form an embayment that will trigger chute cutoff. On the Sacramento River (California, USA), Constantine et al. (2010b) observed that this type of cutoff can appear in areas devoid of natural dams in contrast with cutoff by headcut extension; the phenomenon is independent of sudden changes in conveyance capacity due to changes in channel width. The study concluded that the three primary controls of this particular chute cutoff would be: the steepening of the valley slope enhancing flow energy, the thinning of vegetation which would not provide a suitable protection against erosion, and the reduction in sediment load increasing the flow erosion capacity (Constantine et al., 2010b). Additional literature tackles the origins of chute cutoff by embayment (Hauer and Habersack 2009) in a study of a 1000-year flood impacts on floodplain morphology. In this case study the authors attributed embayment cutoff to an increase of the valley width after millennial flood but also partly due to anthropogenic influences.

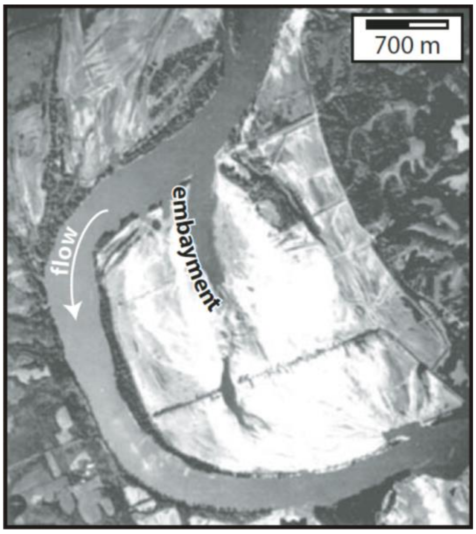

Figure 1.7: Aerial photograph of a meander bend of the Missouri River (USA). This illustrates the formation of an embayment progressing downstream and that can potentially create a chute cutoff (Constantine et al. 2010b).

1.3 Stages of oxbow lake sedimentation

1.3.1 From cutoff to hydraulic disconnection

Cutoff events create oxbow lakes by progressively isolating former meanders by sediment infilling. After cutoff, flow in the former meander reduces and favours deposition of coarse-grained sediment until the abandoned channel ends are partially or completely disconnected. The new channel enlarges progressively as it conveys an increasing discharge. This occurs to the detriment of the former channel which has a lower gradient than the incising channel and supports the blockage of the oxbow lakes ends by a sediment plug. Theoretical and experimental results indicate the existence of a flow separation within the upstream entrance of the former channel, the size of which is determined by the diversion angle (Taylor 1944; Law and Reynolds 1966; Hager and Hutter 1984; Neary and Odgaard 1993; Keshavarzi and Habibi 2005; Constantine et al. 2010a). These studies indicate that the larger the angle, the larger the width of the flow separation. Tiron (2009) also reported a zone of very low flow velocity near the outer bank at the entrance to the channel with a sediment plug forming rapidly, possibly linked to the existence of a flow separation. The size of the flow separation controls the competence of the diverted flow, enhancing plug formation with increases in the width of the separation (Constantine et al. 2010a), though it remains unclear how construction of the plug proceeds. It is important to note as well the recent findings of Le Coz et al. (2010), who provided a rare description of the interaction between flow and sediment at the downstream end of the abandoned channel. Based on both field evidence and laboratory experiment, they revealed that the presence of complex flow circulation with secondary currents caused deposition near the downstream bank due to a decelerating flow along with erosion of the upstream bank due to accelerating flow (see field example of bar deposits on Fig. 1.8).

Figure 1.8: Photographs illustrating both coarse and fine-grained sediment in the studied oxbow lakes of the Towy River.
(a) and (b): Photographs of the downstream end of the oxbow Lake CHU4 taken on different days in 2010. Nine years after cutoff a substantial infilling by coarse-grained sediment is visible and forms a bar.
(c) Photograph of the river bank eroding the upstream end of an abandoned channel. Erosion reveals an outcrop with basal gravel deposit overlaid by a thick layer of clay and silt.
(d) Close up of (c) showing the contact between fine- (clay and silt) and coarse-grained (gravel) sedimentation.

The development of a coarse-grained sediment plug disconnects the channel from the newly-formed oxbow lake. However, the lake is not necessarily fully isolated as it can remain connected to the river at one end or through a tie channel flowing through the plug (Gagliano and Howard 1984; Rowland et al. 2005). The thick sediment plug is often observed to form first at the upstream end of chute cutoff former channels (Allen 1965; Hooke 1995; Piegay et al. 2002; Constantine et al. 2010a). This stage of sedimentation was observed on aerial photographs from the Beni River (Bolivia) by Gautier et al. (2007), they reported that the first stage of sedimentation was the most rapid and lasted between 1 and three years. However, the period of formation of the plug at the extremities of the lake seems quite variable, ranging between months and a decade (Gagliano and Howard 1984; Hooke 1995). Nonetheless, plugs are not always present since observations by Grenfell et al. (2012) indicates that 33 to 67% of the chute cutoffs of three sand-bedded tropical rivers did not infill during the 35 years of study. The downstream end of chute cutoffs usually takes longer to block up and can remain connected to the river for longer due to the formation of complex recirculating flows that scour this zone and counter-balance deposition (Le Coz et al. 2010). For instance in a study of the Ain River (France), upstream plugs were present at all the 17 sites whereas only 30% of them showed downstream plugs (Citterio and Piegay 2000). No such difference has been observed for neck cutoffs yet but Allen (1965) observed that the neck cutoff plugs are usually smaller than those of chute cutoff. This is due to the higher diversion angle these sites cut-off at, which creates a large flow bifurcation zone and enhances local deposition in case of neck cutoff (see 1.3.2). Based on observations within sediment plugs of oxbow lakes in the USA and Papua New Guinea, Rowland et al. (2005) observed that plug deposits were planar bedded and sloped gently toward the oxbow lakes. They hypothesised that the plugs first develop as berms separating the arms of the oxbow lake from the main channel. Material is then advected over these berms, forming a sedimentary ramp that progrades into the lake with time. Citterio and Piegay (2000) examined the controls on plug evolution within abandoned channels along the Upper Rhone River of France using a statistical analysis of measurements made from aerial photographs. They found that oxbow lake plugs can be subject to 3 types of evolution which are: 1) shortening by upstream erosion from channel migration, 2) vegetation development upstream supporting sediment deposition, and 3) downstream extension with progradation. Piegay et al. (2002) presented results of multiple regression analysis showing that the cutoff age had an impact on plug evolution because the number of floods increases with time. Hydraulic connectivity, controlled by the plug, was described as the most significant factor controlling the sedimentation of oxbow lakes (Citterio and Piegay 2009).

Studies reporting the very first stage of sediment transfers following cutoff are rare. Cutoff is a relatively sudden phenomenon and significant infilling can occur within a month. Therefore it is difficult to obtain data in this short time window to report sediment transfers associated with cutoff. Consequently, the volume of sediment transferred during the isolation of the channel is not well documented, especially related to the former channel entrance infill since no study has focused on this question yet. Even though plug formation and extension are key processes defining the oxbow water area, little is known about the rates and extent of plug development. For this reason, Chapter 3 will investigate the initial transfer of bed material and the patterns of sedimentation in two recently cut-off channels of the Ain River (France). This chapter will give a detailed description of the development of the plug at a yearly timescale during a decade, as well as assessing the significance of the bed-load transfers between the river and the former channel (see Appendix 4, Dieras et al. 2013).

1.3.2 From disconnection to terrestrialisation

Once the oxbow lake ends are fully or partially blocked by bed material, sediment deposition occurs at much slower rates (e.g., Gautier et al. 2007). Sedimentation within the oxbow lake is dominated by fine-grained sediment delivered as suspended load during floods though Johnson and Paynter (1967) found that gravel nearly completely filled an abandoned channel of the River Irk (UK). However, sediment can also be scoured by high peak floods (Henry and Amoros 1995; Citterio and Piegay 2009). Floods can scour first by creating turbulent flow which prevents particle settling, and secondly, by draining the particles back to the river through a connected end. Fisk (1947) reported that the thickness of the fine-grained deposit was greatest away from the arms of the oxbow where the form of the lake was least affected by bed material aggradation. Fisk, Gagliano and Howard (1984) summarised the evolutionary cycle of oxbows generated by neck cutoff based on observations along the Lower Mississippi River. They noted that batture, or tie, channels may be eroded into sediment plugs, thereby allowing a hydraulic connection to the main channel during low flow stages. The deposition of sediment at the batture-channel mouths produces muddy deltas within both arms of the lake. Rowland et al. (2005) estimated deposition rates within batture channels along the Lower Mississippi River, the Fly River of Papua New Guinea, and Birch River of Alaska, USA, and found that such channels can supply significant amounts of sediment to the oxbow lake. This finding was also reported by Day et al. (2008) from oxbow lakes along the Fly River. During floods, Gagliano and Howard (1984) reported that flow enters the oxbow from the upstream batture channel and exits through the downstream batture channel, though the fraction of flow being diverted is small relative to the total river discharge. Sutton et al. (2004) have shown through field observations and modelling that flow may not directly enter the oxbow during a flood. Instead, a recirculation zone may develop within both arms once the flood is fully developed, which allows some mixing between the lake and main channel, but not enough to transfer suspended sediment into the distal portions of the lake. In another potential complication, Gagliano and Howard (1984) also stated that because of the low gradient through the oxbow and through the batture channels, there is often a time lag between changes in river stage and changes in lake stage, which may alter the downstream flow pattern through the oxbow. In general, however, suspended sediment deposition is most rapid within the arms of the oxbow, with the upstream arm containing coarser grained particles due to its predominance as the entrance for overbank flow. Conversely, sedimentation rates are lowest within the distal portions of the lake and can be dominated by organic material (Piegay et al. 2008).

After a period reported to last from decades to centuries (Gagliano and Howard 1984; Hooke 1995; Constantine et al. 2010a), sedimentation leads to the complete terrestrialisation of the oxbow lake. Neck cutoff oxbow lakes were observed to persist longer than chute cutoffs (e.g., Gagliano and Howard 1984) yet no study has ever quantified their long term evolution. Chapter 2 will investigate the evolution of the water surface area of 37 oxbow lakes from eight rivers of various geomorphic characteristics to try and determine if there is a general pattern to the evolution of oxbow lakes, notably regarding the cutoff mechanism. Sediment rate in oxbow lakes was reported to range between 3 and 140 $mm.y^{-1}$ (e.g., Lewis and Lewin 1983; Erskine et al. 1992) but only a few surveys looked at the sedimentation patterns even though it participates in building the floodplain sedimentary structure. Neck cutoff oxbow lakes are likely to have the most extensive clay infilling according to Fisk (1947) due to bed-load contributing little to deposits (Allen 1965) (Fig. 1.9) and deposited preferentially at the ends of the channel (see 1.3.2 Diversion angle, geometry and cutoff mechanism). Coarse-grained sediment such as gravel was reported to fill former channels after chute cutoff on the River Irk, UK (Johnson and Paynter 1967). Chute channel deposits also tend to fine upward (Erskine et al. 1982) with thicker fine-grained deposits downstream (Citterio and Piegay 2009; Toonen et al. 2012). As mentioned in this paragraph, previous observations of oxbow lakes offer information regarding sedimentation patterns but a thorough survey of oxbow lakes sediment on several study sites is needed to be able to understand depositional processes. These data will be presented in Chapter 4 in a detailed investigation of the sedimentation of five oxbow lakes of the Towy River in Wales, UK. This chapter will provide a comprehensive study of the sedimentary structure and dynamics of oxbow lakes deposits in the long term (from a decade to over a century). This will help understanding sedimentation processes and provide key information regarding floodplain architecture.

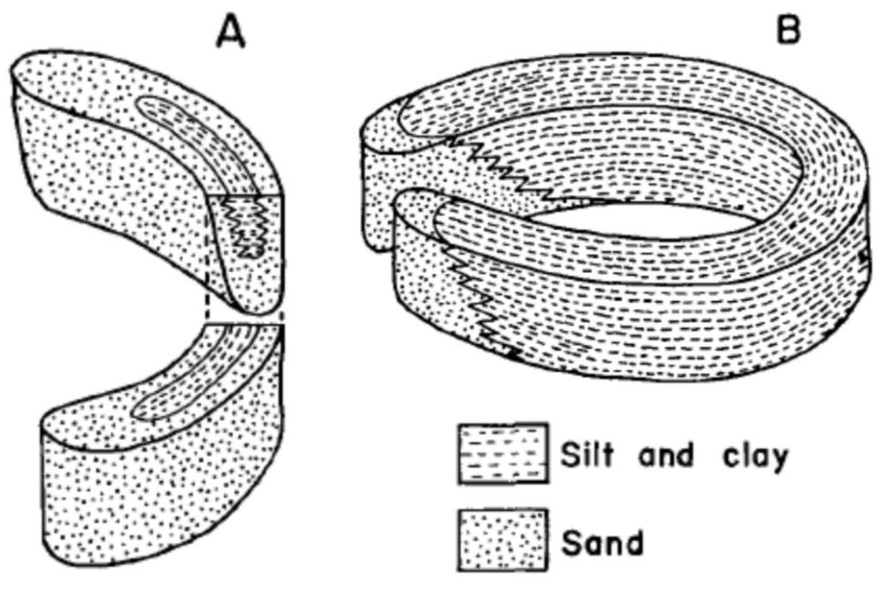

Figure 1.9: Schematic representation of oxbow lakes deposits suggested by Schumm (1960). A) Sediment deposits in chute cutoff channels. B) Sediment deposits in neck cutoff channels (after Schumm 1960; Allen 1965).

1.4 Controls on terrestrialisation

1.4.1 Floods and Hydraulic Connectivity

Oxbow lakes can be directly hydraulically connected to the river, if one or both channel ends are not obstructed, or indirectly connected by overbank flow. Flow conveys sediment to the former channel therefore hydraulic connectivity is recognised as a major control on sedimentation (Shields and Abt 1989; Bornette et al. 1996; Henry and Amoros 1996; Piegay et al. 2000; Piegay et al. 2002; Piegay et al. 2008; Citterio and Piegay 2009; Tiron et al. 2009). Sedimentation is impacted by which end of the channel remains connected to the river according to Citterio and Piegay (2009). For example, if the downstream end is open during overbank flow, the flow input from upstream can scour fine-grained sediment deposited in the submerged area if the shear stress conditions are high (Henry and Amoros 1996; Amoros et al. 2005; Citterio and Piegay 2009). In that case, the opened downstream end acts as an outlet drain. Additionally, a high magnitude flood that reconnects the upstream end is able to transfer coarse-grained sediment to the lake and change the depth distribution of sediment (Henry and Amoros 1996). Hence, high magnitude floods could transfer coarse-grained sediment on top of finer sediment that was already deposited from previous floods of smaller magnitude.

Once the two exits of an oxbow lake are fully disconnected by plugs, the lake fills up mostly with sediment conveyed by overbank flow. River incision lowers down the water level in the main channel and thus supports the isolation of former meander from direct hydraulic connection (Bornette et al. 1996). At this stage, oxbow lake sedimentation rate increases with a higher frequency of high magnitude floods (Citterio and Piegay 2009). However, for an individual flood event deposits thickness in oxbow lakes decreases with increasing distance from the main channel (Erskine et al. 1982; Piegay et al. 2008). For example, Piegay et al. (2008) measurements exhibit a difference of about 3 m between deposits at the upstream end of the oxbow from those at the downstream end on the Ain River, France. River migration can reduce or lengthen the distance between the active and the former channel and modify the impact of overbank flow (Citterio and Piegay 2000; Piegay et al. 2000). Gautier et al.

(2007) reported that meander migration was an important factor controlling oxbow lake sedimentation after observing that former channels located on the concave side of a migrating meander tended to show rapid infilling. Therefore, by affecting overbank flow, the meander belt activity affects hydraulic connectivity and sedimentation.

1.4.2 Diversion angle, geometry and cutoff mechanism

One of the most important physical parameters that appears to impact oxbow lake sedimentation is the “diversion angle” (Fig. 1.10). In a study of diverted channels, Lindner (1953) reported that bed-load deposition was strongly increased by lower diversion angles. In contrast, fine-grained sediment remained in proportion to the diverted flow. Lindner (1953) suggested that a drastic reduction in flow velocity at the point of diversion resulted in bed-load deposition caused by reduced flow velocity and shear stress. Bridge et al. (1986) also confirmed Lindner’s (1953) ideas from observations of bed material deposition on the Calamus River (Nebraska, USA). Constantine et al. (2010a) investigated further the controls on the alluviation of oxbow lakes by bed material load along the Sacramento River, USA. Results from this study highlighted how diversion angle regulates the size of the flow separation zone between the new and the former channel. As a result, the flow separation zone created by the diversion controls boundary shear stress at the former channels entrance, and consequently affects bed material transport capacity.

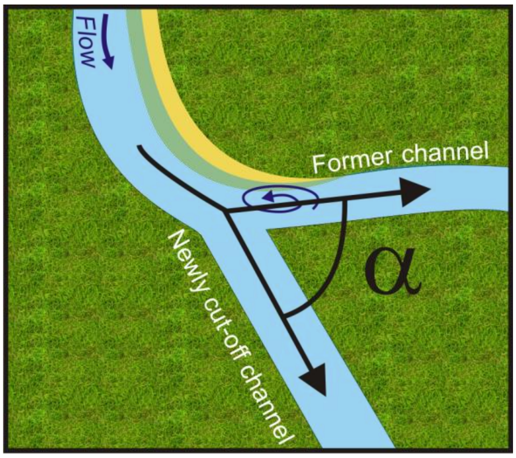

Figure 1.10: Schematic representation of the diversion angle (α).
The small flow whirl at the entrance of the former channel indicate the flow bifurcation zone (adapted from Constantine et al. 2010a).

Bed material deposits in the former channel entrance tend to be affected by the diversion angle and the fraction of bed material load diverted appeared to be inversely proportional to the diversion angle for angles between 0 and 90° (Fisk 1947; Shields and Abt 1989). This means that with lower angles, more flow can be diverted in the abandoned channel, favouring bed material transport (Gagliano and Howard 1984; Kondolf 2007; Constantine et al. 2010a). Kondolf (2007) reported a relationship between sedimentation and diversion angle in a study based on historical aerial photographs, cross sections and sediment cores from the Sacramento River, USA. Results showed that oxbows with diversion angles ≤50° fill up at least five times faster than those with diversion angles >70°. Profiles of the entrance plug of the former channel vary with diversion angles: low angles are associated with long bar deposits and a gradual change of sediment calibre from coarse-grained to fine, while high angles are associated with dominant fine-grained profiles (Shields and Abt 1989; Piegay et al. 2002; Kondolf 2007). Consequently, the diversion angle not only affects the volume of sediment diverted but also where sediments are deposited.

Neck and chute cutoff mechanisms lead to different lake geometries. Neck cutoffs tend to form pear-shaped abandoned channels with a sediment plug at the entrance (Fisk 1947) whereas chute cutoffs form lakes with less curvature, more ‘crescent-shaped’ (Fig. 1.11). This shape difference, depending on the mechanism, tends to naturally form neck cutoffs with higher diversion angles than chute cutoffs which affect sediment infilling as stated above. Johnson and Paynter (1967) noticed a morphological difference between chute and neck cutoff oxbow lakes. Their study of a chute cutoff on the River Irk (UK) reported extended accretion of coarse-grained sediment at both the upper and lower ends of the oxbow with significant deposits in the central part. In comparison, neck cutoff sedimentation in oxbow lakes from the Mississippi River is dominated by fine-grained sediment with coarser sediment only limited to the lake ends (Gagliano and Howard 1984). Hooke’s (1995) survey of four former channels in northwest England indicated that the neck cutoffs underwent faster plug formation than the chute cutoffs. The plug in neck cutoff oxbow lakes blocked the upstream connection to the river and the lake remained deep water bodies after five years whereas chute cutoffs were entirely filled up by this time (Hooke 1995). Channel type and curvature could also affect the rate of infill (Bridge et al. 1986; Hooke 1995; Citterio and Piegay 2009). In Chapter 2 it is hypothesised that the long term evolution of oxbow lakes could depend on the cutoff mechanism since oxbow geometry and diversion angles are significantly different. This hypothesis will be tested in a study of the long term evolution of 37 chute and neck cutoff oxbow lakes.

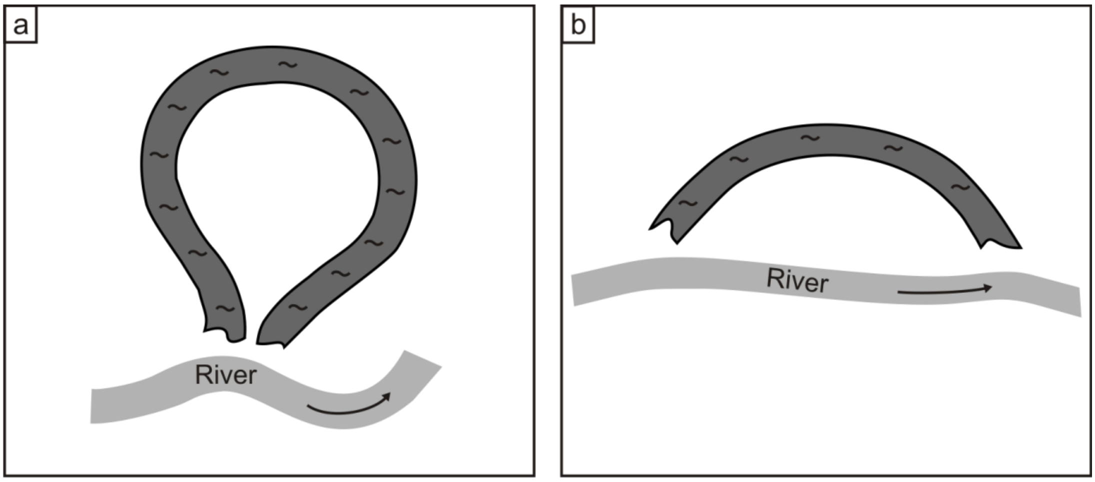

Figure 1.11: Illustration of the typical oxbow lake shape (in dark grey).
(a) Pear-shaped oxbow lake created by neck cutoff.
(b) Crescent-shaped oxbow lake created by chute cutoff.

1.4.3 River sediment supply

Sediment supply transported by the river has the key role of providing the raw material that fills up former channels and leads to terrestrialisation. Shields and Abt (1989) suggested that, while cutoff is occurring, bed-load concentrations have a strong influence on the abandoned channel volume. This is in agreement with the study by Constantine et al. (2010a) showing that aggradation rates within former channel entrances are impacted by the bed material in the main channel in a way that the finer the bed-load size, the higher the transport capacity and greater the amount of sediment diverted into the abandoned channel. Similarly, Erskine et al. (1992) expressed that former channel infilling could differ depending on the availability of coarse-grained sediment and therefore not all cutoff channels show uniform fine-grained deposits. As a results, bed-load size and availability in the main channel impacts former channel aggradation.

Once one or both former channel limbs are plugged with sediment it is common that a batture channel still connects the lake to the river. Rowland et al. (2005) indicated that sediment load is the primary control of tie channels aggradation and deposits extent within the lake from a field study using OSL (optically stimulated luminescence) to date sediment. However, Gautier et al. (2007) did not find an influence of the presence of a tie channel on sedimentation rates. Former channel disconnection can at last be accelerated by a change in sediment supply caused by a dam as suggested by a study focused on sediment dynamic of lower Ain River, France, in an area influenced by dams (Rollet 2007).

1.4.4 Vegetation

On river corridors, vegetation increases bank strength and helps retaining soil with the root network (Prosser and Dietrich 1995; Abernethy and Rutherfurd 2001; Gray and Barker 2004; Pollen et al. 2004) (Fig. 1.12). Dense patches of aquatic plants also support sediment trapping by increasing flow resistance (McKenney et al. 1995; Steiger and Gurnell 2003; Corenblit et al. 2009; Pollen-Bankhead et al. 2011). The presence of riparian vegetation such as shrubs or grass established on floodplain reaches tends to reduce cutbank erosion, channel incision and the rate of riparian buffer expansion (Graf 1978; Marston et al. 1995; Allmendinger et al. 2005). Isolated or widely spaced trees are however less able to protect the floodplain from erosion. Using numerical modelling, Constantine and Dunne (2008) showed that spacing between trees trunks is limited by the extent of their crown. As a result, trees tend to be naturally more spaced then shrubs or smaller vegetation and less able to slow flows down and prevent floodplain erosion. Nonetheless they can indirectly protect the floodplain by providing shade to smaller vegetation (Constantine and Dunne 2008). The protecting role of vegetation can be extrapolated to abandoned channels. Hooke (1995) pointed out that sedimentation of former channels was closely related to the spatial development of vegetation. Grass, shrubs and small trees start spreading in the abandoned channel bars within a few years after cutoff (e.g., Hooke 1995). That favours sediment deposition by decreasing local boundary shear stress, especially in case of high stem density (Constantine and Dunne 2008). The expansion of vegetation patches on oxbow lake upstream and downstream plugs supports sediment aggradation and subsequently oxbow lakes terrestrialisation (Henry and Amoros 1995; Citterio and Piegay 2000). Plants are very sensitive to changes of physical conditions and are easily affected by various factors (e.g., water transparency, flow disturbance, etc.). Frequent floods indirectly affect oxbow lake sedimentation by disturbing vegetation development on river corridors (Henry and Amoros 1995). Large floods generally sweep away most of the macrophytes present (Henry and Amoros 1996) but also affect terrestrial plants as well.

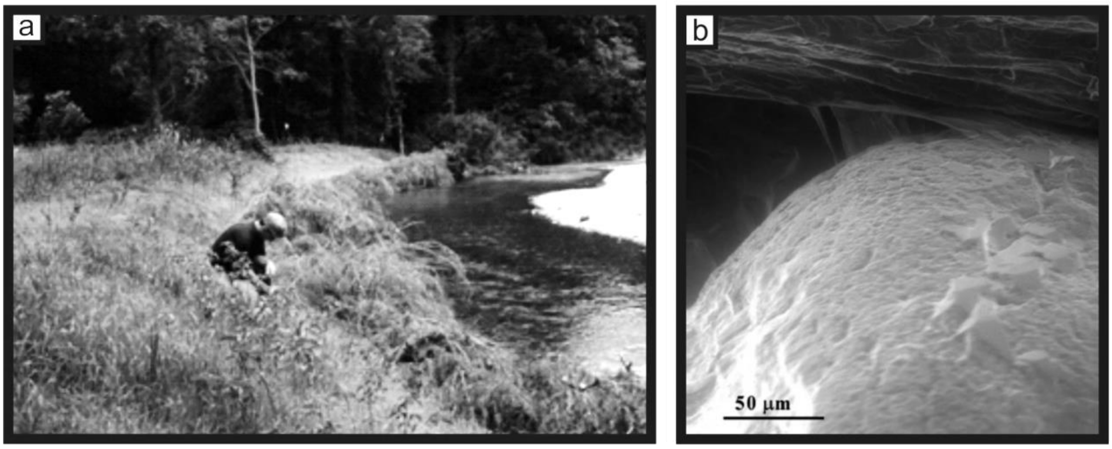

Figure 1.12: Protective effect of vegetation against erosion.
a) The use of Cedar trees and bank vegetation to reduce erosion on Spring Creek by the Oklahoma Department of Wildlife and Conservation (USA).
b) Environmental scanning electron microscope image of rootlets and other material from the root attached to a sand grain revealing how vegetation is able to physically maintain sediment particles (Tal and Paola 2010).

1.5 The Role of oxbow lakes on meandering floodplain

1.5.1 Floodplain architecture

A key geomorphological role of former channels is to participate in the building of the floodplain architecture. Cutoffs abandon water features which mark the boundary of the meander belt (Allen 1965) and also store sediment. In the long term, deposition of fine-grained sediment fills up the depression left by former meanders. Sediment is compacted under its own weight (Fisk 1947), forming cohesive lenses hard to erode especially in the case of neck cutoff oxbow lakes since they tend to be rich in clay (e.g., Gagliano and Howard 1984). When the future channel migration reaches these clay lenses, it meets a highly cohesive zone that can stop progression and forces bend migration in another direction. This is supported by a study of the Mississippi River (USA) that showed migration rates of 14 $m.y^{-1}$ higher in the part of the alluvial valley where the channel was in contact with fewer clay plugs (Hudson and Kesel 2000). Chute cutoffs tend to store larger volumes of bed material than neck cutoff as mentioned above (see 1.3.2); consequently the floodplain architecture is likely to vary depending on the type of cutoff. As a result, oxbow lakes form heterogeneities on the floodplain that are very likely to affect channel migration (Allen 1965; Erskine et al. 1982; Furbish 1991; Sun et al. 1996; Hudson and Kesel 2000).

1.5.2 Storage of contaminants and flood waters

Oxbow lake sediment records river pollution history because pollutants tend to adsorb on sediment particles (e.g., Erskine et al. 1982; Brugam et al. 2003; Glinska-Lewczuk 2005; Babek et al. 2008; Galicki et al. 2008; Glinska-Lewczuk et al. 2009a). Former channels form enclosed depressions when they are disconnected from the river which allows them to potentially store contaminants transported by overbank flow or small tributary streams. In a study of the Morava River, Czech Republic, Babek et al. (2008) suggested that sediment on the studied sites offered a very good stratigraphic resolution for the record of river contamination history, at yearly and seasonal scale, and allowed to trace contamination history up to the early 1980s. Furthermore, they have shown that contamination records obtained with lake sediment such as heavy metals or persistent organic pollutants were consistent with data from other Central European rivers. Glinska-Lewczuk et al. (2009a) also demonstrated that heavy metals were efficiently stored in the oxbow lakes of the River Lyna in Poland, finding 3.24 g of lead and 16 g of zinc in the top 30 cm of sediment.

The issue of the pollution of groundwater by contaminated oxbow lakes is not well documented even though this connection is mentioned (e.g., Amoros and Bornette 2002; Cooper et al. 2003; Kim et al. 2009). Nonetheless a buffer for pollution may be created by the very low permeability of the clay-rich sediment layer lying on the bed of oxbow lakes and the natural filtering effect of vegetation. Galicki et al. (2008) analysed the concentration of several pollutants (e.g., lead, arsenic, phosphorus) in an oxbow lake of the Mississippi River and in its surrounding vegetation. They suggested that even though pollutants originated principally from nearby fertilized cotton fields, pollutants appeared to accumulate preferentially in the lake. An explanation was that vegetation adsorbed the pollutant and then the decomposing litter was transported into the oxbow lake by seasonal floods.

At an early stage of infilling, former meanders create large floodplain topographic depressions which are good flood water stores and help to restrain the volume of water immersing occasionally floodplains (Henry and Amoros 1995; Citterio and Piegay 2000). Fine-grained sediment infilling by overbank flow provides therefore a reliable record of flood history in the long-term (e.g., Wolfe et al. 2006; Wren and Davidson 2011). In a study of the Lower Hunter River (Australia), Erskine et al. (1992) showed that channel change, flood regime shifts and variations in bed material can be determined with the study of sedimentary records in cut-off channels. Former channels constitute a source of information and not only for geomorphologists but also for historians. Ellis and Brown (1998) successfully dated archaeological remains found in paleochannel sediments in Leicester (UK) with the use of archaeomagnetic dating. This method compares the natural remnant magnetisation of minerals in sediment to a reference age curve established for the location (Ellis and Brown 1998). The study revealed that oxbows are ideal environments for archaeomagnetic dating because they are historically associated with settlements and the waterlogged sediment is often preserved. Another example is the investigation of the impact of the first European Settlement in Australia by Leahy et al. (2005) who used sediment deposited in the oxbow lake Bolin (“Bolin Billabong”) from the Yarra River floodplain.

1.5.3 Maintaining diverse aquatic habitats

The particular location of oxbow lakes on the river corridor enables them to be regularly connected to the active channel (Fig. 1.13). These environments are half way between lotic and lentic, with regular lateral water connectivity (between the main channel and the river corridor). The connection to the river distinctively supports a high diversity of habitats for both fauna and flora (Ward and Stanford 1995; Tockner et al. 1999; Ward et al. 1999; Amoros and Bornette 2002; Pringle 2003; Stella et al. 2011). When the former channel is hydraulically connected to the river, the nutrient-loaded water favours the development of vegetation and phytoplankton (Hamilton and Lewis 1987; Kohler and Nixdorf 1994). The developing population of phytoplankton can in turns support planktonic crustacean as shown in a study of a Polish oxbow lake of the Bug River (Strzałek and Koperski 2009). However, hydraulic connection also helps control the overdevelopment of macrophytes by mechanically removing them during high magnitude floods, enhancing successional processes (Amoros and Bornette 2002). Vegetation removal by floods is very important because macrophyte overgrowth can reduce the volume of water available and affect macroinvetebrates (Gallardo et al. 2012). A study of the Lower Ain River, France, shows that 20 to 25 hydrophyte species could be found on perifluvial aquatic zones of the river (Piegay et al. 2000). Vegetation communities found in former channels reflect contrasting ages and hydromorphic characteristics (Piegay et al. 2000) after the succession of different lacustrine stages, leading gradually to terrestrialisation.

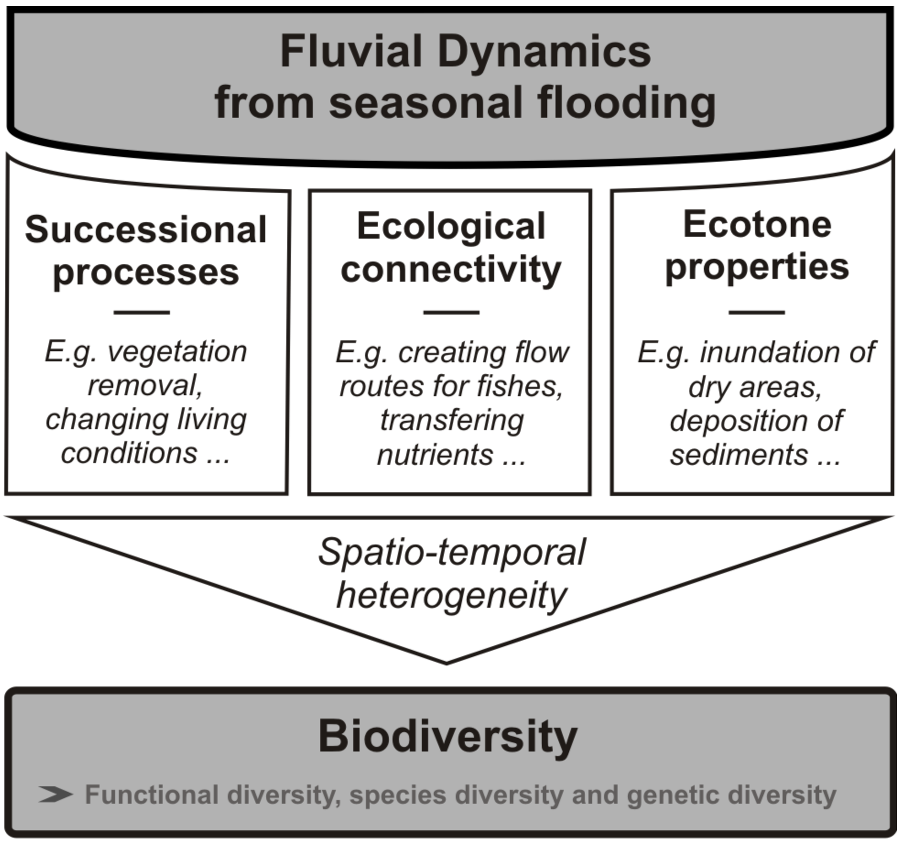

Figure 1.13: Simplified diagram to illustrate the role of fluvial dynamics and seasonal flooding in sustaining biodiversity (adapted from Ward et al. 1999).

Oxbow lakes are the fish nurseries of meandering river floodplains because they provide a calm environment for growth and refuges from predators (Kwak 1988; Schiemer 2000; Amoros and Bornette 2002; Miyazono et al. 2010; Osorio et al. 2011). Connectivity to the river is for these reasons essential for fish habitats and migration (e.g., Copp 1989; Schiemer et al. 1992; Ward et al. 1999; Jungwirth et al. 2000; Schiemer 2000). The water area and the shallowing of aging oxbow lakes also affect fish biodiversity because water depth is responsible for thermal, chemical and light stratification which also affects planktonic photosynthesis (Miranda 2005; Lubinski et al. 2008; Dembkowski and Miranda 2012). However, the primary controls on the water surface area of oxbow lakes have not been defined in the long-term; this question will be explored in Chapter 2 of this thesis. Henry and Amoros (1995) pointed out the importance of wetlands for their support of biodiversity, their sustenance of fishery productivity, and for the refuge they provide to animals from the river; e.g twaite shads and otters on the Tywi River, Wales (JNCC 2009). By sustaining a large variety of habitats for both fauna and flora, oxbow lakes support biodiversity (Miller et al. 2010) and are therefore of high ecological importance.

In contrast, oxbow lakes storing large amounts of suspended sediment and pollutants may have unfavourable consequences for aquatic vegetation (Niethammer et al. 1984; Zablotowicz et al. 2006; Knight et al. 2009; Lizotte et al. 2009; Heimann et al. 2011). Suspended sediments increase turbidity and reduce aquatic flora (Reynolds 1987; Brink et al. 1992). As a result, photosynthesis would be inhibited by suspended sediments and aquatic fauna may become unproductive due to lack of light penetration before sediment settles (Knight et al. 2002). Another interesting point is put forward by a study of the water quality of nine Polish oxbow lakes (Glinska-Lewczuk 2009b); the study confirms that oxbow lakes located in agricultural areas have an important function of regulation (as a sink) of nutrient transfers to the river. On the other hand the authors point out that high input of nutrients trapped in oxbow lakes (i.e. fertilizers) lead to an increase of algal productivity, responsible for eutrophication followed by anoxic conditions which are disastrous for the ecological balance of lakes. Therefore nutrients flux in oxbow lakes and their consequences on trophic state can be significant in the perspective of river corridor restoration.

1.5.4 Socio-economic role

Floodplains provide essential services to populations which have often led communities to live in the proximity of rivers. Services provided by floodplains include water storage and resources, pollution control, fishing and recreation (Sheaffer et al. 2002; Tockner and Stanford 2002). A survey from the Salt and Dupage Counties in Illinois (USA) estimated to £426,000.km^{-2} the recreational value for the 14 km^2 of floodplain area (Sheaffer et al. 2002). Similarly, the Vienna National Park "Donau-Auen" is a site located on a segment of the Danube River Floodplain for which benefits from visitors is evaluated to 11 million pounds per year (Gren et al. 1995). Oxbow lakes provide great value to meandering floodplains as they are good environments for fishing and recreation. Interviews of residents from five villages near the Tana River in Kenya showed that people ranked oxbow lakes as "very important" for fishing and rice growing (Terer et al. 2004). Oxbow lakes also represent valuable recreational values for the neighbouring population. Small lakes are appreciated by fishermen for their fish richness while larger lakes can be actual holiday's destination offering wide areas for water-related activities (swimming, sailing, water-skiing, etc.) and picturesque landscapes. The lower end of the Mississippi River Floodplain is a good example of oxbow lakes importance with over 20 oxbow lakes displaying a water surface area often over 1 km^2 wide. For example, Lake Mary Oxbow Lake is a holiday destinations (Fig. 1.14) with several beaches (Mississippi, USA) and its importance for the communities is highlighted by the fact that the lake even has a dedicated webpage on a social-network website with over 2,000 members. Consequently oxbow lakes such as Lake Mary 4can represent important regional socio-economical hubs.

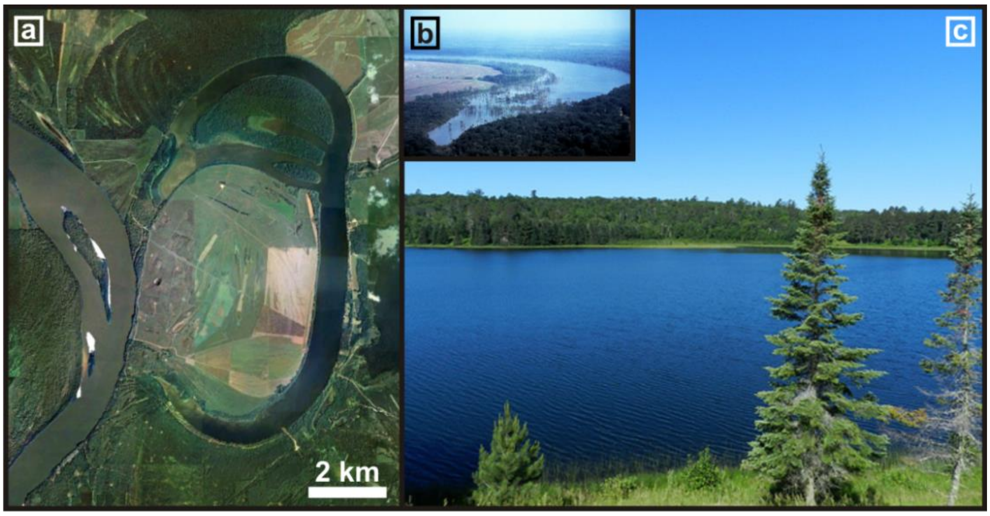

Figure 1.14: The wide open-water area of Lake Mary (Mississippi, USA) seen from (a) vertical and (b) oblique aerial photographs, and (c) from land.
Copyrights: (a) Google Earth, (b) USGS and (c) MWMassa via Flickr.

1.6 Conclusion and thesis highlights

There is a relative scarcity of studies tackling the question of the controls on oxbow lakes longevity or reporting sedimentary processes associated with meander cutoff. Recent research regarding oxbow lakes has mostly been dedicated to their ecology because of the high diversity of habitats they provide. In the context of increasing awareness of the importance of river protection and restoration, understanding the functioning of oxbow lakes is key for restoration projects on meandering rivers because of their high ecological value.

This thesis presents a comprehensive study of oxbow lake sedimentation and longevity at various time-scales to cover the key stages of their life cycle and investigates the rate and sources of sediment infilling. This introduction chapter will be followed by three chapters presenting research findings. Four main hypotheses will be tested:

- Chapter 2:
    - Hypothesis 1: The cutoff mechanism controls long term oxbow lake infilling
    - Hypothesis 2: The slope difference between former and current channel, the diversion angle and the meander size control the evolution of oxbow lakes

- Chapter 3:
  - Hypothesis 3: Former channels are not significant bed material sinks compared to transfers in the active channel
- Chapter 4:
  - Hypothesis 4: Long-term oxbow lake alluviation is driven by several processes and multidimensional flow patterns

An essential control on the persistence of oxbow lakes as open-water area will first be revealed in Chapter 2 by the study of the evolution of 37 oxbow lakes located on eight different rivers from the USA, Wales and France. This manuscript will then present the sedimentary processes of oxbow lakes by focusing on the two main stages of their infilling in Chapter 3 and 4. Chapter 3 will estimates volumes of bed-load transferred in former channels and the incised channel within the first decade after cutoff using three recently cut-off channels of the Ain River, France. Findings from this chapter are also published in the journal Geomorphology (Dieras et al. 2013, Appendix 4). Chapter 4 will complement Chapter 3 by focusing on oxbow lakes sedimentation taking place after disconnection by bed-load. The structure and extent of fine-grained sediment infilling occurring between 10 and 120 years after cutoff will be presented with detailed analyses of sediment from five oxbow lakes of the Towy River, Wales. These three studies are unique in terms of detail and timescale and will provide essential information to geomorphologists, river managers and ecologists.

Chapter 2

Controls on the persistence of oxbow lakes as aquatic habitats

2.1 Introduction

The open-water area of oxbow lakes has a significant geomorphologic and ecological role in river corridors as it traps sediment and produces floodplain habitats. Oxbow lakes appear to evolve as changes in oxbow bed topography affects the amount and calibre of bed material input to the lake. The traditional model of oxbow lake evolution suggests a first phase of rapid sedimentation (Gautier et al. 2007) that within the first decade after cutoff (Gagliano and Howard 1984; Hooke 1995), large bed material inputs delivered from the main channel isolate the oxbow lake. Gautier et al. (2007) suggested then a second sedimentation phase occurs, during which the sedimentation rate decreases significantly as the plug develops. Additional studies from sand- and gravel-bed rivers show that bed material concentrates at the entrance and exit of the former meander, creating a sediment plug (e.g., Gagliano and Howard 1984; Erskine et al. 1992; Hooke 1995; Piegay et al. 2002; Fuller et al. 2003b; Constantine et al. 2010a). A sediment plug prevents significant further input of large volume of bed material during normal flow conditions and, consequently, the oxbow lake becomes a long-term sink for fine-grained sediment by overbank flow (Erskine et al. 1992; Piegay et al. 2000; Lauer and Parker 2008; Piegay et al. 2008; Toonen et al. 2012). A few studies that have investigated the rate of filling suggest that the oxbow fills within years to centuries after cutoff (Gagliano and Howard 1984; Hooke 1995; Wolfe et al. 2006; Constantine et al. 2010a). Recent work has highlighted the need to re-examine this traditional model, particularly as bed material plugs are not always created soon after cutoff. Open bifurcations can form after chute cutoff and remain stable for at least 20 years (Grenfell et al.2012). What remains unclear is whether open bifurcations are common, or whether the traditional model presents a universally observed trend.

Oxbow lakes are of ecological importance because they provide diverse habitats for flora and fauna (e.g., Ward and Stanford 1995; Bornette et al. 1998; Amoros and Bornette 2002). Habitat diversity is controlled by the rate of fine-grained sediment input that varies as a function of water depth, substrate composition, and transparency (Amoros and Bornette 2002). Flood frequency also modifies habitat diversity by conveying nutrients that fertilize and support the development of the aquatic vegetation (Brink et al. 1992; Heiler et al. 1995; Knowlton and Jones 1997; Tockner et al. 1999; Glinska-Lewczuk 2005; Persic and Horvatic 2011) and promoting successional effects by creating a disturbance (Connell 1978; Ward et al. 1999; Amoros and Bornette 2002). Many fish species utilise the variety of habitats provided by oxbow lakes for refuge, spawning or growth (e.g., Copp 1989; Jungwirth et al. 2000; Schiemer 2000; Amoros and Bornette 2002; Borcherding et al. 2002; Lasne et al. 2007; Miyazono et al. 2010). Oxbow lakes also support fish communities since they provide calm areas that are episodically or permanently connected to the main channel, allowing for juvenile fish growth and migration (e.g., Ward et al. 1999; Jungwirth et al. 2000; Borcherding et al. 2002; Dembkowski and Miranda 2012). Numerous reaches of meandering floodplains of the world, such as the Towy River in Wales or the Sacramento River in the USA, are areas of ecological importance notably for fish (Nielsen 2000; Lovering 2008). For example, riparian habitats of the Towy River (Wales) are classified as a "Special Area of Conservation" to protect Twaite Shads and Otters who need refuges for breeding and resting (Lovering 2008). A key element of the protection of these species is an understanding of the dynamics of the oxbow habitats that they live in. Understanding how oxbow lakes fill with sediment could impact these conservation efforts.

Oxbow lakes can persist from years to centuries but few studies have discussed why a large disparity in longevity exists. Gautier et al. (2007) studied 160 oxbow lakes from aerial photographs (one chute cutoff and 159 neck cutoffs) from the Beni River (Bolivia) and reported three types of sedimentary phases: a first rapid infilling, an intermediate sedimentation rate and a stable period of slow or absent sedimentation. Qualitatively, it appears that the cutoff mechanism affects the rate of sedimentation, due to cutoff mechanism causing differences in the lake geometry. The shortening of a meander bend to the profit of a new path, or "meander cutoff", occurs by two most common ways: chute or neck cutoff. Chute cutoff is the result of the isolation of a meander by incision of a chute channel through the floodplain whereas neck cutoff occurs when two meander bends migrate into one another and isolate a meander loop (Lewis and Lewin 1983; Gagliano and Howard 1984; Erskine et al. 1992; Hooke 1995; Constantine et al. 2010a). Neck cutoffs tend to form pear-shaped sinuous abandoned channels with a sediment plug at the exits (Fisk 1947) whereas chute cutoffs form lakes with less curvature, and are more 'crescent-shaped' (Fig. 1.11). More specifically, neck cutoffs can be identified as those in which the distance between the two meander's bends was less than a channel width apart when cutoff occurred, whereas chute cutoffs showed a much longer breach (Lewis and Lewin 1983). Hooke (1995) also mentioned that one of the main differences between the two geometries is that the newly incised channel tends to be more curved for chute cutoffs and straighter for neck cutoffs. Cutoff mechanism could affect sedimentation in a number of ways. Firstly, cutoff mechanism appears to control the formation of a sediment plug that stops the input of bed material (Gagliano and Howard 1984; Shields and Abt 1989; Piegay et al. 2002). Secondly, different oxbow geometries affect the rate of fine-grained sediment transfer into oxbow lakes by floods. This mechanism suggests that flood frequency and magnitude controls sedimentation rate (Gagliano and Howard 1984; Shields and Abt 1989; Erskine et al. 1992; Piegay et al. 2002; Citterio and Piegay 2009). Thirdly, the location of the oxbow on the floodplain controls the impact of floods. If the main channel migrates away from the oxbow, then the input of washload from floods is reduced (Gagliano and Howard 1984; Piegay et al. 2008). Finally, cutoff mechanism affects the diversion angle (see Chapter 1, Fig. 1.10) and difference in slope between the former and current channels (Gagliano and Howard 1984; Shields and Abt 1989; Piegay et al. 2002; Piegay et al. 2008; Citterio and Piegay 2009; Constantine et al. 2010a). Constantine et al. (2010a) showed that diversion angle affects the volume of bed material that is transferred from the main channel to the oxbow. They suggested that the magnitude of the zone of flow separation created at the apex of the divergent channels affects the rate of sediment plug development. In their model, low diversion angle cutoffs result in slower plug formation, with a greater proportion of bed material diverted into the former channel. A lower diversion angle favours the diversion of flow in the former channel, increases shear stress and tends to support the transport of coarse-grained sediment further (Lindner 1953; Bridge et al. 1986). In contrast, a high diversion angle would create a large flow separation zone with low shear stress conditions, supporting coarse-grained deposits near the entrance. However, diversion angle is unlikely to be the only mechanism controlling sedimentation rates, particularly amongst neck cutoffs, where highly sinuous rivers can cut-off channels with similar diversion angles but drastically different channel lengths. One would expect that short channels would fill with sediment faster than long channels with the same diversion angle. Also, more sinuous meander loops would have a shallower slope than shorter channels, promoting sedimentation at the former channel entrance. Cutoff geometry and flood hydrology are prominent in all four of these hypothesised mechanisms for oxbow lake evolution. Despite this, there has been no systematic attempt to understand how cutoff geometry affects the development of oxbow lakes across a range of different rivers.

This Chapter assesses how cutoff mechanism controls oxbow lake infilling. Using water surface area (WSA) as a proxy for sediment infilling, the decrease in WSA was measured for 37 chute and neck cutoff oxbow lakes from a range of geological and hydrological settings. This dataset allows to test whether the rate of sediment plug formation, slope difference between former and current channel, or diversion angle control oxbow evolution. This remote sensing approach provides a simple, yet powerful method for the global assessment of oxbow lake dynamics.

2.2 Study sites

This research examines the evolution of 37 cutoff channels from eight rivers located in the USA, Wales and France. Rivers were chosen from a diverse range of geomorphic and hydrologic settings that had extensive aerial photograph coverage of the cutoff period and most of the lake lifespan (Tab. 2.1). These rivers are mostly located in dry or mild temperate climate areas. Most rivers were located in the USA because this country is one of the best documented in aerial photographs due an early development of this technology during the First World War. Aerial photographs needed to show the development of oxbow lakes' lifespan, limiting the choice of sites. Six rivers are located in the USA: the Mississippi River, the Kansas River, the Smoky Hill River (Kansas), the Pelican River (Minnesota), the Red River of the North (Minnesota) and the Sacramento River (California); and two rivers are located in Europe: the Towy River (Wales) and the Ain River (France). River channel width ranged from 10 m to 1,600 m between the Pelican River and the Mississippi River, (Tab. 2.1). Bed material type varied between the rivers from clayey-sand to gravel, consequently the material infilling the former channels also differs between rivers. Sinuosity and slope also varied between 1.06 and 1.7 and 0.14% and 5% respectively.

Among the 37 cutoffs chosen for the study, 14 sites were classified as neck cutoffs and 23 as chute cutoffs (Tab. 2.2) by comparing aerial photographs before and after cutoff and determining whether cutoff occurred by the migration of two meanders into one another or by the incision of a chute channel. Neck cutoffs contain oxbow lakes with lengths that vary across two orders of magnitude (10^2 to 10^4m), while chute cutoffs vary across one order of magnitude (10^2 to 10^3m) (Fig. 2.1). Cutoffs were measured at all stages of their evolution, with the age of the cutoff events (defined as the time since the cutoff event happened) ranging from 7 to 235 years old. The diversion angle, defined as the downstream-looking angle between the centrelines of the main channel and the former meander, of chute cutoffs ranged between 20°±5 to 90°±5, while those from neck cutoffs ranged between 100°±15 to 160°±15. The Sacramento River and the Towy River exhibited the two cutoff mechanisms occurring within the period covered by aerial photographs, which was not the case with the other sites.

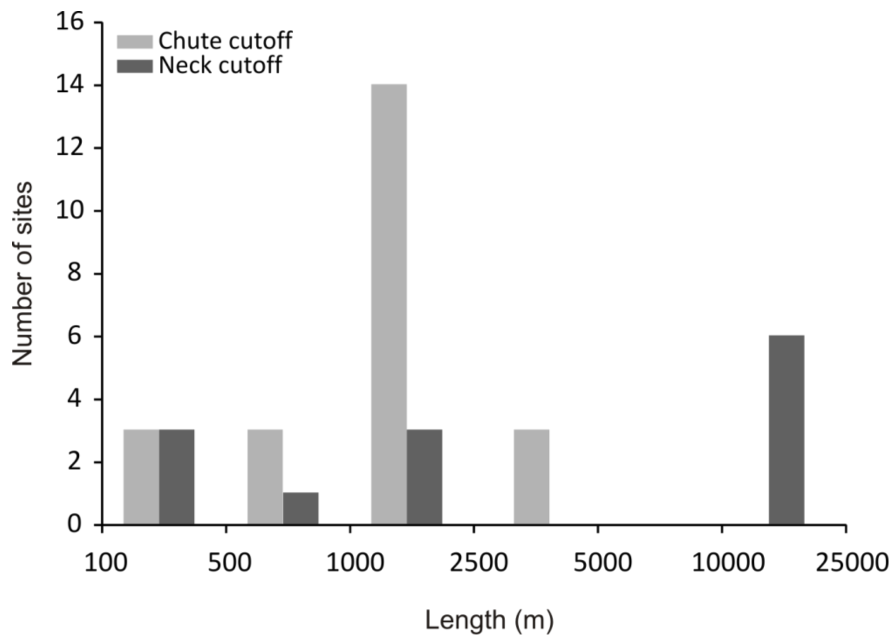

Figure 2.1: Frequency distribution of the initial meander lengths showing the variability of sizes relative to cutoff mechanism.

Table 2.1: Characteristics of the studied rivers

	Mississippi River	**Red River of the North**	**Sacramento River**	**Kansas River**	**Ain River**	**Towy River**	**Pelican River**	**Smoky Hill River**
Country/State	Mississippi, USA	Minnesota, USA	California, USA	Kansas, USA	France	Wales	Minnesota, USA	Colorado and Kansas, USA
Drainage basin *(km²)*	3.21 x10^6 *(Joann 1996)*	116,500 *(Simonovic and Carson 2003)*	68,000 *(Constantine et al. 2010)*	155,000 *(Brady 1998)*	3,672 *(Piegay et al. 2002)*	>1,090 *(McEwen 2006b)*	1,248 *(USGS 2012)*	49,883 *(USGS 2012)*
Bankful width of the study reach *(m)*	900-1600*	35-40*	120-165*	200-300*	85-150*	30-45*	10-15*	60-65*
Slope *(‰)*	*0.14* *(Fisk et al. 1947)*	0.7 -2.6 *(Blanchard 2011)*	0.54 to 0.28 *(Constantine and Dunne 2008)*	0.38 *(Brady 1998)*	1.8 -1.2 *(Piegay et al. 2002)*	1-5 *(McEwen 2006b)*	0.5 *(Dustin and Jacobson 2003)*	0.28 *(EPA 2010)*
Sinuosity	1.06-1.49 *(Joann 1996)*	1.7*	1.33 to 1.5 *(Constantine and Dunne 2008)*	1.23 *(Brady 1998)*	1.26 *(Marston et al. 1995)*	1.1-1.3 *(McEwen 2006b)*	1.26 *(Dustin and Jacobson 2003)*	1.41*
Mean annual discharge *($m^3.s^{-1}$)*	18,400 *near Atchafalaya River* *(Joann 1996)*	115 *at Drayton* *(USGS 2012)*	330 *at Colusa* *(Constantine and Dunne 2008)*	210 *(Brady 1998)*	123 *near Chazey* *(Piegay et al. 2002)*	39 *at Nantgaredig* *(McEwen 2006a)*	2 *near Fergus Falls* *(USGS 2012)*	44 *at Enterprise* *(USGS 2012)*
Sediment transport capacity *($Mt.y^{-1}$)*	532 *(Joann 1996)*	0.08 at Fargo (spring) *(Blanchard 2011)*	0.1-1 *(Singer and Dunne 2004)*	1.67 *(Brady 1998)*	0.03 *(Rollet 2007)*	-	-	1.6 *(EPA 2010)*
Bed material size or d_{50} *(mm)*	Sand to Clay *(Fisk et al. 1947)*	d_{40}: 2-16 *(Blanchard 2011)*	Gravel to Sand *(Micheli and Larsen 2011)*	d_{50}: 1.5 *(Brady 1998)*	d_{50}: 80 *(Marston et al. 1995)*	d_{50}: 53-57 (McEwen 2006b)	-	Gravel to Sand *(EPA 2010)*

- No data
* Personal measurement

Table 2.2: Location and type of cutoff channels

River	Lake reference	Cutoff Type	Latitude (GPS)	Longitude (GPS)
Kansas River	KAN	Chute	39°09'54.35'' N	96°21'37.66'' W
Mississippi River	YUCA	Neck	32°04'26.90'' N	91°09'27.40'' W
Mississippi River	EAGL	Neck	32°29'45.10'' N	91°00'13.13'' W
Mississippi River	MARE	Neck	31°37'07.57'' N	91°30'31.43'' W
Mississippi River	FERG	Neck	33°26'54.18'' N	91°03'31.02'' W
Mississippi River	MARY	Neck	31°11'50.74'' N	91°31'57.89'' W
Mississippi River	LEE	Neck	33°16'30.89'' N	91°02'37.37'' W
Pelican River	PEL1	Neck	46°18'20.88'' N	96°10'10.37'' W
Pelican River	PEL2	Neck	46°17'49.97'' N	96°09'19.93'' W
Pelican River	PEL3	Neck	46°17'43.86'' N	96°09'04.77'' W
Red River of the North	RED1	Neck	46°26'06.80'' N	96°42'56.78'' W
Red River of the North	RED2	Neck	46°43'28.51'' N	96°47'07.31'' W
Sacramento River	rm178	Chute	39°33'38.90'' N	122°00'13.55'' W
Sacramento River	rm179B	Chute	39°34'09.69'' N	121°59'16.38'' W
Sacramento River	rm166	Chute	39°25'45.68'' N	121°59'51.58'' W
Sacramento River	rm219	Chute	39°55'04.03'' N	122°05'39.33'' W
Sacramento River	rm203	Chute	39°48'01.03'' N	122°01'26.78'' W
Sacramento River	rm184N	Chute	39°38'00.37'' N	121°59'45.09'' W
Sacramento River	rm169	Chute	39°27'53.48'' N	122°00'05.20'' W
Sacramento River	rm213	Chute	39°53'00.88'' N	122°02'42.02'' W
Sacramento River	rm214	Chute	39°52'57.23'' N	122°03'22.35'' W
Sacramento River	rm191	Chute	39°40'01.73'' N	121°57'45.08'' W
Sacramento River	rm174	Chute	39°31'27.61'' N	122°00'33.52'' W
Sacramento River	rm202	Chute	39°46'57.16'' N	122°02'02.59'' W
Sacramento River	rm165	Neck	39°25'17.13'' N	122°00'38.81'' W
Smoky Hill River	SMO	Neck	38°58'27.33'' N	96°56'54.35'' W
Towy River	CH1	Chute	51°51'40.74'' N	4°04'33.38'' W
Towy River	CH2	Chute	51°51'35.03'' N	4°04'37.79'' W
Towy River	CH3	Chute	51°51'47.84'' N	4°04'03.60'' W
Towy River	CH4	Chute	51°51'48.61'' N	4°04'21.24'' W
Towy River	NECK	Neck	51°51'51.71'' N	4°05'16.82'' W
Ain River	BRO	Chute	45°47'58.67'' N	5°11'19.13'' E
Ain River	HYE	Chute	45°57'52.61'' N	5°15'52.58'' E
Ain River	M71	Chute	45°56'05.17'' N	5°15'05.88'' E
Ain River	PLA	Chute	45°50'21.64'' N	5°14'39.64'' E
Ain River	MOL	Chute	45°56'49.75'' N	5°15'02.56'' E
Ain River	M54	Chute	45°56'04.23'' N	5°14'53.39'' E

2.3 Methodology

2.3.1 Aerial photographs measurements

2.3.1.1 Water Surface Area (WSA) measurement

The WSA as the area was defined as the area of the pool of water that outlines the oxbow lake. This method has also been used to study the evolution of the tropical river Rio Beni in Bolovia by Gautier et al. (2007). The initial WSA is the extent of the former channel before cutoff (Fig. 2.2) and measured on the youngest pre-cutoff aerial photograph. The initial WSA of the 37 sites varied at each site, making comparison between sites difficult. Each result was normalised by initial WSA, such that 100% corresponds to the initial meander area and 0% corresponding to the absence of water or the complete terrestrialisation of the site. All the inundated areas were included in each WSA measurement regardless of the hydrological state of the main channel. Therefore floods did sometimes temporarily increase the WSA of the lake on some aerial photographs, the magnitude of this effect is discussed in section 2.3.1.2.

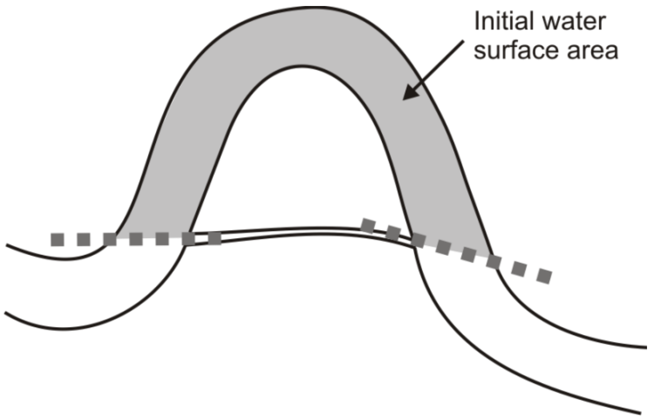

Figure 2.2: Representation of a meander during cutoff.
The grey area represents the initial meander area considered in this study (WSA ≈ 100%).

The WSA evolution of former channels was measured on every available aerial photograph with historical maps used for two measurements of the Towy River (Tab 2.2, Lake NECK). The WSA was measured using digitalized aerial photographs (Tab. 2.3) for the Ain River, the Towy River and the Sacramento River and historical aerial photographs on Google Earth^{TM} for the remaining rivers and for the measurement on the Towy River after 2000.

Table 2.3: Summary of the images used for the study

River	Image Type (*Aerial Photo, Map or Satellite images)*	Date or Period	Temporal resolution	Spatial resolution	Source
Ain River	A	1945 - 2009	1 - 9 years	0.63 - 2.4 m	IGN (National Geography Institute, France)
	A	Apr-Sept 2010	15 days	0.26 m	CNRS - UMR 2600
Kansas River	S	1991 - 2010	1 - 10 years	0.3 - 1 m	Google Earth
Mississippi River	S	1989 - 2010	2 - 11 years	0.3 - 1 m	Google Earth
Pelican River	S	1991 - 2009	1 - 12 years	0.3 - 1 m	Google Earth
Red River of the North	A	1984	one image	2 m	Glovis (EROS-USGS, 2011)
	S	1997 - 2010	1 - 6 years	0.3 - 1 m	Google Earth
Sacramento River	A	1938 - 1999	2 - 9 years	0.46 - 1.85 m	USGS
	S	2004 - 2007	one image per year	1.6 m	Google Earth
Smoky Hill River	S	1991 - 2010	1 - 10 years	0.3 - 1 m	Google Earth
Towy River	M	1889, 1907	one image per year	-	Ordnance Survey
	A	1946 - 1981	3 - 10 years	0.37 - 4.2 m	Welsh Assembly Government
	A	1992, 2002	one image per year	0.72 - 0.86 m	CCW and GEONEX (Countryside Council for Wales)
	A	1999	one image	1 m	Getmapping
	S	2006	one image	0.3 - 1 m	Google Earth

For images analysed on Google Earth™, the WSA was measured manually using the "Polygone" Ruler tool. The source and the resolution of aerial photographs on Google Earth™ varied in each country and image resolution ranged between 0.25 and 2 m in these locations. USGS aerial photographs for the Sacramento River from 1997, Ordnance Survey 1:25,000 maps for the Towy River from 2006 and IGN aerial photographs from 2000 for the Ain River were georeferenced before acquisition as a geotiff or similar format. For the other images, ortho-rectified aerial photographs were georeferenced using ArcGIS (v. 9.2). The orthorectified images varied in spatial resolution from 0.26 m to 4.2 m, but the resolution rarely exceeded 1 m. The root mean square error on georeferencing provided by the GIS software was always lower than 4 m.

2.3.1.2 Error related to the aerial photograph quality

Despite attempts to use high quality images, there were small differences in resolution as discussed above. Discerning the boundary between water and sediment required significant contrast that varied across the images. The visual error was assessed by performing repeat measurements (five times per photograph) of WSA for five sites (25 times total). Results showed that the standard deviation of the visual error accounted for 1 to 7 % of the average WSA.

2.3.1.3 Influence of the river discharge

The variation of the river hydrological stage can affect the WSA of oxbow lakes, especially when the oxbow lake is still hydraulically connected to the river. The effect of different river discharges on the WSA was examined using photographs taken several times a year for the same site and the corresponding record of daily discharge values. This rather rare dataset was only available for one site of the Ain River (“Martinaz”, see Chapter 3 Fig. 3.1) and consisted of aerial photographs taken twice a month from April to September 2010 (26 cm resolution). Unfortunately repeating this test across other sites was not viable as aerial photographs taken at sufficiently high temporal resolution were lacking for these locations.

The Martinaz abandoned channel was cut-off in 2003 and remained connected to the river by the downstream end at the time of the study in 2010. The WSA was measured and compared to the average discharge of the river on the day the aerial photograph was taken. This test showed that the WSA varied by 4,000 m^2 between April and September (blue circles, Fig. 2.3), reflecting the variation due to a difference of ~60 $m^3.s^{-1}$ in discharge. This represents only 13% of the total 30,000 m^2 decrease in WSA between the summers of 2005 and 2009 (squares) caused by the infilling of the oxbow lake (Fig. 2.3).

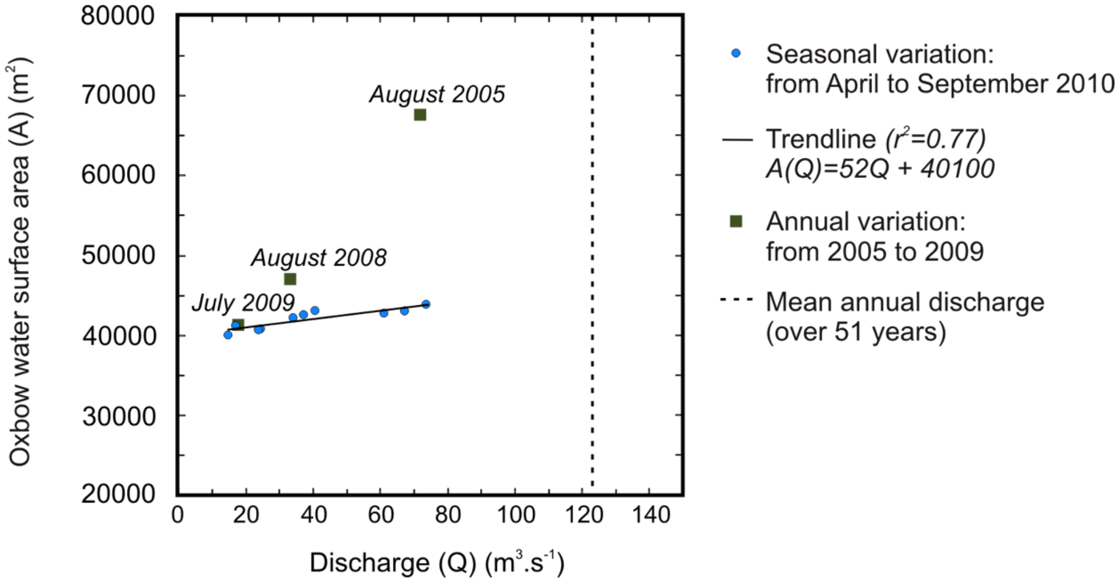

Figure 2.3: Variation of the water surface area of Martinaz oxbow lake, Ain River, France. Blue dots represent bimonthly measurements of water surface area between April and September, 2010. The variability in WSA as a function of discharge is small when compared with the differences due to oxbow infilling shown by the green squares.

2.3.1.4 Dating the cutoff events

The date of cutoff initiation was defined as the midpoint between the latest image before cutoff and the earliest image after cutoff. This method creates an average error of 6 years and a range of 1 year to 23 years for all the oxbows of the dataset. The largest error is associated with the three oxbows of the Towy River that are older than 100 years. Instead of aerial photographs, two Ordnance Survey maps were used from 1840 and 1885 (Jones et al. 2011), or 1863 ±23y. Some oxbows from the Mississippi are even older than those of the Towy River and were dated using historical maps by Gagliano and Howard (1984).

2.3.1.5 Rate of water surface area reduction

The rate of WSA reduction was measured at three points in the oxbow evolution. Multiple, arbitrary points were chosen on the WSA evolution (result 2.5) to reflect the non-linear nature of oxbow lake infilling. The time taken to reduce water surface area by 75%, 50% and 25% of the initial meander area was estimated.

2.3.1.6 Diversion angle

The diversion angle was measured on the earliest aerial photograph after the initiation of cutoff (see Chapter 1, Fig. 1.10) between the centrelines of the main channel and where the former meander would merge on the upstream end. The error on this value was calculated by repeating the measurement five times. Themaximum variation of the angle was ±5°, except for the oldest sites on the Mississippi River. Heavy modification of the floodplain meant that the older (80 to 237 years old) Mississippi River sites had a maximum error of ±7°.

2.3.1.7 Difference in slope between former and active channel

The difference in slope as the ratio of former to current channel length was calculated for each site. The higher the slope difference, the lower the slope of the former channel bed relative to the new channel. Absolute slope was impossible to measure with the resolution of this study's remotely sensed data therefore the ratio of lengths represented the best proxy for the effect of changing slope on oxbow sedimentation. There is some uncertainty in this method for the older oxbows of the Towy and the Mississippi rivers as floodplain sediment was reworked since the cutoffs and the only available aerial photographs do not always show clearly where the meander bend was cut-off. The error on the initial oxbow length for the Mississippi can be up to ±800 m but is really difficult to estimate.

2.3.1.8 Initial meander length

The initial meander length was measured along the centreline of each former channel on the earliest aerial photograph after cutoff. There is some error in this measurement because floodplain sediment has been remobilised and removed a portion of the former channel ends. On very old sites such as those on the Mississippi River, the uncertainty is at its highest since about 20% of the former channels could have been remobilised. Wide rivers conveying large volumes of water naturally create wider meanders and oxbow lakes than smaller ones. Therefore, to account for this bias, the initial meander length after cutoff was normalised and divided by the river bankfull width.

2.3.1.9 Statistical analysis

Statistical analyses were conducted to understand what variable, between the slope, the diversion angle and the meander length was the best predictor of the water surface area decrease rate. After the calculation of the decrease rate at three stages of the lake evolution (when 25%, 50%, 75% of the water remains) a multiple regression analysis was performed on the three variables and decrease rates. A Mann-Witney U test was also performed to compare the decrease rate between chute and neck cutoffs.

2.4 Results

2.4.1 Evolution of neck and chute cutoff channels.

There is a distinctive difference between the patterns of sedimentation in chute and neck cutoffs, with the open water area of neck cutoff sites persisting for much longer than that of chute sites (Fig. 2.4). The WSA of oxbows created by neck cutoff remains for decades with 30 to 60% of the initial surface area persisting longer than 70 years for all sites, which corresponds to WSA decrease rate of 0.4% to 0.9% per year. There is some overlap between chute and neck cutoff oxbow lakes with short sedimentation record; however those with long records define two distinctive fields. Within the neck cutoff domain, the Mississippi and Sacramento oxbows tend to infill more slowly than those of the Towy River, Wales.

Chute cutoffs show a rapid decrease in WSA in the first 5-20 years followed by a slower decrease. Analyses showed that the decrease rate of chute cutoffs was not significantly different from neck cutoff when the area was reduced by 25% (n= 26 Chute and 6 Neck, $p=0.055$) probably due to the small sample size. Additionally, the decrease rates could not be compared at later stages of the reduction (-50% and -75% WSA) due to the smaller sample size. However, the calculated average difference between the rates is about $9\%.y^{-1}$. The WSA initially decreases by 4% to 16% per year until only 20% of the WSA remains. The rate decreases for the following 50 years with an average 0.4% per year between 20 and 70 years after cutoff. This trend holds for most of the data except those from the from the Towy River oxbows (Fig. 2.4, diamond markers). For these oxbows, up to 20% of the WSA remains in the Towy River's former channel after 70 years. An investigation was conducted to know whether the difference in the Towy River represented a primary trend or was likely to be caused by a systematic error in the data. Of the 4 Towy chute cutoffs, two sites (Lake CHU1 and CHU3) were pre-1885 cutoffs so were estimated from Ordnance Survey mapping and have an uncertainty of ±23 years. There is a maximum of 7% error in the measurement of water surface area across all of the chute cutoff WSA estimates. This error is likely to be randomly distributed and is unlikely to produce the systematic difference in WSA shown by these data.

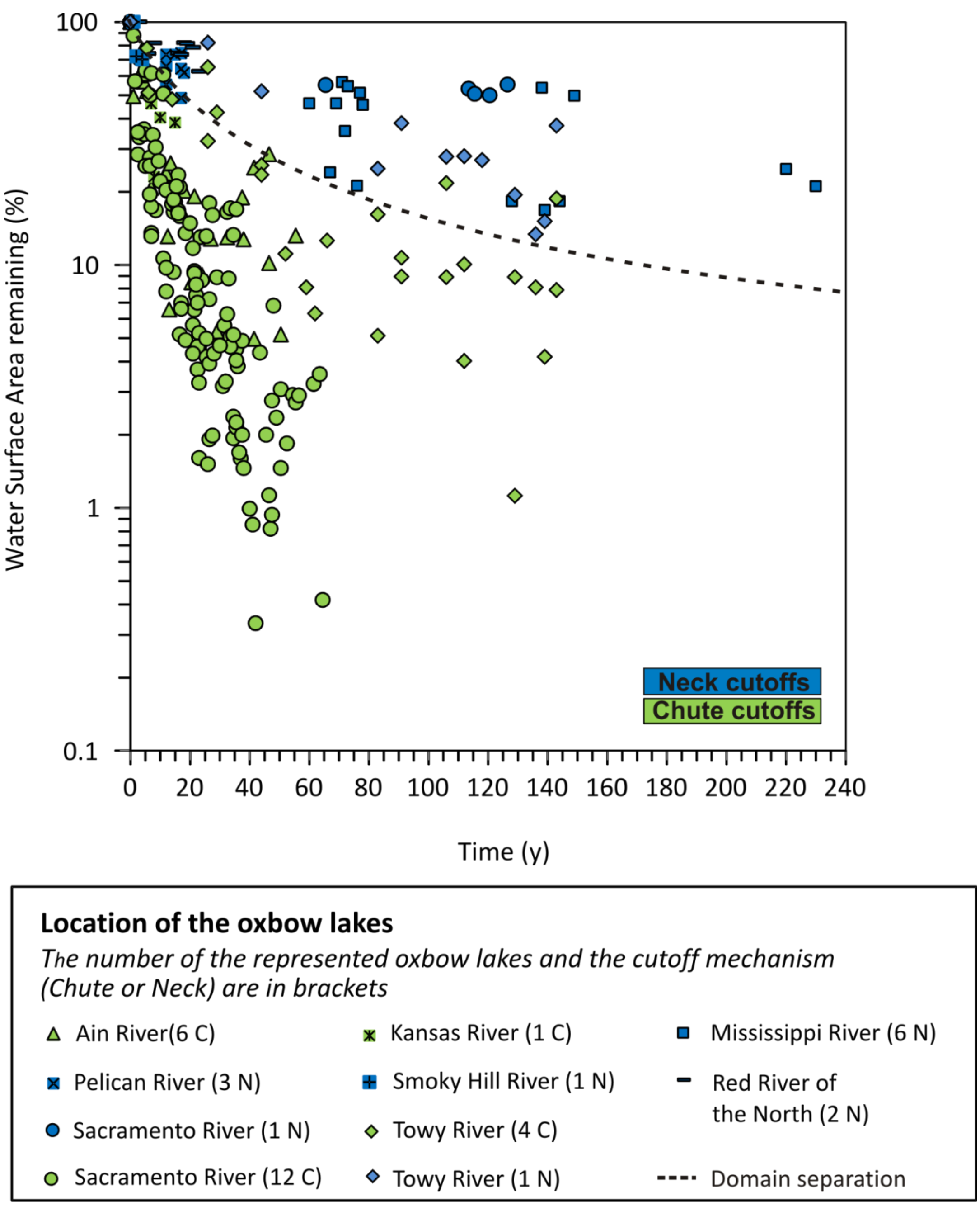

Figure 2.4: The water surface area of 37 cutoff channels as percentage of the initial meander area against time.
Time "0" corresponds to the date of cutoff and 100% of water surface area corresponds to the initial meander area when cutoff occurred. Blue markers represent the water surface area evolution of oxbow lakes created by neck cutoff whereas green markers are oxbows created by chute cutoff. Each symbol corresponds to a specific river and these symbols can be of two colours when both chute and neck cutoff sites were measured on a single river (e.g., Sacramento and Ain Rivers). Dashes are used to provide an approximate separation of chute and neck cutoffs oxbow lakes.

2.4.2 Effect of different factors on WSA rate of decrease.

The ratio of lengths and diversion angle show a relationship with the rate of WSA decrease at any stage: when 25%, 50% or 75% of the WSA remains. Analyses of the relationship between these two variables (lengths ratio and angle) and the decrease rate showed that the variables were both significant predictors of the decrease rate ($n = 26$, $p<0.01$). However, this statistical analysis was only significant for the decrease rate calculated when the water has reduced by 75% but not at earlier stages of the oxbow life, when 25% or 50% of the WSA remains. The correlation was highest when the water had reduced by 50% (Fig. 2.5b,e). A positive linear correlation exists between slope difference (ratio of lengths) and infilling time, however the value is always higher for neck cutoff oxbow lakes than chute cutoffs with a ratio of lengths of 4.3 and 15.3 respectively (Fig. 2.5d-f).

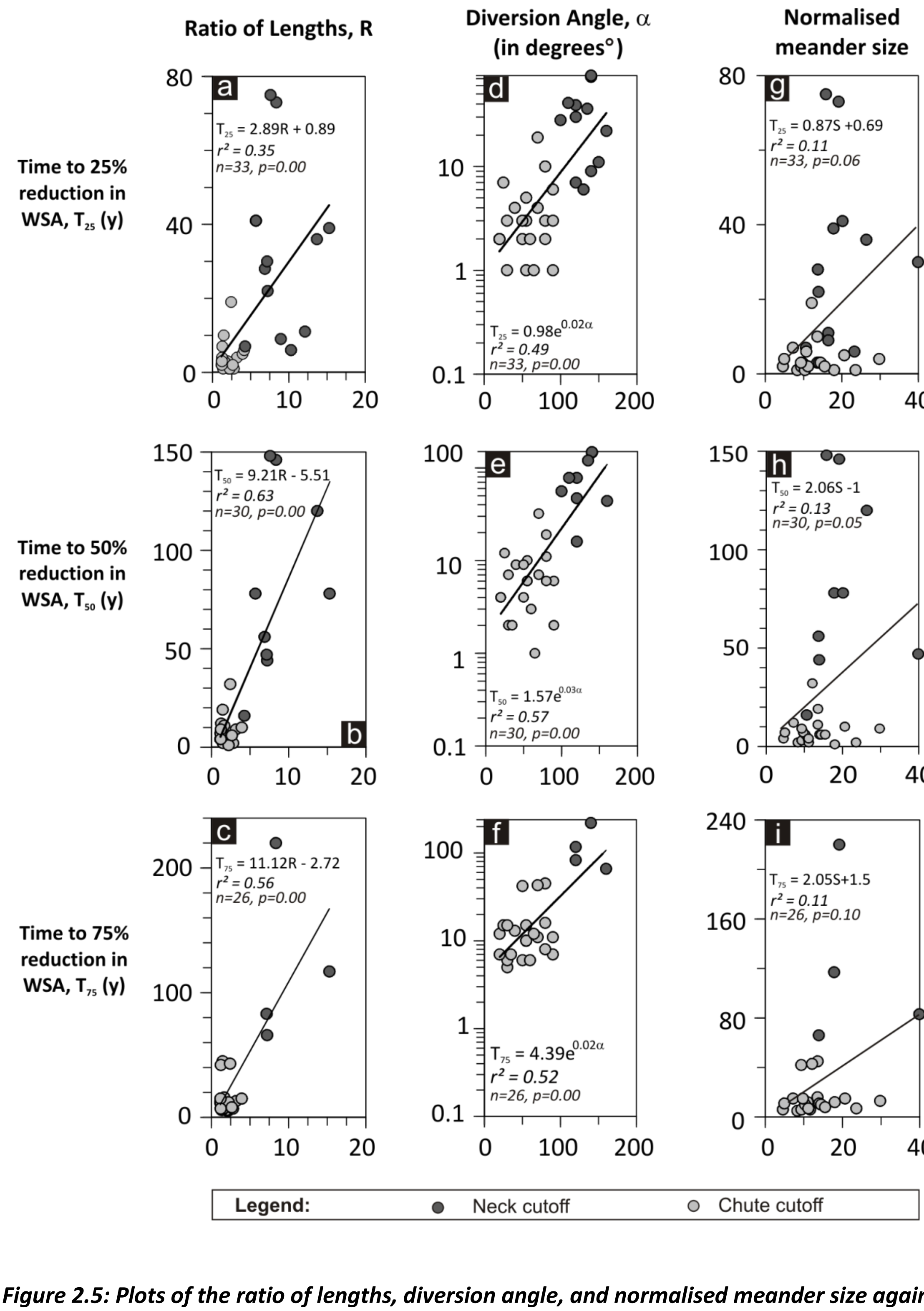

Figure 2.5: Plots of the ratio of lengths, diversion angle, and normalised meander size against the WSA decrease rate at several stages of oxbow evolution.
(a,b,c) Plots showing the relationship between WSA reduction and ratio of lengths defined as the former meander length divided by the new channel. (d,e,f) Plots showing the relationship between WSA reduction and diversion angle. (g,h,i) Plots showing the relationship between WSA reduction and initial meander length divided by the river bankfull width.

The diversion angle shows a positive exponential relationship with the time to reduce the WSA (Fig. 2.5d, e, f). Diversion angle data have a relatively even spread, with a range of angle from 20° to 160°. Sites with a diversion angle of 50° took 5 years to reduce the WSA by 50% whereas sites with a diversion of 100° took at least 20 years to reach the same stage. The spread of the neck and chute cutoffs sites relative to diversion angle is similar to the ratio of lengths. All the neck cutoffs oxbow lakes were formed at higher angle than chute cutoffs and took longer to reduce in WSA. Chute cutoff oxbows lakes were created at diversion angles ranging from 20° to 90° and took 1 to 20 years to reduce by 50% whereas oxbows lakes created by neck cutoffs ranged between 100° and 160° and took 20 to 120 years to reduce by the same proportion.

The relationship between meander size and the persistence of oxbow lakes was assessed using measurements of the normalised initial oxbow length plotted against the time to reduce the WSA by 25, 50 and 75% (Fig.2.6g, h, i). No significant relationship was found between the initial meander length and the reduction of WSA at any stage of the terrestrialisation ($n = 26$, $p > 0.05$).

2.4.3 Relationship between Ratio of Lengths and Diversion Angle

There is a positive exponential correlation ($r^2 = 0.76$) between diversion angle and ratio of lengths (Fig. 2.6), with oxbow lakes with higher diversion angles express higher ratio of lengths. The distinct separation between the two mechanisms shows that oxbow lakes formed by chute cutoff always have both lower diversion angles and ratio of lengths compared to neck cutoff sites (Fig. 2.6). The overall trend is consistent with averaged values of diversion angle and length ratio reported for chute channels from the Southern Hemisphere by Grenfell et al. (2012).

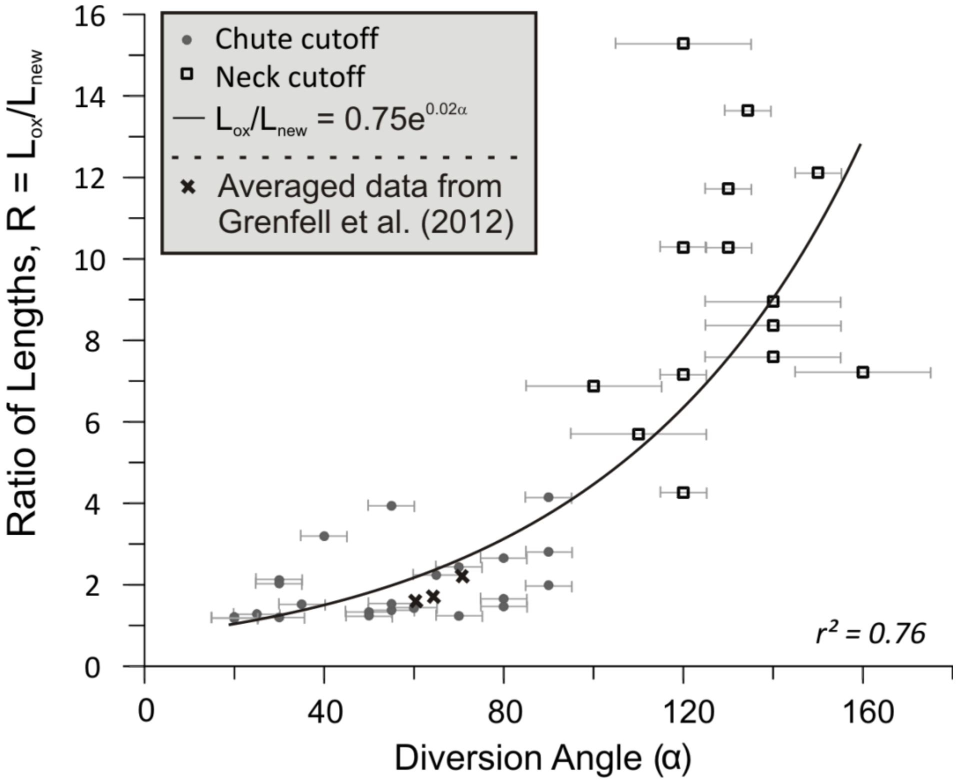

Figure 2.6: Plot of the diversion angle against the oxbow length ratio for the 37 study sites. Chute and neck cutoffs oxbow lakes are represented using different markers, which reveal two distinct groups of data. Data for chute cutoff from Grenfell et al. (2012) are presented on this graph in addition to data from the eight rivers of this study. These additional data are mean values of diversion angle and length ratio calculated for stable chute bifurcations on three sand-bedded rivers.

2.5 Discussion

2.5.1 Controls on oxbow lakes longevity

2.5.1.1 Cutoff mechanism

The persistence of oxbow lakes as aquatic environments depends on the sediment infilling rate. Results from this chapter show that oxbow lakes created by neck cutoff persist for at least a few centuries whereas a large majority of those created by chute cutoff become totally terrestrial within 60-100 years (Fig. 2.4). The water surface area of chute cutoffs appears to decrease rapidly after cutoff, down to 20% remaining within 20 years, and then reduces slowly for the next 50 years until becoming completely terrestrial around 80 years after cutoff. In the case of neck cutoffs, the water surface does not show the sharp reduction characteristic of chute cutoffs, instead up to 60% of the water can remain in the oxbow for 100 years at some sites. Findings for neck cutoff oxbow lakes are similar to the evolution of the majority of the neck cutoffs studied on the Beni River by Gautier et al. (2007). On this tropical river, the WSA was reduced by only 0 to 5% within the first 14 years after cutoff for 65% of the sites. However, 10% of the sites were almost completely terrestrial after 14 years on the Beni River contrary to this study where over 50% of the WSA remained at this stage. This suggests either that tropical rivers could have different evolution or that the neck cutoffs of this study may not be representative of the whole range of lake evolutions. Where both cutoff mechanisms exist on the same river, and therefore similar hydrologic conditions and bed material loads (e.g., Sacramento River, Ain River) the difference in WSA evolution can most logically be attributed to a cutoff mechanism control. In contrast, the reduction of water surface area with time was less distinctive for sites of the Towy River as these chute cutoff sites exhibit an evolution somewhere between most chute and neck cutoff sites (Fig. 2.4). The water surface area reduction for the oxbows of the Towy River occurred at an intermediate rate between those of other rivers. There was 5 to 10% of water remaining after 100 years on chute cutoffs sites of the Towy River whereas most chute cutoffs sites of other rivers were fully terrestrial at this stage and most neck cutoff sites exhibited 25-60% of their initial water surface area. The data for the Towy River showing an intermediate pattern are those of two sites, Lake CHU1 and CHU3, that cut-off around 1863 with a large uncertainty of ±23 years. The oldest former channels of the Towy River have potentially received less sediment relative to those of other rivers. This could be caused by a sediment deficit in the main channel. The Towy River channel was subject to gravel extraction since the 1920s and Llyn Brianne reservoir was constructed in 1973 upstream of the study site. Both disturbances caused an important sediment deficit in the main channel and probably reduced the material transferred to former channels; however no study has yet quantified this deficit.

2.5.1.2 The role of diversion angle and slope

Neck and chute cutoff mechanisms create oxbow lakes with different diversion angles and ratio of lengths. Neck cutoffs have higher diversion angles (100°±15 to 160°±15) and ratio of lengths than chute cutoffs (20°±5 to 90°±5) (Fig. 2.6). Lindner (1953) observed that higher diversion angles reduce the volume of flow and sediment (wash and bed-load) to a bifurcated channel. This is supported by field observations that suggest high diversion angles promote the growth of the sediment plug at the entrance within former channels (Shields and Abt 1989) and reduce sediment infilling (Shields and Abt 1989; Piegay et al. 2000). Constantine et al. (2010a) inferred that the diversion angle controls the size of the zone of flow separation between former and current channels, affecting the ability of sediment to enter the former channel. Neck cutoffs have high diversion angles and form a large flow separation that lowers shear stress and limits flow entering the former channel. Low shear stresses within the flow separation favour bed material deposition leading to rapid oxbow disconnection (Fisk 1947; Constantine et al. 2010a). Results from this chapter show a correlation between diversion angle and the rate of oxbow infilling, suggesting the diversion angle plays a role in the development of oxbow lakes (Hooke 1995; Constantine et al. 2010a; Toonen et al. 2012). However, the R^2 of these correlations suggest that diversion angle alone can only account for about 50% of the variability in oxbow infilling rate.

The ratio of lengths, or difference in slope between the former and current channels, shows a simple linear correlation with oxbow infilling rate (Fig. 2.6). Neck cutoffs tend to create longer oxbows, thus have a higher slope difference (Fig. 2.7a) than chute cutoffs. The difference in slope between the main and former channels contains two different effects that are difficult to separate with these data; the first is that a larger ratio of lengths will divert more flow through the main channel, limiting the bed material load transferred to the former channel; the second is that higher ratio of lengths typically correlate with low gradient oxbow lakes. Gradient was a key influence on oxbow alluviation rate identified by Gagliano and Howard (1984).

Separating the effects of diversion angle and ratio of lengths is difficult because there is a strong positive relationship between diversion angle and ratio of lengths (Fig. 2.6). Chute cutoffs take place at low diversion angles and tend to isolate a smaller portion of meander than higher diversion angles (Fig. 2.7a) therefore the ratio of length is smaller. Neck cutoffs create a new channel that is always more or less equal to two channel widths, since it results from the migration of two channels. Therefore sedimentation is primarily a function of absolute slope when comparing different neck cutoffs from rivers of the same width (Fig. 2.7b). While there is a general positive correlation between diversion angle and length ratio, there is no correlation when comparing only neck cutoffs or only chute cutoffs (Fig. 2.6). This suggests that the positive relationship between both ratio of lengths and diversion angle may represent different processes of sedimentation occurring in oxbow lakes.

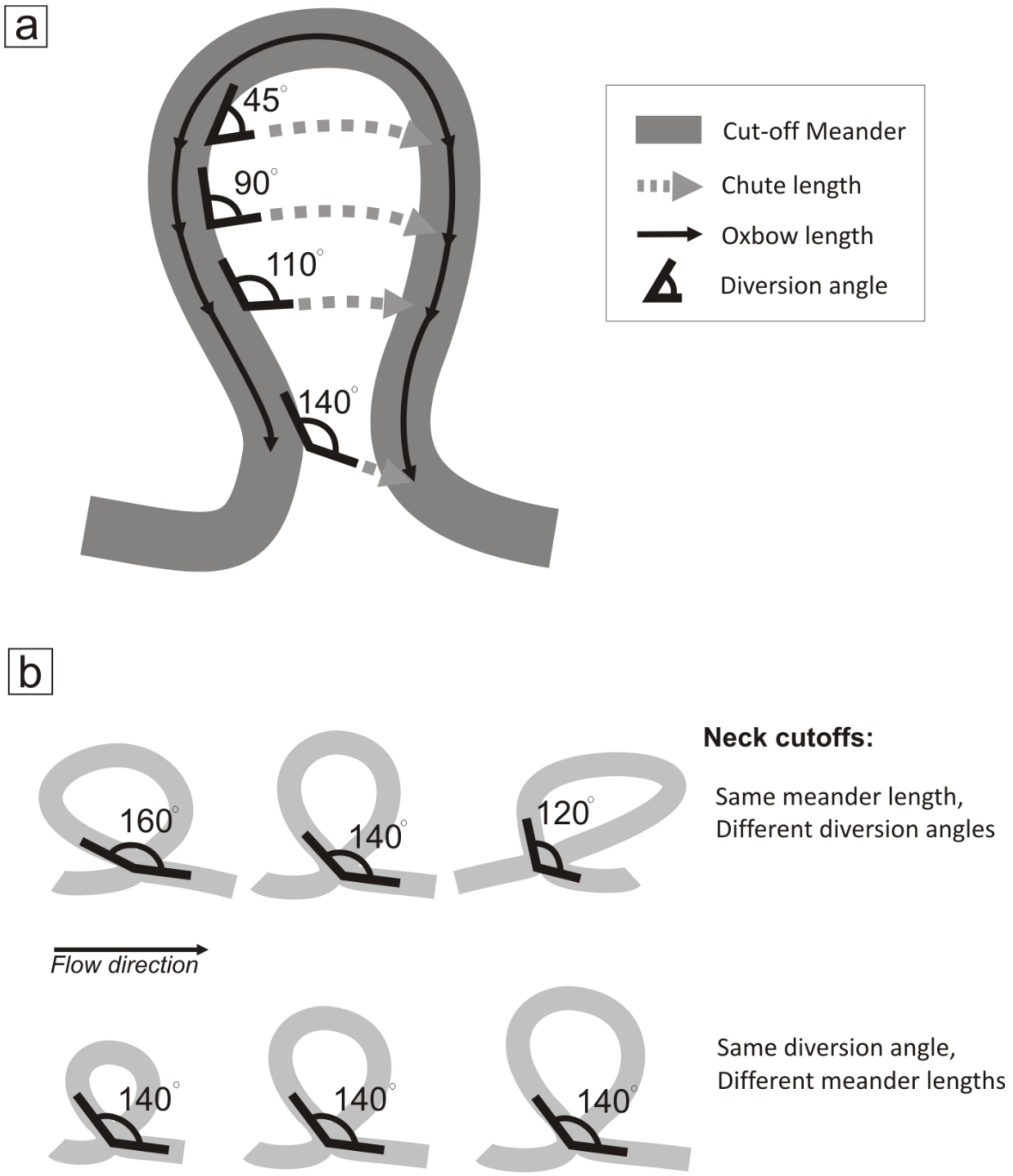

Figure 2.7: Illustration of the relationship between diversion angle and cut-off meander length.
a) Cartoon showing diversion angle variation depending on the cutoff location on a meander bend. The two upper cutoffs correspond to diversion angle more observed with chute cutoff (45°, 90°) whereas the bottom one (140°) is at an angle more common for neck cutoffs. The figure also shows how high diversion angle are often naturally related to higher oxbow ratio of lengths for chute cutoffs.b) Scheme highlighting how meander length (slope) and diversion angle can vary independently for neck cutoffs.

2.5.2 Sedimentary processes associated with cutoff type

Chute cutoffs take longer to form a sediment plug, as rapid bar growth is the driver of rapid reduction in WSA. As a sediment plug develops at the upper entrance of chute cutoff oxbows, less flow is diverted in the former channel, reducing the sediment load and rate of WSA decrease (Gagliano and Howard 1984; Rowland et al. 2005). The expansive accumulation of sediment that characterises the first 5-20 years of chute cutoff development occur prior to upstream disconnection of the channel by a sediment plug. This two-phase decrease with a rapid pre-sediment plug decrease in WSA followed by a slower post-plug decrease is similar to rates of sedimentation presented by Citterio and Piegay (2009). Oxbow lakes created by neck cutoffs have a distinctly different pattern of water surface area decrease. Within the first 20 years after cutoffs there is typically a reduction of only 30-40% of the initial WSA. This is followed by a very slow rate of decrease consistent with low rates of sediment input. It appears that neck cutoffs form a sediment plug more quickly, limiting sediment input to the former channel. This is consistent with the observations of Constantine et al. (2010) showing that neck cutoff channels rapidly form a short upstream bed-load plug. After disconnection the infilling of both neck and chute cutoff can only occur by overbank flow, sediment transport through tie channels (Hooke 1995; Piegay et al. 2000; Piegay et al. 2002; Rowland et al. 2005) or backwater decantation if the downstream exit is still connected (Piegay et al. 2000). At this stage, only fine-grained sediment fills up the oxbow at slow rate which depends directly on the frequency of hydraulic connectivity (Citterio and Piegay 2009).

2.5.3 Environmental impacts of the type of cutoff

Oxbow lakes are features of high ecologic importance due to their diverse habitats that promote biodiversity of river corridors. As a result, the substantial difference in the longevity between the two types of oxbows has important implications for river management. Freely meandering rivers are becoming increasingly rare as floodplains have undergone important entropic changes during the last century. The Sacramento River is the most diverse river ecosystem in California (Golet 2003) where over the last 150 years several dams, weirs and bank protections were built along the river and riparian vegetation was cleared for developing agriculture (Singer and Dunne 2001;

Golet 2003). As a result, the Sacramento River channel has straightened and the dominant cutoff process has changed from neck to chute cutoff (Micheli and Larsen 2011). Such a change in oxbow type should have ecological consequences knowing that the chute cutoff oxbows of this study have a lifespan 200 years shorter than neck cutoffs. This suggests that the Sacramento River has transitioned from producing long-term aquatic habitats to rapidly infilling, and possibly disturbance-driven environments.

In contrast to the Sacramento, the Purus River, tributary of the Amazon in Brazil, is of similar size but remains mostly unmanaged. The meandering reach of the Purus River is dominated by neck cutoffs that form at a lower frequency (about 0.08 oxbows per km) than the Sacramento River (about 0.3 oxbows per km). The average length of the neck cutoff oxbows of the Purus River (6,960 m long or 14 $m.m^{-1}$) when normalised by bankfull width are substantially longer than the chute cut-off oxbows of the Sacramento River (1,600 m or 11 $m.m^{-1}$). This highlights the trade-off between cutoff frequency and habitat preservation. The result of the drastic change in the style of cutoff on the Sacramento River would probably lead to a loss of aquatic habitats and a change to a more disturbance driven ecosystem. More analyses are required and should ideally document habitat transformations in rivers between before and after a change in channel pattern.

2.6 Conclusion

Measurements of the evolution of 37 oxbow lakes located on eight different rivers across the planet revealed that the reduction of the water surface area of oxbow lakes is primarily dictated by the cutoff mechanism. In the first 10 years after cutoff, the WSA reduction of oxbow lakes created by chute cutoff occurs more than twice as fast compared to neck cutoff. This difference could be explained by the higher diversion angle and slope difference between the two types of cutoff types, which favours short sediment plugs in the case of neck cutoff. After a century, the oxbow lakes created by chute cutoff have been completely terrestrialised, whereas 25 to 60% of the water surface area still remains in oxbows created by neck cutoff. In conclusion, these results have important implications for the management and restoration of meandering rivers as they can help in predictions of the longevity of oxbow lakes as aquatic habitats. Further research is required, however, to understand the physical processes responsible for sediment transport through oxbows and their resulting evolution. To support the hypothesis that the cutoff mechanism significantly affects sediment infilling in former channels, detailed field evidence is required to show that chute and neck cutoffs undergo very different style of sedimentary evolution. These issues will be tackled in Chapters 3 and 4, which describe detailed sedimentation patterns of chute and neck cutoff of oxbow lakes at both early and late sedimentary stages of their evolution.

Chapter 3

Initial bed material transfers and storage after cutoff

3.1 Introduction

Cutoff events are a source of significant geomorphological changes and mobilise large volumes of sediment within river channels. The incision of a new channel during cutoff can deliver to the downstream river segment a volume of sediment one to five orders of magnitude larger than erosion by lateral channel migration, as shown in the study of a chute cutoff of the Wabash River, USA (Zinger et al. 2011). The excess sediment load following incision tends to accumulate on bars (Fuller et al. 2003b; Zinger et al. 2011), triggering channel migration and affecting the dynamics of meandering rivers (e.g., Dietrich and Smith 1983; Whiting and Dietrich 1993; Hudson and Kesel 2000; Constantine 2006). The former meander bend is progressively abandoned as the chute enlarges and is the location of sediment transfers that may also affect sediment balance in the main channel. Chute incision is associated with a decrease of flow in the former channel as the newly-incised channel becomes the main conveyor of the discharge. Bed material accumulates in the former channel as a result of the decreasing discharge until a sediment plug obstructs the upper end. Sediment plugs prevent further coarse material infilling and isolate an oxbow lake that will then gradually fill up with fine sediment transported by overbank flow.

Depending on the duration of the hydraulic connection to the main channel, former channels can be a potential sink for a large volume of bed material since about a third of the bed-load can be stored on the floodplain during a flood (Nittrouer et al. 2012). Oxbow lakes have previously been considered as sediment sinks (Lauer and Parker 2008) but often for the storage of fine-grained sediment during floods (e.g., Gagliano and Howard 1984; Piegay et al. 2000; Citterio and Piegay 2009). At reach scale, bed material accumulation and transfer in former channels has rarely been the focus of quantitative studies even though these water bodies can completely fill up and become terrestrial environments within decades (Constantine et al. 2010a). According to Lindner (1953) up to 85% of the river segment bed material supply can be stored in former channels.

Three concurrent and closely located former channels on the Ain River (France) provide a rare opportunity to study bed material transfers associated with meander cutoff. Bed material transfer mechanism and volumes were assessed using a combination of field survey, remote sensing and GIS. Results from this chapter provide detailed information about oxbow lakes initial infilling and questions the significance of former channels as bed material sinks. This chapter also aims to inform theory regarding bed material transfers and effects on freely meandering rivers (see also Dieras et al. 2013, Appendix 4).

3.2 Study Setting

The 185-km long Ain River drains 3,672 km^2 of eastern France (Fig. 3.1), emptying into the Rhône River with an average annual discharge of 120 $m^3 s^{-1}$ (as determined at the Chazey-sur-Ain gauging station for the period 1958-2011). The 2- and 10-year discharges for the river near its junction with the Rhône are 760 and 1,200 $m^3 s^{-1}$. The upper 160 km of river is incised within the limestone gorges of the Jura Mountains, and the lower 40 km flows largely unhindered through a large alluvial plain (Piegay et al. 2000), though outcrops of Jurassic limestone and the presence of resistant Pleistocene moraine deposits limit bank erosion at locations. Declining grazing activity from a maximum during the early 20th century has enabled recent riparian forest growth, which may have resulted in channel narrowing at some locations (Marston et al. 1995).

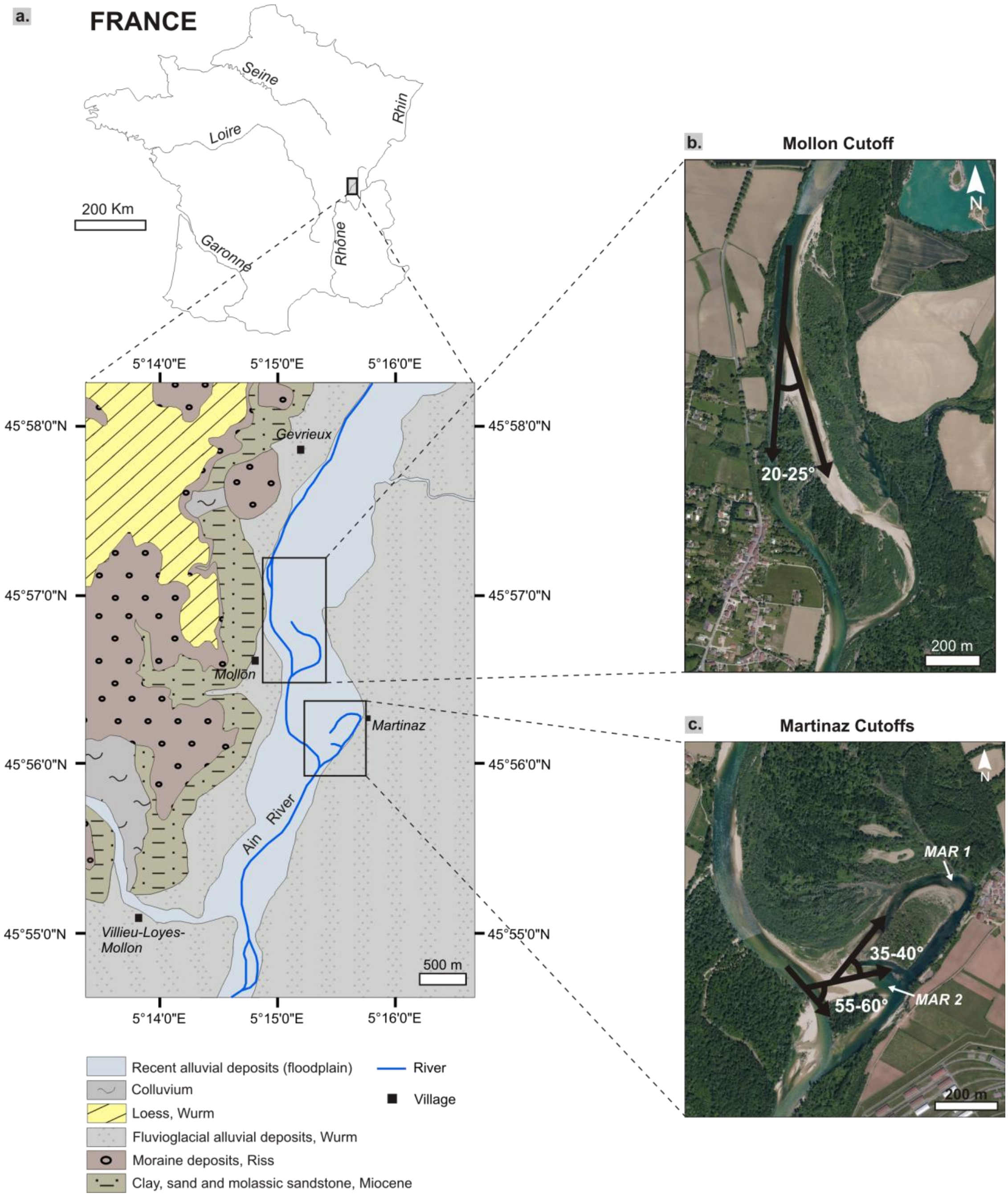

Figure 3.1: Location maps and aerial photographs of the study area.
(a) Map showing the location of the study area (black rectangle) relative to the major rivers of France. The inset shows a generalised geological map of the study area highlighting the study reaches. Key villages in the study area are also highlighted. (b) Aerial photograph of the Mollon (MOL) study reach in 2005. The abandoned channel is shown only 2-3 years after cutoff and is almost completely filled. The arrows show the angle between the active channel and the abandoned channel, the diversion angle, which equals 20°-25° for MOL. Images are courtesy of Google Earth™ mapping service. (c) Aerial photograph of the Martinaz (MAR) study reach in 2005. There were two cutoff events that isolated MAR1 in 2002-2003 (diversion angle of 35°-40°) and MAR2 in 2005 (diversion angle of 55°-60°).

The study reach was located 20 km upstream of the confluence of the Ain and the Rhône, where chute cutoffs isolated three channel segments near the villages of Mollon and Martinaz (Fig. 3.1). Downstream bed slope within the study reach ranges between 1.2 to 1.8‰ (Piegay et al. 2002), the channel maximum depth varies between 3 and 7 m, the bankfull width ranges from 70 to 80 m, and the median grain size of surface bar sediment gradually fines downstream from 46 to 22 mm (Rollet 2007; Lassettre et al. 2008). Dam construction from 1928 to 1970 reduced sediment delivery to the study site, but the geomorphic effects have not yet been observed in the study reach (Rollet et al. 2005), possibly due to minimal impacts on flood flows (Fig. 3.2). Rollet (2007) estimated the modern bed material transport capacity for the reach to equal 37,000 t yr^{-1} (or 14,000 m^3 yr^{-1}) using bed material transport calculations applied at cross-sections. The calculations were supported by field observations during different flow events using PIT-tags and scour chains for detecting entrainment discharge, particle transport distance, and scour layer thickness.

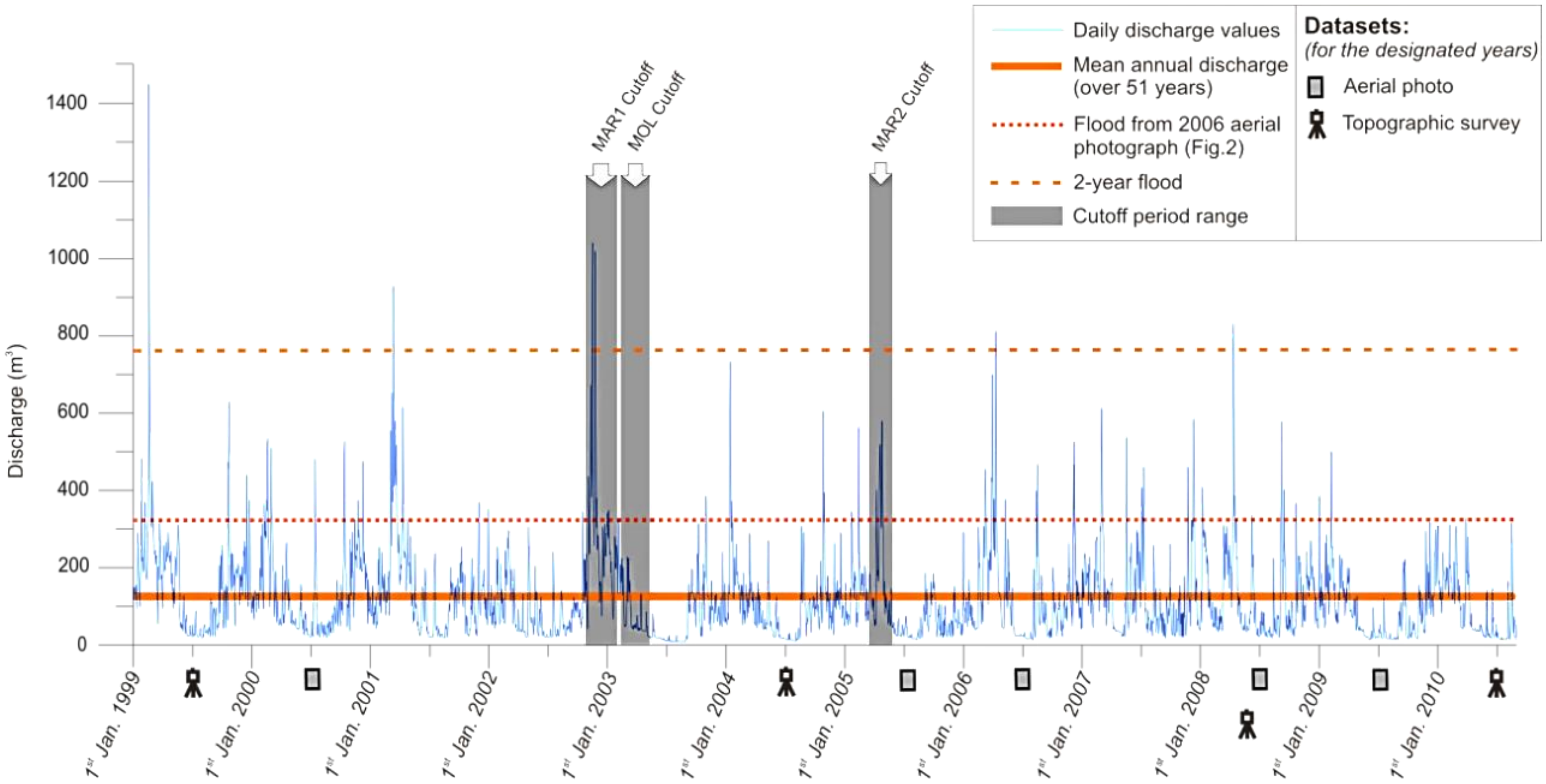

Figure 3.2: Plot of the average daily discharge at gauging station Chazey-sur-Ain, Ain River, for the period January 1, 1999 to August 31, 2010. The solid line is the average annual discharge calculated over 51 years. The dashed line is the two-year flood measured over the same period. The dotted line is the discharge corresponding to the flood event that inundated the former channels in 2006. The vertical grey bars represent the periods over which each of the cutoffs developed. Key times of data collection either from topographic surveys or aerial photographs are also shown.

Unlike the cutoff channels reported by Rollet et al. (2005), the channel segments under study have not been restored, and land use practices have not interfered with natural patterns of sediment transfer and deposition. Two channel segments were successively produced by chute incision near Martinaz, hereafter denoted *MAR1* and *MAR2*. *MAR1* formed after a major flood event (greater than 10^3 m^3 s^{-1}) which occurred between October 2002 and February 2003, and *MAR2* formed between March and May 2005 (Figs. 3.2 and 3.4). The third channel segment was produced in 1996 by chute incision nearly a kilometre upstream of the *MAR* sites near the village of Mollon (hereafter *MOL*). The incision lead to a stable bifurcation (see Grenfell et al. 2012) until the chute evolved into the dominant conveyor of discharge between February and May 2003, forcing the gradual abandonment of a 1.42-km long channel segment (Fig. 3.4).

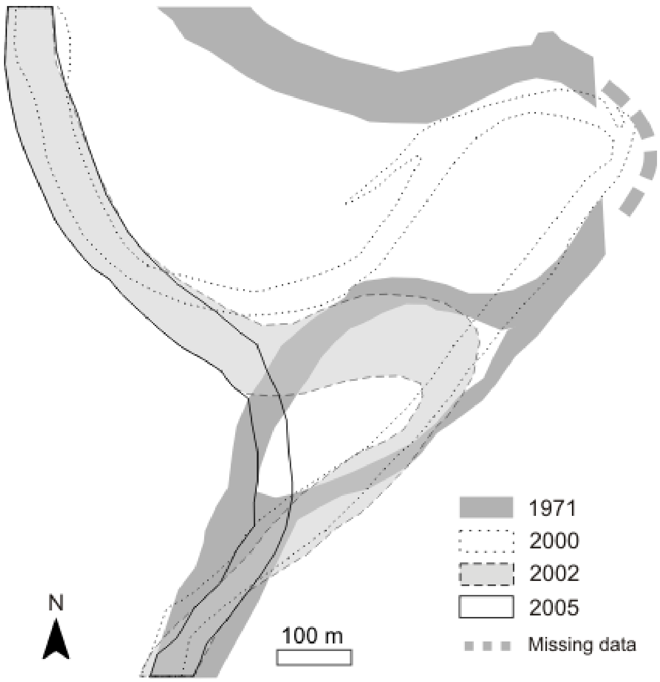

Figure 3.3: Channel change at MAR1 and MAR2 sites for the period 1971-2005.
Each polygon represents the river based on aerial photo interpretation. Both the 2002 and 2005 cutoffs occurred in similar locations to the path of the 1971 channel.

Theoretical and experimental results indicate the existence of a flow separation within the upstream entrances of hydraulically connected channel segments, the size of which is determined by the angle by which flow is diverted from the main channel (Taylor 1944; Law and Reynolds 1966; Hager and Hutter 1984; Neary and Odgaard 1993; Keshavarzi and Habibi 2005; Constantine et al. 2010a); the larger the angle, the larger the width of the flow separation. The size of the flow separation controls the competence of the diverted flow, enhancing plug formation with increases in the width of the separation (Fisk 1947; Bridge et al. 1986; Shields and Abt 1989; Constantine et al. 2010a). In the case of the study sites, *MOL* had a diversion angle of 20-25°, *MAR1* a diversion angle of 35-40°, and *MAR2* a diversion angle of 55-60° (Fig. 3.1), measured using the earliest available images following cutoff (Fig. 3.4).

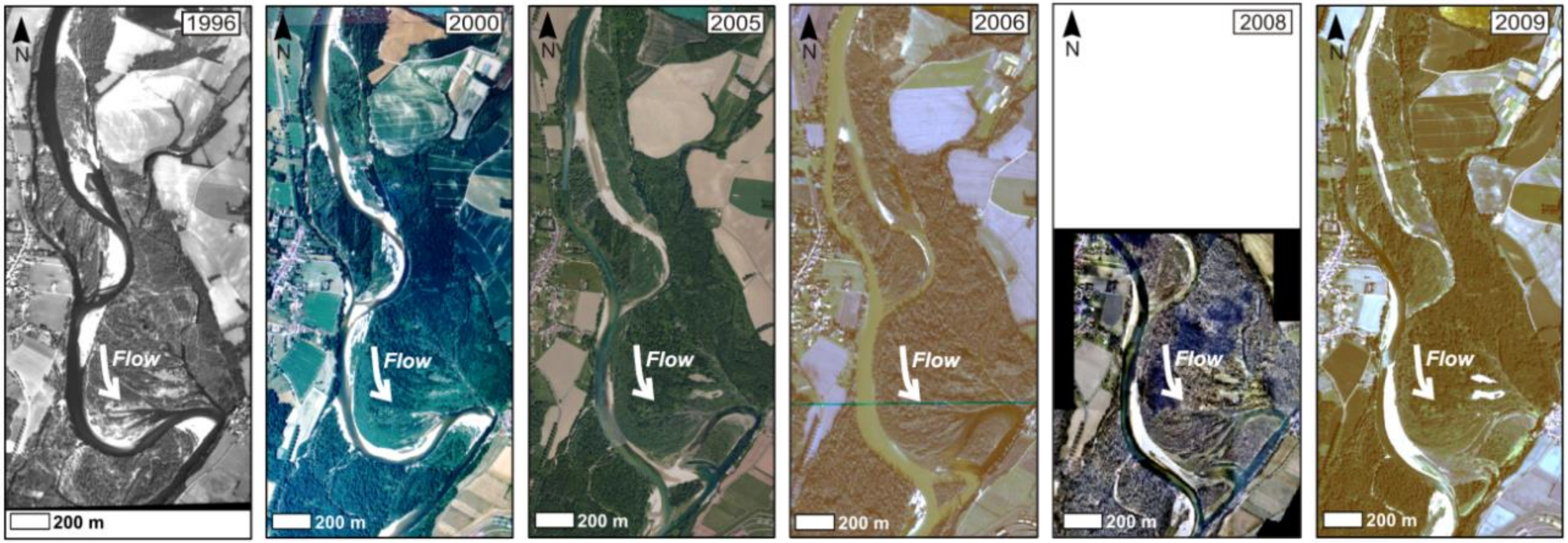

Figure 3.4: Aerial photographs showing the Ain River in the study area between 1996 and 2009.
The studied cutoff events occur between the 2000 and 2005 photographs. The 2005 photograph highlights the rapid sedimentation in the upstream (MOL) reach. The 2006 photo shows inundation of the cutoff channels during a flooding discharge of 264 m^3 s^{-1}

3.3 Methodology

3.3.1 Field surveys and topographic measurements

A range of data sets was used to assess morphologic change within the channel segments of the study reach. Subaerial bar growth within the river and channel segments was monitored using regularly taken aerial photos between 1996 and 2009 (Fig. 3.4), which were georeferenced with an average root mean square error of 1.99 m. The aerial photos were supplemented with low resolution (15-30 m) Landsat images obtained from the Earth Resources Observation Systems Data Centre of the USGS and available for the period 1999-2010 with a frequency of every 15 days to a month, allowing to date cutoff initiation (Table 3.1). A longitudinal profile along the main channel was collected in 1999 during low-flow conditions using a total station (measurement uncertainty of <5 cm) with an average of 1 point per 50 m, distributed along geomorphic forms so that all changes in slope conditions were surveyed (i.e., all riffles were precisely located) (Citterio and Piegay 2000; Piegay et al. 2002; Rollet et al. 2005). The profile provided a reference of the channel prior to the three incidents of chute cutoff. Regularly spaced topographic cross-sections of the channel and floodplain were also collected through the study reach in 2004 and in 2008 by researchers from CNRS and Cemagref. An airborne LiDAR survey was conducted in 2008, which provided a Digital Elevation Model (horizontal scale 25 cm) of the reach at low flow. Finally, subaerial oxbow topography was surveyed with a differential-GPS (hereafter DGPS) in the summer of 2010, with measurements having an average vertical and a horizontal precision of ±2.5 cm. Longitudinal profiles through the oxbows in 2008 and 2010 were constructed along the 1999 profile course using the LiDAR and field survey data.

Table 3.1: Summary of the images used for the study

Images type	Period	Temporal resolution	Spatial resolution	Use	Source
Aerial photos	1945 -1996	1-9 years	0.63 -1 m	To observe the channel evolution	IGN (National Geography Institute, France)
Aerial photos	1996 -2009	1-5 years	0.63 -2.4 m	To measure the diversion angles and the growth of bars	IGN
Landsat images	1999 -2010	15 days to monthly	15 -30 m	To date the cutoffs	USGS (L7 ETM)

3.3.2 Sediment Budgets

Volumetric storage of sediment along the river reach was calculated using three different methods based on data availability. The morphologic budget approach was used first (e.g.,Goff and Ashmore 1994; Martin and Church 1995; Lane 1997; Ham and Church 2000; Fuller et al. 2002; Martin 2003; Surian and Cisotto 2007), which calculates volumetric change using topographic differences between similarly located cross sections taken at different times (in this case, in 2004 and 2008) multiplied by the reach length. The morphologic budget approach does not consider changes in topography between cross-sections and so may underestimate volumetric flux (Lane et al. 1995; Fuller et al. 2003a; Bertoldi et al. 2009).

The second approach was based on differences in a DEM interpolated from the survey data collected in 2010 and the 2008 LiDAR-based DEM. The sensitivity of the quality of the 2010 DEM to interpolation schemes was assessed by comparing differences in the DEM when it was constructed using inverse distance weighted, kriging, natural neighbour, and triangulated irregular network methods. Data interpolated using the IDW method were calculated using a linear-weighted combination of known sample points. Natural neighbour interpolation is also based on weighted average but the interpolation uses the area of influence of the nearest points or “Thiessen polygons” (Thiessen 1911). Kriging is a statistical method which assumes a spatial correlation between distance or directions of points and involves the interactive investigation of the spatial variations (e.g., Child 2004; Naoum and Tsanis 2004). TIN method partitions geographic space using irregularly spaced data points and connects them to form non-overlapping triangles forming a continuous surface. IDW and Natural Neighbour methods have similar principles based on weighed averaged; kriging is statiscal and can modify initial points whereas a TIN calculation does not. The standard deviation of the volumes obtained by the different interpolation schemes was equal to 10% of the mean value for *MOL* and 30% for *MAR1* and *MAR2* (Table 3.2).

The third approach provided an estimate of the overall volumetric aggradation within submerged portions of the channel segments from the moment each formed until the DGPS survey in 2010. For this, it was assumed that the deepest portion of the 2010 submerged surface roughly represented the elevation of the original channel surface. Post-cutoff alluvium thickness was then estimated as the elevation difference across the submerged surface and the elevation of the deepest portion. The point measurements of alluvium thickness were integrated across the submerged surveyed surfaces to provide minimum estimates of volume.

Table 3.2: Budgets calculated using different interpolation methods

Interpolation method	**Volume at MOL (m^3)**	**Volume at MAR1 + MAR2 (m^3)**
IDW (Inverse distance weighted)	6771	-4838
Kriging	5880	-5200
Natural Neighbor	7156	-8641
TIN	7408	-8345
Mean value for interpolations	6804	-6756
% deviation from mean	10	-30
Calculation from cross sections	6101	–

3.4 Results

3.4.1 Patterns of Channel Adjustment Following Cutoff

The longitudinal profiles provided an indication of how the study reach responded to the three incidents of chute cutoff. The 1999 and 2008 longitudinal profiles represent the channel form before and after the formation of the three channel segments; the 2008 topographic data were collected five years after cutoff for *MOL* and *MAR1* and three years after cutoff for *MAR2* (Fig. 3.5). The discontinuities observed in the 1999 profile (points 9 and 23) were natural breaks in slope that can also be observed at several other locations on the river and did not appear to be associated with major changes in bar development. Within this time frame, nearly 0.3 m of degradation occurred within the riverbed upstream of *MOL* while up to 1.5 m of aggradation occurred throughout the length of *MOL*. Similarly, nearly 1.5 m of aggradation occurred within the first 500 m of *MAR1*, although 0.5 m of degradation occurred over the next 250 m of the channel. In spite of this degradation, sediment plugs fully disconnected the upstream entrances of the channel segments from continuous flow by 2008. Between 2008 and 2010, *MOL* aggraded by as much as 0.2 m within its entrance, but degraded by roughly 0.4 m throughout the remainder of its length (Fig. 3.5). During this time frame, *MAR1* experienced up to 0.2 m of degradation within its upstream limb and then 0.75 m of degradation within its downstream limb.

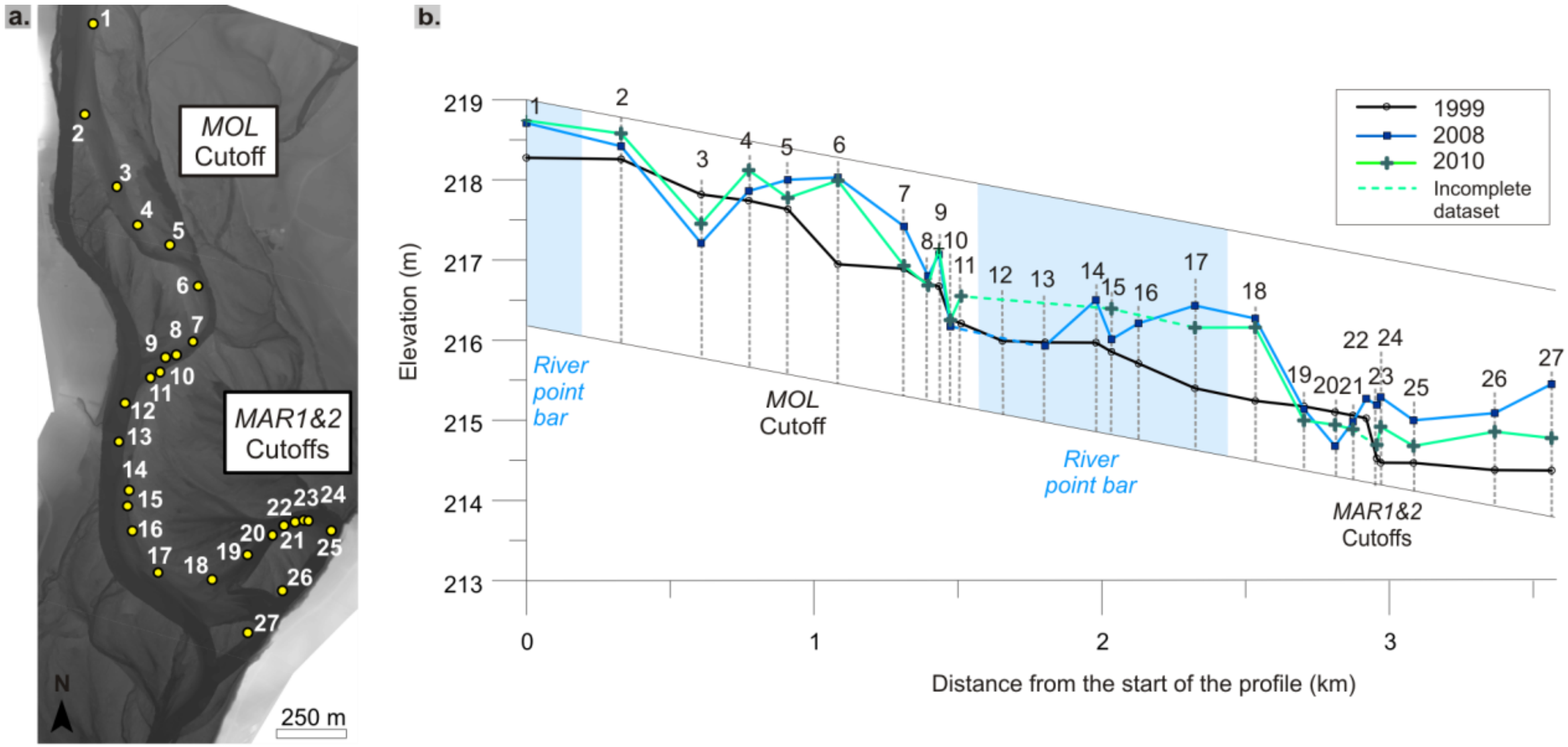

Figure 3.5: Changes in the longitudinal profile for the study reach.
(a) LiDAR image from 2008 showing location of data points used for the longitudinal profile. (b) Longitudinal profiles collected on bars using a total station and DGPS for the years 1999, 2008, and 2010. The 1999 profile was taken before cutoff, and changes in sedimentation were estimated for the study reach by differencing the 2008 and 2010 profiles. Major river features (cutoffs and point bars) are shown on the plot for reference.

Five locations of cross-section data for the study reach were available for years 2004, 2008, and 2010. Each location was assigned a letter for ease of reference as shown in Figure 3.6. The cross sections from 2004 represent the topography one year after the abandonment of *MOL* and *MAR1* and one year before the abandonment of *MAR2*. Between 2004 and 2008, net aggradation occurred at all locations except for location *A*, the main channel upstream of the entrance to *MOL*. Much of the aggradation, up to 1-2 m, occurred within the entrances into the channel segments (see locations *B* and *D*). Further, the channel bed at location *E* aggraded by up to 0.5 m, with aggradation occurring uniformly across the section from bank to bank. Between 2008 and 2010, the upstream entrance to *MOL* aggraded by between 0.2 and 0.5 m, in contrast to the entrances to the *MAR* sites, which degraded by between 0.3 and 0.8 m (Fig. 3.6).

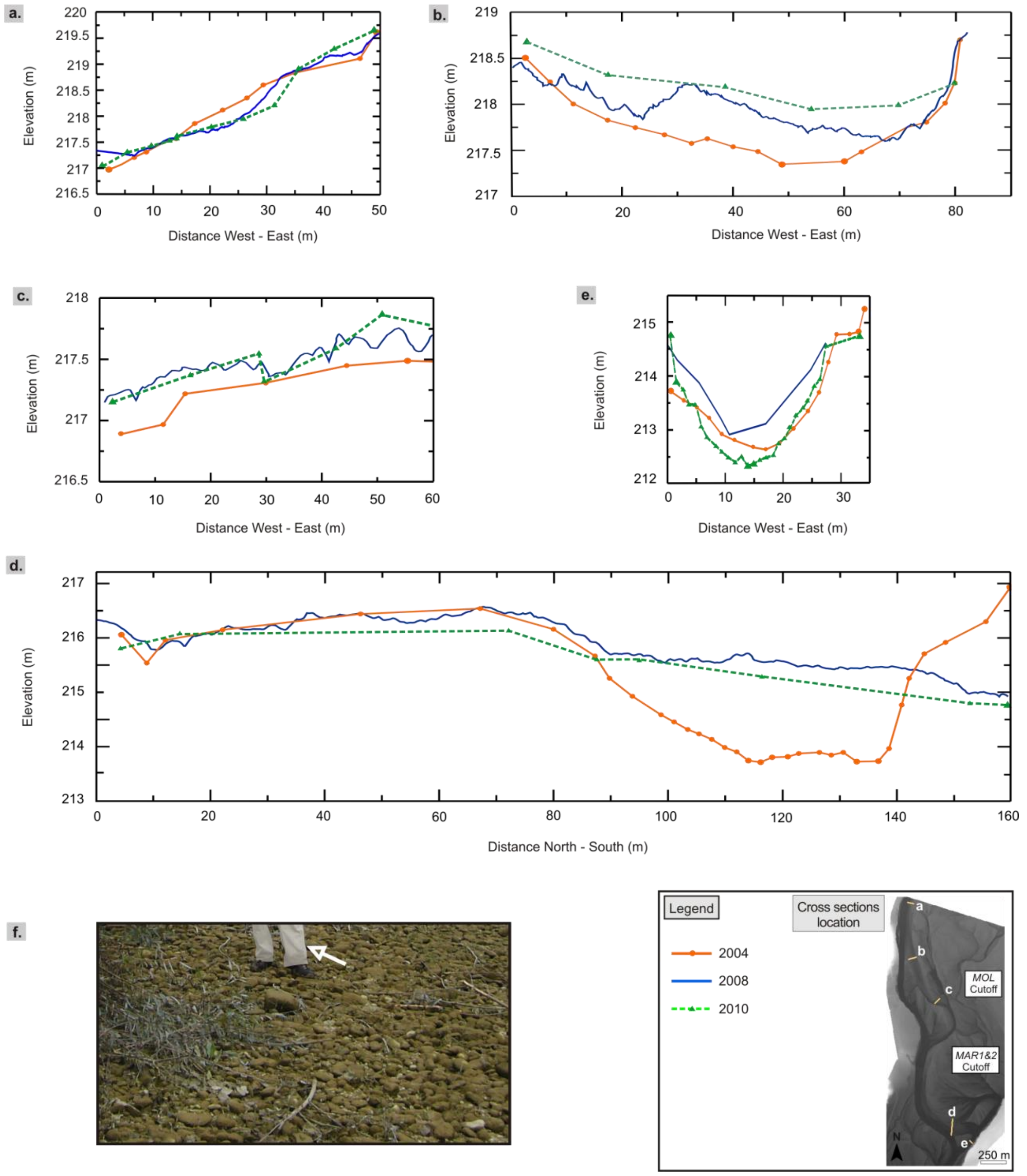

Figure 3.6: Cross sections collected along the study reach for the years 2004, 2008, and 2010. Cross section locations are shown on a LiDAR image from 2008, with cross section "a" representing the most upstream location. Differencing of cross sections allowed to calculate a sediment budget for 2004-2008 and 2008-2010. (f) Photograph of the coarse-grained infill of the MOL cutoff taken in 2011 near cross section "c"; the deposits represent the typical infill of all the cutoff channels in the study reach.

Bed aggradation followed similar temporal patterns within the three channel segments, occurring most rapidly immediately after cutoff in each case and primarily along a pre-existing point bar. For example, between 2000 and 2009, the point bar within the upstream entrance to *MOL* increased by nearly two fold in surface area, from 81,000 to 160,000 m^2, similar to the bar within the upstream entrance to *MAR1*, which increased in surface area from 58,000 to 116,000 m^2 (Figs. 3.4, 3.6, 3.7). Results from the 2010 DGPS survey of the inundated portions of the channel segments also indicated the role of bar growth in the alluviation process within *MOL* (Fig. 3.8A). At this site, the submerged bar extended across the channel to considerably narrow the pool along the outer bank. The extent of bar growth within the *MAR* sites was not clear from the DGPS data, however, with the deepest portions of the channels existing downstream of the apices, between presumable zones of aggradation within the upstream and downstream limbs (Fig. 3.8B).

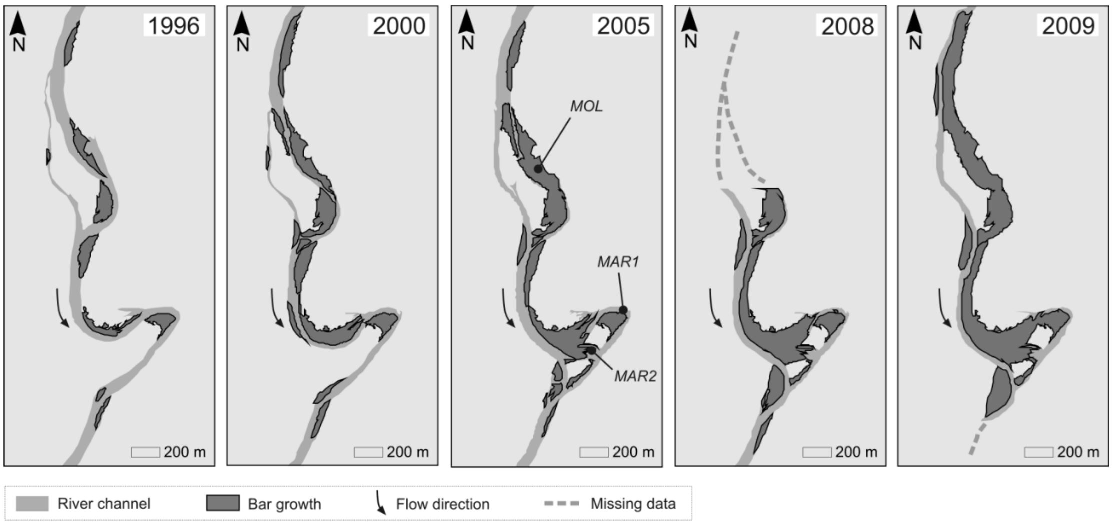

Figure 3.7: Bar development along the study area between the 1996-2009 measured from aerial photographs.
Major changes in channel planform corresponded to increases in the surface area of sediment. In particular, there was rapid infilling of the MOL reach and progressive expansion of the MAR1&2 plugs after cutoff between 2000 and 2005.

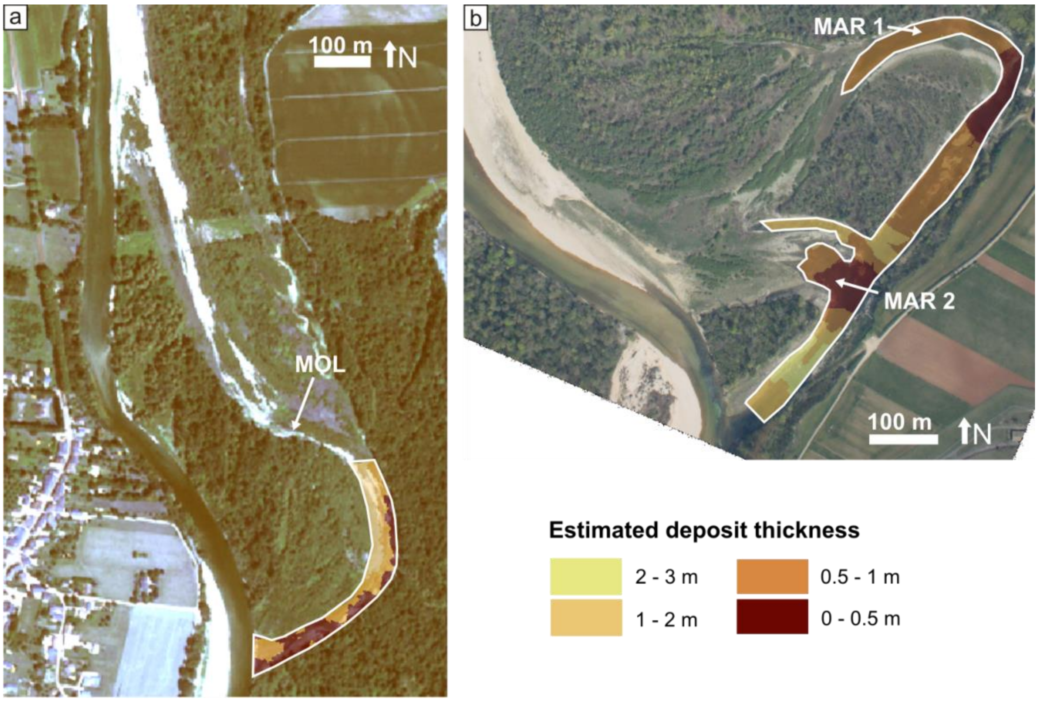

Figure 3.8: Estimates of sediment infill thickness in submerged areas of the abandoned channels seven years after cutoff based on the DGPS survey in 2010
(a) Infill thickness data of MOL portrayed within the aerial photo of the site in 2009
(b) Infill thickness data of MAR1 and MAR2 portrayed within the aerial photo of the sites in 2010.

3.4.2 Estimates of Off-Channel Bed material Storage

Estimates of the volumetric storage of sediment throughout the study used the morphologic budget approach for the time period between 2004 and 2008, DEM differencing over subaerial bars for the time period between 2008 and 2010, and the DGPS survey for the time period between 2003 and 2010 (see Section 3.3). The results of the morphologic budget approach were combined with those of the DEM differencing for the subaerial sections of the channel segments, producing an estimate of volumetric exchange for the period between 2004 and 2010 within the entrances to each of the sites. The estimates revealed that the main channel was net-degradational from 2004-2008, losing 70,000 m^3 (or 17,500 m^3 y^{-1}) of sediment as the river continued to evolve in response to the abandonment of *MOL* (Fig. 3.9). Conversely, *MOL* was a site of net aggradation between 2003 and 2010, gaining 34,000 m^3 (or 4,900 m^3 y^{-1}) of sediment as increasingly less discharge was being routed through it. Using Rollet's (2007) calculation of the average bed material transport capacity (see Section 3.2) as an estimate of the annual bed material load into the reach, *MOL* was able to sequester nearly 40% of the 14,000 m^3 y^{-1} supply into the reach between 2003 and 2010. Slightly complicating the assessment of *MOL* is that the portion of the reach immediately upstream of the entrance to *MOL* lost at least 9,000 m^3 of sediment between 2004 and 2008, or 2,250 m^3 y^{-1} (Fig. 3.9). Assuming that Rollet's (2007) estimate is most relevant for graded (i.e., inputs of bed material equal outputs) sections of the river, the additional loading likely due to chute enlargement would lower the amount sequestered to 34% of the supply.

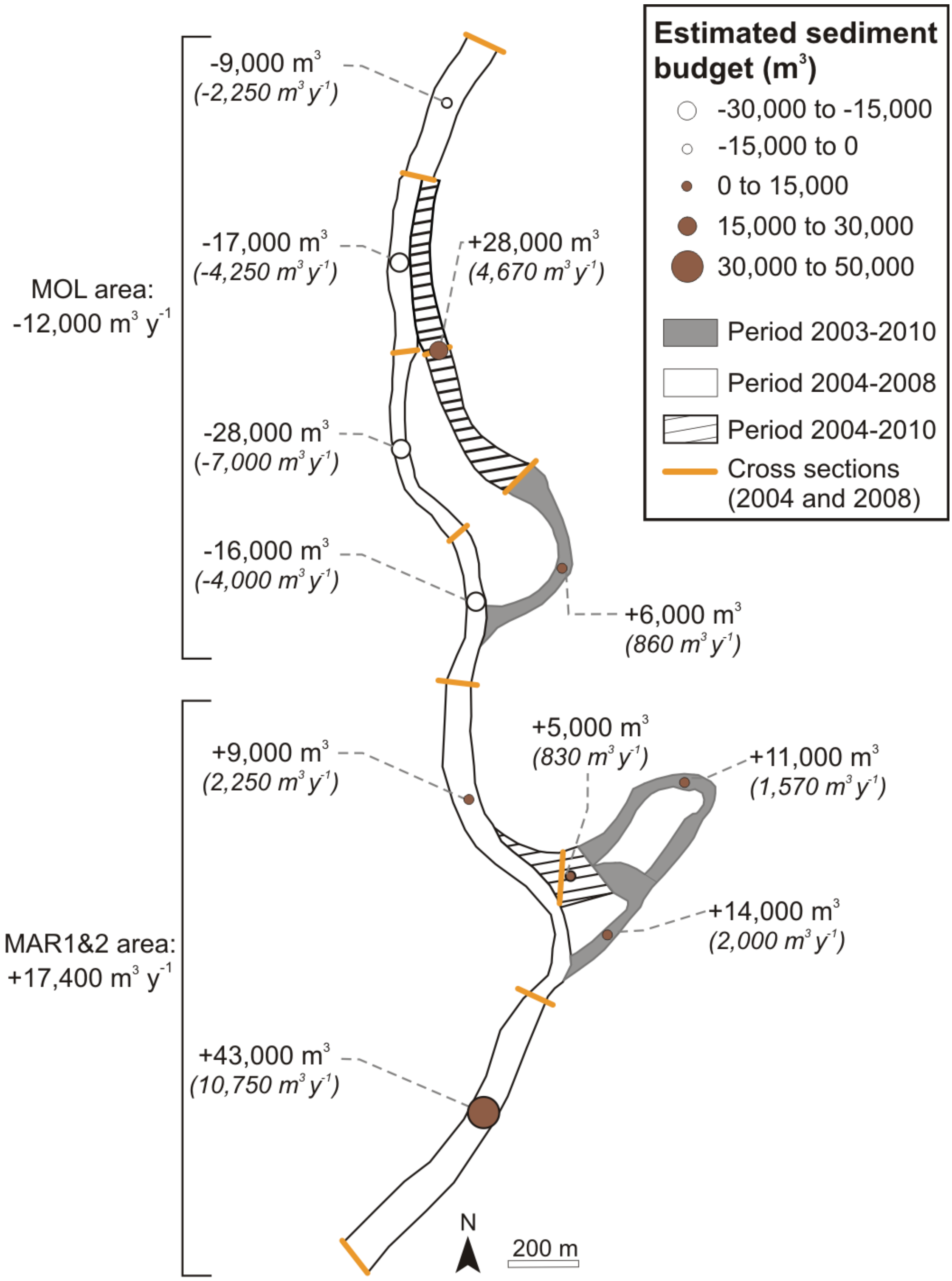

Figure 3.9: Schematic representation of the sediment budget for the study area between 2003 and 2010.
The reach was divided into segments based on the distribution of cross sections and an individual budget (represented by circles) calculated for each sub-reach. The MOL area showed net erosion while the MAR1&2 zones showed net deposition during this period. White circles indicate the dominance of aggradation over degradation, whereas dark circles indicate the dominance of degradation over aggradation. Grey areas represent the budget calculated from a 2010 DTM of the submerged areas (see also Fig. 3.7). White areas represent the budget calculated from 2004 and 2008 cross sections. Striped areas represent the budget calculated using cross sections for the period 2004-2008 and DTMs from 2008-2010.

Between 2004 and 2008, chute enlargement at *MOL* delivered at least 61,000 m^3 (or 15,250 m^3 y^{-1}) of sediment to the downstream reach hosting the *MAR* sites. The total loading to the downstream reach was likely higher given additional upstream bed material inputs. For instance, if the 2,250 m^3 y^{-1} of loading derived from the upstream entrance to the study reach were entirely sequestered by *MOL,* the site would only be able to sequester 3,280 m^3 y^{-1} of the annual bed material load into the reach. Consequently, the total loading into the downstream reach was on the order of 26,000 $m^3.y^{-1}$ (i.e., 14,000 m^3 y^{-1} + 15,300 m^3 y^{-1} - 3,300 m^3 y^{-1}). From the estimates of volumetric storage (Fig. 3.9), the main channel adjacent to the *MAR* sites gained 9,000 m^3 (or 2,250 $m^3.y^{-1}$) of sediment, or 9% of the supply from chute enlargement and upstream loading. The *MAR* sites, on the other hand, gained 30,000 m^3 (or 4,400 m^3 y^{-1}) of sediment between 2003 and 2010. Comparing average annual rates, the *MAR* sites were able to sequester 17% of the chute-enlargement supply, 43-50% less than rates of bed material sequestration at *MOL*. The main channel downstream of the *MAR* sites gained 43,000 m^3 (or 10,750 m^3 y^{-1}) of sediment between 2004 and 2008, or more than 41% of the chute-enlargement supply, implying that the majority of sediment derived from chute enlargement at *MOL* was stored within the river and the channel segments at *MAR*.

Estimates of the volumetric storage of sediment between 2008 and 2010 using DEM differencing (see Section 3.3) indicated that the entrance to *MOL* gained only 6,800 m^3 (or 3,400 m^3 y^{-1}) of sediment, nearly three times less than the preceding period, and the upstream entrance to the *MAR* sites began to erode (Fig. 3.10). In particular, 2,300 m^3 of sediment was removed from the entrance to *MAR1*, and 2,000 m^3 of sediment was removed from the entrance to *MAR2* during this time period. The reason for the erosion of plug deposits at the *MAR* sites remains unclear, , but 85 m of bank erosion occurred between 2005 and 2010 (Figs. 3.3 & 3.10), shifting the channel margin closer to the sediment plugs and probably making it easier for flood flows to access and mobilise plug deposits.

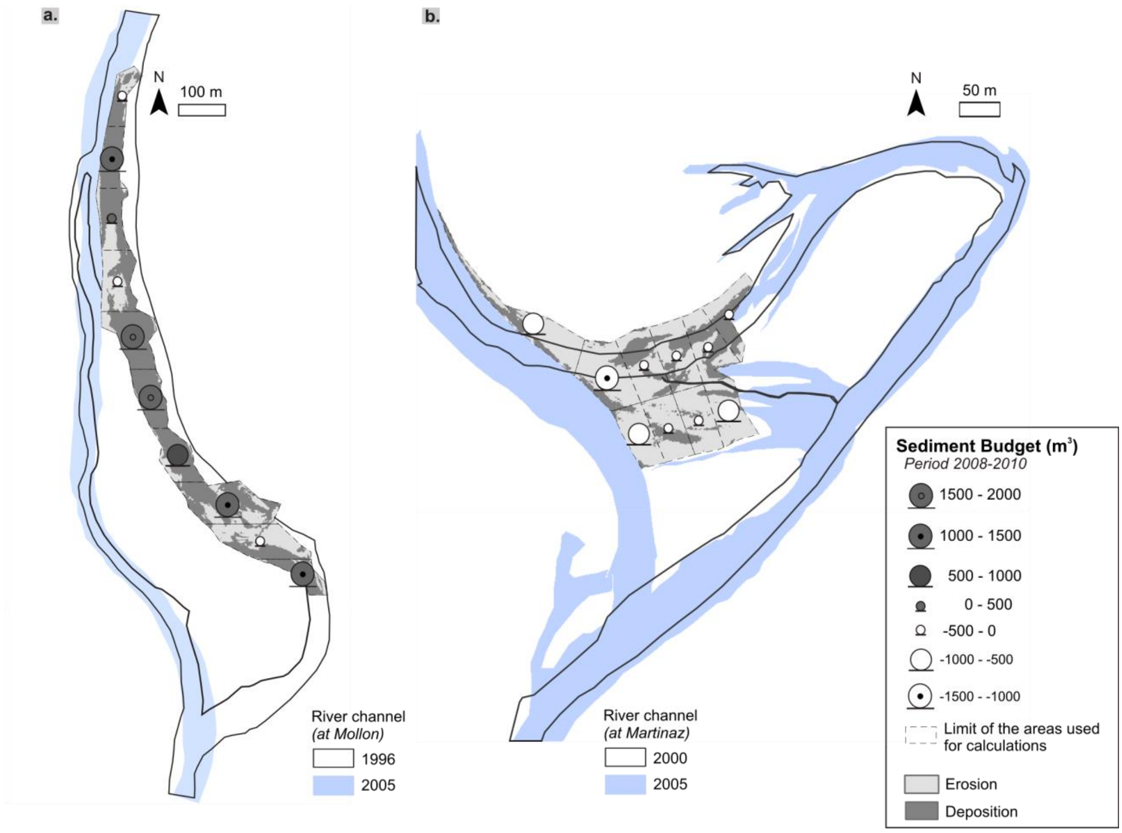

Figure 3.10: Representation of sediment mobilisation for the period 2008-2010. (a) The MOL cutoff site primarily shows areas of net aggradation (dark grey) with up to 2000 m^3 of deposition of sediment in sub-reaches (dark circles). (b) The MAR1&2 cutoff site is primarily erosional with up to 1500 m^3 of sediment loss in sub reaches (white circles). The pre- (dark lines) and post-cutoff (grey shaded area) channel forms show the magnitude of channel change caused by the cutoffs.

3.5 Discussion

3.5.1 Sediment transfers in the reach

The transfer of bed material from the river to an abandoned channel segment while it is still hydraulically connected reduces the bed material load to the downstream reach, which could instigate the removal of bed material from within the main channel cut-off reach that are not stabilised show a tendency to cutoff a second time (Hooke 1995) as seen at *MAR* sites. In cases of chute cutoff, the evolving chute significantly increases the bed material load of the river (see also Zinger et al. 2011), more than compensating for off-channel sequestration. Within the study reach, chute enlargement at *MOL* delivered up to 15,250 m^3.yr^{-1} to the river between 2004 and 2008, nearly equivalent to the bed material transport capacity of the river. Given that chute enlargement occurs concomitantly with a reduction in discharge through the abandoned channel, chute enlargement should then effectively limit the duration that bed material is transported through the abandoned channel. Bed material sequestration would also reduce the discharge diverted into the abandoned channel, thereby facilitating the chute enlargement process. Further, and consistent with observations from this study, Fuller et al. (2003b) found that a chute incised within the floodplain of the River Coquet, UK, continued to supply sediment to the downstream reach years after the abandoned channel was plugged. Results suggest that the predominant effect of chute cutoff on the reach-scale sediment budget of a meandering river is a net-increase in the bed material supply that could last for years after the initial chute incision. This increase in bed material supply should instigate bar building and potentially increased bank erosion as bar growth would alter flow conditions within downstream meander bends, increasing boundary shear stress conditions along riverbanks due to excess stream energy (Dietrich and Smith 1983; Whiting and Dietrich 1993; Fuller et al. 2003b, Constantine 2006). Fuller et al. (2003b) also observed that mid-channel bars were fed by sediment release due to bank erosion just upstream which is similar to *MAR* sites where a bar was created mid_channel, following the incision of the upstream site (*MOL*).

3.5.2 Former channel sediment transfers

The sedimentary deposits of oxbows have been shown to influence meander migration rates (Hudson and Kesel 2000), the width of the meander belt (Allen 1965; Howard 1996; Sun et al. 1996), and the hydrogeological characteristics of alluvial reservoirs (Richardson et al. 1987), but many efforts that examine the role of oxbow deposits in meandering behaviour and floodplain development presume that they consist primarily of the finest fractions of sediment in transport. Although bed material storage within the abandoned channel segments of this study did not compensate for the delivery of sediment by chute incision, the sites managed to sequester between 17 and 40% of the bed material supply over seven years. In agreement with empirical evidence that much of the deposits of oxbows formed by chute cutoff tend to be coarse (i.e., bed material derived) (Fisk 1947; Bridge et al. 1986; Hooke 1995; Constantine et al. 2010a) (Fig. 3.6F), it appears that chute cutoff creates important off-channel sites for bed material storage and that oxbows do not always create the clay plugs that are commonly associated with them. The coarse deposits within the study sites also remained mobile as aggradation proceeded. The plugs of the *MAR* sites became a source of sediment as 4,300 m^3 of sediment was mobilised between 2008 and 2010 during overbank flows. Hooke (1995) suggested that old channels are often more erodible because the material is coarse and unconsolidated which is supported by the observation of erosion at *MAR* sites. This is potentially significant as oxbows may have a dualistic function with regards to the bed material budget of a meandering reach, functioning as significant sinks for bed material immediately following cutoff, but then as sources in the long term as flood flows or the lateral shifting of the meandering river mobilises the coarse deposits.

3.5.3 Former channel depositional processes

Results from this study provide insight into the mechanisms driving the transfer and storage of bed material within oxbows. The blockage of the former channels ends occurred within 2 years after the cutoff, consistent with observations by Hooke (1995) of <1-7 years on the Dane and Bollin Rivers (UK) and by Gagliano and Howard (1984) of 2-10 years on the Lower Mississippi. Aggradation primarily occurred along inner bends of pre-existing point bars (Fig. 3.7) and the role of point bar growth in oxbow aggradation was also observed within abandoned channels of the Yangtze River, China (Li et al., 2007) and the Sacramento River, USA (Constantine et al. 2010a). Some evidence for the process was reported from sedimentological work along the Mississippi River, USA (Fisk 1947), the Calamus River, USA (Bridge et al. 1986), and the Rhine delta apex, Netherlands (Toonen et al. 2012). The pervasiveness of the observations suggests that the transverse transport of bed material driven by cross-stream currents is an important mechanism in transforming the open-water volume of abandoned channel segments. If true, then the planform curvature of abandoned channels is an important control on both plug development and the open-water volume that oxbows inherit upon their formation. However, the ability of curvature-induced forces to alter the downstream flow path through an abandoned channel will depend on the magnitude of discharge diverted from the main channel. This diverted discharge is a function of the discharge conditions in the main channel, the conveyance capacity of the entrance, and the diversion angle (see Section 3.2) (Constantine et al., 2010). As described, the diversion angle limits the diverted discharge by controlling the size of a flow separation within the entrance that induces pressure drag on the diverted current. Low diversion angles should allow for the maintenance of downstream currents capable of transporting bed material and perhaps also the cross-stream currents responsible for bar development. Indeed, the three sites each had relatively low diversion angles (Fig. 3.1), consistent with previous observations that such angles allowed for sustained bed material transport and alluviation by point bar growth (see figure 4 of Constantine et al., 2010). Neck cutoff results as the consequence of meander growth and so should produce diversion angles that are greater than those produced by chute cutoff, whose diversion angles will be determined by the planform curvature of the abandoned channel segment and the location where the chute is incised. A global analysis of typical diversion angles associated with each meander cutoff process is required, but that cutoff processes may produce oxbow lakes with characteristically different diversion angles has important implications for the development of the floodplain. The prevalence of either cutoff mechanism may lead to distinct floodplain environments as the abandoned channels they create undergo distinct patterns of alluviation (Fisk, 1947; Constantine et al., 2010).

3.6 Conclusion

The study of three cutoff sites of the Ain River (France) provided important information regarding initial oxbow lake sedimentation and sediment transfers within a river reach. Results were based on an extensive topographic survey associated with remote controlled measurements and GIS, allowing calculating sediment budgets. Bed material accumulating in the former channels appears to have extended pre-existing point bars until the upstream end is completely obstructed by sediment. One site did not exhibit a local sediment plug at the upstream end but progressively lost surface area uniformly throughout its length. This may be promoted by the low diversion angle and point bar curvature at the upstream end. Former channels are not only fine-grained sediment stores, as often referred to, but can be significant bed material sinks since about 34% of the supply to the river segment deposited in the upstream former channel. The downstream site also stored a significant volume of sediment since 17% of the bed material transferred by channel incision accumulated in the downstream former channels. Chute cutoff creation caused larger sediment transfers by channel incision than by accumulation in former channels. About 41% of the bed material eroded after cutoff was deposited on the nearest downstream point bar. During the same period, this point bar bend migrated by about 85 m towards the downstream former channel by eroding the bed material plug. This highlights the probable effect of cutoffs on channel dynamics and suggests that former channels can have the dualistic function of sink and source of bed material.

Chapter 4

Long-term depositional patterns and processes in oxbow lakes along the Towy River, Wales

4.1 Introduction

As meandering rivers increase the space they occupy in their floodplains by the growth of meander bends, incidents of meander cutoff remove segments of river channel that are then isolated as off-channel water bodies (Leopold and Wolman 1960; Brice 1974). In many cases, these abandoned channels transition into oxbow lakes that may persist as aquatic habitat for centuries (Gagliano and Howard 1984; Wolfe et al. 2006), but this transition may not be commonplace along all meandering rivers. Instead, some abandoned channels maintain a hydraulic connection to the main channel, narrowing with time by continued point bar growth until they become colonised by terrestrial vegetation (Constantine et al. 2010a). Whether an abandoned channel successfully transitions into an oxbow depends upon the formation of sediment plugs (bars of coarse sediment) within the entrances of the channel that prevent the continuous diversion of flow and bed material from the main channel (Citterio and Piegay 2000; Piegay et al. 2002). The rate of plug formation determines the duration that the abandoned channel is hydraulically connected, thus controlling the extent to which diverted bed material aggrades the original channel form (Fisk 1947; Constantine et al. 2010a). Rapid plug formation improves the potential for the original channel form to be preserved, maximizing the open-water volume that the oxbow inherits and thus the accommodation space for storing suspended sediment delivered during floods. The occurrence of moderate floods appears to favour oxbow lake sedimentation at least during the first decade after cutoff (Hooke 1995, Gautier et al. 2007). The obstruction of former channel ends by aggradation of coarse-grained sediment prevents further bed-material input in the site and allows exclusively fine-grained sediment infill.

One of the most comprehensive reviews of oxbow alluviation made to date was provided by Fisk (1947) based on observations along the Lower Mississippi River, USA. In a report provided to the Mississippi River Commission, Fisk identified the major control on oxbow alluviation without attributing a cutoff mechanism. In his words (Fisk, 1947, p. 38), “The nature of the sedimentary deposit in the old channel is dependent upon the duration of flow through the old course which in turn is dependent upon the alignment of the river with respect to both upstream and downstream arms of the abandoned loop.” Fisk termed the alignment between the river and the upstream arm as the angle of diversion, or diversion angle. He noted that when the diversion angle was small, the abandoned loop receives continuous flow from the main channel for a longer duration and the upstream arm becomes gradually plugged by coarse bed-load (sand in the case of the Lower Mississippi River). Fisk also pointed out that abandoned loops became narrowed as a result of bed material aggradation, finding that the width of clay plugs within chute cutoff generated loops (which tend to have small diversion angles) were narrower than clay plugs found within neck cutoff generated loops (which tend to have large diversion angles). The field observations of Hooke (1995) of oxbow alluviation along rivers of northwest England are consistent with Fisk (1947). Shields and Abt (1989) similarly concluded that the diversion angle was an important control on oxbow alluviation. From empirical measurements of the rates of infilling within oxbows of the Lower Mississippi River, Shields and Abt found that differences in diversion angle and sediment load explained over 90% of the variability in rates of bed material aggradation. Although Erskine et al. (1992) did not examine the control of the diversion angle, they too argued for the importance of the nature of sediment moving through the reach on oxbow alluviation. Based on an analysis of sediment auger flights taken from the Hunter River of New South Wales, Australia, Erskine et al. (1992) found that the character of sediment (coarse against fine) stored within oxbows and oxbow sedimentation rates correlated with the character of sediment in transport. In essence, they found that the finer the sediment in transport, the finer the sediment being stored and the faster the sedimentation rate.

As noted by Fisk (1947), given that neck cutoff results as the consequence of meander growth, the mechanism should produce diversion angles that are greater than those produced by chute cutoff, whose diversion angles will be determined by the planform curvature of the abandoned channel and the location where the chute is incised. The prevalence of either cutoff mechanism along meandering rivers may lead to distinct sedimentary environments in the floodplain as the abandoned channels they create undergo distinct patterns of alluviation (Fisk 1947; Constantine et al. 2010a). To assess the role of cutoff mechanism in the evolution of cutoff-produced water bodies, this chapter will examine the processes governing depositional processes in oxbow lakes at different stages of their lifespan using a very detailed record of sedimentation from five oxbows of the River Towy, Wales. This Chapter explores the importance of the controls on oxbow alluviation and then identifies the conditions required for the successful oxbow transition. Results of the chapter will provide detailed field evidence of the nature and multidimensional patterns of oxbow deposits. Findings are essential to any prediction of the persistence of oxbow lakes as aquatic habitat but also provide important information regarding the composition of meandering floodplain sediment.

4.2 Study Site

The 105-km long River Towy drains 1,090 km^2 of west Wales, emptying into Bristol Channel near the town of Carmarthen. The River Towy catchment experiences average annual precipitation of between 1,000 and 2,400 mm each year, which results in a mean annual discharge of 39 $m^3.s^{-1}$ at the Nantgaredig gauging station (McEwen and Milan 2006). Most of the river course flows within Ordovician and Silurian sedimentary rocks (clay and siltstone, siltstone and sandstone dominated, Fig. 4.1b) in a valley that contains 8-11 alluvial terraces (Jones et al. 2011). Three distinct channel forms exist along the river: a bedrock-controlled single wandering channel from Llyn Brianne dam to Llandovery; a braided channel between Llandovery and Llangadog; and a meandering channel between Llangadog and the river mouth. The median size of bed material (d_{50}) ranges from 53 to 57 mm according to McEwen and Milan (2006). The geomorphic effects of the construction of the Llyn Brianne in 1973 remain uncertain. The river has also been affected in its upstream reaches by a large lead and zinc mine. The Nant-y-mwyn mine shut in 1932, but may have been in operation since the Bronze Age according to archaeological findings (Hughes 1992). A large part of the River Towy corridor is now classified as a “Special Area of Conservation” for the protection of several species of fish and otters (McEwen and Milan 2006).

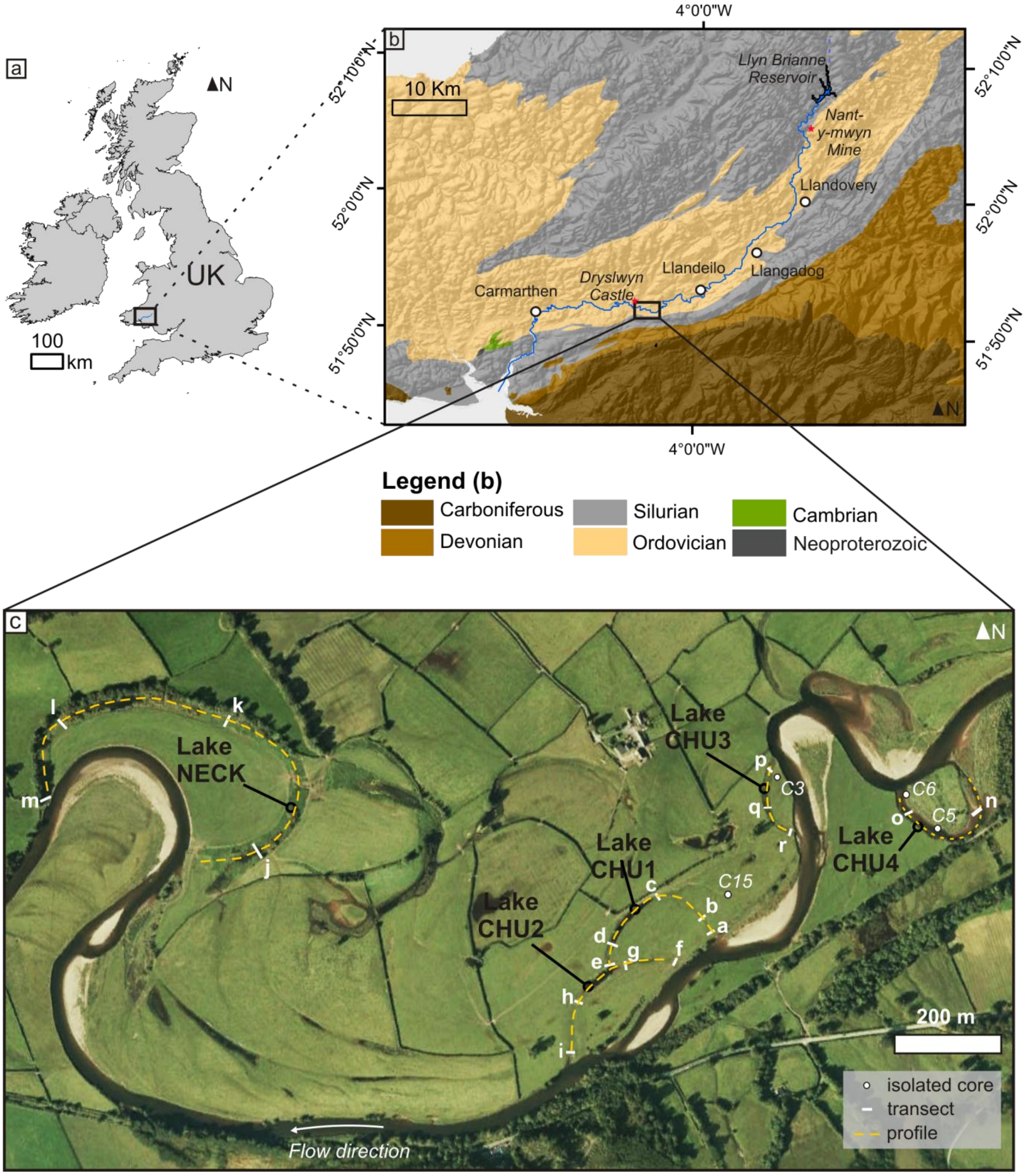

Figure 4.1: Location maps of the study sites and coring survey.
(a) Sketch map of the UK showing the location of the study area in Wales (black rectangle).
(b) Map showing the geological ages of the area and the location of key cities and features.
(c) Aerial photograph of the five studied oxbow lakes in 2009 (Google Earth™). The dashed lines are longitudinal profiles, the circles are isolated auger flights and the dashes with letters are transects of three to four auger flights.

This study examined five oxbow lakes located in the lower and meandering section of the River Towy, between river kilometres 40 and 44, near Dryslwyn Castle (Fig. 4.1b). At the study sites, the Towy River is on the order of 3 m deep and 30 m wide. This specific group of oxbow lakes was chosen because it comprised sites of various ages and cutoff mechanisms. The close proximity of the oxbows allows the assumption that they underwent comparable hydrological and sedimentation histories. From OS maps and aerial photographs, Lake CHU1, CHU3 and NECK cut-off around 1863 (±23y), whereas Lake CHU2 and CHU4 cut-off more recently, respectively in 1940 (±5y) and 2001 (±2y). The mechanism of cutoff was chute incision for Lakes CHU1, 2, 4 whereas Lake NECK was formed by neck cutoff. The mechanism of cutoff that initiated Lake CHU3 is not easy to assess due to the lack of historical maps but its curvature and location suggest a chute cutoff.

4.3 Methods

4.3.1 Field sampling and topographic measurements

The five oxbow lakes of the study were surveyed during the summer 2010. A total of 59 auger flights were collected using a peat auger along 18 transects regularly distributed throughout the sites (Fig. 4.1c). The peat auger allowed sampling of fine-grained sediment composed of sand and clay, but could not penetrate gravel-rich layers such as the former river bed. Two soil auger flights were also collected within the floodplain to allow comparison with the surrounding alluvium (Fig. 4.1c, auger flights C15 and C3). Lake CHU4 was still submerged by at least of 1.5 m of water which prevented sampling near the lake apex. Consequently two of the soil auger flights do not occur along a transect (Fig. 4.1c, auger flights C5 and C6), and the remaining flights were taken close to the banks where the shallow water allowed sampling. Fine-grained sediment was sampled every 20 cm of each flight until a coarse-grained surface of gravel was reached that prevented deeper sampling. The gravel surface likely represented either the original abandoned channel bed or the surface of aggraded bed material that was delivered prior to plug formation. The location of each auger flight was recorded using a differential-GPS (vertical and horizontal precision: ±2 cm). The surface elevation of the flight locations was used to reconstruct the three-dimensional alluvial stratigraphy of each study site.

4.3.2 Grain size analyses

The grain size distribution of sediment samples was assessed by wet sieving (e.g., Folk 1974). Each 20 cm subsample from the auger flights was mixed, and then 60 g were extracted from the bag sampled on the field and transferred to a 1L-plastic bottle. To assess how each 60g sample was representative of the bag composition, the measurement was replicated ten times for the first sample. Results showed a standard deviation of only 0.8% in composition of mud, sand or gravel for the ten replicates. Five mL of 30% Hydrogen Peroxide was added in order to oxidize the organic matter. After leaving the sample to react overnight, a solution of 500 mL of 1% Sodium Hexametaphosphate was added to disaggregate clay particles. The sample was left to react overnight once again before sieving. Wet sieving was then done using a stack of sieves that isolated every ϕ fraction between 0.063 mm and 2 mm: >2 mm , 2-1 mm, 1-0.5 mm, 0.5-0.25 mm, 0.25-0.125 mm, 0.125-0.063 mm, <0.063 mm. Six empty aluminium trays were weighed prior to receiving the samples. The size-fraction finer than 0.063 mm was not actually measured but calculated by weight difference (see below). The sampled size-fractions were then poured in a tray and dried for a minimum of 12h in an oven at 100°C. The aluminium trays were then weighed when the samples were dry and had cooled down. The dry weight of each size fraction was calculated by subtracting the tray weight from the final weight of the tray and dry sample.

A loss-on-ignition procedure was conducted to decipher the weight of the organic matter and the water content in the samples (e.g. Dean 1974, ASTM 2000). Five grams of sediment was taken from each subsample and then placed in an aluminium tray and weighed. To evaporate the water, the sediment was heated in an oven at 100°C for a minimum of 12h. Once dry, the tray containing the sample was weighed again. The water content was calculated by subtracting the wet weight (initial 5 g of sample) from the weight of the tray containing the dry sample. In order to know the organic matter content, the same protocol was then used on the water-free sample with the only difference that the temperature of 450°C was applied to combust the organic matter for a minimum of 6h. The organic matter weight was calculated by subtracting the initial weight of the tray containing the water-free sample from the tray containing the combusted sample. The weight of water and organic matter were also converted to percentages to obtain the actual weight in the 60 g sample. To calculate the weight of silt and clay (fraction <0.063 mm), all the measured weights were added (size fractions + water + organic matter). The obtained value was then subtracted from the 60 g of the initial wet sample to obtain the silt and clay weight. The potential errors associated with this protocol are the precision of the scale (±0.003 g) and the uncertainty related to the completeness of the sieving or the potential loss of sediment between protocol steps.

4.3.3 Statistical Analysis

To find out if the sediment composition of the former channels varied significantly a Kruskal-Wallis test was performed on the average grain size distribution per auger flight for each lake (Fig. 4.3). Ten pair comparisons were done on CHU1, CHU2, CHU3, CHU4 and NECK sites.

4.4 Results

4.4.1 Oxbow lakes longitudinal profiles

The spatial distribution of fine-grained sediment (i.e. sand and finer) through the abandoned-channel centre was mapped for each of the sites except for lake CHU4, whose profile represents the fill along the outer bank (Fig. 4.2). The data demonstrated different patterns of both coarse and fine-grained sedimentation. Gravel was exposed at the surface at two locations within different oxbows: within the upstream entrance of Lake NECK and CHU4 , between 0 and 100 m, and within the downstream entrance of Lake CHU4, between 250 and 300 m. The surface of the remaining lakes was composed entirely of fine-grained sediment, sloping in planar fashion in the downstream direction. The surface of buried gravel (or more precisely, the depth to coring resistance) within the sites (i.e. Lakes CHU1-3) was also planar in nature, sloping in the downstream direction (left to right, Fig. 4.2a,b,c,e). In detail, Lake CHU1 contained evenly distributed fine-grained deposits ranging from 1 to 2 m in thickness, with a difference in the depth to gravel between the upstream entrance and downstream exit of 2.5 m. The surface of Lake CHU2 sediment was quite undulated, with the depth to gravel decreasing uniformly by about 0.5 m from upstream to downstream. The thickness of fine-grained deposits in Lake CHU2 was between 1 and 2.5 m in thickness. The ground surface of Lake NECK gradually decreased in elevation from upstream to downstream, but also rapidly increased in elevation by about 0.8 m near the downstream exit. The depth to gravel within Lake NECK decreased by 2 m on the first 100 m upstream and gradually decreases by 1.5 m for the remaining 830 m. Fine-grained deposits in Lake NECK ranged from 0.5 to almost 3 m, occurring uniformly throughout the lake's length. Lake CHU4 demonstrated a very uneven distribution of sediment deposits, with a gravel depth of 80 cm near the apex and fine-grained sediment thickness between 0 and 2 m throughout. Similar to Lake NECK, the surface of Lake CHU3 was higher by about 20 cm at the upstream and downstream ends than the apex. It is important to note, however, that only 160 m of Lake CHU3 remained after the river eroded much of the ends of the abandoned channel. For Lake CHU3, the depth to gravel decreased gradually by about 0.5 m and fine-grained deposits are 1.5 to 2 m thick.

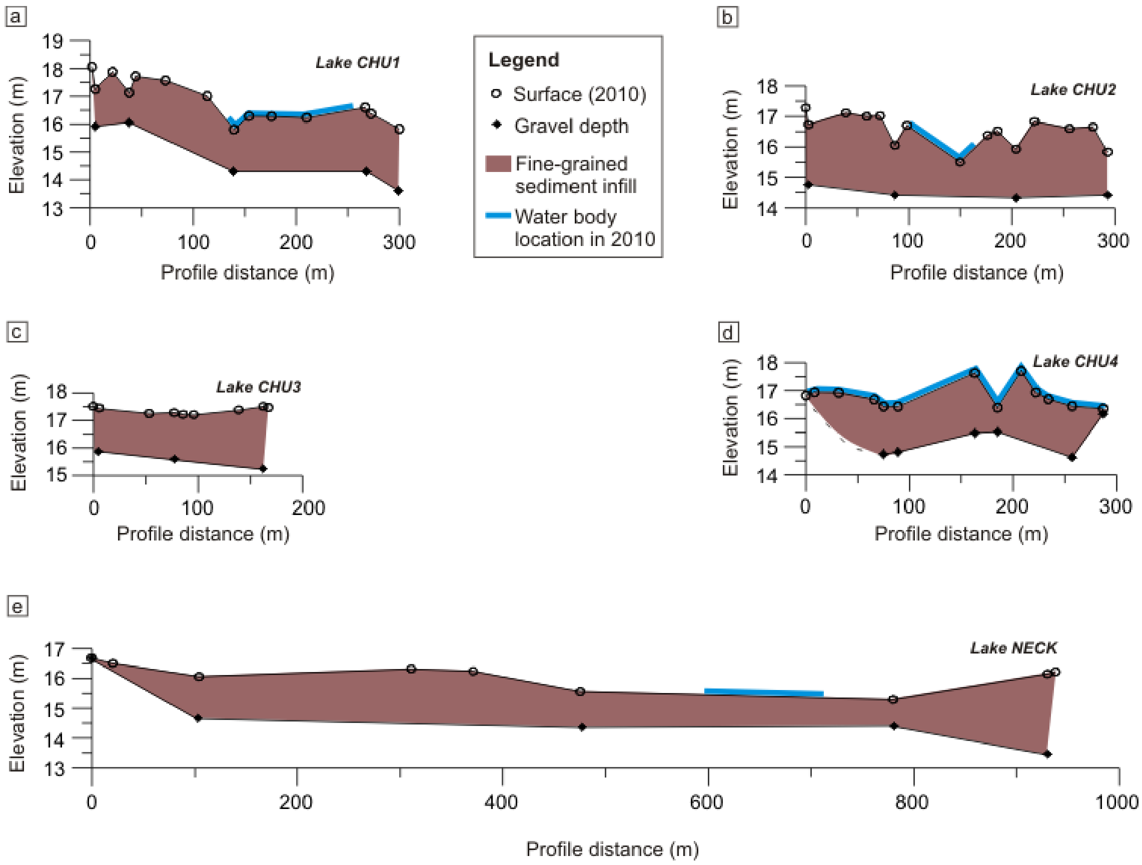

Figure 4.2: Longitudinal profiles of (a) Lake CHU1, (b) Lake CHU2, (c) Lake CHU3, (d) Lake CHU4 and (e) Lake NECK.
Circles represent the ground surface in 2010 which correspond to the top of fine-grained sediment. The diamonds are the measured gravel layer elevations representing either the initial channel bed or the post-cutoff gravel infill which deposited on the former bed. All the profiles are oriented in the downstream direction towards the right.

4.4.2 Fine-grained sediment distribution

4.4.2.1 Averaged grain size per auger flight

Grain size was measured at different depths according to three size fractions: clay and silt (≤63 µm), sand (from >63 µm to ≤2 mm) and gravel (>2 mm) after Wentworth (1922). Data presented below (Fig. 4.3) correspond to average values for each core. The dominant size fraction of sediment infill of the five study sites was fine-grained with the infill containing 0 to 35 % of gravel (Fig. 4.3). Lake CHU1 was dominated by clay and silt sized deposits, with auger flights containing 35-95 % of clay and silt, 5-60 % of sand, and 0-30 % of gravel. Lake CHU2 was dominated by fine-grained deposits, with auger flights containing 30-75 % of clay and silt, 25-60 % of sand and 0-35 % of gravel. Lake CHU3 was dominated by clay and silt, with auger flights containing 50-90 % of clay and silt, 10-45 % of sand, and only 0-15 % of gravel. Lake CHU4 was evenly dominated by fine-grained deposits with two types of sediment infill: the first type contained 60-75 % of clay and silt, 25-40 % of sand and only 0-5 % of gravel and the second type contained 10-35 % of clay and silt, 65-85 % of sand and only 0-15 % of gravel. Lake NECK was dominated by clay and silt, with auger flights containing 45-95 % of clay and silt, 5-30 % of sand, and 0-35 % of gravel.

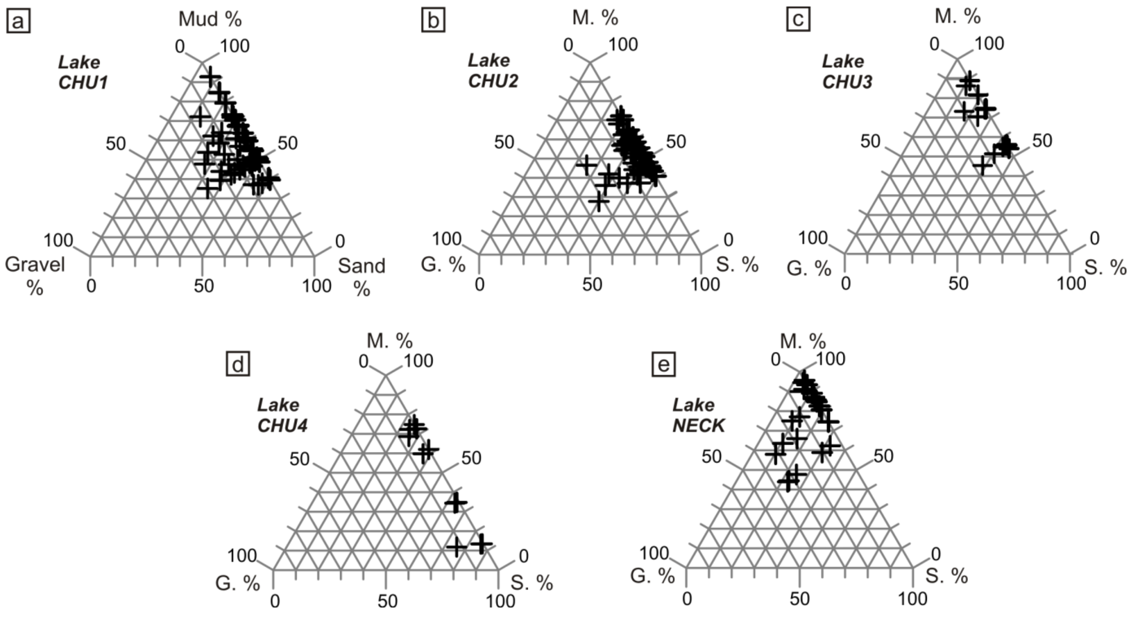

Figure 4.3: Averaged grain size distribution per auger flight.
The size fractions considered are clay and silt (≤63 µm), sand (from >63 µm to ≤2 mm) and gravel (>2 mm).

Statistical analyses showed that all the chute cutoff's sedimentary contents differed significantly from the neck cutoff site. All the chute cutoff contents were not significantly different except for the pair CHU2-CHU3 (Tab. 4.1).

Table 4.1. Comparison of the average grain size per core between oxbow lakes based on a Kruskal-Wallis test.

Pairwise Comparison	n	p
CHU1/CHU2	34	0.15
CHU1/CHU3	29	0.10
CHU1/CHU4	26	0.74
CHU1/NECK	32	0.00
CHU2/CHU3	21	0.01
CHU2/CHU4	18	0.77
CHU2/NECK	24	0.00
CHU3/CHU4	13	0.21
CHU3/NECK	19	0.01
CHU4/NECK	16	0.00

4.4.2.2 Chute cutoff oxbow lake "CHU1"

Lake CHU1 was one of the oldest sites and formed some time between 1840 and 1885. The downstream third of the oxbow's length was eroded by channel migration that created the meander at Lake CHU2. Twenty auger flights were taken along five transects at this site (Fig. 4.4). The depth to gravel decreased by up to 1.5 m in the downstream direction (Fig. 4.4, C17 and C1). The thickness of fine-grained sediment increased along the stream-wise axis (upstream to downstream) with a difference of about 1 m in depth between transect "a" and transect "e". Transect "b" was an exception, being on average 0.49 m shallower than the upstream transect (Fig. 4.4, transect "a"). The overall depth to gravel appeared as a berm at the transect with a pool-like area downstream of the transect where a thick layer of fine-grained deposits was stored. Grain size generally fined upward in both the oxbow and floodplain auger flights. Three oxbow auger flights did not exhibit this fining, however, and were located within the downstream end and contained the thickest fine-grained deposits; auger flights C7, C3 and C4 contained 2.09 m, 2.64 m and 1.97 m of fine sediment, respectively. The sorting of fine-grained deposits appeared more variable in the downstream auger flights than those upstream. Upstream auger flights, such as in transect “a” and “b”, exhibited a smooth upward increase in clay and silt content from 25% to about 75%. Downstream auger flights varied more in grain size through depth and coarsened upward at locations (e.g., Fig. 4.4, C1). Sediment within the downstream auger flights fined downstream, with clay and silt accounting for about 50 to over 75 % of the total content.

There was no obvious pattern of fining or coarsening in the cross-stream direction. Nonetheless, the gravel depth was always deeper in the central part of the abandoned channel relative to the edges, except for core “C2”. The difference in gravel depth between the central auger flights and those on the edges of the abandoned channel were more significant within the downstream auger flights than those of the upstream. For example, there was a 2 m difference between the gravel depths of C7 and C8 whereas there was a difference of less than 50 cm between C19 and C20. Grain sizes fined upward from the inner to the outer banks of the upstream transects (Fig. 4.4, Transects a,b,c), but not those of the downstream. The downstream transects fined upward only for the inner bank auger flights, whereas auger flights close to the outer bank had high proportions of nearly 90% clay and silt (Fig. 4.4, Auger flights C7, C3, C4).

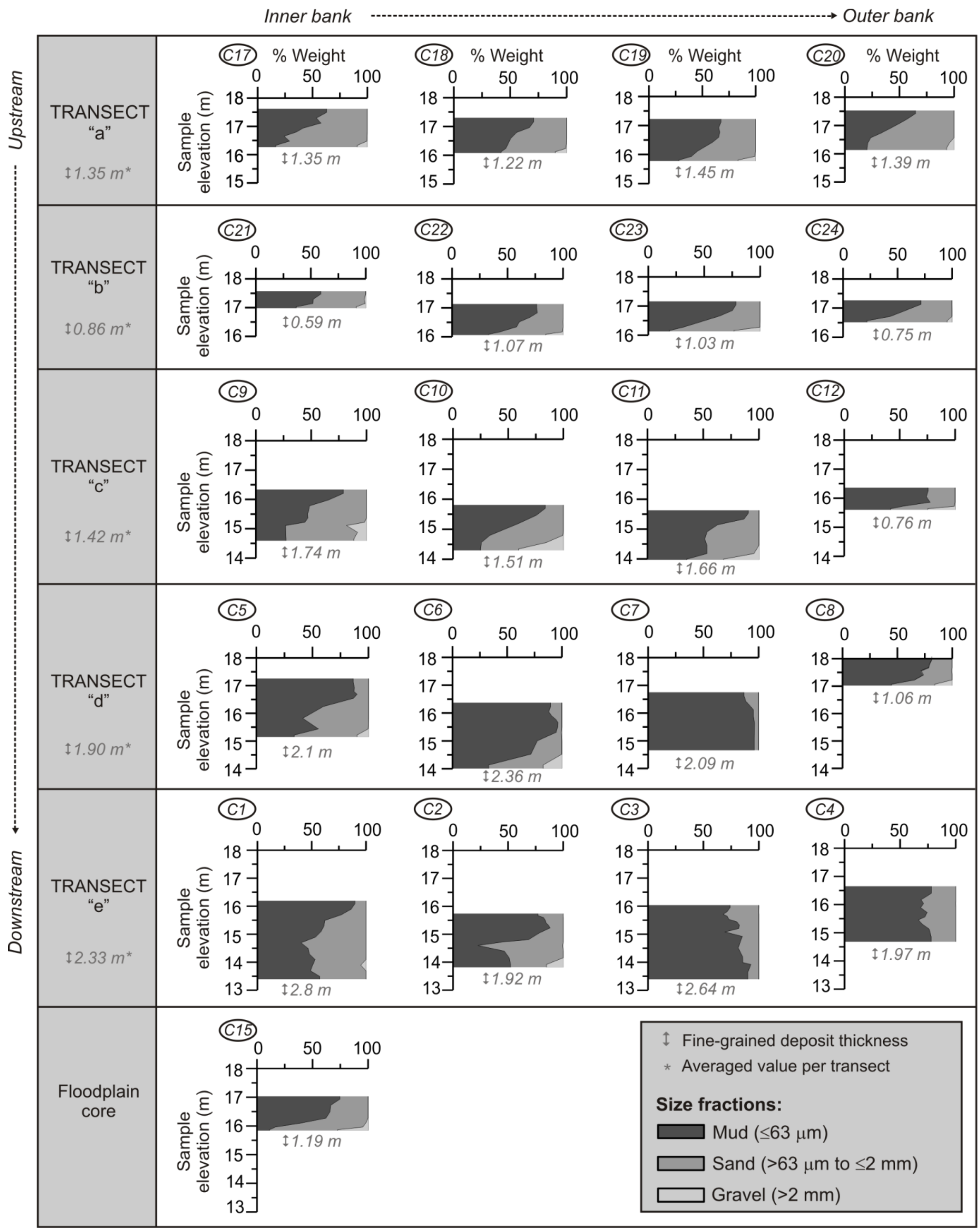

Figure 4.4: Grain size distribution and fine-grained deposit thickness at Lake CHU1. It was measured for 20 auger flights from 5 transects in the abandoned channel and one core (auger flight) from the nearby floodplain. The location references "Upstream-Downstream" and "Inner to Outer Bank" are showing the relative location of auger flights between one another.

4.4.2.3 Chute cutoff oxbow lake "CHU2"

Lake CHU2 was a more recent chute cutoff than Lake CHU1 and formed between 1935 and 1945. The distribution of grain sizes was measured for this site using 13 auger flights along four cross-channel transects. There was no apparent stream-wise (upstream-downstream) sorting of sediment, and the gravel depth appeared at a uniformly distributed elevation of 15.5 m, which may have resulted from the prolonged diversion of bed material into the oxbow. Fine-grained deposits thinned near the apex, with deposits (Fig. 4.5, transect "g" and "h") on average being 1.7 m thick whereas the upstream and downstream deposits were up to 30 cm thicker (Fig. 4.5, transect "f" and "I"). Deposits were also about 10 cm (Fig. 4.5, C12 compared to C13) to 20 cm thinner (Fig. 4.5, C9 compared to C8) in the apex than along either bank. Gravel depths were deepest along the outer bank, occurring at elevations of 14.2 and 13.8 m (Fig. 4.5, C4 and C13).

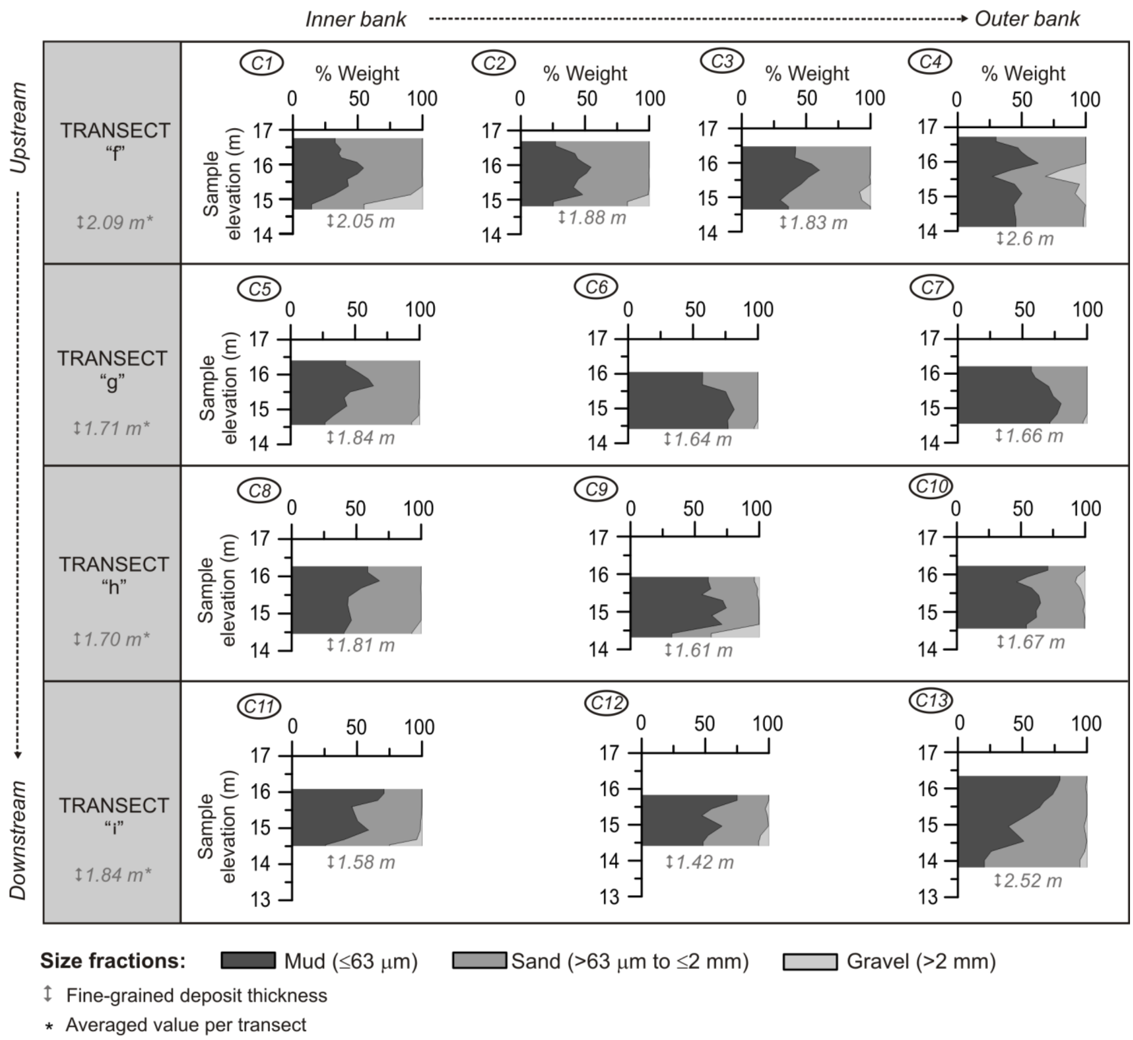

Figure 4.5: Grain size distribution and fine-grained deposit thickness at Lake CHU2.
It was measured for 13 auger flights from 4 transects located in the abandoned channel. The location references "Upstream-Downstream" and "Inner to Outer Bank" are showing the relative location of auger flights between one another.

4.4.2.4 Chute cutoff oxbow lake "CHU3"

Lake CHU3 was one of the oldest sites, having formed sometime between 1840 and 1885. Because of its age, half of its length may have been eroded by channel migration. The spatial pattern of sediment infill was mapped using three transects that contained seven auger flights in total and one additional flight from the floodplain (Fig. 4.6). Auger flights sampled at this site generally coarsened upward to about 1 m from the ground surface. Sediment deposits measured in the floodplain were 1.13 m thick, thinner than the average of 1.83 m thickness in the abandoned channel. Similar to Lake CHU1, the gravel surface sloped in the downstream direction, occurring at lower elevation downstream with a difference of up to 1 m between C1 and C8 (Fig. 4.6). No obvious stream-wise sorting of grain sizes deposit thickness was observed in the auger flights. Gravel depths were lower along the outer bank compared to the inner bank, with a difference of about 1 m between C6 and C5 (Fig. 4.6). Conversely, proportions of sand were higher near the inner bank, making up more than 50% of the sediment compared to the sediment infill near the gravel base (Fig. 4.6, C6, C9, C3). There was no obvious cross-channel trend in the thickness of fine-grained deposits.

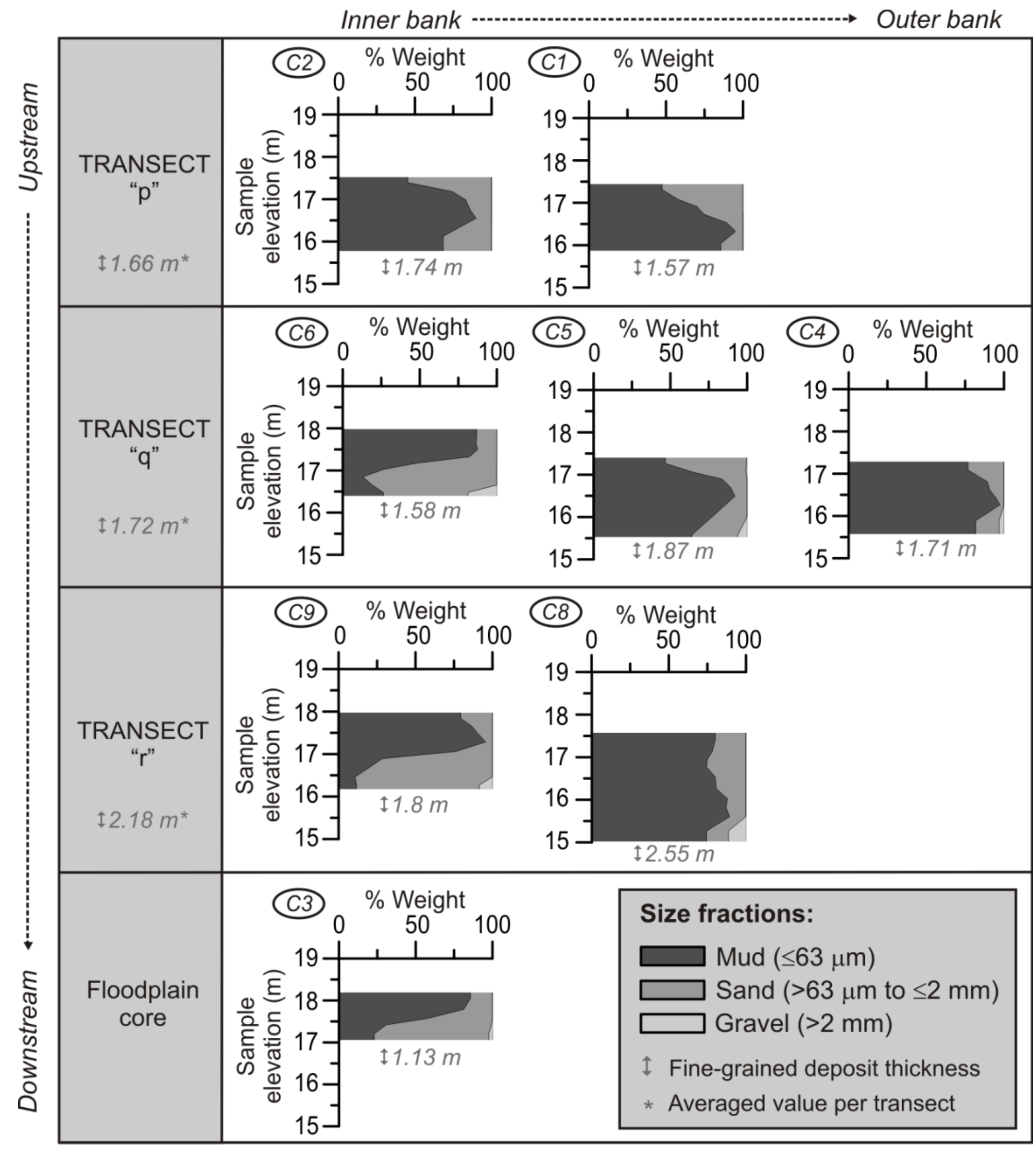

Figure 4.6: Grain size distribution and fine-grained deposit thickness at Lake CHU3. It was measured for seven auger flights from three transects located in the abandoned channel and one core from the nearby floodplain. The location references "Upstream-Downstream" and "Inner to Outer Bank" are showing the relative location of auger flights between one another.

4.4.2.5 Chute cutoff oxbow lake "CHU4"

Only six auger flights were sampled at Lake CHU4 due to the difficulty of field access. Its recent formation between 1999 and 2003 meant that much of the oxbow remained submerged by 1.5 m of water in 2010. Auger flights were thus only retrieved from along the inner and outer banks of the channel. Subsamples from the auger flights were difficult to obtain on occasion due to the liquefied nature of the near-surface deposits (e.g., Fig. 4.7 C5). Samples did not demonstrate any obvious patterns in the stream wise or cross-channel directions. Nonetheless, the proportion of sand relative to clay and silt was greater near the outer bank (Fig. 4.7, auger flights C4, C5, D6, D9).

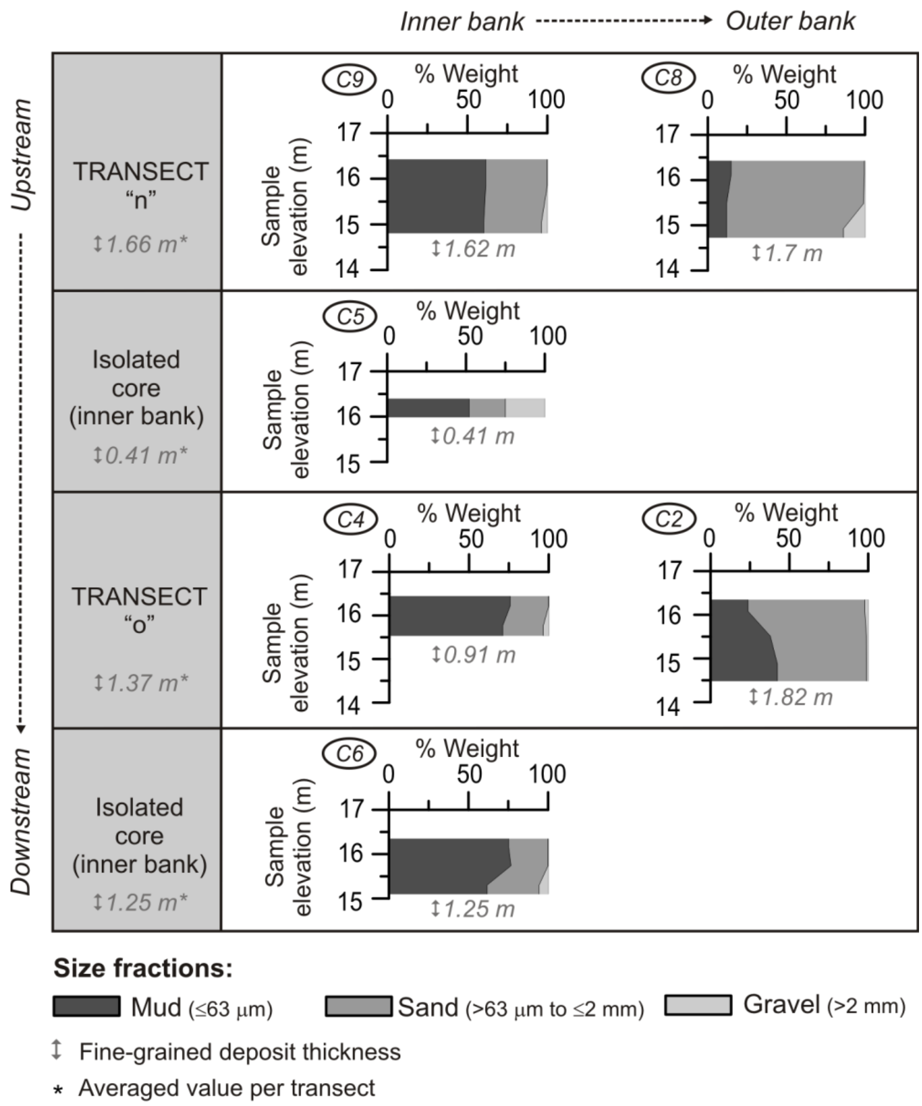

Figure 4.7: Grain size distribution and fine-grained deposit thickness at Lake CHU4. It was measured for six auger flights from four transects located in the abandoned channel. The location references "Upstream-Downstream" and "Inner to Outer Bank" are showing the relative location of auger flights between one another.

4.4.2.6 Neck cutoff oxbow lake "NECK"

Lake NECK was the longest (see Fig. 4.2c) and amongst the oldest sites, having formed some time between 1840 and 1885. Four transects and 11 auger flights were sampled at Lake NECK (Fig. 4.8). Longitudinally, deposits were thinner in the central part of the abandoned channel with a difference of 1.46 m in thickness between sediment from transect "k" and transect "m". Gravel depths decreased in the downstream direction, with differences between auger flights C2 and C11 of 1.26 m. Grain sizes fined upward within the upstream auger flights (Fig. 4.8, C1, C2 and C3), exhibiting uneven sorting in flights located near the apex (Fig. 4.8, C5 and C9), and coarsened upward in downstream flights (Fig. 4.8, C10, C11 and C12). The thickness of fine-grained deposits varied greatly in the cross-stream direction, though gravel depths were generally lower towards the outer bank (e.g., Fig. 4.8, C8 and C9). Sediment was coarser along the inner bank, however, and especially within the downstream auger flights. A pipe surrounded by a small concrete pier was noticed at the downstream end of the oxbow during the field campaign, suggesting that sediment could have been artificially redistributed in the area of transect “m” (Fig. 4.8). Grain size proportion tended to vary in the cross-stream direction with an increase in clay and silt content by up to 40% between the inner and the outer banks (Fig. 4.8, C7 and C9). Clay and silt proportion was generally high throughout all of the auger flights for this oxbow, representing between 50 and 100 % of the deposits.

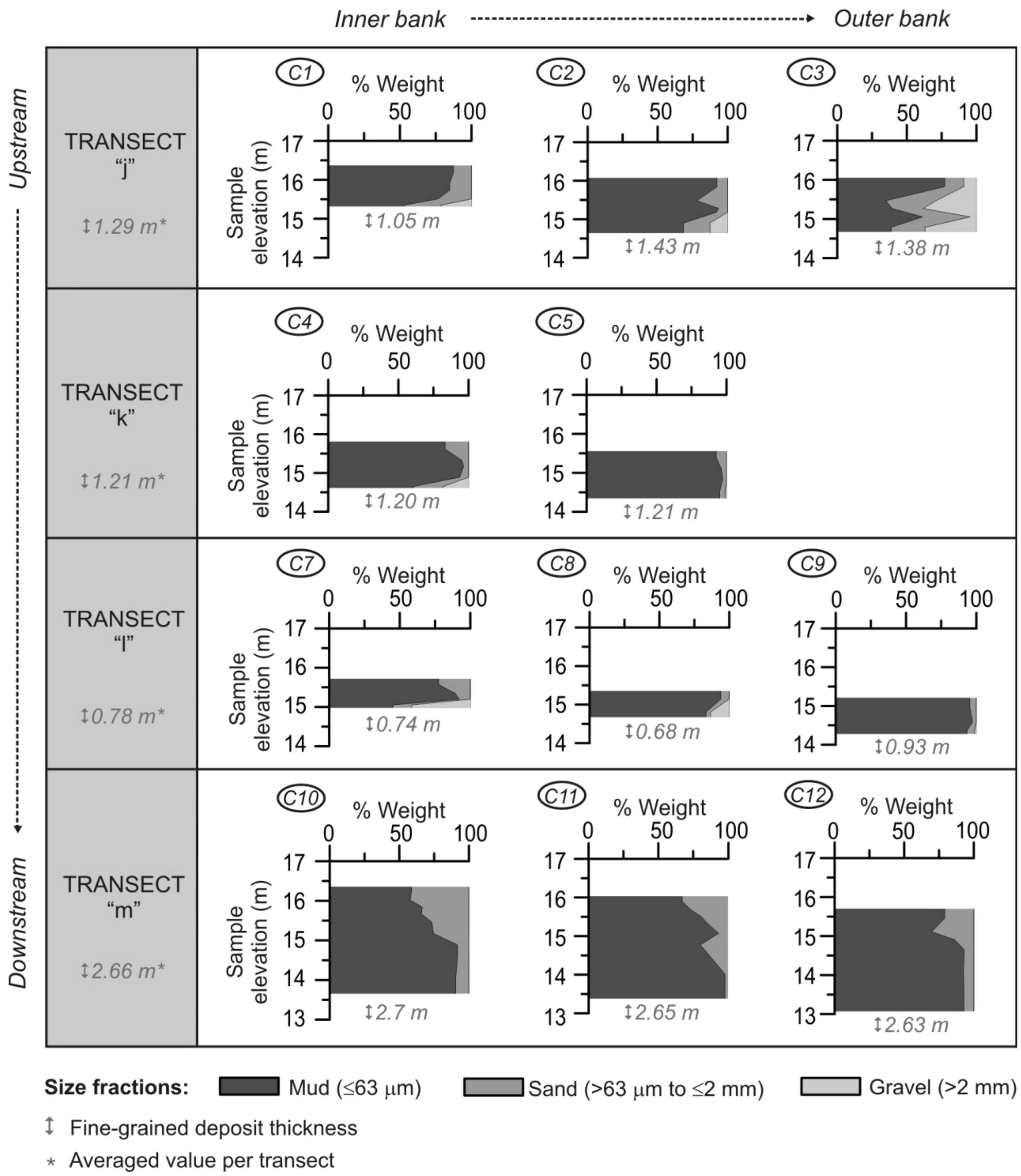

Figure 4.8: Grain size distribution and fine-grained deposit thickness at Lake NECK.
It was measured for 11 auger flights from 4 transects located in the abandoned channel. The location references "Upstream-Downstream" and "Inner to Outer Bank" are showing the relative location of auger flights between one another.

4.5 Discussion

4.5.1 Variations in fine-grained sedimentation: neck cutoff versus chute cutoff

Detailed analyses of sediment from the five abandoned channels of the River Towy highlighted a significant difference between neck and chute cutoff sites. Even though this study examined only a single neck cutoff site, the findings are consistent with the findings previously reported in the literature. As such, the neck cutoff site (Lake NECK) contained a thick layer of clay and silt that was more extensive than any of the chute cutoff sites (Fisk 1947; Allen 1965; Bridge et al. 1986; Hooke 1995). The average grain-size per core was also significantly different between all the chute cutoffs and the neck cutoff. However CHU2 and CHU3 sediments were also statistically different (Tab. 4.1, $p<0.05$) which could be due to several factors such as the different flood history (up to 80 years difference between the sites) or the fact that a part of the sites has been eroded. The average percentage of clay and silt in the auger flights from Lake NECK varied between 65 and 100 % and between 35 to 85 % in the chute cutoffs. Lake NECK was the only abandoned channel that had a large inundated area even though it was over a century old, consistent with conclusions from Chapter 2, which demonstrates that neck cutoff oxbows persist as aquatic habitat for substantially much longer than chute cutoff oxbows. This clear difference in sedimentation may be the result of a strong difference in gradient reported in Chapter 2. The Ratio of Length for neck cutoff oxbow lakes was much higher than in the case of chute cutoff meaning that the gradient in neck cutoff was much lower. This favours an initial deposition of sediment at the entrance of neck cutoff oxbows and rapidly isolates a large WSA. In contrast, the relatively high gradients in chute cutoff oxbows favours extended sediment infilling within the former channels. Fine-grained deposits in the chute cutoff were generally well sorted and fined both upward (66% of the auger flights) and downstream, as also reported by earlier work (e.g., Erskine et al. 1982; Bridge et al. 1986; Erskine et al. 1992; Citterio and Piegay 2009; Toonen et al. 2012). Conversely, these patterns were not observed in the Lake NECK. Results suggest that sedimentation occurs differently in oxbows formed by chute cutoff than those formed by neck cutoff.

4.5.2 Cutoff depositional processes

Differences in the four chute cutoff sites are difficult to explain, but may be due to each of them experiencing different flood histories as they were of significantly different ages. Lake CHU4 in particular, did not exhibit any fining upward trend like the other sites, possibly due to its very recent formation. This site was almost fully inundated and connected at the downstream end at the time of the study, which suggests that sediment could still be regularly mixed by flow currents. Nonetheless, the sedimentary composition and patterns observed at the five sites of the River Towy highlight the processes controlling sedimentation at different stages of oxbow evolution.

4.5.2.1 Cutoff Stage

During cutoff, discharge decreases progressively in the abandoned channel because of the combined effects of oxbow aggradation and the evolution of the newly incised channel, this diverts more flow as it enlarges with time. This should cause a decrease in sediment-transport capacity of the abandoned channel as flow competence decreases (Tiron et al. 2009). Coarser-grained sediment (e.g., bed material derived) should then gradually be deposited throughout the length of the oxbow as the diverted discharge is gradually reduced. This study did not allow to confidently determine whether the gravel encountered in the auger survey represented the original channel bed or the surface of aggraded bed material during the gradual closure of the oxbow. Nonetheless, the gravel surface of three of the study sites (CHU1-3) sloped in the downstream direction, suggesting that the surface did indeed represent post-cutoff deposits; a gravel ramp would not necessarily be seen otherwise. For example, the large difference in the gravel elevation recorded at Lake CHU1 revealed significant bed material deposition with up to 1.5 m difference in the elevation of the gravel surface between the upstream and downstream limbs (300 m long segment), comparable to the chute cutoff oxbows examined by Johnson and Paynter (1967) and Erskine et al. (1992). Moreover, this gradient in gravel is about 50‰, which is significantly higher than the valley slope in the area of about 0.5‰.

4.5.2.2 Plugging stage by bed material

The incision of the main channel creates a bifurcation that affects the conveyance of flow and sediment (Fisk 1947; Shields and Abt 1989; Constantine et al. 2010a). An area of low flow velocity caused by a flow separation within the entrance of bifurcated channels (Lindner 1953; Tiron et al. 2009; Constantine et al. 2010a) would restrict the diverted discharge. A separation zone was observed near the inner bank at the entrance of an oxbow in a hydrographic survey of Tiron et al. (2009). The width of this zone is controlled by the diversion angle (Chapter 1, Fig. 1.10): high diversion angles are associated with wide separation zones and reduce the diverted discharge (Constantine et al. 2010a). The low flow velocity associated with lower shear stress in the separation zone results in the accumulation of bed material in the entrance of the abandoned channel, eventually forming a plug (e.g., Gagliano and Howard 1984; Hooke 1995). Constantine et al. (2010a) suggested that the diversion angle and the flow separation zone controlled the rate and extent of coarse-grained sediment aggradation in the oxbow; the higher the diversion angle, the more rapid the aggradation at the entrance and the less extended the deposits. The sediment plug finally isolates the abandoned channel from further coarse sediment input (Fisk 1947; Erskine et al. 1992).

A gravel plug was observed at the upstream end of Lake NECK, with exclusively gravel deposits exposed at the surface along the first 10 m of the oxbow (Fig. 4.9). The upstream part of the abandoned channel was entirely filled by coarse-grained sediment, confined to the entrance of the abandoned channel and absent in the central part of the abandoned channel, similar to observations of Allen (1965) and Erskine et al. (1982). The pervasiveness of the observations may suggest the role of the separation zone near the entrance, which could cause a significant decrease in flow competence, which would promote deposition at the abandoned channel entrance (Constantine et al. 2010a). The diversion angle is about 120°±10 at this location, though there may be even greater uncertainty of this measure of the diversion angle given that channel migration partially eroded the ends of the oxbow. The upstream plug of the Lake NECK was probably created rapidly because bed material was restricted to the entrance, indicated by the mid-channel auger flights containing 50 to 100% of clay and silt. It is important to note, however, that the gravel surface within

Lake NECK exhibited a small gradient, which could be the result of gravel progradation from the upstream entrance to the downstream.

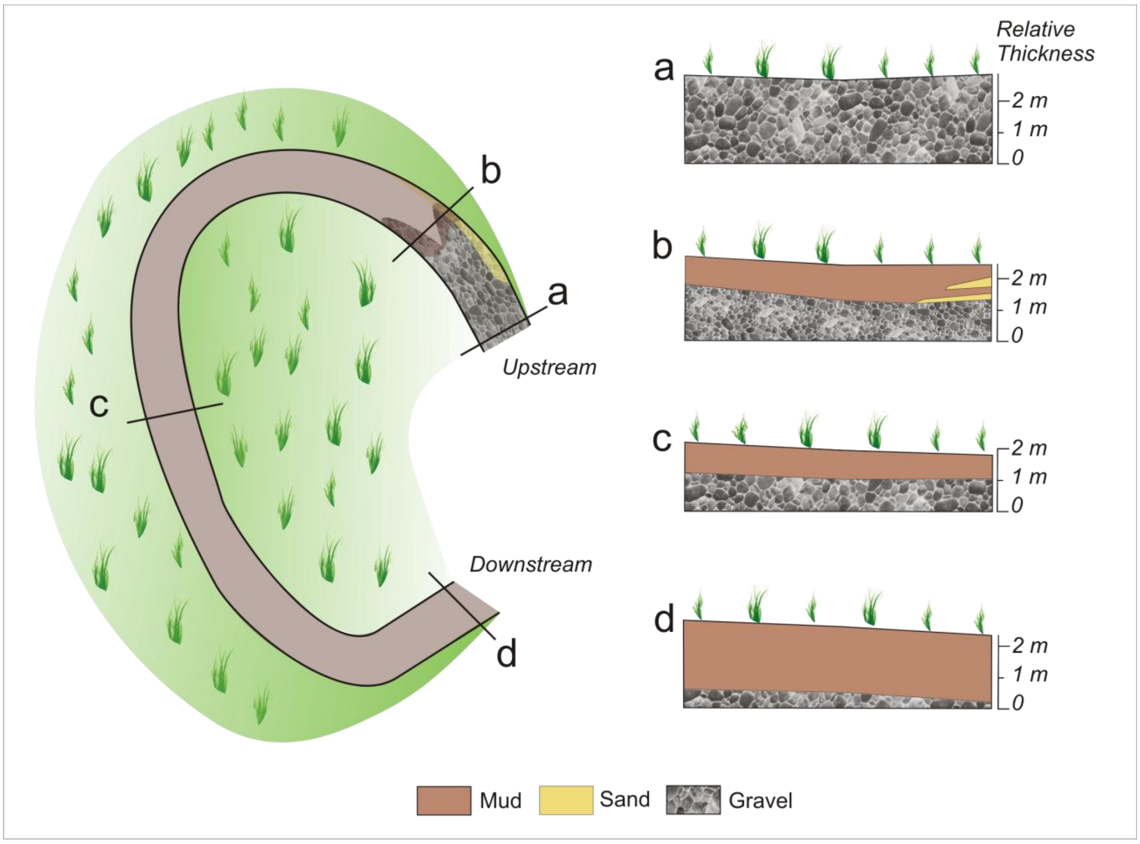

Figure 4.9: Interpretative scheme showing the sedimentary patterns of Lake Neck. A sky view of sedimentary patterns is presented on the left and cross sections are presented on the right. The cross sections showing the relative sediment thickness are based on Fig.4.9 and drawn from the same elevation for comparison purpose.

The chute cutoff oxbows of this study all had a diversion angle less than 90°, which should have favoured the maintenance of the diverted discharge and potentially aggradation of bed material throughout the length of the sites. The interpreted gravel ramp observed at the three chute cutoff sites suggests both that gravel thickness was higher at the upstream end and that an extensive plug was present (Fig. 4.10). Possibly complicating a generic interpretation of the sedimentary data, the recent channel (CHU4, Fig.4.8) did not contain a ramp, though the lack of extensive auger data could distort the findings presented here.

4.5.2.3 Fine-grained sedimentation stage

Once the upstream end of the abandoned channel is obstructed by a plug, direct bed material input is slowed and the oxbow will primarily fill by sediment transported during overbank flow events (e.g., Citterio and Piegay 2009). Sedimentation after plug formation is mostly fine-grained because the flow velocity through the oxbow would presumably be much slower, even during floods, as the shallower depth and surface roughness would sufficiently extract momentum from the floodwater. Further, only the wash- and suspended load would be diverted into the oxbow. The data from Lake NECK support this conceptual understanding, as plug formation converted much of the relatively unaltered channel-form into a large sink available for storing silt and clay. The lack of sediment sorting with depth suggests that the magnitude of flood velocities and flood suspended-sediment concentrations were relatively uniform throughout the history of the oxbow. Possibly due to floodwater being trapped in the lake during the receding flood discharge, suspended sediment appears to have been deposited by settling in quiescent conditions.

In the case of chute cutoff oxbows, the fine-grained infill showed trends both in the stream-wise (upstream to downstream end) and cross-stream directions (inner to outer bank) (Fig. 4.4-7), suggesting that continuous flow diversion occurred for a significant amount of time following cutoff, potentially providing the tractive force responsible for the infill patterns observed. Fine-grained sediment tended to fine downstream, which was also observed by Tiron et al. (2009) who demonstrated decreasing downstream flow velocities through the diversion. In CHU1, fine-grained sediment contained 75% of sand in the upstream limb compared to only 25-50% in the downstream limb (Fig. 4.4). CHU2 and CHU3 also demonstrated this pattern (Fig. 4.6-7), but the least amount of sand was found within the apex, suggesting that flow entered both the upstream and downstream entrances during floods, supplying sediment to both limbs. In addition, auger flights of the downstream half of most of the sites contained 50 to 75 % of clay and silt in relatively unchanging proportions (not fining upward or coarsening) near the outer bank (Fig 4.5,6,8, Lake CHU1, 2, and 4). The thickness of sediment deposits at the centreline appears to follow the former bed topography for two study sites (Fig. 4.2a,d), similarly observed by Citterio and Piegay (2009), who noted that this could result by decantation of particles across the bed. In Lakes CHU1 and CHU2, sediment deposits consisted of coarser sediment, but were thinner along the bar near the inner bank, with up to 1.1 m difference in thickness between the inner and outer banks. This pattern was also observed by Fisk (1947) and

Toonen et al. (2012) and could be caused by the effect of the former bend curvature and topography on the transverse transport of bed material, similar to depositional processes on the point bars of active channels (e.g., Dietrich and Smith 1983).

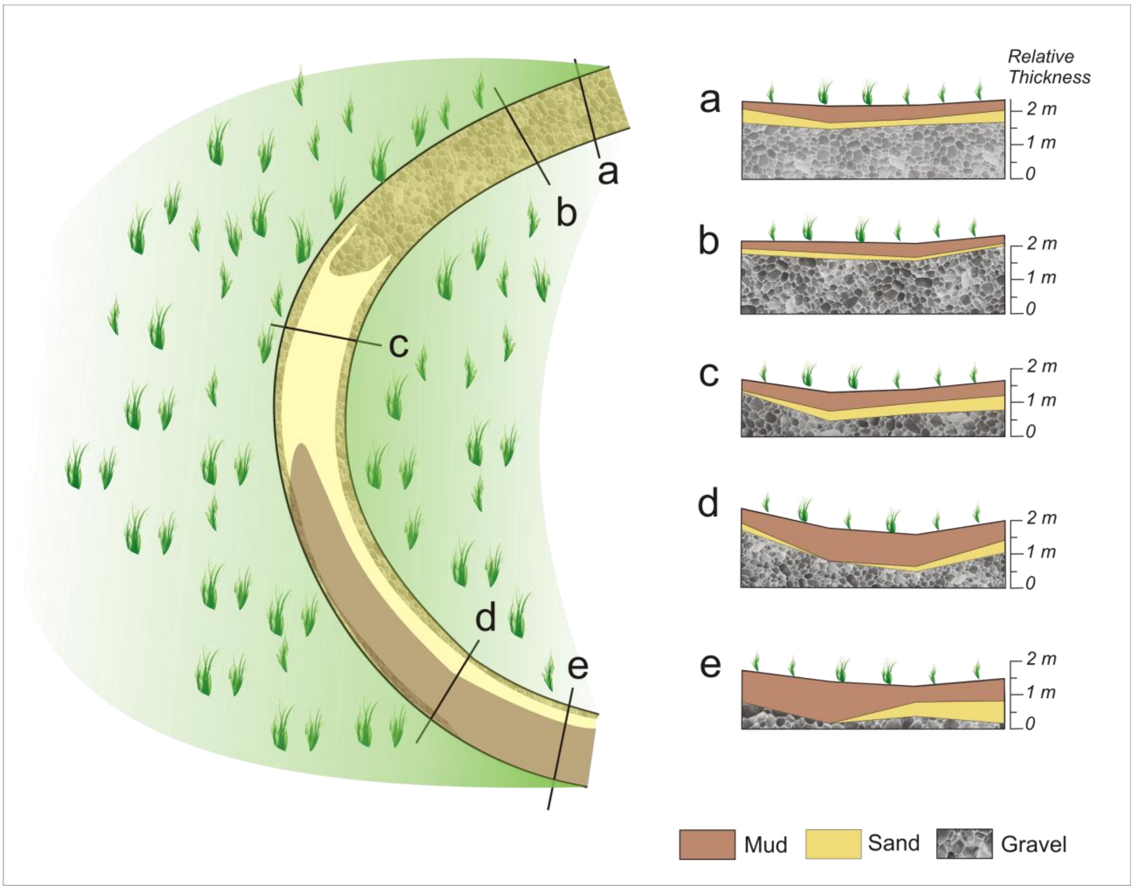

Figure 4.10: Interpretative scheme showing the sedimentary patterns of Lake CHU1. A sky view of sedimentary patterns is presented on the left and cross sections are presented on the right. The cross sections showing the relative sediment thickness are based on Fig.4.5 and drawn from the same elevation for comparison purpose.

4.6 Conclusion

The study of fine-grained sedimentation in five oxbow lakes of the River Towy provided essential evidence for the understanding of depositional processes in abandoned channels. Abandoned channel infilling appeared to be driven by at least four processes: (1) the effect of the flow separation zone, where the flow velocity is low, which creates a sediment plug within the entrance of all the study sites; (2) decreasing discharge through the abandoned channel as the deposition of bed material aggrades the riverbed, thus promoting the fining upward sequences observed in the chute cutoff sites; (3) the development of a gravel-bed ramp sloping in the downstream direction, which would cause a downstream fining of both bed material and potentially of suspended sediment delivered to the oxbow during floods; and (4) steady and uniformly occurring fine-grained sedimentation that occurs in both types of cutoffs in the later stages of evolution.

Deposits in the neck cutoff site were significantly different from those of chute cutoff sites. The neck cutoff oxbow was dominated by large volumes of fine-grained sediment (principally silt and clay) and was blocked by a distinct gravel plug. Conversely, the chute cutoff oxbows had coarser, better sorted, and more complex sedimentary structures. Even though more studies of the deposits of neck cutoff oxbows are needed, results from this chapter suggest that the sedimentary composition of abandoned channel deposits differs quite significantly depending on the cutoff mechanism responsible, creating unique zones within the alluvial architecture of the floodplain. Such a difference in granulometry and structure of sediment could have implications for meander migration rates and the hydrogeological characteristics of valley alluvium. A better sense of how the different types of oxbows evolve could be accomplished by repeated measurements of bathymetry and hydraulic conditions during and after cutoff, key data for any attempt to model the oxbow alluviation process.

Chapter 5

Conclusions

This thesis has presented a comprehensive study of oxbow lakes sedimentation and geomorphic evolution to date. Results notably revealed a major difference in the evolution and sedimentation of oxbow lakes depending on the mechanism of cutoff creation which has consequences for both the biodiversity and the channel dynamics of meandering rivers.

5.1 General Discussion

Former channels abandoned by meander cutoff progressively infill with sediment until complete terrestrialisation. The primary aim of this thesis was to provide a detailed understanding of the depositional patterns and processes of oxbow lakes during their lifespan. The four main hypotheses of this study will be discussed in the following sections.

5.1.1 Hypothesis 1: The cutoff mechanism controls long term oxbow lake infilling

The evolution of the oxbow lakes was first assessed by measuring the reduction in water surface area of 37 oxbow lakes using aerial photographs and maps from eight different rivers analysed using GIS. Oxbow lakes are created either through the migration of river meanders into one another (neck cutoff) or through erosion of a new channel across the floodplain (chute cutoff). These mechanisms both isolate a former meander which is quickly obstructed by sediment accumulation. Findings from this study illustrate that the specific mechanism by which an oxbow is formed is critical to its persistence as a lake, proving the initial hypothesis. As a result, oxbow lakes can persist for as little as a few years to as long as several centuries depending on their mechanism of creation. Within the first 10 years following cutoff, the water surface area of oxbow lakes created by chute cutoff reduced at least twice as fast than those created by neck cutoff. Comparisons of WSA decrease rates showed that the lake area lost every year was ten times wider for chute cutoff oxbows compared to neck cutoffs. This suggested that oxbow lakes created by chute cutoff are likely to lose 10% per year whereas the decrease rate of neck cutoff oxbows is on average 1% per year. About 100 years after cutoff, most chute cutoff oxbow lakes of the study were fully terrestrial whereas those created by neck cutoff exhibited 25 to 60% of their initial water surface area

The importance of sediment supply and load was previously suggested by several studies showing that the bed-load concentration and size had a strong influence on abandoned channel infilling (Shields and Abt 1989, Constantine et al. 2010a, Erskine et al. 1992). A variation in sediment supply could have influenced the results for the Towy River which showed an intermediate evolution at three sites. The relatively slow sedimentation in these chute cutoffs could reflect a lack in sediment supply in the Towy River during the former channel lifespan.

Sites from this study were located in areas of under dry and mild temperate climate and did not include temperate rivers that could show different patterns due to different hydrology. The range of sinuosity (1.06 to 1.7) and slope (0.14 to 2.6‰) were also relatively narrow which may limit extrapolation to other meandering rivers. Gautier et al. (2007) studied the first 14 years of evolution of the water surface area of neck cutoff oxbow lakes of the tropical river Rio Beni (Bolivia). This river was actively migrating, exhibits a low slope (0.1 to 0.07‰) and a high sinuosity (1.6 to 2.5). They found that the WSA decreased very slowly for 65% of the site which is similar to the neck cutoff oxbows of this study. However, 10% of the sites were almost completely infilled with sediment during the same period, similarly to the chute cutoffs of this study. This suggests that oxbow lakes of tropical rivers may have a different evolution or that there were too few neck cutoffs to exhibit a wide range of evolutions.

5.1.2 Hypothesis 2: The slope difference between former and current channel, the diversion angle and the meander size control the evolution of oxbow lakes

Parameters related to oxbow lake geometry appear to affect the reduction of the lake. The diversion angle, between the upstream end of the former channel and the main channel, as well as the oxbow lake slope showed a good correlation with the rate of decrease of the water surface area. Lakes with higher diversion angle or lower slope took longer to reduce than other lakes. Lower diversion angles probably facilitated flow and sediment transfers within the former channel after cutoff and therefore led to a rapid reduction of the lake. Similarly, a steep slope for the lake bed tends to ease extensive sediment transfers and would cause rapid terrestrialisation. Therefore the initial hypothesis is proven for these two parameters even though their distinct role remains unclear since they appear to be related parameters, at least for chute cutoffs. Therefore the specific physical control of each parameter on oxbow lake terrestrialisation has yet to be analysed. Furthermore, data did not exhibit a significant relationship between oxbow lake size (length) and water surface area reduction, disproving the hypothesis. This is due to the fact that oxbow lakes size is linked to main channel dimension and consequently an oxbow lake may naturally receive large volumes of sediment if it was created by a big river.

5.1.3 Hypothesis 3: Former channels are not significant bed material sinks compared to transfers in the active channel

Depositional processes and the importance of sediment transfers associated with oxbow lake infilling was assessed using two complementary field surveys of oxbow lakes on the Ain River (France) and the Towy River (Wales). Two closely located oxbow lakes of the Ain River cut-off within a decade before this study and were investigated to measure the volume and location of the initial sediment transfers after cutoff. The infilling of abandoned meanders occurs mostly by bed-load transfers until the entrance of the oxbow lake is isolated by sediment accumulation. That stage was monitored on the Ain River sites using topographic measurements (cross sections, profiles and general mapping) and LiDAR data for several consecutive years. Five oxbow lakes of the Towy River which cut-off between 1863 (±23y) and 2001 (±2y) were studied to analyse the long term sedimentation of former channels. Findings from my surveys of the Ain River oxbow lakes revealed that the initial bed-load transfers (gravel here) in oxbow lakes can be significant with the equivalent of 34% and 17% of the river supply deposited in the studied sites, proving the hypothesis. Consequently, oxbow lakes are not necessarily only fine-grained sediment sinks, as often referred to, but can also store large volumes of coarser material. Nevertheless, the calculated volumes of sediment transferred due to the incision of the new channels were much greater than the volumes deposited in the former channels. The volume of bed material transferred by channel incision was equal to 15,250 m^3 y^{-1} which is greater than the bed material supply rate to the reach (14,000 m^3 y^{-1}). In addition, up to 41% of the sediment eroded from the incision of the upstream new channel deposited on the point bar immediately downstream. Oxbow lakes can also rapidly become a source of bed material after cutoff since about 2,300 m^3 of sediment was removed from the upstream end, showing the dualistic role of oxbow lakes of both sources and sinks for sediment. This study also showed that initial bed material infilling occurred differently at the two sites. One (*MOL* site) had extensive bed material deposition which progressively narrowed the former channel until the upstream end was blocked whereas the other site (*MAR*) was obstructed mostly by the growth of a pre-existing point bar upstream, forming a plug. The lower diversion angle of the first site may have facilitated extensive bed material infilling although more study sites would be needed to confirm this hypothesis.

5.1.4 Hypothesis 4: Long-term oxbow lake alluviation is driven by several processes and multidimensional flow patterns

Long-term depositional patterns analysed from oxbow lakes sediment of the Towy River showed very different structures depending on the cutoff mechanism. The neck cutoff oxbow lake studied exhibits a much extended central lens of suspended sediment composed mostly of mud and clay and little to no grain size sorting with depth for most cores. The size fraction of sediment in all the chute cutoff oxbows was also estimated to be significantly different from the neck cutoff (NECK). The neck cutoff oxbow lake also showed a sharp change in sediment composition at the upstream end with very coarse bed material deposits made of gravel positioned next to the fine-grained sediment lens (Fig. 5.1). The fact that this site formed by neck cutoff probably led to a high diversion angle which created a large flow separation zone and caused the accumulation of large volumes of gravel at the entrance of the former channel. The gravel plug efficiently isolated the oxbow lake which then filled up exclusively with fine-grained sediment as shown by the large clay and silt deposits. This last infilling process was observed to be slow and has caused a wide lake to remain on the site for over a century. These findings from field surveys on the Towy River (Chapter 4) are consistent with the evolution of the water surface area observed at 37 sites (Chapter 2).

Sediment in the four chute cutoff oxbow lakes was generally coarser than the neck cutoff but also demonstrated some patterns in grain size sorting both stream-wise (upstream to downstream) and cross-stream (bank to bank). This suggests more complex interaction between flow and sediment in chute oxbow lakes. Abandoned channel infilling was driven by several processes. The smaller flow separation zone favoured extensive coarse-grained deposits further within the former channel with a long gravel ramp and also the presence of sand at the apex (Fig 5.1). Stream-wise flow gradients and a general decreasing discharge caused the sediment to be sorted and fine upward as well as toward the downstream end. Finally, a silt-and clay lens near the apex and where the former channel pool used to be suggests that decantation and sediment in calm flow condition occurred. These various sedimentary processes observed on the Towy River (Chapter 4) are consistent with the non-linear evolution of chute cutoff oxbow lakes shown in Chapter 2 and also suggested by Gautier et al. (2007). The log-shaped evolution of the water surface area probably reflects the succession of sedimentary processes including a rapid decrease of the WSA during the first 5-10 years whilst gravel accumulates, followed by a slower decrease as the channel becomes obstructed and finally a very slow infilling depending on silt and clay decantation.

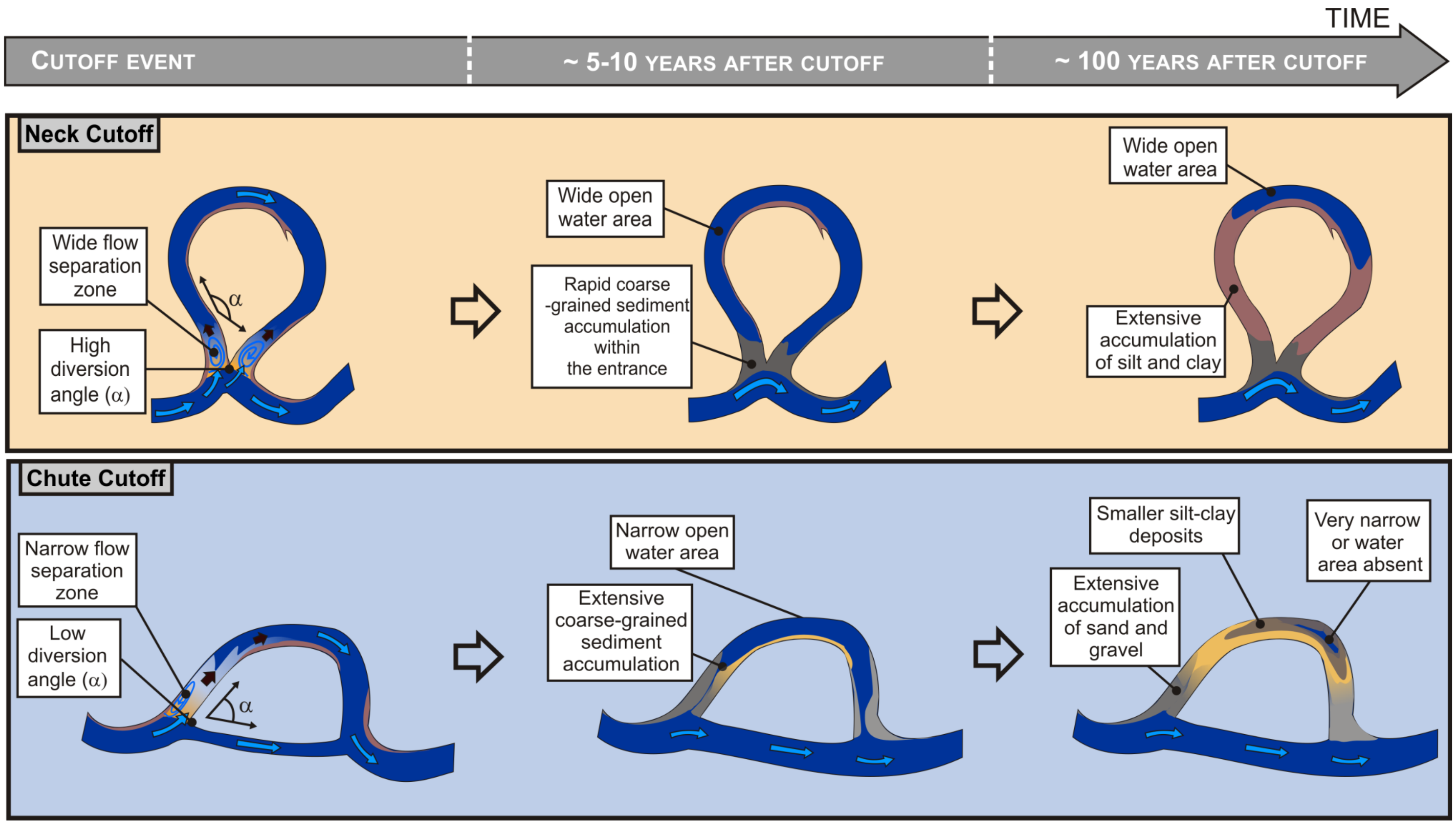

Figure 5.1: Schematic representation of the geomorphic evolution of oxbow lakes based on the type of cutoff.

5.2 Significance

5.2.1 Overview

This study addressed the critical issues of oxbow lake persistence as aquatic habitats and depositional processes involved in their terrestrialisation. Sediment transfers associated with meander cutoffs have received relatively little research attention probably because they occur at short timescale like most geomorphic processes. Meander cutoffs are not easy to predict, especially since chute channel incised in the floodplain can take over a decade to become the main conveyor of the discharge or the cutoff may never occur in some cases. Cutoff can also take place suddenly after, for example, a flood of important magnitude. Lastly, significant geomorphic changes can take place at the timescale of few months in former channels which make their monitoring difficult. This study provided a comprehensive research about oxbow lakes depositional processes at various timescales, from the annual changes within the first decade after cutoff until long-term evolution during at least a century. Results allow discriminating between the importance of the cutoff mechanism for both oxbow lake longevity and sedimentation processes which is significant as well as useful to river managers, geomorphologists and ecologists.

5.2.2 Ecological implications

Findings from this study about the control by cutoff mechanism on the persistence of the oxbow lake as an aquatic habitat have important implications for floodplain ecology. The fact that chute cutoffs create short-term lakes compared to neck cutoffs affects aquatic habitats on meandering floodplains. River channel creating dominantly neck cutoffs are likely to provide long-term habitats for fauna and flora and durably support biodiversity by offering water bodies for over a century. The aquatic environment provided by oxbow lakes offers notably remote environments key to the development of fish species (e.g., Twaite Shads, Slamons). Varying physical conditions such as varying depth, substrate composition and regular flooding are essential to floral diversity. The sedimentary composition of chute cutoff oxbow lakes varies between mud (silt and clay), sand and gravel, which offers a larger variety of habitats in relatively small areas. Conversely, neck cutoffs are wider and last longer, but have a substrate composed of mud only and consequently provide a less diverse range of environments. The knowledge of the persistence of a water body on the floodplain as well as the soil composition of infilled former channels based on the cutoff mechanism also has implications for land use. For example, the prediction of the longevity of a water body on pasture land is useful information for farmers. Additionally, the difference in soil composition of former channels is of interest for better managing cultivated lands and choosing the most adapted crops.

Neck cutoff oxbow lakes are likely to provide the most durable habitats. This is very relevant in situations when river channels have evolved from neck cutoff dominated to chute cutoff dominated due to human pressure and change in land use such as the Sacramento River Valley. The drastic straightening of the Sacramento River changed the dominant mechanism of formation of oxbow lakes and is now only creating chute cutoff oxbow lakes which are short-lasting habitats. According to the findings of this study, oxbow lake slope and diversion angle control the infilling of chute cutoffs, such as those on the Sacramento River nowadays. Being able to predict the longevity of oxbow lake from their mechanism and their geometry provides useful information to river managers and scientists to evaluate the quality of habitats of meandering rivers, to anticipate the consequence of channel style change on biodiversity and, finally, to better restore river corridors.

5.2.3 Significance for fluvial geomorphology

Oxbow lakes are widespread features of meandering floodplain therefore a detailed understanding of the sediment transfers associated with meander cutoff as well as the complete analyses of oxbow lake depositional processes during their lifespan is very important to understand both past floodplain architecture and present channel dynamics. Results presented in this study highlighted that former channels can be significant bed-load stores in case of chute cutoff and also source since this material can be eroded and transferred to the main channel only within a few years. It is known that cutoff affect channel dynamics by reducing sinuosity and transferring large volume of sediment downstream. Measurements from this study suggest that sediment eroded by channel incision are redeposited in large volume on the bars directly downstream the cutoff which probably caused an acceleration in channel migration opposite these bars. The abandonment of channels can consequently have two antagonistic effects of reducing and increasing the amplitude of meanders. This study also showed a strong difference in oxbow lakes sediments depending on the cutoff mechanism, with neck cutoffs generally forming extensive fine-grained sediment lenses, whereas chute cutoff infill with a much larger proportion of bed-load and coarser-grained sediment than neck cutoff. The tendency for pollutants, such as heavy metals, to adsorb on fine-grained particles suggests that neck-cutoff oxbow lakes constitute better stores for contaminants in polluted rivers. Moreover, the difference in sediment composition should affect the dynamics of rivers eroding past former channels deposits. The large deposits of coarse-grained sediment in the chute cutoff oxbow lakes analysed on the Towy and the Ain Rivers may create a weaker obstacle to channel migration than the large, cohesive, mud and clay lenses in neck cutoffs. For these reasons, this study provides new and important information for the understanding of the fluvial dynamics and architecture of meandering rivers.

5.3 Future work and perspectives

This research highlighted the influence of at least two geometrical parameters on the evolution of oxbow lakes: oxbow slope and diversion angle. Future work should focus on providing a mechanistic explanation and evidences on the distinct effect of each of these parameters on lakes' longevity in the long term. This could be achieved using numerical models integrating flow and sediment transport. With this knowledge, it should be possible to inform and produce models enabling the prediction of oxbow lake lifespan according to their initial geometry.

The sediment deposits structure and composition in oxbow lakes vary significantly depending on the type of cutoff according to this study and could therefore affect future channel migration. In order to evaluate the effect of oxbow lake deposits on channel migration, further research should focus on the consequence of floodplain deposits on river migration. For instance, using flume modelling and in situ surveys it would be interesting to quantify the changes bank erodibility and channel migration rate caused by former channel deposits to assess their effect on fluvial dynamics.

Oxbow lakes offer various aquatic habitats for many species and the persistence of these habitats relies on their terrestrialisation. However, it is not yet known how, for example, aquatic vegetation communities may respond to progressive terrestrialisation or how exactly their habitats differ between chute and neck cutoff oxbow lakes. In order to provide a comprehensive study of oxbow lakes habitats, a long term survey of the evolution of flora and fauna oxbow lakes with time should be conducted as some sites infill with sediment.

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Appendices

Appendix 1

GIS measurements

Table A1.1: Oxbow lakes parameters in Chapter 2. Part ½

River	Lake ID	Oxbow initial length (m)	New channel length (m)	Oxbow length ratio	Diversion angle (degrees)	Time to plug (y)	Transition time for the WSA (y)
Sacramento River	rm178	1190	563	2.11	30	3	14
Sacramento	rm179B	1659	818	2.03	30	4	9
Sacramento	rm166	652	492	1.33	50	4	9
Sacramento	rm219	1334	936	1.43	60	4.5	14.0
Sacramento	rm203	3360	1198	2.80	90	2.5	17
Sacramento	rm184N	1566	1334	1.17	20	4.5	13
Sacramento	rm169	1596	1052	1.52	35	2.5	7
Sacramento	rm213	4244	1330	3.19	40	8.5	19
Sacramento	rm214	1028	804	1.28	25	11	20
Sacramento	rm191	2944	748	3.94	55	10	25
Sacramento	rm174	1932	1167	1.66	80	13	24
Sacramento	rm202	1470	1070	1.37	55	4.5	
Sacramento	rm165	2290	675	3.39	80		
Ain River	BRO	1647	828	1.99	90	5.5	
Ain River	HYE	1697	1112	1.53	55	4.5	16
Ain River	M71	580	471	1.23	70	8.5	9
Ain River	PLA	2115	946	2.24	65	4.5	8
Ain River	M54	1145	956	1.20	30	4.5	6
Ain River	MOL	1310	1081	1.21	20	1	9
Towy River	CH1	510	349	1.46	80		
Towy River	CH2	350	282	1.24	50		
Towy River	NECK	1497	209	7.16	120		
Towy River	CH3	402	97	4.14	90		
Towy River	CH4	455	187	2.43	70		
Mississippi River	EAGL	21400	1400	15.29	120		
Mississippi	YUCA	16500	2400	6.88	100		
Mississippi	MARY	23000	2750	8.36	140		
Mississippi	FERG	16670	2310	7.22	160		
Mississippi	MARE	24200	4250	5.69	110		
Mississippi	LEE	19000	2500	7.60	140		
Pelican River	PEL3	206	17	12.12	150		
Pelican	PEL2	133	31.2	4.26	120		
Pelican	PEL1	206	23	8.96	140		
Red River of the North	RED1	874	85	10.28	130		
Red River	RED2	1184	101	11.72	130		
Smoky Hill River	SMO	1542	150	10.28	120		
Kansas River	KAN	3875	1460	2.65	80		

Table A1.2: Oxbow lakes parameters in Chapter 2. Part 2/2

River	Lake ID	Time to -25% of WSA (y)	Decrease rate until -25% of WSA (% per year)	Time to -50% of WSA (y)	Decrease rate until -50% of WSA (% per year)	Time to -75% of WSA (y)	Decrease rate until -75% (% per year)
Sacramento River	rm178	1	25.0	2	25.0	5	15.0
Sacramento	rm179B					6	12.5
Sacramento	rm166	2	12.5	4	12.5	6	12.5
Sacramento	rm219	2	12.5	3	16.7	6	12.5
Sacramento	rm203	1	25.0	2	25.0	7	10.7
Sacramento	rm184N	2	12.5	4	12.5	12	6.3
Sacramento	rm169			2	25.0	7	10.7
Sacramento	rm213	4	6.3	9	5.6	13	5.8
Sacramento	rm214	7	3.6	12	4.2	15	5.0
Sacramento	rm191	5	5.0	10	5.0	15	5.0
Sacramento	rm174	3	8.3	11	4.5	16	4.7
Sacramento	rm202	1	25.0	6	8.3	10	7.5
Sacramento	rm165	36	0.7	120	0.4		
Ain River	BRO	3	8.3	6	8.3	11	6.8
Ain River	HYE	3	8.3	6	8.3	10	7.5
Ain River	M71	4	6.3	7	7.1	11	6.8
Ain River	PLA	1	25.0	1	50.0	12	6.3
Ain River	M54	3	8.3	7	7.1	15	5.0
Ain River	MOL	2	12.5	4	12.5	7	10.7
Towy River	CH1	10	2.5	19	2.6	45	1.7
Towy River	CH2	3	8.3	9	5.6	42	1.8
Towy River	NECK	30	0.8	47	1.1	83	0.9
Towy River	CH3	6	4.2				
Towy River	CH4	19	1.3	32	1.6	43	1.7
Mississippi River	EAGL	39	0.6	78	0.6	117	0.6
Mississippi	YUCA	28	0.9	56	0.9		
Mississippi	MARY	73	0.3	146	0.3	220	0.3
Mississippi	FERG	22	1.1	44	1.1	66	1.1
Mississippi	MARE	41	0.6	78	0.6		
Mississippi	LEE	75	0.3	148	0.3		
Pelican River	PEL3	11	2.3				
Pelican	PEL2	7	3.6	16	3.1		
Pelican	PEL1	9	2.8				
Red River of the North	RED1	6	4.2				
Red River	RED2						
Smoky Hill River	SMO						
Kansas River	KAN	2	12.5	6	8.3	8	9.4

Table A1.3: Discharge in the main channel and water surface area at MAR oxbow lake when the photograph was taken (data used in Chapter 2).

Note that the discharge at the dates marked with an "" are average daily discharge whereas others are discharge measured within an hour before the photograph was taken*

Date of the Aerial Photograph	**Discharge (m^3/s)**	**Water Surface Area (m^2)**
19/04/2010	40.6	43192
27/04/2010	37.3	42714
24/05/2010	24.4	40860
04/06/2010	34.1	42341
23/06/2010	23.8	40841
07/072010	16.9	41418
26/07/2010	14.8	40164
07/08/2010	61.1	42851
24/08/2010	73.7	43995
06/09/2010	67.2	43134
29/07/2009 *	17.6	41541
02/08/2008 *	33.0	47189
08/01/2005 *	71.9	67789

Table A1.4: Water Surface Area evolution over time (data used in Chapter 2).

River Name	Lake ID	Cutoff date	Year of measure of WSA	Water Surface Area (m^2)	Time since cutoff (y)	% of initial area remaining
Sacramento	rm169	1971.5	1972	153056	0	100.0
Sacramento	rm169	1971.5	1974	43611	2.5	28.5
Sacramento	rm169	1971.5	1978	42301	6.5	27.6
Sacramento	rm169	1971.5	1980	25711	8.5	16.8
Sacramento	rm169	1971.5	1986	25354	14.5	16.6
Sacramento	rm169	1971.5	1988	24276	16.5	15.9
Sacramento	rm169	1971.5	1993	14419	21.5	9.4
Sacramento	rm169	1971.5	1995	19920	23.5	13.0
Sacramento	rm169	1971.5	1997	20104	25.5	13.1
Sacramento	rm169	1971.5	1998	27473	26.5	17.9
Sacramento	rm169	1971.5	1999	24542	27.5	16.0
Sacramento	rm169	1971.5	2004	25293	32.5	16.5
Sacramento	rm169	1971.5	2005	26147	33.5	17.1
Sacramento	rm169	1971.5	2006	20312	34.5	13.3
Sacramento	rm169	1971.5	2007	25918	35.5	16.9
Sacramento	rm178	1983	1983	134852	0	100.0
Sacramento	rm178	1983	1986	45248	3	33.6
Sacramento	rm178	1983	1988	34403	5	25.5
Sacramento	rm178	1983	1990	23422	7	17.4
Sacramento	rm178	1983	1993	29749	10	22.1
Sacramento	rm178	1983	1994	14335	11	10.6
Sacramento	rm178	1983	1995	27405	12	20.3
Sacramento	rm178	1983	1997	23995	14	17.8
Sacramento	rm178	1983	1998	24503	15	18.2
Sacramento	rm178	1983	1999	22607	16	16.8
Sacramento	rm178	1983	2004	7634	21	5.7
Sacramento	rm178	1983	2005	10091	22	7.5
Sacramento	rm178	1983	2006	6181	23	4.6
Sacramento	rm178	1983	2007	11666	24	8.7
Sacramento	rm179	1957	1957	208789	0	100.0
Sacramento	rm179	1957	1958	183620	1	87.9
Sacramento	rm179	1957	1964	28216	7	13.5
Sacramento	rm179	1957	1969	16211	12	7.8
Sacramento	rm179	1957	1974	14552	17	7.0
Sacramento	rm179	1957	1978	24491	21	11.7
Sacramento	rm179	1957	1980	10951	23	5.2
Sacramento	rm179	1957	1986	18550	29	8.9
Sacramento	rm179	1957	1988	6608	31	3.2
Sacramento	rm179	1957	1990	18355	33	8.8
Sacramento	rm179	1957	1993	7973	36	3.8
Sacramento	rm179	1957	1994	3326	37	1.6
Sacramento	rm179	1957	1995	3038	38	1.5
Sacramento	rm179	1957	1997	2069	40	1.0
Sacramento	rm179	1957	1999	699	42	0.3
Sacramento	rm179	1957	2004	1711	47	0.8
Sacramento	rm179	1957	2005	14192	48	6.8
Sacramento	rm179	1957	2006	4903	49	2.3
Sacramento	rm179	1957	2007	0	50	0.0
Sacramento	rm184	1942.5	1943	133942	0	100.0
Sacramento	rm184	1942.5	1947	48453	5	36.2
Sacramento	rm184	1942.5	1964	12366	22	9.2
Sacramento	rm184	1942.5	1969	9662	27	7.2
Sacramento	rm184	1942.5	1974	7545	31.5	5.6

River Name	Lake ID	Cutoff date	Year of measure of WSA	Water Surface Area (m^2)	Time since cutoff (y)	% of initial area remaining
Sacramento	rm184	1942.5	1978	6019	35.5	4.5
Sacramento	rm184	1942.5	1980	6523	37.5	4.9
Sacramento	rm184	1942.5	1986	5825	43.5	4.3
Sacramento	rm184	1942.5	1988	2675	45.5	2.0
Sacramento	rm184	1942.5	1990	3701	47.5	2.8
Sacramento	rm184	1942.5	1993	4120	50.5	3.1
Sacramento	rm184	1942.5	1995	2467	52.5	1.8
Sacramento	rm184	1942.5	1997	3901	54.5	2.9
Sacramento	rm184	1942.5	1998	3632	55.5	2.7
Sacramento	rm184	1942.5	1999	3888	56.5	2.9
Sacramento	rm184	1942.5	2004	4330	61.5	3.2
Sacramento	rm184	1942.5	2006	4754	63.5	3.5
Sacramento	rm184	1942.5	2007	559	64.5	0.4
Sacramento	rm213	1971.5	1972	418590	0	100.0
Sacramento	rm213	1971.5	1986	77641	14.5	18.5
Sacramento	rm213	1971.5	1988	87533	16.5	20.9
Sacramento	rm213	1971.5	1990	56440	18.5	13.5
Sacramento	rm213	1971.5	1993	27316	21.5	6.5
Sacramento	rm213	1971.5	1994	15513	22.5	3.7
Sacramento	rm213	1971.5	1997	17512	25.5	4.2
Sacramento	rm213	1971.5	1998	8020	26.5	1.9
Sacramento	rm213	1971.5	1999	8294	27.5	2.0
Sacramento	rm213	1971.5	2005	21159	33.5	5.1
Sacramento	rm213	1971.5	2006	8098	34.5	1.9
Sacramento	rm213	1971.5	2007	8964	35.5	2.1
Sacramento	rm219	1951.5	1952	92172	0	100.0
Sacramento	rm219	1951.5	1956	31849	5	34.6
Sacramento	rm219	1951.5	1958	17989	7	19.5
Sacramento	rm219	1951.5	1974	6432	22.5	7.0
Sacramento	rm219	1951.5	1986	2187	34.5	2.4
Sacramento	rm219	1951.5	1988	1557	36.5	1.7
Sacramento	rm219	1951.5	1998	1038	46.5	1.1
Sacramento	rm219	1951.5	1999	862	47.5	0.9
Sacramento	rm219	1951.5	2004	0	52.5	0.0
Sacramento	rm203	1971.5	1972	451346	0	100.0
Sacramento	rm203	1971.5	1974	158786	2.5	35.2
Sacramento	rm203	1971.5	1978	115573	6.5	25.6
Sacramento	rm203	1971.5	1986	42095	14.5	9.3
Sacramento	rm203	1971.5	1988	23313	16.5	5.2
Sacramento	rm203	1971.5	1990	22121	18.5	4.9
Sacramento	rm203	1971.5	1994	20797	22.5	4.6
Sacramento	rm203	1971.5	1997	22438	25.5	5.0
Sacramento	rm203	1971.5	1998	17706	26.5	3.9
Sacramento	rm203	1971.5	2004	28253	32.5	6.3
Sacramento	rm203	1971.5	2005	20780	33.5	4.6
Sacramento	rm203	1971.5	2006	23285	34.5	5.2
Sacramento	rm203	1971.5	2007	18246	35.5	4.0
Sacramento	rm202	1997.5	1998	102651	0	100.0
Sacramento	rm202	1997.5	1999	58447	1.5	56.9
Sacramento	rm202	1997.5	2004	51190	6.5	49.9
Sacramento	rm202	1997.5	2005	35204	7.5	34.3
Sacramento	rm202	1997.5	2006	31300	8.5	30.5
Sacramento	rm202	1997.5	2007	27483	9.5	26.8
Sacramento	rm166	1957	1957	64118	0	100.0
Sacramento	rm166	1957	1964	8418	7	13.1

River Name	Lake ID	Cutoff date	Year of measure of WSA	Water Surface Area (m^2)	Time since cutoff (y)	% of initial area remaining
Sacramento	rm166	1957	1969	6234	12	9.7
Sacramento	rm166	1957	1974	4229	17	6.6
Sacramento	rm166	1957	1978	2762	21	4.3
Sacramento	rm166	1957	1980	1027	23	1.6
Sacramento	rm174	1983	1983	279177	0	100.0
Sacramento	rm174	1983	1986	197343	3	70.7
Sacramento	rm174	1983	1988	176781	5	63.3
Sacramento	rm174	1983	1990	171700	7	61.5
Sacramento	rm174	1983	1994	141188	11	50.6
Sacramento	rm174	1983	1999	65452	16	23.4
Sacramento	rm174	1983	2003	41445	20	14.8
Sacramento	rm174	1983	2005	23150	22	8.3
Sacramento	rm174	1983	2006	9127	23	3.3
Sacramento	rm174	1983	2009	4218	26	1.5
Sacramento	rm191	1942.5	1943	156132	0	100.0
Sacramento	rm191	1942.5	1958	32877	15.5	21.1
Sacramento	rm191	1942.5	1978	3509	35.5	2.2
Sacramento	rm191	1942.5	1980	3120	37.5	2.0
Sacramento	rm191	1942.5	1993	2276	50.5	1.5
Sacramento	rm214	1958	1958	128564	0	100.0
Sacramento	rm214	1958	1969	77917	11	60.6
Sacramento	rm214	1958	1974	20982	16	16.3
Sacramento	rm214	1958	1986	5547	28	4.3
Sacramento	rm214	1958	1988	5986	30	4.7
Sacramento	rm214	1958	1990	4253	32	3.3
Sacramento	rm165	1872.5	1873	439326	0	100.0
Sacramento	rm165	1872.5	1938	241571	65.5	55.0
Sacramento	rm165	1872.5	1986	233358	113.5	53.1
Sacramento	rm165	1872.5	1988	222407	115.5	50.6
Sacramento	rm165	1872.5	1993	219102	120.5	49.9
Sacramento	rm165	1872.5	1999	242748	126.5	55.3
Ain	BRO	1959.5	1960	95983.6	0	100.0
Ain	BRO	1959.5	1965	49900	5.5	52.0
Ain	BRO	1959.5	1971	22571	11.5	23.5
Ain	BRO	1959.5	1980	8126.16	20.5	8.5
Ain	HYE	1958.5	1959	82724	0	100.0
Ain	HYE	1958.5	1963	47000.2	4.5	56.8
Ain	HYE	1958.5	1971	10845.5	12.5	13.1
Ain	HYE	1958.5	1991	10740.3	32.5	13.0
Ain	HYE	1958.5	1996	15663.6	37.5	18.9
Ain	HYE	1958.5	2000	4095.29	41.5	5.0
Ain	HYE	1958.5	2005	8414.91	46.5	10.2
Ain	HYE	1958.5	2009	4274.83	50.5	5.2
Ain	M71	1967	1967	25274	0	100.0
Ain	M71	1967	1971	19537	4	77.3
Ain	M71	1967	1980	1656	13	6.6
Ain	M71	1967	1991	2294.35	24	9.1
Ain	M71	1967	1996	1342	29	5.3
Ain	PLA	1953	1953	104935	0	100.0
Ain	PLA	1953	1954	51916	1	49.5
Ain	PLA	1953	1965	24972	12	23.8
Ain	PLA	1953	1971	21154	18	20.2
Ain	PLA	1953	1980	13423	27	12.8
Ain	PLA	1953	1991	13365	38	12.7
Ain	MOL	2002	2002	53286.5	0	100.0

River Name	Lake ID	Cutoff date	Year of measure of WSA	Water Surface Area (m^2)	Time since cutoff (y)	% of initial area remaining
Ain	MOL	2002	2005	32090.5	3	60.2
Ain	MOL	2002	2009	11051	7	20.7
Ain	M54	1949.5	1950	23808	0	100.0
Ain	M54	1949.5	1954	14536	4.5	61.1
Ain	M54	1949.5	1963	6233	13.5	26.2
Ain	M54	1949.5	1971	4562	21.5	19.2
Ain	M54	1949.5	1991	5982	41.5	25.1
Ain	M54	1949.5	1996	6794.03	46.5	28.5
Ain	M54	1949.5	2005	3139.87	55.5	13.2
Towy	LA	1863	1863	10564	0	100.0
Towy	LA	1863	1889	3415	26	32.3
Towy	LA	1863	1907	2719	44	25.7
Towy	LA	1863	1946	540	83	5.1
Towy	LA	1863	1954	945	91	8.9
Towy	LA	1863	1969	942	106	8.9
Towy	LA	1863	1975	424	112	4.0
Towy	LA	1863	1992	942	129	8.9
Towy	LA	1863	1999	854	136	8.1
Towy	LA	1863	2002	442	139	4.2
Towy	LA	1863	2006	1980	143	18.7
Towy	LB	1940	1940	9900	0	100.0
Towy	LB	1940	1946	5066	6	51.2
Towy	LB	1940	1954	4755	14	48.0
Towy	LB	1940	1969	4205	29	42.5
Towy	LB	1940	1992	1100	52	11.1
Towy	LB	1940	1999	800	59	8.1
Towy	LB	1940	2002	625	62	6.3
Towy	LB	1940	2006	1245	66	12.6
Towy	LD	2000.5	2001	11020	0	100.0
Towy	LD	2000.5	2006	8586	6	77.9
Towy	LE	1863	1863	5445	0	100.0
Towy	LE	1863	1889	3550	26	65.2
Towy	LE	1863	1907	1279	44	23.5
Towy	LE	1863	1946	878	83	16.1
Towy	LE	1863	1954	583	91	10.7
Towy	LE	1863	1969	1183	106	21.7
Towy	LE	1863	1975	547	112	10.1
Towy	LE	1863	1992	61	129	1.1
Towy	LE	1863	2006	429	143	7.9
Towy	LC	1863	1863	54410	0	100.0
Towy	LC	1863	1889	44777	26	82.3
Towy	LC	1863	1907	28178	44	51.8
Towy	LC	1863	1946	13559	83	24.9
Towy	LC	1863	1954	20862	91	38.3
Towy	LC	1863	1969	15183	106	27.9
Towy	LC	1863	1975	15232	112	28.0
Towy	LC	1863	1981	14705	118	27.0
Towy	LC	1863	1992	10571	129	19.4
Towy	LC	1863	1999	7283	136	13.4
Towy	LC	1863	2002	8233	139	15.1
Towy	LC	1863	2006	20371	143	37.4
Mississippi	YUCA	1929	1929	1600000	0	100.0
Mississippi	YUCA	1929	1989	860000	60	46.3
Mississippi	YUCA	1929	1998	860000	69	46.3
Mississippi	YUCA	1929	2007	870000	78	45.6

River Name	Lake ID	Cutoff date	Year of measure of WSA	Water Surface Area (m^2)	Time since cutoff (y)	% of initial area remaining
Mississippi	EAGL	1866	1866	2080000	0	100.0
Mississippi	EAGL	1866	1994	1700000	128	18.3
Mississippi	EAGL	1866	2005	1730000	139	16.8
Mississippi	EAGL	1866	2010	1700000	144	18.3
Mississippi	MARE	1933	1933	1820000	0	100.0
Mississippi	MARE	1933	2004	790000	71	56.6
Mississippi	MARE	1933	2006	830000	73	54.4
Mississippi	MARE	1933	2010	890000	77	51.1
Mississippi	FERG	1933	1933	1040000	0	100.0
Mississippi	FERG	1933	2000	790000	67	24.0
Mississippi	FERG	1933	2005	670000	72	35.6
Mississippi	FERG	1933	2009	820000	76	21.2
Mississippi	MARY	1776	1776	1330000	0	100.0
Mississippi	MARY	1776	1996	1000000	220	24.8
Mississippi	MARY	1776	2006	1050000	230	21.1
Mississippi	LEE	1858	1858	14860000	0	100.0
Mississippi	LEE	1858	1996	7980000	138	53.7
Mississippi	LEE	1858	2007	7390000	149	49.7
Smoky Hill	SUP	2004	2005	86604	1	100.0
Smoky Hill	SUP	2004	2006	62471	2	72.1
Smoky Hill	SUP	2004	2008	60862	4	70.3
Kansas	CHU	1995	1995	520000	0	100.0
Kansas	CHU	1995	2002	240000	7	46.2
Kansas	CHU	1995	2003	120000	8	23.1
Kansas	CHU	1995	2005	210000	10	40.4
Kansas	CHU	1995	2010	200000	15	38.5
Red River of the North	RED2	1987	1987	47900	0	100.0
Red River	RED2	1987	1997	29980	10	62.6
Red River	RED2	1987	2003	35600	16	74.3
Red River	RED2	1987	2004	35190	17	73.5
Red River	RED2	1987	2005	39390	18	82.2
Red River	RED2	1987	2006	39130	19	81.7
Red River	RED2	1987	2008	37720	21	78.7
Red River	RED2	1987	2010	37720	23	62.6
Red River	RED1	2000	2003	27396	3	100.0
Red River	RED1	2000	2006	20312	6	74.1
Red River	RED1	2000	2008	22451	8	81.9
Pelican River	PEL1	1991	1991	2140	0	100.0
Pelican River	PEL1	1991	2003	1408	12	65.8
Pelican River	PEL1	1991	2008	1591	17	74.3
Pelican River	PEL2	1991	1991	1101	0	100.0
Pelican River	PEL2	1991	2003	607	12	55.1
Pelican River	PEL2	1991	2009	536	17	48.7
Pelican River	PEL3	1991	1991	2700	0	100.0
Pelican River	PEL3	1991	2003	1980	12	73.3
Pelican River	PEL3	1991	2006	1980	15	73.3
Pelican River	PEL3	1991	2008	1730	17	64.1
Pelican River	PEL3	1991	2009	1670	18	61.9

Appendix 2

Topographic measurements: longitudinal profiles and cross sections.

Table A2.1: Longitudinal profiles data for the Ain River (data used in Chapter 3).

Point number	Distance start profile (km)	Elevation in 1999 (m)	Elevation in 2008 (m)	Elevation in 2010 (m)
1	0.00	218.3	218.7	218.7
2	0.33	218.3	218.4	218.6
3	0.61	217.8	217.5	217.5
4	0.77	217.7	217.9	218.1
5	0.91	217.6	218.0	217.8
6	1.08	216.9	218.0	218.0
7	1.31	216.9	217.4	216.9
8	1.40	216.7	216.8	216.7
9	1.43	216.7	217.1	217.1
10	1.47	216.3	216.2	216.3
11	1.51	216.2		216.6
12	1.66	216.0		
13	1.80	216.0	215.9	
14	1.98	216.0	216.5	
15	2.03	215.9	216.0	216.4
16	2.13	215.7	216.2	
17	2.32	215.4	216.4	216.2
18	2.53	215.2	216.3	216.2
19	2.70	215.2	215.1	215.0
20	2.81	215.1	214.7	214.9
21	2.87	215.1	215.0	214.9
22	2.92	215.0	215.3	
23	2.96	214.5	215.2	214.7
24	2.97	214.5	215.3	214.9
25	3.08	214.5	215.0	214.7
26	3.37	214.4	215.1	214.9
27	3.56	214.4	215.5	214.8

Table A2.2: Cross Sections at location “a” (data used in Chapter 3).
Note that only a fourth of the data for 2008 are shown for presentation purpose.

C.S. "a" Distance, 2004 (m)	C.S. "a" Elevation, 2004 (m)	C.S. "a" Distance, 2008 (m)	C.S. "a" Elevation, 2008 (m)	C.S. "a" Distance, 2010 (m)	C.S. "a" Elevation, 2010 (m)
2.09	216.98	0.00	217.35	1.01	217.04
4.33	217.08	0.73	217.33	5.29	217.31
6.62	217.22	1.52	217.32	9.69	217.43
8.66	217.32	2.50	217.31	12.55	217.52
11.25	217.47	3.28	217.30	14.08	217.58
13.92	217.58	4.07	217.29	14.14	217.63
17.26	217.86	4.86	217.28	20.58	217.81
22.26	218.12	5.83	217.26	25.97	217.96
26.47	218.35	6.62	217.25	31.32	218.21
29.38	218.60	7.41	217.33	32.18	218.07
34.92	218.84	8.19	217.36	35.62	218.91
46.40	219.11	9.17	217.39	41.72	219.29
49.29	219.60	9.95	217.41	49.12	219.66
56.64	219.54	10.20	217.42		
		10.44	217.44		
		10.50	217.45		
		10.74	217.46		
		10.98	217.47		
		11.23	217.49		
		11.47	217.50		
		11.53	217.51		
		11.77	217.53		
		12.01	217.54		
		12.26	217.55		
		12.50	217.56		
		12.56	217.57		
		12.80	217.57		
		13.05	217.58		
		13.29	217.58		
		13.53	217.58		
		13.59	217.58		
		13.83	217.59		
		14.08	217.60		
		14.32	217.62		
		14.56	217.63		
		14.81	217.63		
		15.59	217.64		
		16.38	217.66		
		17.17	217.68		
		17.96	217.72		
		18.93	217.71		
		19.72	217.70		
		20.50	217.75		
		21.29	217.74		
		22.26	217.79		
		23.05	217.81		
		23.84	217.85		

C.S. "a" Distance, 2004 (m)	C.S. "a" Elevation, 2004 (m)	C.S. "a" Distance, 2008 (m)	C.S. "a" Elevation, 2008 (m)	C.S. "a" Distance, 2010 (m)	C.S. "a" Elevation, 2010 (m)
		24.63	217.95		
		25.60	218.01		
		26.39	218.05		
		27.17	218.11		
		27.96	218.18		
		28.94	218.29		
		29.72	218.38		
		30.51	218.50		
		31.30	218.58		
		32.57	218.76		
		33.36	218.81		
		34.33	218.85		
		35.12	218.88		
		35.91	218.89		
		36.69	218.92		
		37.67	218.95		
		38.45	219.00		
		39.24	219.04		
		40.03	219.11		
		41.00	219.16		
		41.79	219.17		
		42.58	219.17		
		43.36	219.18		
		44.34	219.21		
		45.13	219.20		
		45.91	219.20		
		46.70	219.24		
		47.67	219.40		
		48.46	219.47		
		49.25	219.56		
		50.04	219.60		
		51.55	219.74		
		52.34	219.77		
		53.13	219.79		
		54.10	219.81		
		54.89	219.84		
		55.68	219.85		
		56.46	219.83		
		57.44	219.85		
		58.22	219.82		
		59.01	219.81		

Table A2.3: Cross Sections at location “b” (data used in Chapter 3).
Note that only a fourth of the data for 2008 are shown for presentation purpose.

C.S "b" Distance, 2004 (m)	C.S "b" Elevation, 2004 (m)	C.S "b" Distance, 2008 (m)	C.S "b" Elevation, 2008 (m)	C.S "b" Distance, 2010 (m)	C.S "b" Elevation, 2010 (m)
2.45	218.51	0.16	218.40	2.72	218.68
6.97	218.24	0.95	218.44	17.26	218.32
11.10	218.01	1.74	218.46	38.45	218.19
17.31	217.83	2.53	218.39	53.94	217.95
22.35	217.75	3.32	218.36	69.60	217.99
27.72	217.67	4.11	218.30	79.82	218.23
32.37	217.58	4.90	218.26		
35.23	217.63	5.69	218.20		
39.99	217.54	6.48	218.21		
44.29	217.49	7.27	218.22		
48.65	217.35	8.23	218.22		
59.95	217.38	9.02	218.30		
63.09	217.49	9.81	218.27		
71.09	217.75	10.60	218.21		
74.78	217.81	11.39	218.20		
78.16	218.02	12.18	218.17		
79.81	218.24	12.97	218.16		
80.81	218.70	13.76	218.21		
		14.55	218.12		
		15.34	218.07		
		16.13	218.08		
		16.92	218.02		
		17.71	217.95		
		18.67	217.95		
		19.46	217.95		
		20.25	218.00		
		21.04	217.96		
		21.83	217.90		
		22.62	217.87		
		23.41	217.86		
		24.20	217.91		
		24.99	217.97		
		25.78	217.99		
		26.57	218.01		
		27.36	218.06		
		28.15	218.06		
		29.11	218.10		
		29.90	218.15		
		30.69	218.19		
		31.48	218.22		
		32.27	218.21		
		33.06	218.21		
		33.85	218.16		
		34.64	218.15		
		35.43	218.12		
		36.22	218.11		
		37.25	218.11		
		38.04	218.08		
		38.83	218.05		
		39.62	218.03		
		40.41	218.02		

C.S "b" Distance, 2004 (m)	C.S "b" Elevation, 2004 (m)	C.S "b" Distance, 2008 (m)	C.S "b" Elevation, 2008 (m)	C.S "b" Distance, 2010 (m)	C.S "b" Elevation, 2010 (m)
		41.20	217.99		
		41.99	218.01		
		42.95	217.95		
		43.74	217.93		
		44.53	217.90		
		45.32	217.86		
		46.11	217.86		
		46.90	217.85		
		47.69	217.84		
		48.48	217.82		
		49.27	217.81		
		50.06	217.80		
		50.85	217.78		
		51.64	217.75		
		52.43	217.75		
		53.39	217.69		
		54.18	217.72		
		54.97	217.73		
		55.76	217.76		
		56.55	217.74		
		57.34	217.74		
		58.13	217.72		
		58.92	217.73		
		59.71	217.74		
		60.50	217.72		
		61.29	217.68		
		62.08	217.67		
		62.87	217.66		
		63.83	217.66		
		64.62	217.66		
		65.41	217.66		
		66.20	217.65		
		66.99	217.61		
		67.78	217.61		
		68.57	217.64		
		69.36	217.62		
		70.15	217.66		
		70.94	217.73		
		71.73	217.77		
		72.52	217.78		
		73.31	217.75		
		74.27	217.82		
		75.06	217.89		
		75.85	217.94		
		76.64	218.00		
		77.43	218.09		
		78.22	218.13		
		79.01	218.25		
		79.80	218.56		
		80.59	218.69		
		81.38	218.74		

Table A2.4: Cross Sections at location “c” (data used in Chapter 3).
Note that only a fourth of the data for 2008 are shown for presentation purpose.

C.S. "c" Distance, 2004 (m)	C.S. "c" Elevation, 2004 (m)	C.S. "c" Distance, 2008 (m)	C.S. "c" Elevation, 2008 (m)	C.S. "c" Distance, 2010 (m)	C.S. "c" Elevation, 2010 (m)
3.82	216.89	0.74	217.15	2.34	217.15
11.45	216.97	1.63	217.20	16.40	217.37
15.38	217.22	2.33	217.21	28.65	217.55
29.87	217.31	3.04	217.22	29.66	217.32
44.49	217.45	3.75	217.23	42.60	217.59
55.36	217.49	4.45	217.24	50.80	217.87
62.45	217.48	5.16	217.25	65.59	217.72
		5.87	217.22		
		6.57	217.16		
		7.28	217.25		
		8.00	217.26		
		8.71	217.29		
		9.41	217.30		
		10.12	217.33		
		10.83	217.36		
		11.53	217.35		
		12.24	217.37		
		12.95	217.40		
		13.65	217.41		
		14.36	217.40		
		15.07	217.44		
		15.77	217.43		
		16.48	217.42		
		17.19	217.42		
		17.89	217.41		
		18.60	217.41		
		19.32	217.43		
		20.02	217.47		
		20.73	217.47		
		21.44	217.45		
		22.15	217.43		
		22.85	217.42		
		23.56	217.44		
		24.27	217.45		
		24.97	217.48		
		25.68	217.49		
		26.39	217.47		
		27.09	217.43		
		27.80	217.41		
		28.51	217.44		
		29.21	217.47		
		29.92	217.41		
		30.64	217.37		
		31.34	217.38		
		32.05	217.39		
		32.76	217.40		
		33.46	217.37		
		34.17	217.41		
		34.88	217.46		
		35.58	217.50		
		36.29	217.53		

C.S. "c" Distance, 2004 (m)	C.S. "c" Elevation, 2004 (m)	C.S. "c" Distance, 2008 (m)	C.S. "c" Elevation, 2008 (m)	C.S. "c" Distance, 2010 (m)	C.S. "c" Elevation, 2010 (m)
		37.00	217.54		
		37.71	217.55		
		38.41	217.53		
		39.12	217.58		
		39.83	217.58		
		40.53	217.55		
		41.24	217.48		
		41.96	217.56		
		42.66	217.68		
		43.37	217.70		
		44.08	217.65		
		44.78	217.61		
		45.49	217.66		
		46.20	217.69		
		46.90	217.67		
		47.61	217.66		
		48.32	217.62		
		49.02	217.59		
		49.73	217.58		
		50.44	217.62		
		51.14	217.65		
		51.85	217.70		
		52.56	217.72		
		53.28	217.75		
		53.98	217.75		
		54.69	217.73		
		55.40	217.67		
		56.10	217.61		
		56.81	217.57		
		57.52	217.57		
		58.22	217.58		
		58.93	217.62		
		59.64	217.68		

Table A2.5: Cross Sections at location “d” (data used in Chapter 3).
Note that only a fourth of the data for 2008 are shown for presentation purpose.

C.S. "d" Distance, 2004 (m)	C.S. "d" Elevation, 2004 (m)	C.S. "d" Distance, 2008 (m)	C.S. "d" Elevation, 2008 (m)	C.S. "d" Distance, 2010 (m)	C.S. "d" Elevation, 2010 (m)
4.50	216.08	0.00	216.34	4.43	215.83
8.93	215.56	1.00	216.33	14.65	216.09
12.18	215.98	2.00	216.31	72.17	216.15
22.19	216.17	3.00	216.28	87.51	215.62
46.25	216.46	4.00	216.24	94.97	215.63
67.21	216.56	5.00	216.17	116.11	215.32
80.01	216.18	6.00	216.08	152.65	214.82
87.26	215.69	7.00	215.99	159.46	214.79
89.79	215.28	8.00	215.95		
93.79	214.95	9.00	215.92		
98.79	214.61	10.00	215.80		
101.07	214.48	11.00	215.79		
103.47	214.34	12.00	215.87		
105.43	214.26	13.00	215.94		
107.66	214.16	14.00	215.95		
109.93	214.01	15.00	215.92		
112.02	213.93	16.00	215.90		
114.05	213.77	17.00	216.03		
116.20	213.74	18.00	216.05		
118.21	213.83	19.00	216.08		
120.95	213.84	20.00	216.09		
122.86	213.90	21.00	216.10		
126.46	213.92	22.00	216.16		
128.54	213.87	23.00	216.22		
130.64	213.92	24.00	216.20		
133.00	213.75	25.00	216.19		
136.79	213.76	26.00	216.17		
138.64	213.99	27.00	216.16		
140.85	214.79	28.00	216.17		
142.15	215.28	29.00	216.17		
144.80	215.73	30.00	216.20		
148.52	215.94	31.00	216.24		
155.56	216.32	32.00	216.21		
159.82	216.95	33.00	216.16		
		34.00	216.23		
		35.00	216.33		
		36.00	216.35		
		37.00	216.47		
		38.00	216.47		
		39.00	216.40		
		40.00	216.38		
		41.00	216.40		
		42.00	216.41		
		43.00	216.43		
		44.00	216.42		
		45.00	216.44		
		46.00	216.46		
		47.00	216.45		
		48.00	216.40		
		49.00	216.38		
		50.00	216.36		

C.S. "d" Distance, 2004 (m)	C.S. "d" Elevation, 2004 (m)	C.S. "d" Distance, 2008 (m)	C.S. "d" Elevation, 2008 (m)	C.S. "d" Distance, 2010 (m)	C.S. "d" Elevation, 2010 (m)
		51.00	216.34		
		52.00	216.37		
		53.00	216.33		
		54.00	216.30		
		55.00	216.29		
		56.00	216.30		
		57.00	216.33		
		58.00	216.33		
		59.00	216.36		
		60.00	216.37		
		61.00	216.43		
		62.00	216.42		
		63.00	216.42		
		64.00	216.43		
		65.00	216.48		
		66.00	216.53		
		67.00	216.56		
		68.00	216.58		
		69.00	216.56		
		70.00	216.52		
		71.00	216.48		
		72.00	216.47		
		73.00	216.47		
		74.00	216.44		
		75.00	216.45		
		76.00	216.47		
		77.00	216.40		
		78.00	216.38		
		79.00	216.35		
		80.00	216.30		
		81.00	216.27		
		82.00	216.26		
		83.00	216.15		
		84.00	216.08		
		85.00	216.06		
		86.00	216.00		
		87.00	215.93		
		88.00	215.89		
		89.00	215.78		
		90.00	215.71		
		91.00	215.72		
		92.00	215.71		
		93.00	215.73		
		94.00	215.69		
		95.00	215.71		
		96.00	215.68		
		97.00	215.68		
		98.00	215.61		
		99.00	215.58		
		100.00	215.59		
		101.00	215.60		
		102.00	215.62		
		103.00	215.58		
		104.00	215.62		
		105.00	215.63		

C.S. "d" Distance, 2004 (m)	C.S. "d" Elevation, 2004 (m)	C.S. "d" Distance, 2008 (m)	C.S. "d" Elevation, 2008 (m)	C.S. "d" Distance, 2010 (m)	C.S. "d" Elevation, 2010 (m)
		106.00	215.58		
		107.00	215.58		
		108.00	215.56		
		109.00	215.56		
		110.00	215.59		
		111.00	215.63		
		112.00	215.70		
		113.00	215.69		
		114.00	215.73		
		115.00	215.62		
		116.00	215.58		
		117.00	215.56		
		118.00	215.57		
		119.00	215.60		
		120.00	215.58		
		121.00	215.56		
		122.00	215.52		
		123.00	215.49		
		124.00	215.50		
		125.00	215.49		
		126.00	215.50		
		127.00	215.47		
		128.00	215.45		
		129.00	215.44		
		130.00	215.47		
		131.00	215.45		
		132.00	215.46		
		133.00	215.45		
		134.00	215.45		
		135.00	215.48		
		136.00	215.47		
		137.00	215.48		
		138.00	215.47		
		139.00	215.48		
		140.00	215.48		
		141.00	215.45		
		142.00	215.43		
		143.00	215.43		
		144.00	215.41		
		145.00	215.38		
		146.00	215.37		
		147.00	215.33		
		148.00	215.27		
		149.00	215.22		
		150.00	215.17		
		151.00	215.14		
		152.00	215.05		
		153.00	214.99		
		154.00	215.01		
		155.00	215.02		
		156.00	214.99		
		157.25	214.98		
		158.25	214.97		
		159.25	214.96		

Table A2.6: Cross Sections at location “e” (data used in Chapter 3).

C.S. "e" Distance, 2004 (m)	C.S. "e" Elevation, 2004 (m)	C.S. "e" Distance, 2008 (m)	C.S. "e" Elevation, 2008 (m)	C.S. "e" Distance, 2010 (m)	C.S. "e" Elevation, 2010 (m)
0.55	213.73	0.00	214.60	0.48	214.76
2.86	213.56	1.72	214.31	1.56	213.90
5.13	213.43	5.49	213.89	2.74	213.76
7.24	213.23	9.23	213.23	3.77	213.49
9.39	212.93	10.72	212.93	4.91	213.49
11.61	212.82	17.01	213.13	5.92	213.08
14.86	212.69	21.66	213.73	6.91	212.87
17.04	212.65	24.78	214.13	8.52	212.71
19.46	212.77	27.39	214.63	9.55	212.60
21.79	213.04			10.66	212.50
24.30	213.36			11.75	212.42
26.23	213.71			12.80	212.52
27.82	214.27			13.90	212.35
29.26	214.78			14.99	212.39
31.49	214.79			16.00	212.46
33.09	214.83			17.13	212.51
34.04	215.26			18.25	212.54
				19.24	212.78
				20.27	212.86
				21.28	213.06
				22.31	213.29
				23.32	213.40
				24.35	213.56
				25.37	213.83
				26.38	213.94
				27.38	214.56
				33.23	214.76

Table A2.7: Longitudinal profiles at Lake CHU1 and Lake CHU2 on the Towy River, Wales (data used in Chapter 4).

Lake CHU1				**Lake CHU2**			
Gravel		Ground Surface		Gravel		Ground Surface	
Distance (m)	Elevation (m)	Distance (m)	Elevation (m)	Distance (m)	Elevation (m)	Distance (m)	Elevation (m)
4.96	15.92	1.90	18.06	2.69	14.75	0.00	17.28
37.49	16.06	5.00	17.26	86.67	14.41	2.69	16.73
139.09	14.30	21.45	17.88	204.24	14.32	38.82	17.11
268.15	14.30	37.75	17.13	293.00	14.41	59.22	17.00
298.95	13.60	43.95	17.72			72.19	17.02
		73.24	17.57			86.67	16.05
		113.52	17.01			98.20	16.70
		139.64	15.81			150.00	15.50
		153.95	16.29			176.28	16.38
		176.00	16.28			186.10	16.52
		210.00	16.23			204.24	15.93
		267.00	16.60			222.00	16.83
		272.60	16.37			256.00	16.60
		300.00	15.83			279.00	16.65
						293.00	15.83

Table A2.8: Longitudinal profiles at Lake CHU3 and Lake CHU4 on the Towy River, Wales (data used in Chapter 4).

Lake CHU3				**Lake CHU4**			
Gravel		Ground Surface		Gravel		Ground Surface	
Distance (m)	Elevation (m)	Distance (m)	Elevation (m)	Distance (m)	Elevation (m)	Distance (m)	Elevation (m)
4.60	15.87	0.00	17.50	75.00	14.73	0.00	16.82
77.21	15.57	4.60	17.43	89.00	14.81	8.43	16.94
162.00	15.22	53.50	17.25	163.00	15.48	31.57	16.92
		77.21	17.28	185.00	15.53	66.00	16.68
		86.00	17.21	257.00	14.62	75.00	16.43
		96.00	17.20	287.00	16.17	89.00	16.43
		139.00	17.37			163.00	17.63
		162.00	17.50			185.00	16.39
		167.00	17.46			208.00	17.70
						222.00	16.93
						234.00	16.69
						257.00	16.44
						287.00	16.35

Table A2.9: Longitudinal profiles at Lake NECK on the Towy River, Wales (data used in Chapter 4).

Lake NECK			
Gravel		Ground Surface	
Distance (m)	Elevation (m)	Distance (m)	Elevation (m)
0.00	16.68	0.00	16.68
104.00	14.65	21.00	16.50
475.00	14.35	104.00	16.06
780.00	14.40	311.00	16.31
930.00	13.45	371.00	16.24
		475.00	15.56
		780.00	15.29
		930.00	16.15
		938.00	16.22

Appendix 3

Grain size measurements

Table A3.1: Average grain size fraction per core from the Towy River oxbow lakes

The considered fractions considered are mud (≤63 µm), sand (from >63 µm to ≤2 mm) and gravel (>2 mm).

Core ID	% Gravel per core	% Sand per core	% Mud per core
CHU1-C1	0	40	60
CHU1-C2	1	32	67
CHU1-C3	0	21	79
CHU1-C4	0	27	73
CHU1-C5	1	29	70
CHU1-C6	2	15	83
CHU1-C7	0	7	93
CHU1-C8	2	27	71
CHU1-C9	6	47	47
CHU1-C10	6	47	47
CHU1-C11	5	35	61
CHU1-C12	5	31	64
CHU1-C15	5	47	48
CHU1-C17	1	59	40
CHU1-C18	2	44	54
CHU1-C19	2	44	54
CHU1-C2	1	60	39
CHU1-C21	3	47	50
CHU1-C22	2	38	60
CHU1-C23	4	44	53
CHU1-C24	1	51	48
CHU2-C1	5	56	39
CHU2-C2	2	55	43
CHU2-C3	2	54	44
CHU2-C4	6	49	45
CHU2-C5	1	53	46
CHU2-C6	0	28	72
CHU2-C7	0	30	70
CHU2-C8	1	48	51
CHU2-C9	6	33	61
CHU2-C10	2	38	60
CHU2-C11	4	45	51
CHU2-C12	3	40	57
CHU2-C13	1	44	55
NECK-C1	4	19	77
NECK-C2	3	13	85
NECK-C3	24	26	50
NECK-C4	4	10	86
NECK-C5	0	2	33
NECK-C7	10	14	76
NECK-C8	7	6	33
NECK-C9	0	4	95
NECK-C10	0	25	75
NECK-C11	0	17	83
NECK-C12	0	14	86
CHU4-C2	1	64	35
CHU4-C4	2	25	73
CHU4-C6	2	27	71
CHU4-C8	5	82	13
CHU4-C9	2	37	61
CHU3-C1	0	26	74
CHU3-C2	0	25	75
CHU3-C3	1	43	56
CHU3-C4	1	11	89
CHU3-C5	1	25	74
CHU3-C6	2	45	53
CHU3-C8	1	18	81
CHU3-C9	1	44	55

Table A3.2: Grain size variation with depth for cores of the five oxbow lakes studied on the Towy River, Wales (data used in Chapter 4).

Sample ID/Location	Sample Elevation (m)	%Gravel	%Sand	%Mud (Silt-Clay)
Ground surface	16.19	100.0	100.0	89.8
CHU1-C1-D1	16.09	100.0	100.0	89.8
CHU1-C1-D2	15.89	100.0	100.0	86.3
CHU1-C1-D3	15.69	100.0	100.0	77.2
CHU1-C1-D4	15.49	100.0	100.0	62.1
CHU1-C1-D5	15.29	100.0	100.0	61.3
CHU1-C1-D6	15.09	100.0	100.0	58.5
CHU1-C1-D7	14.89	100.0	100.0	53.4
CHU1-C1-D8	14.69	100.0	100.0	40.2
CHU1-C1-D9	14.49	100.0	100.0	46.7
CHU1-C1-D10	14.29	100.0	100.0	47.8
CHU1-C1-D11	14.09	99.8	100.0	53.1
CHU1-C1-D12	13.89	95.1	100.0	50.8
CHU1-C1-D13	13.69	100.0	100.0	48.7
CHU1-C1-D14	13.49	100.0	100.0	57.3
Gravel Depth	13.39	100.0	100.0	57.3
Ground Surface	15.74	99.9	100.0	77.0
CHU1-C2-D1	15.67	99.9	100.0	77.0
CHU1-C2-D2	15.60	100.0	100.0	82.2
CHU1-C2-D3	15.51	100.0	100.0	83.7
CHU1-C2-D4	15.43	100.0	100.0	84.2
CHU1-C2-D5	15.32	100.0	100.0	86.7
CHU1-C2-D6	15.23	100.0	100.0	88.2
CHU1-C2-D7	15.05	100.0	100.0	78.4
CHU1-C2-D8	14.81	100.0	100.0	68.6
CHU1-C2-D9	14.73	100.0	100.0	46.0
CHU1-C2-D10	14.60	99.4	100.0	22.6
CHU1-C2-D11	14.40	100.0	100.0	46.6
CHU1-C2-D12	14.16	100.0	100.0	51.0
CHU1-C2-D13	13.92	84.9	100.0	52.2
Gravel Depth	13.82	84.9	100.0	52.2
Ground Surface	16.04	100.0	100.0	74.0
CHU1-C3-D1	15.95	100.0	100.0	74.0
CHU1-C3-D2	15.80	99.8	100.0	71.3
CHU1-C3-D3	15.71	100.0	100.0	67.9
CHU1-C3-D4	15.64	100.0	100.0	71.4
CHU1-C3-D5	15.58	100.0	100.0	72.3
CHU1-C3-D6	15.53	100.0	100.0	73.3
CHU1-C3-D7	15.44	100.0	100.0	80.3
CHU1-C3-D8	15.32	100.0	100.0	82.5
CHU1-C3-D9	15.21	100.0	100.0	81.8
CHU1-C3-D10	15.08	100.0	100.0	69.5
CHU1-C3-D11	14.92	100.0	100.0	85.1
CHU1-C3-D12	14.74	100.0	100.0	83.3
CHU1-C3-D13	14.51	100.0	100.0	81.4
CHU1-C3-D14	14.20	100.0	100.0	85.3
CHU1-C3-D15	13.99	100.0	100.0	85.6
CHU1-C3-D16	13.92	100.0	100.0	92.8
CHU1-C3-D17	13.64	100.0	100.0	90.1
Gravel Depth	13.40	100.0	100.0	90.1
Ground Surface	16.65	100.0	100.0	78.1

Sample ID/Location	Sample Elevation (m)	%Gravel	%Sand	%Mud (Silt-Clay)
CHU1-C4-D1	16.55	100.0	100.0	78.1
CHU1-C4-D2	16.40	100.0	100.0	78.0
CHU1-C4-D3	16.29	100.0	100.0	73.6
CHU1-C4-D4	16.17	100.0	100.0	68.8
CHU1-C4-D5	16.04	99.8	100.0	71.1
CHU1-C4-D6	15.89	100.0	100.0	68.4
CHU1-C4-D7	15.72	100.0	100.0	74.2
CHU1-C4-D8	15.57	100.0	100.0	72.4
CHU1-C4-D9	15.46	100.0	100.0	66.4
CHU1-C4-D10	15.31	100.0	100.0	69.9
CHU1-C4-D11	15.14	100.0	100.0	75.8
CHU1-C4-D12	15.06	100.0	100.0	76.6
CHU1-C4-D13	14.86	100.0	100.0	77.9
Gravel Depth	14.68	100.0	100.0	77.9
Ground Surface	17.25	100.0	100.0	86.4
CHU1-C5-D1	17.13	100.0	100.0	86.4
CHU1-C5-D2	16.92	100.0	100.0	87.3
CHU1-C5-D3	16.79	100.0	100.0	87.1
CHU1-C5-D4	16.69	100.0	100.0	89.9
CHU1-C5-D5	16.55	100.0	100.0	86.6
CHU1-C5-D6	16.25	100.0	100.0	59.8
CHU1-C5-D7	15.82	100.0	100.0	41.3
CHU1-C5-D8	15.44	99.7	100.0	55.3
CHU1-C5-D9	15.22	89.8	100.0	33.7
Gravel Depth	15.15	89.8	100.0	33.7
Ground Surface	16.37	100.0	100.0	89.7
CHU1-C6-D1	16.23	100.0	100.0	89.7
CHU1-C6-D2	16.05	100.0	100.0	88.1
CHU1-C6-D3	15.91	100.0	100.0	90.4
CHU1-C6-D4	15.77	100.0	100.0	94.6
CHU1-C6-D5	15.66	100.0	100.0	96.4
CHU1-C6-D6	15.50	100.0	100.0	96.2
CHU1-C6-D7	15.31	99.6	100.0	94.7
CHU1-C6-D8	15.01	100.0	100.0	77.5
CHU1-C6-D9	14.53	100.0	100.0	71.6
CHU1-C6-D10	14.14	82.9	100.0	33.1
Gravel Depth	14.01	82.9	100.0	33.1
Ground Surface	16.75	100.0	100.0	86.7
CHU1-C7-D1	16.63	100.0	100.0	86.7
CHU1-C7-D2	16.43	100.0	100.0	88.4
CHU1-C7-D3	16.28	100.0	100.0	91.9
CHU1-C7-D4	16.13	100.0	100.0	95.2
CHU1-C7-D5	15.89	100.0	100.0	95.2
CHU1-C7-D6	15.64	100.0	100.0	96.2
CHU1-C7-D7	15.11	100.0	100.0	95.9
Gravel Depth	14.66	100.0	100.0	95.9
Ground Surface	18.08	100.0	100.0	81.3
CHU1-C8-D1	17.98	100.0	100.0	81.3
CHU1-C8-D2	17.80	100.0	100.0	79.1
CHU1-C8-D3	17.69	100.0	100.0	78.7
CHU1-C8-D4	17.57	99.3	100.0	71.5
CHU1-C8-D5	17.42	100.0	100.0	73.8
CHU1-C8-D6	17.23	100.0	100.0	65.7
CHU1-C8-D7	17.07	84.0	100.0	44.6
Gravel Depth	17.02	84.0	100.0	44.6

Sample ID/Location	Sample Elevation (m)	%Gravel	%Sand	%Mud (Silt-Clay)
Ground Surface	16.34	100.0	100.0	79.2
CHU1-C9-D1	16.21	100.0	100.0	79.2
CHU1-C9-D2	15.98	100.0	100.0	65.7
CHU1-C9-D3	15.78	100.0	100.0	48.4
CHU1-C9-D4	15.62	100.0	100.0	47.7
CHU1-C9-D5	15.51	100.0	100.0	46.8
CHU1-C9-D6	15.37	100.0	100.0	47.0
CHU1-C9-D7	15.22	98.3	100.0	44.4
CHU1-C9-D8	15.11	82.0	100.0	27.0
CHU1-C9-D9	14.88	91.9	100.0	27.0
CHU1-C9-D10	14.65	88.5	100.0	27.3
Gravel Depth	14.60	88.5	100.0	27.3
Ground Surface	15.81	100.0	100.0	83.6
CHU1-C10-D1	15.69	100.0	100.0	83.6
CHU1-C10-D2	15.47	100.0	100.0	75.7
CHU1-C10-D3	15.19	100.0	100.0	59.5
CHU1-C10-D4	14.94	100.0	100.0	43.0
CHU1-C10-D5	14.79	99.4	100.0	33.4
CHU1-C10-D6	14.56	84.6	100.0	25.7
CHU1-C10-D7	14.34	59.5	100.0	25.0
Gravel Depth	14.30	59.5	100.0	25.0
Ground Surface	15.63	100.0	100.0	90.5
CHU1-C11-D1	15.53	100.0	100.0	90.5
CHU1-C11-D2	15.34	100.0	100.0	86.6
CHU1-C11-D3	15.14	100.0	100.0	62.9
CHU1-C11-D4	14.91	100.0	100.0	53.4
CHU1-C11-D5	14.67	100.0	100.0	51.4
CHU1-C11-D6	14.45	100.0	100.0	53.4
CHU1-C11-D7	14.18	95.5	100.0	53.3
CHU1-C11-D8	13.99	68.1	100.0	35.2
Gravel Depth	13.97	68.1	100.0	35.2
Ground Surface	16.36	100.0	100.0	75.7
CHU1-C12-D1	16.26	100.0	100.0	75.7
CHU1-C12-D2	16.05	100.0	100.0	74.1
CHU1-C12-D3	15.86	100.0	100.0	77.4
CHU1-C12-D4	15.72	99.4	100.0	52.7
CHU1-C12-D5	15.64	75.3	100.0	41.8
Gravel Depth	15.60	75.3	100.0	41.8
Ground Surface	17.03	100.0	100.0	74.6
CHU1-C15-D1	16.93	100.0	100.0	74.6
CHU1-C15-D2	16.72	100.0	100.0	66.4
CHU1-C15-D3	16.49	100.0	100.0	65.6
CHU1-C15-D4	16.27	100.0	100.0	62.1
CHU1-C15-D5	16.11	97.9	100.0	40.5
CHU1-C15-D6	15.96	95.2	100.0	16.7
CHU1-C15-D7	15.87	72.5	100.0	11.3
Gravel Depth	15.84	72.5	100.0	11.3
Ground Surface	17.62	100.0	100.0	63.0
CHU1-C17-D1	17.50	100.0	100.0	63.0
CHU1-C17-D2	17.30	100.0	100.0	53.5
CHU1-C17-D3	17.12	100.0	100.0	57.7
CHU1-C17-D4	16.94	100.0	100.0	41.5
CHU1-C17-D5	16.81	100.0	100.0	35.4
CHU1-C17-D6	16.66	99.8	100.0	24.1
CHU1-C17-D7	16.48	99.6	100.0	29.1

Sample ID/Location	Sample Elevation (m)	%Gravel	%Sand	%Mud (Silt-Clay)
CHU1-C17-D8	16.33	90.7	100.0	16.5
Gravel Depth	16.27	90.7	100.0	16.5
Ground Surface	17.30	100.0	100.0	70.8
CHU1-C18-D1	17.16	100.0	100.0	70.8
CHU1-C18-D2	16.96	100.0	100.0	67.1
CHU1-C18-D3	16.79	100.0	100.0	55.8
CHU1-C18-D4	16.58	100.0	100.0	50.4
CHU1-C18-D5	16.39	99.9	100.0	48.0
CHU1-C18-D6	16.23	99.2	100.0	46.1
CHU1-C18-D7	16.12	90.0	100.0	42.0
Gravel Depth	16.08	90.0	100.0	42.0
Ground Surface	17.23	100.0	100.0	67.5
CHU1-C19-D1	17.12	100.0	100.0	67.5
CHU1-C19-D2	16.93	100.0	100.0	65.5
CHU1-C19-D3	16.77	100.0	100.0	66.4
CHU1-C19-D4	16.59	100.0	100.0	65.3
CHU1-C19-D5	16.42	100.0	100.0	59.5
CHU1-C19-D6	16.27	100.0	100.0	52.7
CHU1-C19-D7	16.12	100.0	100.0	45.5
CHU1-C19-D8	15.94	99.1	100.0	39.8
CHU1-C19-D9	15.81	83.4	100.0	28.1
Gravel Depth	15.78	83.4	100.0	28.1
Ground Surface	17.53	100.0	100.0	64.7
CHU1-C20-D1	17.42	100.0	100.0	64.7
CHU1-C20-D2	17.23	100.0	100.0	57.3
CHU1-C20-D3	17.08	100.0	100.0	50.1
CHU1-C20-D4	16.91	100.0	100.0	42.0
CHU1-C20-D5	16.73	100.0	100.0	33.1
CHU1-C20-D6	16.57	100.0	100.0	23.7
CHU1-C20-D7	16.38	95.6	100.0	20.9
CHU1-C20-D8	16.21	93.2	100.0	20.4
Gravel Depth	16.14	93.2	100.0	20.4
Ground Surface	17.58	100.0	100.0	59.1
CHU1-C21-D1	17.47	100.0	100.0	59.1
CHU1-C21-D2	17.29	98.5	100.0	52.1
CHU1-C21-D3	17.15	99.3	100.0	51.8
CHU1-C21-D4	17.03	91.2	100.0	36.7
Gravel Depth	16.99	91.2	100.0	36.7
Ground Surface	17.13	100.0	100.0	76.2
CHU1-C22-D1	17.02	100.0	100.0	76.2
CHU1-C22-D2	16.83	100.0	100.0	76.9
CHU1-C22-D3	16.67	100.0	100.0	70.1
CHU1-C22-D4	16.52	99.9	100.0	60.6
CHU1-C22-D5	16.34	100.0	100.0	58.1
CHU1-C22-D6	16.17	99.3	100.0	43.4
CHU1-C22-D7	16.09	84.4	100.0	33.0
Gravel Depth	16.06	84.4	100.0	33.0
Ground Surface	17.16	100.0	100.0	78.5
CHU1-C23-D1	17.05	100.0	100.0	78.5
CHU1-C23-D2	16.85	100.0	100.0	75.2
CHU1-C23-D3	16.66	100.0	100.0	63.8
CHU1-C23-D4	16.47	100.0	100.0	47.2
CHU1-C23-D5	16.28	99.8	100.0	31.4
CHU1-C23-D6	16.16	76.6	100.0	19.0
Gravel Depth	16.13	76.6	100.0	19.0

Sample ID/Location	Sample Elevation (m)	%Gravel	%Sand	%Mud (Silt-Clay)
Ground Surface	17.27	99.8	100.0	71.5
CHU1-C24-D1	17.13	99.8	100.0	71.5
CHU1-C24-D2	16.91	100.0	100.0	56.3
CHU1-C24-D3	16.72	100.0	100.0	43.3
CHU1-C24-D4	16.57	95.4	100.0	21.9
Gravel Depth	16.52	95.4	100.0	21.9
Ground Surface	16.76	100.0	100.0	32.6
CHU2-C1-D1	16.63	100.0	100.0	32.6
CHU2-C1-D2	16.44	100.0	100.0	37.1
CHU2-C1-D3	16.31	100.0	100.0	35.4
CHU2-C1-D4	16.19	100.0	100.0	37.4
CHU2-C1-D5	16.06	100.0	100.0	49.5
CHU2-C1-D6	15.90	100.0	100.0	54.6
CHU2-C1-D7	15.73	99.7	100.0	49.9
CHU2-C1-D8	15.58	100.0	100.0	41.9
CHU2-C1-D9	15.38	100.0	100.0	42.7
CHU2-C1-D10	15.13	90.9	100.0	31.9
CHU2-C1-D11	14.86	54.8	100.0	14.5
Gravel Depth	14.71	54.8	100.0	14.5
Ground Surface	16.69	100.0	100.0	27.0
CHU2-C2-D1	16.55	100.0	100.0	27.0
CHU2-C2-D2	16.33	100.0	100.0	42.1
CHU2-C2-D3	16.18	100.0	100.0	44.2
CHU2-C2-D4	16.07	100.0	100.0	48.5
CHU2-C2-D5	15.94	100.0	100.0	54.7
CHU2-C2-D6	15.77	99.7	100.0	51.3
CHU2-C2-D7	15.60	100.0	100.0	44.9
CHU2-C2-D8	15.36	100.0	100.0	40.9
CHU2-C2-D9	15.14	99.3	100.0	48.3
CHU2-C2-D10	14.94	83.1	100.0	25.4
Gravel Depth	14.81	83.1	100.0	25.4
Ground Surface	16.48	100.0	100.0	41.8
CHU2-C3-D1	16.36	100.0	100.0	41.8
CHU2-C3-D2	16.15	100.0	100.0	41.3
CHU2-C3-D3	15.97	100.0	100.0	54.2
CHU2-C3-D4	15.79	99.9	100.0	60.3
CHU2-C3-D5	15.58	99.3	100.0	51.8
CHU2-C3-D6	15.38	100.0	100.0	46.3
CHU2-C3-D7	15.16	91.5	100.0	37.5
CHU2-C3-D8	14.92	93.2	100.0	29.9
CHU2-C3-D9	14.73	100.0	100.0	36.3
Gravel Depth	14.65	100.0	100.0	36.3
Ground Surface	16.72	100.0	100.0	29.9
CHU2-C4-D1	16.59	100.0	100.0	29.9
CHU2-C4-D2	16.40	100.0	100.0	47.1
CHU2-C4-D3	16.29	100.0	100.0	49.7
CHU2-C4-D4	16.14	100.0	100.0	54.9
CHU2-C4-D5	15.96	100.0	100.0	63.0
CHU2-C4-D6	15.77	80.9	100.0	42.1
CHU2-C4-D7	15.58	68.4	100.0	27.3
CHU2-C4-D8	15.35	95.0	100.0	44.4
CHU2-C4-D9	15.08	91.7	100.0	50.2
CHU2-C4-D10	14.75	99.8	100.0	43.8
CHU2-C4-D11	14.34	98.2	100.0	45.4
Gravel Depth	14.12	98.2	100.0	45.4

Sample ID/Location	Sample Elevation (m)	%Gravel	%Sand	%Mud (Silt-Clay)
Ground Surface	16.40	100.0	100.0	42.7
CHU2-C5-D1	16.27	100.0	100.0	42.7
CHU2-C5-D2	16.06	100.0	100.0	52.5
CHU2-C5-D3	15.87	100.0	100.0	60.3
CHU2-C5-D4	15.67	100.0	100.0	64.3
CHU2-C5-D5	15.50	100.0	100.0	46.4
CHU2-C5-D6	15.33	100.0	100.0	41.6
CHU2-C5-D7	15.10	99.3	100.0	43.6
CHU2-C5-D8	14.83	99.5	100.0	33.3
CHU2-C5-D9	14.63	93.9	100.0	26.7
Gravel Depth	14.56	93.9	100.0	26.7
Ground Surface	16.05	100.0	100.0	57.4
CHU2-C6-D1	15.91	100.0	100.0	57.4
CHU2-C6-D2	15.69	100.0	100.0	57.2
CHU2-C6-D3	15.49	100.0	100.0	75.1
CHU2-C6-D4	15.24	100.0	100.0	78.2
CHU2-C6-D5	14.97	100.0	100.0	81.7
CHU2-C6-D6	14.66	100.0	100.0	76.7
CHU2-C6-D7	14.45	97.1	100.0	77.1
Gravel Depth	14.41	97.1	100.0	77.1
Ground Surface	16.21	100.0	100.0	56.9
CHU2-C7-D1	16.08	100.0	100.0	56.9
CHU2-C7-D2	15.88	100.0	100.0	60.0
CHU2-C7-D3	15.63	100.0	100.0	70.3
CHU2-C7-D4	15.35	100.0	100.0	73.8
CHU2-C7-D5	15.14	100.0	100.0	80.0
CHU2-C7-D6	14.83	100.0	100.0	76.8
CHU2-C7-D7	14.60	96.8	100.0	71.4
Gravel Depth	14.55	96.8	100.0	71.4
Ground Surface	16.27	100.0	100.0	58.7
CHU2-C8-D1	16.11	100.0	100.0	58.7
CHU2-C8-D2	15.88	100.0	100.0	67.9
CHU2-C8-D3	15.69	99.7	100.0	53.8
CHU2-C8-D4	15.45	100.0	100.0	43.6
CHU2-C8-D5	15.22	100.0	100.0	43.3
CHU2-C8-D6	14.82	100.0	100.0	46.1
CHU2-C8-D7	14.48	92.8	100.0	40.3
Gravel Depth	14.46	92.8	100.0	40.3
Ground Surface	15.93	96.2	100.0	60.5
CHU2-C9-D1	15.81	96.2	100.0	60.5
CHU2-C9-D2	15.61	98.8	100.0	62.4
CHU2-C9-D3	15.46	98.3	100.0	55.4
CHU2-C9-D4	15.30	99.8	100.0	71.6
CHU2-C9-D5	15.10	100.0	100.0	74.4
CHU2-C9-D6	14.90	100.0	100.0	63.2
CHU2-C9-D7	14.66	100.0	100.0	71.1
CHU2-C9-D8	14.42	62.8	100.0	32.2
Gravel Depth	14.32	62.8	100.0	32.2
Ground Surface	16.23	100.0	100.0	70.9
CHU2-C10-D1	16.11	100.0	100.0	70.9
CHU2-C10-D2	15.94	93.6	100.0	55.1
CHU2-C10-D3	15.80	92.3	100.0	46.6
CHU2-C10-D4	15.64	96.1	100.0	58.3
CHU2-C10-D5	15.44	98.1	100.0	63.8
CHU2-C10-D6	15.24	99.7	100.0	65.2

Sample ID/Location	Sample Elevation (m)	%Gravel	%Sand	%Mud (Silt-Clay)
CHU2-C10-D7	15.03	98.5	100.0	61.9
CHU2-C10-D8	14.86	99.9	100.0	62.1
CHU2-C10-D9	14.67	99.5	100.0	54.3
Gravel Depth	14.56	99.5	100.0	54.3
Ground Surface	16.09	100.0	100.0	70.9
CHU2-C11-D1	15.97	100.0	100.0	70.9
CHU2-C11-D2	15.77	100.0	100.0	66.0
CHU2-C11-D3	15.60	100.0	100.0	46.0
CHU2-C11-D4	15.40	99.8	100.0	48.1
CHU2-C11-D5	15.20	99.0	100.0	50.4
CHU2-C11-D6	14.95	98.7	100.0	58.8
CHU2-C11-D7	14.69	96.0	100.0	40.4
CHU2-C11-D8	14.54	75.0	100.0	25.9
Gravel Depth	14.51	75.0	100.0	25.9
Ground Surface	15.83	100.0	100.0	75.0
CHU2-C12-D1	15.68	100.0	100.0	75.0
CHU2-C12-D2	15.45	97.2	100.0	55.0
CHU2-C12-D3	15.26	98.8	100.0	47.4
CHU2-C12-D4	14.96	99.7	100.0	63.2
CHU2-C12-D5	14.70	93.5	100.0	52.2
CHU2-C12-D6	14.52	92.0	100.0	48.3
Gravel Depth	14.41	92.0	100.0	48.3
Ground Surface	16.34	100.0	100.0	79.1
CHU2-C13-D1	16.24	100.0	100.0	79.1
CHU2-C13-D2	16.04	99.0	100.0	76.8
CHU2-C13-D3	15.83	100.0	100.0	73.4
CHU2-C13-D4	15.64	100.0	100.0	66.8
CHU2-C13-D5	15.47	100.0	100.0	63.2
CHU2-C13-D6	15.26	100.0	100.0	54.1
CHU2-C13-D7	14.95	97.9	100.0	39.1
CHU2-C13-D8	14.54	99.9	100.0	51.3
CHU2-C13-D9	14.27	98.4	100.0	25.9
CHU2-C13-D10	14.02	94.5	100.0	20.6
Gravel Depth	13.82	94.5	100.0	20.6
Ground Surface	16.37	100.0	100.0	87.3
NECK-C1-D1	16.17	100.0	100.0	87.3
NECK-C1-D2	15.90	100.0	100.0	84.7
NECK-C1-D3	15.73	100.0	100.0	84.9
NECK-C1-D4	15.51	100.0	100.0	76.4
NECK-C1-D5	15.35	78.7	100.0	52.8
Gravel Depth	15.32	78.7	100.0	52.8
Ground Surface	16.07	100.0	100.0	92.3
NECK-C2-D1	15.84	100.0	100.0	92.3
NECK-C2-D2	15.48	100.0	100.0	78.0
NECK-C2-D3	15.28	100.0	100.0	93.5
NECK-C2-D4	15.18	100.0	100.0	92.0
NECK-C2-D5	14.90	87.4	100.0	68.5
Gravel Depth	14.64	87.4	100.0	68.5
Ground Surface	16.05	90.9	100.0	77.3
NECK-C3-D1	15.83	90.9	100.0	77.3
NECK-C3-D2	15.47	70.9	100.0	34.9
NECK-C3-D3	15.27	61.9	100.0	39.6
NECK-C3-D4	15.05	95.6	100.0	61.4
NECK-C3-D5	14.79	63.2	100.0	38.7
Gravel Depth	14.67	63.2	100.0	38.7

Sample ID/Location	Sample Elevation (m)	%Gravel	%Sand	%Mud (Silt-Clay)
Ground Surface	15.81	100.0	100.0	83.3
NECK-C4-D1	15.61	100.0	100.0	83.3
NECK-C4-D2	15.33	100.0	100.0	95.2
NECK-C4-D3	15.17	100.0	100.0	96.4
NECK-C4-D4	14.89	100.0	100.0	93.7
NECK-C4-D5	14.65	81.9	100.0	60.7
Gravel Depth	14.61	81.9	100.0	60.7
Ground Surface	15.56	100.0	100.0	92.7
NECK-C5-D1	15.40	100.0	100.0	92.7
NECK-C5-D2	15.10	100.0	100.0	96.3
NECK-C5-D3	14.83	100.0	100.0	97.3
NECK-C5-D4	14.52	99.1	100.0	95.1
Gravel Depth	14.35	99.1	100.0	95.1
Ground Surface	15.72	100.0	100.0	77.5
NECK-C7-D1	15.57	100.0	100.0	77.5
NECK-C7-D2	15.35	100.0	100.0	89.3
NECK-C7-D3	15.20	100.0	100.0	92.1
NECK-C7-D4	15.05	58.6	100.0	45.1
Gravel Depth	14.98	58.6	100.0	45.1
Ground Surface	15.35	100.0	100.0	94.0
NECK-C8-D1	15.14	100.0	100.0	94.0
NECK-C8-D2	14.80	86.6	100.0	83.4
Gravel Depth	14.67	86.6	100.0	83.4
Ground Surface	15.21	100.0	100.0	95.3
NECK-C9-D1	14.96	100.0	100.0	95.3
NECK-C9-D2	14.58	100.0	100.0	97.3
NECK-C9-D3	14.36	98.8	100.0	93.4
Gravel Depth	14.28	98.8	100.0	93.4
Ground Surface	16.36	100.0	100.0	58.8
NECK-C10-D1	16.24	100.0	100.0	58.8
NECK-C10-D2	16.02	100.0	100.0	57.7
NECK-C10-D3	15.84	100.0	100.0	66.5
NECK-C10-D4	15.67	100.0	100.0	65.9
NECK-C10-D5	15.47	100.0	100.0	73.3
NECK-C10-D6	15.18	100.0	100.0	74.5
NECK-C10-D7	14.89	99.9	100.0	91.8
NECK-C10-D8	14.62	100.0	100.0	91.8
NECK-C10-D9	14.06	100.0	100.0	90.6
Gravel Depth	13.66	100.0	100.0	90.6
Ground Surface	16.03	100.0	100.0	67.0
NECK-C11-D1	15.90	100.0	100.0	67.0
NECK-C11-D2	15.69	100.0	100.0	73.3
NECK-C11-D3	15.50	100.0	100.0	81.0
NECK-C11-D5	15.32	100.0	100.0	85.5
NECK-C11-D6	15.07	100.0	100.0	93.2
NECK-C11-D4	14.77	100.0	100.0	80.2
NECK-C11-D7	14.01	100.0	100.0	97.9
Gravel Depth	13.38	100.0	100.0	97.9
Ground Surface	15.70	100.0	100.0	79.1
NECK-C12-D1	15.46	100.0	100.0	79.1
NECK-C12-D2	15.11	100.0	100.0	69.8
NECK-C12-D3	14.91	100.0	100.0	86.3
NECK-C12-D5	14.65	100.0	100.0	93.1
NECK-C12-D4	14.10	100.0	100.0	92.6
NECK-C12-D6	13.39	100.0	100.0	93.0

Sample ID/Location	Sample Elevation (m)	%Gravel	%Sand	%Mud (Silt-Clay)
Gravel Depth	13.07	100.0	100.0	93.0
Ground Surface	16.35	97.8	100.0	23.7
CHU4-C2-D1	16.08	97.8	100.0	23.7
CHU4-C2-D2	15.52	98.9	100.0	37.8
CHU4-C2-D3	14.87	99.0	100.0	42.4
Gravel Depth	14.48	99.0	100.0	42.4
Ground Surface	16.44	100.0	100.0	75.8
CHU4-C4-D1	16.22	100.0	100.0	75.8
CHU4-C4-D2	15.76	96.6	100.0	71.2
Gravel Depth	15.53	96.6	100.0	71.2
Ground Surface	16.39	75.0	100.0	51.9
CHU4-C5-D1	16.19	75.0	100.0	51.9
Gravel Depth	15.98	75.0	100.0	51.9
Ground Surface	16.35	100.0	100.0	75.2
CHU4-C6-D1	16.16	100.0	100.0	75.2
CHU4-C6-D2	15.74	100.0	100.0	76.7
CHU4-C6-D3	15.30	94.3	100.0	61.7
Gravel Depth	15.10	94.3	100.0	61.7
Ground Surface	16.43	99.6	100.0	14.8
CHU4-C8-D1	16.13	99.6	100.0	14.8
CHU4-C8-D2	15.48	99.0	100.0	11.9
CHU4-C8-D3	14.93	86.3	100.0	11.9
Gravel Depth	14.73	86.3	100.0	11.9
Ground Surface	16.43	100.0	100.0	61.5
CHU4-C9-D1	15.86	100.0	100.0	61.5
CHU4-C9-D2	15.05	96.3	100.0	60.2
Gravel Depth	14.81	96.3	100.0	60.2
Ground Surface	17.44	99.8	100.0	47.5
CHU3-C1-D1	17.31	99.8	100.0	47.5
CHU3-C1-D2	17.08	99.7	100.0	57.7
CHU3-C1-D3	16.91	99.8	100.0	70.3
CHU3-C1-D4	16.73	100.0	100.0	74.7
CHU3-C1-D5	16.53	100.0	100.0	89.4
CHU3-C1-D6	16.33	100.0	100.0	95.2
CHU3-C1-D7	16.04	100.0	100.0	85.7
Gravel Depth	15.87	100.0	100.0	85.7
Ground Surface	17.52	100.0	100.0	45.4
CHU3-C2-D1	17.39	100.0	100.0	45.4
CHU3-C2-D2	17.18	100.0	100.0	74.4
CHU3-C2-D3	16.99	100.0	100.0	83.1
CHU3-C2-D4	16.76	100.0	100.0	85.9
CHU3-C2-D5	16.55	100.0	100.0	89.9
CHU3-C2-D6	16.12	99.9	100.0	68.5
Gravel Depth	15.78	99.9	100.0	68.5
Ground Surface	18.19	100.0	100.0	85.7
CHU3-C3-D1	18.05	100.0	100.0	85.7
CHU3-C3-D2	17.79	100.0	100.0	81.4
CHU3-C3-D3	17.58	100.0	100.0	58.6
CHU3-C3-D4	17.42	99.2	100.0	30.7
CHU3-C3-D5	17.20	97.6	100.0	23.0
Gravel Depth	17.06	97.6	100.0	23.0
Ground Surface	17.28	100.0	100.0	76.9
CHU3-C4-D1	17.09	100.0	100.0	76.9
CHU3-C4-D2	16.81	100.0	100.0	89.3
CHU3-C4-D3	16.62	100.0	100.0	90.8

Sample ID/Location	Sample Elevation (m)	%Gravel	%Sand	%Mud (Silt-Clay)
CHU3-C4-D4	16.42	100.0	100.0	94.9
CHU3-C4-D5	16.26	100.0	100.0	97.5
CHU3-C4-D6	15.89	96.9	100.0	81.7
Gravel Depth	15.57	96.9	100.0	81.7
Ground Surface	17.40	99.4	100.0	46.7
CHU3-C5-D1	17.27	99.4	100.0	46.7
CHU3-C5-D2	17.06	99.3	100.0	64.5
CHU3-C5-D3	16.90	100.0	100.0	83.8
CHU3-C5-D4	16.70	100.0	100.0	89.2
CHU3-C5-D5	16.49	100.0	100.0	92.1
CHU3-C5-D6	16.01	100.0	100.0	77.3
CHU3-C5-D7	15.58	94.0	100.0	64.1
Gravel Depth	15.53	94.0	100.0	64.1
Ground Surface	17.98	100.0	100.0	86.9
CHU3-C6-D1	17.85	100.0	100.0	86.9
CHU3-C6-D2	17.65	100.0	100.0	86.5
CHU3-C6-D3	17.49	100.0	100.0	87.5
CHU3-C6-D4	17.32	100.0	100.0	82.1
CHU3-C6-D5	17.17	99.9	100.0	47.9
CHU3-C6-D6	17.03	99.9	100.0	27.0
CHU3-C6-D7	16.85	99.8	100.0	13.0
CHU3-C6-D8	16.65	100.0	100.0	19.2
CHU3-C6-D9	16.48	81.2	100.0	26.4
Gravel Depth	16.40	81.2	100.0	26.4
Ground Surface	17.57	100.0	100.0	80.1
CHU3-C8-D1	17.41	100.0	100.0	80.1
CHU3-C8-D2	17.13	100.0	100.0	78.2
CHU3-C8-D3	16.94	100.0	100.0	74.8
CHU3-C8-D4	16.76	100.0	100.0	74.6
CHU3-C8-D5	16.54	100.0	100.0	80.0
CHU3-C8-D6	16.26	100.0	100.0	80.7
CHU3-C8-D7	16.03	100.0	100.0	87.9
CHU3-C8-D8	15.82	100.0	100.0	87.0
CHU3-C8-D9	15.60	100.0	100.0	89.4
CHU3-C8-D10	15.27	88.6	100.0	74.4
Gravel Depth	15.02	88.6	100.0	74.4
Ground Surface	17.97	100.0	100.0	79.4
CHU3-C9-D1	17.84	100.0	100.0	79.4
CHU3-C9-D2	17.65	100.0	100.0	86.8
CHU3-C9-D3	17.51	100.0	100.0	89.8
CHU3-C9-D4	17.28	100.0	100.0	95.5
CHU3-C9-D5	17.06	100.0	100.0	76.1
CHU3-C9-D6	16.89	100.0	100.0	28.5
CHU3-C9-D7	16.67	100.0	100.0	19.5
CHU3-C9-D8	16.46	100.0	100.0	10.6
CHU3-C9-D9	16.27	91.5	100.0	11.6
Gravel Depth	16.17	91.5	100.0	11.6

Appendix 4

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The role of oxbow lakes in the off-channel storage of bed material along the Ain River, France

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ABSTRACT

Incidents of chute cutoff redistribute floodplain sediment into rivers, causing downstream bar growth while simultaneously creating accommodation space for the storage of sediment within the floodplain in the form of oxbow lakes. Oxbows may be able to sequester enough sediment to balance the amount produced by chute incision, but the long-term consequences of chute cutoff on reach-scale sediment budgets have so far remained unclear. This has been due to a relative paucity of field observations that quantify the exchange of coarse sediment between the channel and floodplain. Here, we take advantage of a unique opportunity to document the sediment budget of a reach of the Ain River, France, that has experienced three recent incidents of chute cutoff. Monitoring of the river prior to chute incision allowed us to precisely quantify the rates of bed-material transfer over a thirteen-year period using a combination of bathymetric surveys, LiDAR data, and aerial photographs. The abandoned channels under study sequestered between 17 and 40% of the sediment introduced to the channel, with most of the rest of the sediment being stored within the river itself. Aggradation of the abandoned channels was not evenly distributed, instead occurring by the growth of point bars and thus implying that the abandoned channel planform may be an important control on aggradation rates. Our results make clear that although oxbows may provide a significant sink for bed material, the amount of sediment sequestered within them cannot compensate for the loading caused by chute incision.

1. Introduction

The incision of chutes into floodplains can introduce substantial volumes of sediment into meandering rivers, enhancing downstream bar development and potentially riverbank erosion as well (Dietrich and Smith, 1983; Hooke, 1995; Constantine, 2006; Kean et al., 2009; Le Coz et al., 2010; Zinger et al., 2011). Along the Wabash River, USA, Zinger et al. (2011) documented incidents of chute incision that introduced over a million cubic meters of sediment to the channel or more than six times the average yearly load introduced by bank erosion alone. Although such loadings of sediment result in bar formation downstream of where the floodplain is incised, chute incision might also affect channel dynamics via the evolution of the oxbow lakes it produces. Chute incision causes the river to bifurcate into two channel segments, and in many cases, the older channel is transformed into an oxbow that sequesters fine-grained sediment delivered during floods (Gagliano and Howard, 1984). During the transition to an oxbow lake, however, bed material (i.e., coarse riverbed sediment) is delivered to the older channel segment until sufficient riverbed aggradation produces sediment plugs that disconnect the channel from the continuous supply of flow and sediment (Fisk, 1947; Bridge et al., 1986; Erskine et al., 1992; Hooke, 1995; Rowland et al., 2005; Citterio and Piegay, 2009; Constantine et al., 2010; Gautier et al., 2010; van Dijk et al., 2012). Bed material that is transferred from the river during this time should limit the downstream supply of sediment that would otherwise be available for bar building. Recent empirical work along the Mississippi River, USA, has indicated that nearly a third of the bed-material load in transport during flood conditions may be sequestered within the floodplain (Nittrouer et al., 2012). Channel segments that result from chute cutoff access a range of flows over a relatively continuous duration and so may sequester even greater proportions of the bed-material supply.

Although oxbows have been identified as important sinks for sediment (Lauer and Parker, 2008), it remains unclear what the long-term (i.e., decadal) effects of chute cutoff are on the reach-scale sediment budget of a meandering river. In essence, can oxbows sequester enough bed material to balance the volume introduced to the river by chute incision? So far, efforts to quantify the role of oxbows in sequestering sediment have either focused solely on fine-grained sedimentation during floods (Aalto et al., 2008) or been intermittent and qualitative, thus preventing their inclusion in reach-scale sediment budgets. Complicating attempts to assess the role of oxbows as sinks for bed material is that any influence of an abandoned channel segment on the reach-scale bed-material budget of a freely meandering river would likely persist only over a short duration. Field observations suggest

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that aggradation by bed material rapidly reduces the open-water volume of the channel segment and can promote the transition of the channel into terrestrial habitat within decades of cutoff (Constantine et al., 2010; Kleinhans et al., 2010). Nonetheless, even if the maximum capacity for storing bed material is achieved within decades, an abandoned channel segment may capture up to 85% of the upstream bed-material supply while it remains hydraulically connected to the main channel (Lindner, 1953).

Recent chute cutoffs along the Ain River, France, provide a unique and important opportunity to assess the role of oxbows in the storage of bed material from freely meandering rivers. Bed-material exchange between the channel segments and the river was documented from

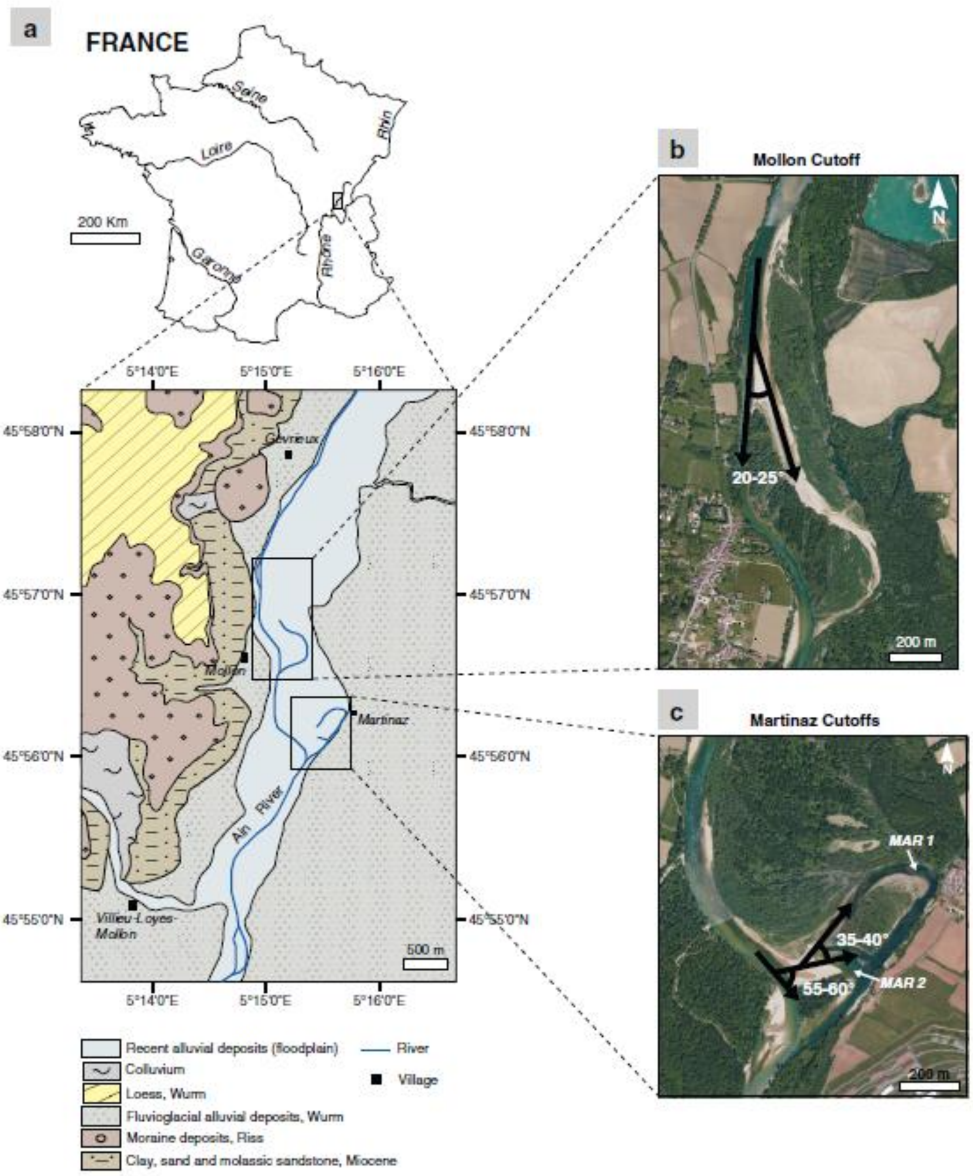

Fig. 1. Location maps and aerial photographs of the study area. (a) Map showing the location of the study area (black rectangle) relative to the major rivers of France. The inset shows a generalized geological map of the study area highlighting our study reaches. Key villages in the study area are also highlighted. (b) Aerial photograph of the Mollon (*MOL*) study reach in 2005. The abandoned channel is shown only 2–3 years after cutoff and is almost completely filled. The arrows show the angle between the active channel and the abandoned channel, the diversion angle, which equals 20°–25° for *MOL*. Images are courtesy of Google Earth™ mapping service. (c) Aerial photograph of the Martinaz (MAR) study reach in 2005. There were two cutoff events that isolated *MAR1* in 2002–2003 (diversion angle of 35°–40°) and *MAR2* in 2005 (diversion angle of 55°–60°).

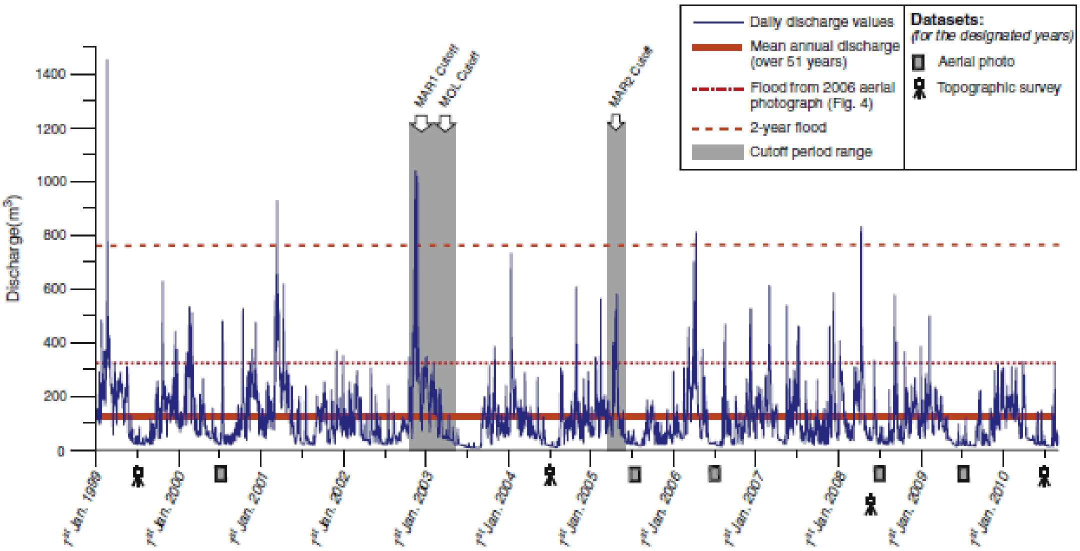

Fig. 2. Plot of the average daily discharge at gaging station Chazey-sur-Ain, Ain River, for the period January 1, 1999 to August 31, 2010. The solid line is the average annual discharge calculated over 51 years. The dashed line is the two-year flood measured over the same period. The dotted line is the discharge corresponding to the flood event that inundated the former channels in 2006. The vertical gray bars represent the periods over which each of the cutoffs developed. Key times of data collection either from topographic surveys or aerial photographs are also shown.

detailed, unpublished bathymetric data prior to cutoff and periodically after cutoff. Here, we supplement the data with our own efforts to examine in detail not only the historical transfer of sediment into the water bodies, but also the potential for abandoned channel segments to function as sources of bed material to the main channel. We assess the potential controls on bed-material transfer and demonstrate the importance of this transfer on the reach-scale sediment budget. In addition to providing important observations of the controls on the alluviation of oxbows by bed material, the findings should inform theory that attempts to explain the transfer of bed material through freely meandering rivers and the effects of this transfer on meandering dynamics.

2. Study setting

The 185-km long Ain River drains 3672 km^2 of eastern France (Fig. 1), emptying into the Rhône River with an average annual discharge of 120 m^3 s^{-1} (as determined at the Chazey-sur-Ain gaging station for the period 1958–2011). The 2- and 10-year discharges for the river near its junction with the Rhône are 760 and 1200 m^3 s^{-1}. The upper 160 km of the river is incised within the limestone gorges of the Jura Mountains, and the lower 40 km flows largely unhindered through a large alluvial plain (Piegay et al., 2000), though outcrops of Jurassic limestone and the presence of resistant Pleistocene moraine deposits limit bank erosion at locations. Declining grazing activity from a maximum during the early 20th century has enabled recent riparian forest growth, which may have resulted in channel narrowing at locations (Marston et al., 1995).

Our study reach was located 20 km upstream of the confluence of the Ain and the Rhône, where chute cutoff isolated three channel segments near the villages of Mollon and Martinaz (Fig. 1). Downstream bed slope within the study reach ranges between 1.2 and 1.8‰ (Piegay et al., 2002), and the median grain size of surface bar sediment gradually fines downstream from 46 to 22 mm (Rollet, 2007; Lassettre et al., 2008). Dam construction that occurred between

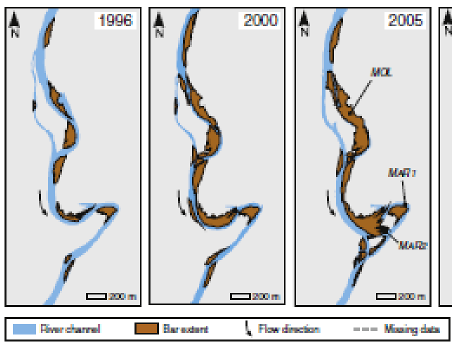

Fig. 3. Bar development along our study area between 1996 and 2009 measured from aerial photographs. Major changes in channel planform correspond to increases in the surface area of sediment. In particular there is rapid infilling of the MOL reach and progressive expansion of the MAR1&2 plug after cutoff between 2000 and 2005.

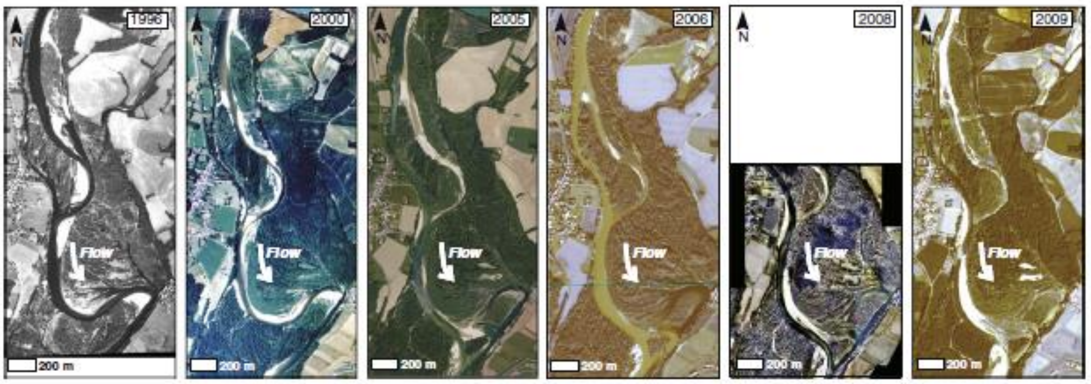

Fig. 4. Aerial photographs showing the Ain River in our study area between 1996 and 2009. Our studied cutoff events occur between the 2000 and 2005 photographs. The 2005 photograph highlights the rapid sedimentation in the upstream (*MOL*) reach. The 2006 photograph shows inundation of the cutoff channels during a flooding discharge of 264 $m^3 s^{-1}$.

1928 and 1970 reduced sediment delivery to the study site, but the geomorphic effects have not yet been observed in our study reach (Rollet et al., 2005), perhaps due to minimal impacts on flood flows (Fig. 2). Rollet (2007) estimated the modern bed-material transport capacity for the reach to equal 37,000 t yr^{-1} (or 14,000 $m^3 yr^{-1}$) using bed-material transport calculations applied at cross-sections. The calculations were supported by field observations during different flow events using PIT-tags and scour chains for detecting entrainment discharge, particle transport distance, and scour layer thickness.

Unlike the cutoff channels reported by Rollet et al. (2005), the channel segments under study have not been restored, and land use practices have not interfered with natural patterns of sediment transfer and deposition. Two channel segments were successively produced by chute incision near Martinaz, hereafter denoted *MAR*1 and *MAR*2. *MAR*1 formed after a major flood (discharge was greater than $10^3 m^3 s^{-1}$) between October 2002 and February 2003, and *MAR*2 formed between March and May 2005 (Figs. 2–4). The third channel segment was produced in 1996 by chute incision nearly a kilometer upstream of the *MAR* sites near the village of Mollon (hereafter *MOL*). The incision lead to a stable bifurcation (see Grenfell et al., 2012) until the chute evolved into the dominant conveyor of discharge between February and May 2003, forcing the gradual abandonment of a 1.42-km long channel segment (Figs. 3 and 4).

Theoretical and experimental results indicate the existence of a flow separation within the upstream entrances of hydraulically connected channel segments, the size of which is determined by the angle by which flow is diverted from the main channel (Taylor, 1944; Law and Reynolds, 1966; Hager, 1984; Neary and Odgaard, 1993; Keshavarzi and Habibi, 2005; Constantine et al., 2010); the larger the angle, the larger the width of the flow separation. The size of the flow separation controls the competence of the diverted flow, enhancing plug formation with increases in the width of the separation (Fisk, 1947; Bridge et al., 1986; Shields and Abt, 1989; Constantine et al., 2010). In the case of our study sites, *MOL* had a diversion angle of 20–25°, *MAR*1 a diversion angle of 35–40°, and *MAR*2 a diversion angle of 55–60° (Fig. 1), measured using the earliest available images following cutoff (Fig. 4).

3. Methodology

We used a range of data sets to assess morphologic change within the channel segments of our study reach. Subaerial bar growth within the river and channel segments was monitored using regularly taken aerial photos between 1996 and 2009 (Figs. 3 and 4), which were georeferenced with an average root mean square error of 1.99 m. The aerial photos were supplemented with low resolution (15–30 m) Landsat images obtained from the Earth Resources Observation Systems Data Center of the USGS and available for the period 1999–2010 with a frequency of every 15 days to a month, allowing us to date cutoff initiation (Table 1). A longitudinal profile along the main channel was collected in 1999 during low-flow conditions using a total station (measurement uncertainty of <5 cm) with an average of 1 point per 50 m, distributed along geomorphic forms so that all changes in slope conditions were surveyed (i.e., all riffles were precisely located) (Citterio and Piegay, 2000; Piegay et al., 2002; Rollet et al., 2005). The profile provided a reference of the channel prior to the three incidents of chute cutoff. Regularly spaced topographic cross-sections of the channel and floodplain were also collected through the study reach in 2004 and in 2008 by researchers from CNRS and Cemagref. An airborne LiDAR survey was conducted in 2008, which provided a bare-Earth DEM (horizontal scale 25 cm) of the reach at low flow. Finally, we surveyed subaerial oxbow topography with a differential-GPS (hereafter DGPS) in the summer of 2010, with measurements having an average vertical and a horizontal precision of ±2.5 cm. Longitudinal profiles through the oxbows in 2008 and 2010 were constructed along the 1999 profile course using the LiDAR and field survey data.

Volumetric storage of sediment along the river reach was calculated using three different methods based on data availability. We first used the morphologic budget approach (Goff and Ashmore, 1994; Martin and Church, 1995; Lane, 1997; Ham and Church, 2000; Fuller et al., 2002; Martin, 2003; Surian and Cisotto, 2007), which calculates volumetric change using topographic differences between similarly located cross sections taken at different times (in our case, in 2004 and 2008) multiplied by the reach length. The morphologic budget approach does not consider changes in topography between cross-sections and

Table 1
Summary of the images used for the study.

Images type	Period	Temporal resolution	Spatial resolution	Use	Source
Aerial photos	1945–1996	1–9 years	0.63–1 m	To observe the channel evolution	IGN (National Geography Institute, France)
Aerial photos	1996–2009	1–5 years	0.63–2.4 m	To measure the diversion angles and the growth of bars	IGN
Landsat images	1999–2010	15 days to monthly	15–30 m	To date the cutoffs	USGS (L7 ETM)

Table 2
Budgets calculated using different interpolation methods for the period 2008-2010.

Interpolation method	Volume at MOL (m^3)	Volume at MAR1 + MAR2 (m^3)
IDW (inverse distance weighted)	6770	−4840
Kriging	5880	−5200
Natural neighbor	7160	−8640
TIN	7410	−8350
Mean value for interpolations	6800	−6760
% deviation from mean	10	−30
Calculation from cross sections	6100	–

so may underestimate volumetric flux (Lane et al., 1995; Fuller et al., 2003a; Bertoldi et al., 2009). The second approach was based on differences in a DEM interpolated from the survey data collected in 2010 and the 2008 LiDAR-based DEM. We assessed the sensitivity of the quality of the 2010 DEM to interpolation schemes by comparing differences in the DEM when it was constructed using inverse distance weighted, kriging, natural neighbor, and triangulated irregular network methods. The standard deviation of the volumes obtained by the different interpolation schemes was equal to 10% of the mean value for *MOL* and 30% for *MAR*1 and *MAR*2 (Table 2). The third approach provided an estimate of the overall volumetric aggradation within submerged portions of the channel segments from the moment each formed until the DGPS survey in 2010. For this, we assumed that the deepest portion of the 2010 submerged surface roughly represented the elevation of the original channel surface. Post-cutoff alluvium thickness was then estimated as the elevation difference across the submerged surface and the elevation of the deepest portion. The point measurements of alluvium thickness were integrated across the submerged surveyed surfaces to provide minimum estimates of volume.

4. Results

4.1. Patterns of channel adjustment following cutoff

The longitudinal profiles provided an indication of how the study reach responded to the three incidents of chute cutoff. The 1999 and 2008 longitudinal profiles represent the channel form before and after the formation of the three channel segments; the 2008 topographic data were collected five years after cutoff for *MOL* and *MAR*1 and three years after cutoff for *MAR*2 (Fig. 5). The discontinuities observed in the 1999 profile (points 9 and 23) were natural breaks in slope that can also be observed at several other locations on the river and did not appear to be associated with major changes in bar development. Within this time frame, nearly 0.3 m of degradation occurred within the riverbed upstream of *MOL* while up to 1.5 m of aggradation occurred throughout the length of *MOL*. Similarly, nearly 1.5 m of aggradation occurred within the first 500 m of *MAR*1, although 0.5 m of degradation occurred over the next 250 m of the channel. In spite of this degradation, sediment plugs fully disconnected the upstream entrances of the channel segments from continuous flow by 2008. Between 2008 and 2010, *MOL* aggraded by as much as 0.2 m within its entrance, but degraded by roughly 0.4 m throughout the remainder of its length (Fig. 5). During this time frame, *MAR*1 experienced up to 0.2 m of degradation within its upstream limb and then 0.75 m of degradation within its downstream limb.

Five locations of cross-section data for the study reach were available for years 2004, 2008, and 2010. Each location was assigned a letter for ease of reference as shown in Fig. 6. The cross sections from 2004 represent the topography one year after the abandonment of *MOL* and *MAR*1 and one year before the abandonment of *MAR*2. Between 2004 and 2008, net aggradation occurred at all locations except for location *A*, the main channel upstream of the entrance to *MOL*. Much of the aggradation, up to 1–2 m, occurred within the entrances into the channel segments (see locations *B* and *D*). Further, the channel bed at location *E* aggraded by up to 0.5 m, with aggradation occurring uniformly across the section from bank to bank. Between 2008 and 2010, the upstream entrance to *MOL* aggraded by between 0.2 and 0.5 m, unlike at the entrances to the *MAR* sites, which degraded by between 0.3 and 0.8 m (Fig. 6).

Bed aggradation followed similar temporal patterns within the three channel segments, occurring most rapidly right after cutoff in each case and primarily along a pre-existing point bar. For example, between 2000 and 2009, the point bar within the upstream entrance to *MOL* increased by nearly two fold in surface area, from 81,000 to 160,000 m^2, similar to the bar within the upstream entrance to *MAR*1, which increased in surface area from 58,000 to 116,000 m^2 (Figs. 3 and 6). Results from the 2010 DGPS survey of the inundated portions of the channel segments also indicated the role of bar

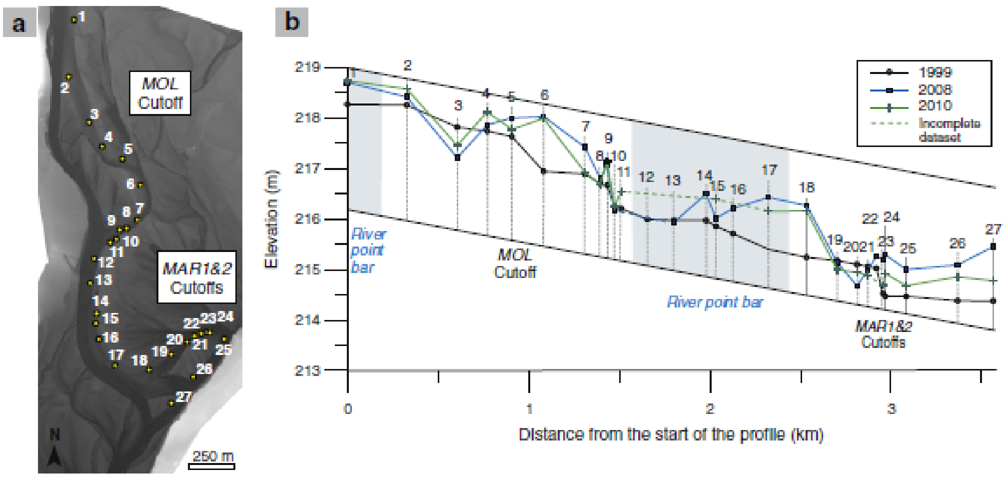

Fig. 5. Changes in the longitudinal profile for our study reach. (a) LiDAR image from 2008 showing the location of data points used for the longitudinal profile. (b) Longitudinal profiles collected on bars using a total station and differential GPS for the years 1999, 2008, and 2010. The 1999 profile was taken before cutoff, and we estimated changes in sedimentation for the study reach by differencing the 2008 and 2010 profiles. Major river features (cutoffs and point bars) are shown on the plot for reference.

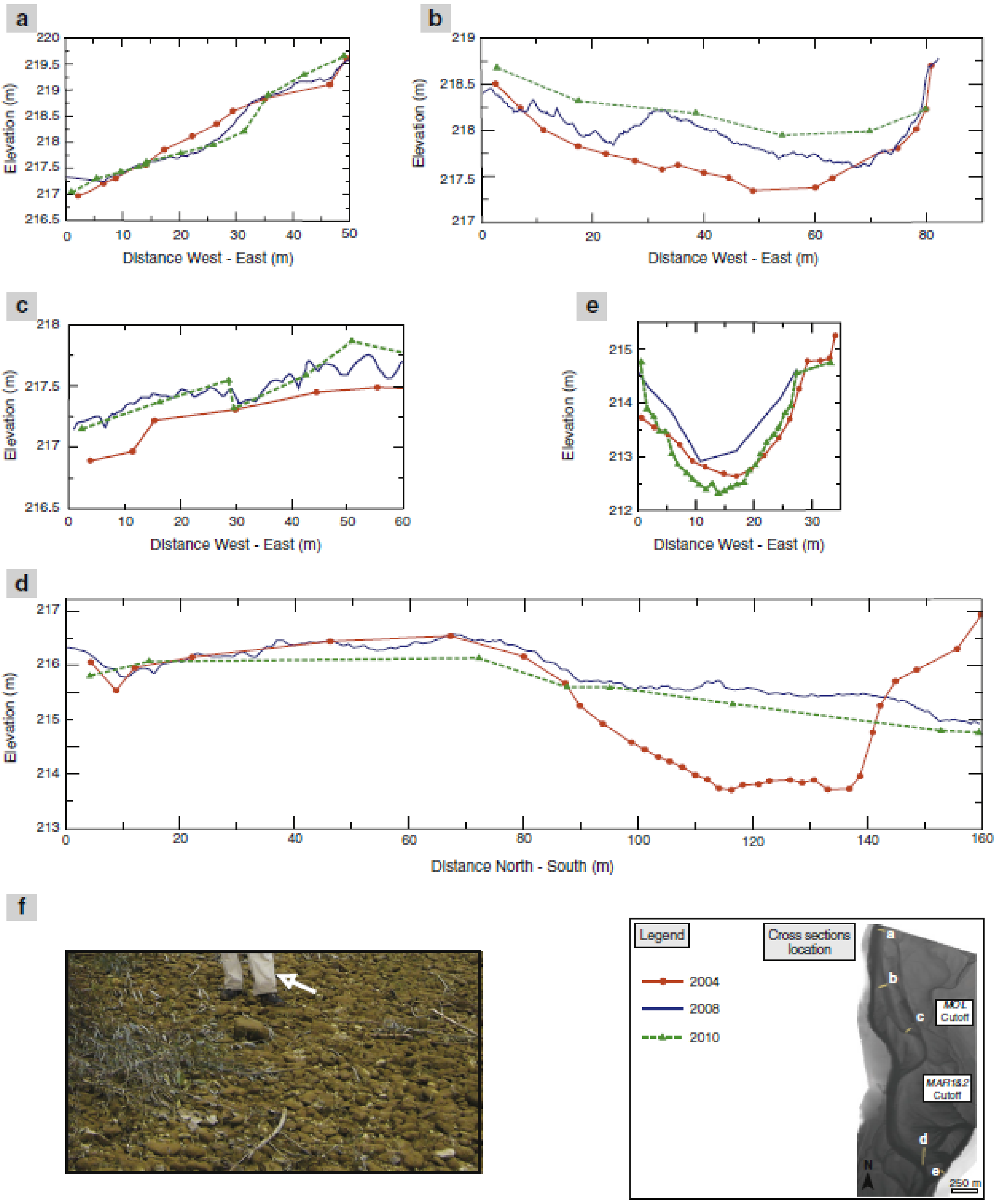

Fig. 6. Cross sections collected along our study reach for the years 2004, 2008, and 2010. Cross section locations are shown on a LiDAR image from 2008, with cross section "a" representing the most upstream location. Differencing of cross sections allowed us to calculate a sediment budget for 2004–2008 and 2008–2010. (f) Photograph of the coarse-grained infill of the *MOL* cutoff taken in 2011 near cross section "c"; the deposits represent the typical infill of all the cutoff channels in our study reach.

growth in the alluviation process within *MOL* (Fig. 7a). At this site, the submerged bar extended across the channel to considerably narrow the pool along the outer bank. The extent of bar growth within the MAR sites was not clear from the DGPS data. The deepest portions of the channels were downstream of the apices, between presumable zones of aggradation within the upstream and downstream limbs.

4.2. Estimates of off-channel bed-material storage

Estimates of the volumetric storage of sediment throughout the study utilized the morphologic budget approach for the time period between 2004 and 2008, DEM differencing over subaerial bars for the time period between 2008 and 2010, and the DGPS survey for the time period between 2003 and 2010 (see Section 3). We combined the results of the morphologic budget approach with those of the DEM differencing for the subaerial sections of the channel segments, producing an estimate of volumetric exchange for the period between 2004 and 2010 within the entrances to each of the sites. The estimates revealed that the main channel was net-degradational from 2004 to 2008, losing 70,000 m^3 (or 17,500 $m^3\ y^{-1}$) of sediment as the river continued to evolve in response to the abandonment of *MOL* (Fig. 8). Conversely, *MOL* was a site of net aggradation between 2003 and 2010, gaining 34,000 m^3 (or 4900 $m^3\ y^{-1}$) of sediment as increasingly less discharge was being routed through it. Using Rollet's (2007) calculation of the average bed-material transport capacity (see Section 2) as an estimate of the annual bed-material load into the reach, *MOL* was able to sequester nearly 40% of the 14,000 $m^3\ yr^{-1}$ supply into the reach between 2003 and 2010. Slightly complicating the assessment of *MOL* is that the portion of the reach immediately upstream of the entrance to *MOL* lost at least 9000 m^3 of sediment between 2004 and 2008, or 2250 $m^3\ yr^{-1}$ (Fig. 8). Assuming that Rollet's (2007) estimate is most relevant for graded (i.e., inputs of bed material equal outputs) sections of the river, the additional loading likely due to chute enlargement would lower the amount sequestered to 34% of the supply.

Between 2004 and 2008, chute enlargement at *MOL* delivered at least 61,000 m^3 (or 15,250 $m^3\ y^{-1}$) of sediment to the downstream reach hosting the *MAR* sites. The total loading to the downstream reach was likely higher given additional upstream bed-material inputs. For instance, if the 2250 $m^3\ y^{-1}$ of loading derived from the upstream entrance to the study reach was entirely sequestered by *MOL*, the site would only be able to sequester 3280 $m^3\ y^{-1}$ of the annual bed-material load into the reach. Consequently, the total loading into the downstream reach was on the order of 26,000 $m^3\ y^{-1}$ (i.e., 14,000 $m^3\ y^{-1}$ + 15,300 $m^3\ y^{-1}$–3,300 $m^3\ y^{-1}$). From the estimates of volumetric storage (Fig. 8), the main channel adjacent to the *MAR* sites gained 9000 m^3 (or 2250 $m^3\ y^{-1}$) of sediment, or 9% of the supply from chute enlargement and upstream loading. The *MAR* sites, on the other hand, gained 30,000 m^3 (or 4400 $m^3\ y^{-1}$) of sediment between 2003 and 2010. Comparing average annual rates, the *MAR* sites were able to sequester 17% of the chute-enlargement supply, 43–50% less than rates of bed-material sequestration at *MOL*. The main channel downstream of the *MAR* sites gained 43,000 m^3 (or 10,750 $m^3\ y^{-1}$) of sediment between 2004 and 2008, or more than 41% of the chute-enlargement supply, implying that the majority of sediment derived from chute enlargement at *MOL* was stored within the river and the channel segments at *MAR*.

Estimates of the volumetric storage of sediment between 2008 and 2010 using DEM differencing (see Section 3) indicated that the entrance to *MOL* gained only 6800 m^3 (or 3400 $m^3\ y^{-1}$) of sediment and the upstream entrance to the *MAR* sites began to erode (Fig. 9). In particular, 2300 m^3 of sediment was removed from the entrance to *MAR*1, and 2000 m^3 of sediment was removed from the entrance to *MAR*2 during this time period. It remains unclear the reason for the erosion of plug deposits at the *MAR* sites, but 85 m of bank erosion occurred between 2005 and 2010 (Figs. 3 and 9), shifting the channel margin closer to the sediment plugs, perhaps making it easier for flood flows to access and mobilize plug deposits.

5. Discussion

The transfer of bed material from the river to an abandoned channel segment while it is still hydraulically connected reduces the bed material load to the downstream reach, which could instigate the removal of bed material from within the main channel. In cases of

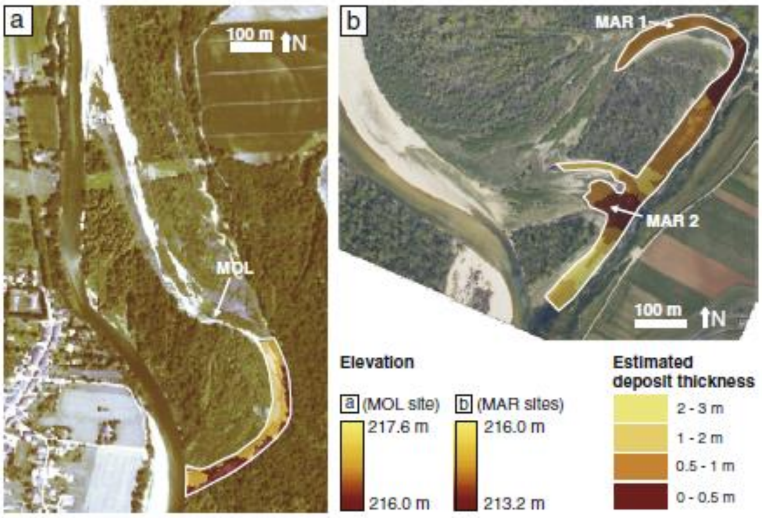

Fig. 7. Estimates of sediment infill thickness in submerged areas of the abandoned channels seven years after cutoff based on our DGPS survey in 2010. (a) Infill thickness data of *MOL* portrayed within the aerial photo of the site in 2009. (b) Infill thickness data of *MAR*1 and *MAR*2 portrayed within the aerial photo of the sites in 2010.

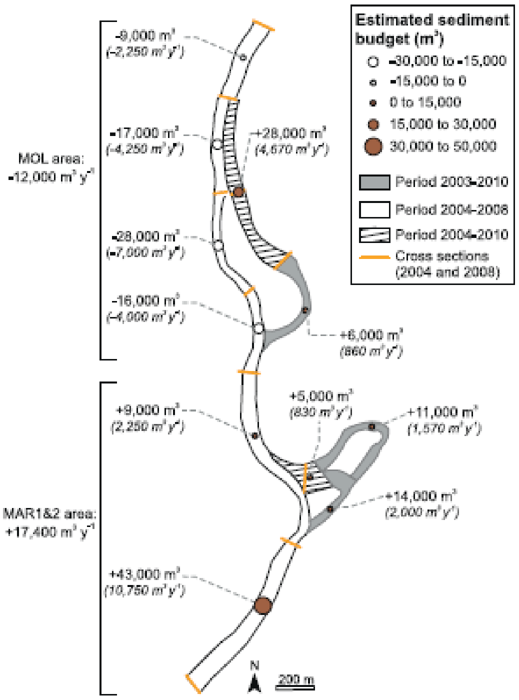

Fig. 8. Schematic representation of the sediment budget for the study area between 2003 and 2010. The reach was divided into segments based on the distribution of cross sections and an individual budget (represented by circles) calculated for each sub-reach. The *MOL* zone showed net erosion while the *MAR1* & 2 zone showed net deposition during this period. Dark circles indicate the dominance of aggradation over degradation, whereas white circles indicate the dominance of degradation over aggradation. Gray areas represent the budget calculated from a 2010 DTM of the submerged areas (see also Fig. 3). White areas represent the budget calculated from 2004 and 2008 cross sections. Striped areas represent the budget calculated using cross sections for the period 2004–2008 and DTMs from 2008 to 2010.

chute cutoff, however, the evolving chute significantly increases the bed-material load of the river (see also Zinger et al., 2011), more than compensating for off-channel sequestration. Within our study reach, chute enlargement at *MOL* delivered up to 15,250 $m^3\ yr^{-1}$ to the river between 2004 and 2008, nearly equivalent to the bed-material transport capacity of the river. Given that chute enlargement occurs contemporaneously with a reduction in discharge through the abandoned channel, chute enlargement should then effectively limit the duration that bed-material is transported through the abandoned channel. Bed-material sequestration would also reduce the discharge diverted into the abandoned channel, thereby facilitating the chute enlargement process. Further, and consistent with our observations, Fuller et al. (2003b) found that a chute incised within the floodplain of the River Coquet, UK, continued to supply sediment to the downstream reach years after the abandoned channel was plugged. Our results suggest that the predominant effect of chute cutoff on the reach-scale sediment budget of a meandering river is a net-increase in the bed-material supply that could last for years after the initial chute incision. This increase in bed-material supply should instigate bar building and potentially increased bank erosion as bar growth would alter flow conditions within downstream meander bends, increasing boundary shear stress conditions along riverbanks (Dietrich and Smith, 1983; Whiting and Dietrich, 1993; Constantine, 2006).

The sedimentary deposits of oxbows have been shown to influence meander migration rates (Hudson and Kesel, 2000), the width of the meander belt (Allen, 1965; Howard, 1996; Sun et al., 1996), and the hydrogeological characteristics of alluvial reservoirs (Richardson et al., 1987), but many efforts that examine the role of oxbow deposits in meandering behavior and floodplain development presume that they consist primarily of the finest fractions of sediment in transport. Although bed-material storage within the abandoned channel segments of our study did not compensate for the delivery of sediment by chute incision, the sites managed to sequester between 17 and 40% of the bed-material supply over seven years. In concert with empirical evidence that much of the deposits of oxbows formed by chute cutoff tend to be coarse (i.e., bed-material derived) (see Fisk, 1947; Bridge et al., 1986; Hooke, 1995; Constantine et al., 2010) (Fig. 6F), it appears that chute cutoff creates important off-channel sites for bed-material storage and that oxbows do not always create the clay plugs that are commonly associated with them. The coarse deposits within our study sites also remained mobile as aggradation proceeded. The plugs of the *MAR* sites became a source of sediment as 4300 m^3 of sediment was mobilized between 2008 and 2010 during overbank flows. This is potentially significant as oxbows may have a dualistic function with regard to the bed-material budget of a meandering reach, functioning as significant sinks for bed material immediately following cutoff, but then as sources in the long term as flood flows or the lateral shifting of the meandering river mobilizes the coarse deposits.

Our results provide insight into the mechanisms driving the transfer and storage of bed material within oxbows. Aggradation primarily occurred along inner bends of pre-existing point bars (Fig. 3), and the role of point bar growth in oxbow aggradation was also observed within abandoned channels of the Yangtze River, China (Li et al., 2007) and the Sacramento River, USA (Constantine et al., 2010). Some evidence for the process was reported from sedimentological work along the Mississippi River, USA (Fisk, 1947), the Calamus River, USA (Bridge et al., 1986), and the Rhine delta apex, Netherlands (Toonen et al., 2012). The pervasiveness of the observations suggests that the transverse transport of bed material driven by cross-stream currents is an important mechanism in transforming the open-water volume of abandoned channel segments. If true, then the planform curvature of abandoned channels is an important control on both plug development and the open-water volume that oxbows inherit upon their formation. However, the ability of curvature-induced forces to alter the downstream flow path through an abandoned channel will depend on the magnitude of discharge diverted from the main channel. This diverted discharge is a function of the discharge conditions of the main channel, the conveyance capacity of the entrance, and the diversion angle (see Section 2) (Constantine et al., 2010). As described, the diversion angle limits the diverted discharge by controlling the size of a flow separation within the entrance that induces pressure drag on the diverted current. Low diversion angles should allow for the maintenance of downstream currents capable of transporting bed material and perhaps also the cross-stream currents responsible for bar development. Indeed, the three sites each had relatively low diversion angles (Fig. 1), consistent with previous observations that such angles allowed for sustained bed-material transport and alluviation by point bar growth (see Fig. 4 of Constantine et al., 2010). Neck cutoff results as the consequence of meander growth and so should produce diversion angles that are greater than those produced by chute cutoff, whose diversion angles will be determined by the planform curvature of the abandoned channel segment and the location where the chute is incised. A global analysis of typical diversion angles associated with each meander cutoff process is required, but that cutoff processes may produce oxbow lakes with characteristically different diversion angles has important implications for the development of the floodplain. The prevalence of either cutoff mechanism may lead to distinct floodplain environments as the abandoned channels they create undergo distinct patterns of alluviation (Fisk, 1947; Constantine et al., 2010).

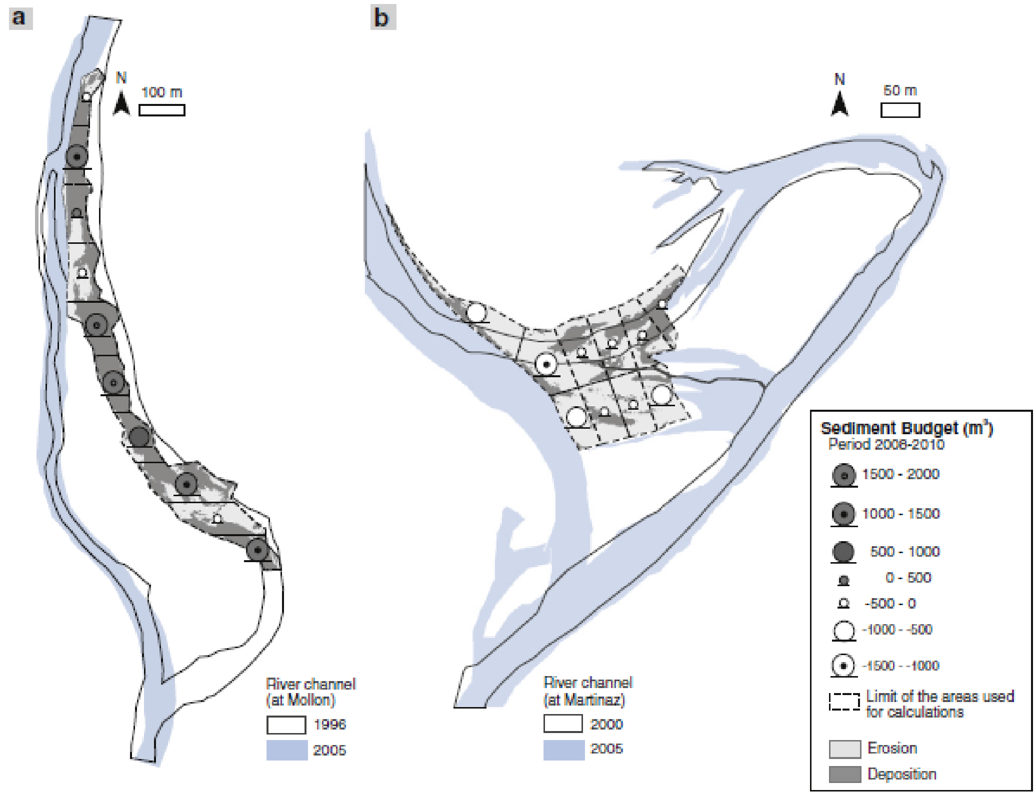

Fig. 9. Representation of sediment mobilization for the period 2008–2010. (a) The *MOL* cutoff site primarily shows areas of net aggradation (dark gray) with up to 2000 m^3 of the deposition of sediment in sub-reaches (dark circles). (b) The *MAR*1 & 2 cutoff site is primarily erosional with up to 1500 m^3 of sediment loss in sub reaches (white circles). The pre- (dark lines) and post-cutoff (gray shaded area) channel forms show the magnitude of channel change caused by the cutoffs.

5. Conclusions

Detailed sediment budget calculations at the reach scale provide a unique opportunity to understand the long-term consequences of chute cutoff to the sediment budget of freely meandering rivers. We investigated a reach of the Ain River, France, where three chute cutoff events supplied significant volumes of sediment to the river. We present a sediment budget for the period immediately post cutoff (2003–2010) calculated from topographic surveys of river cross sections combined with differencing of LiDAR and survey-derived DEM's. After cutoff, 17–40% of the bed material load transport capacity of the river was sequestered within abandoned channel segments, and most of the remaining material was stored within the river where it contributed to bar growth. The predominant effect of chute cutoff on the reach-scale sediment budget of meandering rivers is a net-increase in the bed-material supply that could last for years after chute incision. Within the abandoned channels, pre-existing point bars provided surfaces over which much of the aggradation occurred, suggesting that the planform of abandoned channels may be an important control on aggradation rates. Given the prevalence of chute cutoff as a process along many meandering rivers, the majority of oxbow deposits in nature may not be clay plugs that are often reported, but instead lenses of coarse sediment with significant implications for the alluvial architecture and hydrogeological characteristics of the floodplain.

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