Sediment wave-induced channel evolution following the 2006 avulsion of the Suncook River in Epsom, New Hampshire

by

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S.B. Earth, Atmospheric, and Planetary Sciences (2007)

Massachusetts Institute of Technology

Submitted to the Department of Earth, Atmospheric and Planetary Sciences in Partial Fulfillment of the Requirements for the Degree of Master of Science in Earth, Atmospheric and Planetary Sciences

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ABSTRACT

Large volumes of sediment can be released into a river when an avulsion carves a new channel in the landscape. Gilbert (1917) described the evolution of a similar pulse of material from mining along the Sacramento River, California as a sediment wave. Sediment waves are transient accumulations of sand and gravel that locally increase the elevation of the bed and reduce the transport capacity of the channel, and diffuse and translate down the channel over time.

The Suncook River in Epsom, New Hampshire, avulsed in May 2006. This event created a new channel and mobilized approximately 100,000 m^3 of sand into the river in a period of 12 to 24 hours (Perignon, 2007; Wittkop et al., 2007). In April 2007, a new channel formed through a meander bend downstream of the site of the first avulsion, where sediments mobilized the year before had increased the bed elevation by one meter.

We propose that the material released in 2006 is traveling down the channel as a sediment wave, increasing the elevation of the bed and driving avulsions. The purpose of this study is to model the evolution of a sediment wave in the Suncook River in order to understand how it can increase the risk of floods and avulsions in the system over time.

We developed a mathematical model using the equations of Lisle et al. (1997, 2001) to observe the evolution of the sediment wave under bankfull conditions. We found that the wave evolved mostly through diffusion and showed minimal translation downstream. These findings suggest that the risk of avulsions will be contained near the center of mass of the sediment wave, which we place near the site of the 2007 meander cutoff. Likewise, the diffusive nature of the wave implies that the river could reach a new equilibrium profile with no restoration work and without significantly affecting populated areas downstream.

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I would also like to thank Henry Hallam and Brian Kardon for helping me tackle MATLAB, and Drew Loney for attempting to calculate backwater effects with me late at night. I owe them, and everyone else at pika, cookies.

Andrew Wickert served as my field assistant in September 2007. He also revised my drafts, debugged my code, lent me his computer, and provided me with enough caffeine and chocolate to write all night, every night. He also believed I could finish this thesis more than I ever did, for which I am eternally grateful.

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Chapter 1

Introduction

River channels are not stable features in the landscape. They are constantly but gradually moving side to side as sediments are eroded from the banks and redeposited along the channel. In some cases, they can also switch abruptly to a new position, creating a new channel that captures all or part of the flow of the river. These sudden changes, known as avulsions, take paths that are shorter and steeper than the channels they abandon. Over time, however, the gradual migration of meanders will lengthen the new river, once again prompting new avulsions to occur. The constant evolution of the planform of rivers contributes to the distribution of sediments on the floodplain and the architecture of the landscape.

Avulsions take place in many different environments and over varied length scales. Sudden switches in the positions of channels occur frequently on alluvial fans and deltas, where changes in slope cause rivers to slow down and release the sediment they carry. The high sedimentation rate in these locations causes rivers to become unstable in their channels, triggering avulsions. Rivers also sometimes avulse to shorten their path as they meander on a floodplain, cutting off a large section of the river or only a single bend. This case, in which a straight channel replaces a single meander, is also known as a meander cutoff or a chute.

The Mississippi River has undergone avulsions at all scales. The positions of the individual bends of the river have changed over a period of decades to centuries and have been mapped extensively by the U.S. Army Corps of Engineers (e.g., Figure 1).

Likewise, the Mississippi River delta has changed position at least seven times in the past 5,000 years (Kolb and Van Lopik, 1966) as a result of larger-scale avulsions (Figure 2). Currently, the avulsion of the Mississippi River into the steeper channel of the Atchafalaya River is prevented by the Old River Control Structure, a complex of dams and locks that allocates water between the two rivers. If allowed to flow free, the Atchafalaya would capture most or all of the flow of the Mississippi. Farther downstream, high levees keep the river flowing through New Orleans in a controlled channel with a bed that is higher than the city itself. The position of the channel is gravitationally unstable – without the levees, the Mississippi would quickly avulse to a new path away from its current location.

Figure 1 – Map of the Lower Mississippi River and meander deposits. The active river is white. The mid-gray area on the northwest corner is at a higher elevation than the floodplain (light gray). The darker gray shows meander deposits from previous locations of the channel (Modified from Fisk, 1944).

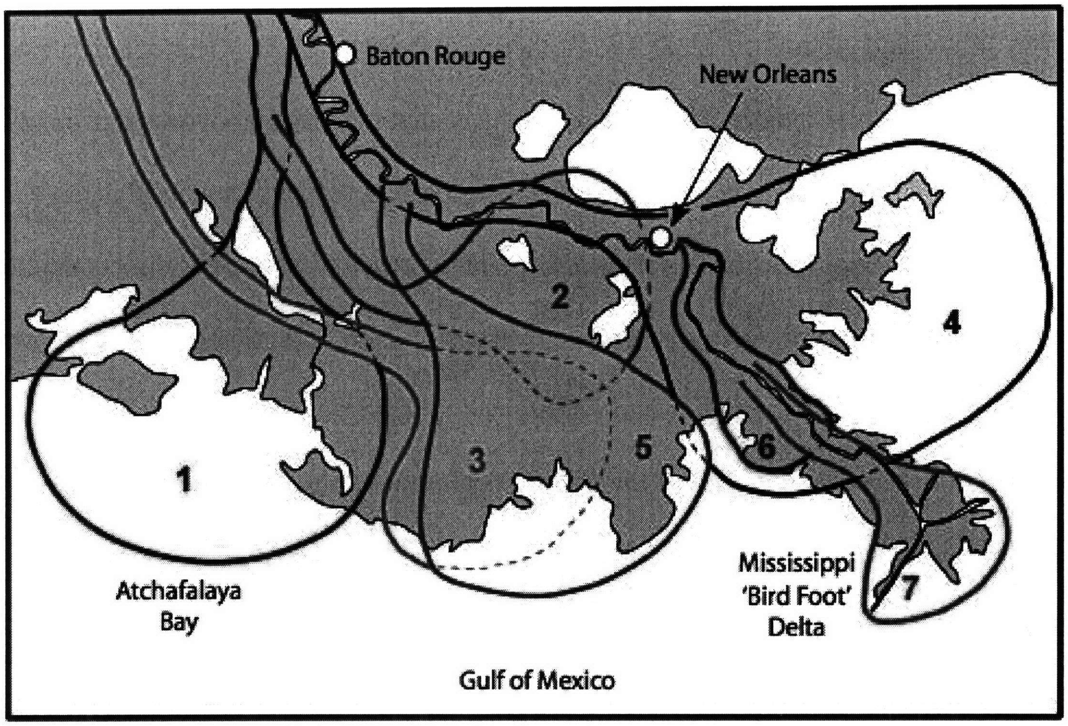


Figure 2: Delta lobes of the Mississippi River. (1) Sale-Cypremont lobe, 4.6 ka. (2) Teche lobe, 3.5-2.8 ka. (3) St. Bernard lobe, 2.8-1.0 ka. (4) Lafourche lobe, 1.0-0.3 ka. (5) Plaquemine lobe, 750-500 years ago. (6) Balize lobe, 550 years ago to present. (Modified from Kolb and Van Lopik, 1966).

Avulsions are a product of the spatial variation of sediment deposition in the landscape. Deposition rates are highest in channels and along their immediate banks (Pizzuto, 1987), creating levee systems and causing the bed elevation of rivers to increase while keeping their cross-sectional shape and transport capacity constant (Mohrig et al., 2000, Makaske, 2001; Makaske et al., 2002; Törnqvist and Bridge, 2002). Two models have been proposed to explain the mechanisms that drive avulsions based on this pattern of sedimentation.

The first model states that avulsions can occur when there is a high ratio between the slope from the water surface to the potential base elevation for a new channel, and the slope of the water surface along the length of the channel (e.g., Allen, 1965; Hooke and

Rohrer, 1979; Wells and Dorr, 1987; Mackey and Bridge, 1995; Slingerland and Smith, 1998, Jones and Schumm, 1999, Törnqvist and Bridge, 2002). The second model suggests that a river avulses when the channel is superelevated above its surrounding floodplains. A superelevated river is one where the bed of the channel is at the same elevation as the floodplain around it. At this point, a breach in the levees directs the flow to the floodplain and drives the river to create a new path (e.g., Brizga and Finlayson, 1990; Bryant et al., 1995; Heller and Paola, 1996; Mohrig et al., 2000). Although they observe different characteristics of the river to determine the potential for avulsions, both models fundamentally describe the same process: a river will avulse when there is a shorter and steeper path to a point downstream.

While the gradual movement of a river in the floodplain is responsible for the continuous erosion and deposition of sediments in a channel, an avulsion can cause the sudden release of a large volume of material into the river that the system might not have the capacity to transport. This causes the patterns of flooding and sedimentation to change drastically, affecting the downstream ecosystems and nearby human environments. Similar catastrophic releases of sediments into the fluvial system can occur from landslides, the erosion of deforested areas, or the release of material from behind a removed dam, as well as with various other human activities. Grove Karl Gilbert studied one of such cases, where debris from hydraulic gold mining in the Sierra Nevada in California severely affected the Sacramento River and its tributaries. By observing the systematic rise and fall of the bed of these rivers over a period of 60 years, Gilbert determined that the material traveled downstream as a wave, much like those in water (Gilbert, 1917). Sediment waves are transient zones of accumulation of sediment that exceed the sediment transport capacity of the river, locally increasing the bed elevation but reducing the flow capacity of the system and thus increasing the risk of floods (Gilbert, 1917; Hoey, 1992; Nicholas et al., 1995; Bartley and Rutherford, 2005). Sediment waves translate and attenuate over time, increasing their length and reducing their height.

The purpose of this study is to understand how the evolution of a sediment wave formed from sediments released during an avulsion can increase the risk of floods and avulsions in the system over time. We specifically studied the Suncook River in Epson, New Hampshire.

In mid-May 2006, heavy rains caused extensive flooding throughout New England. Between 14 May and 15 May, the Suncook River exceeded the discharge expected for a 100-year flood (Perignon, 2007). In the town of Epsom, New Hampshire, the extensive flooding caused the river to avulse. An estimated 100,000 m^3 of sand were removed and released into the river over a period of 12 hours as the river cut into the landscape (Perignon, 2007; Wittkop et al., 2007). Some of those sediments now blanket downstream floodplains, destroying agricultural and grazing lands. Sediments also remain in the channel, where they have raised the bed and increased the flood risk for hundreds of homes (Orff, 2006).

In April 2007, a flood with a recurrence interval of approximately 90 years (Perignon, 2007) occurred in the Suncook River. Because of the effects of the 2006 event, this flood affected numerous homes that had never been flooded before. It further eroded the unstable banks of the newly formed channel and mobilized sediments that had been deposited in 2006. Downstream of the site of the previous avulsion, the flooding river carved a chute through the inside bank of a meander bend, dividing the flow of the Suncook River between two channels.

The purpose of this study is not to develop a new system of equations to describe the movement of sediment waves in alluvial channels, but to use pre-existing models to show that sediment waves can cause avulsions downstream of the input site of a large pulse of sediment. We first present background information on the study site, including the geographic and geologic setting, the 2006 event, and the observations from the 2007 event. We then consider evidence for the presence of a sediment wave in the channel, and adopt a pre-existing mathematical model to understand its behavior. Afterwards, we present the results of a simulation of the behavior of this wave, and observe the effects that it could have on the channel downstream of the site. Finally, we offer our analysis of possible environmental recovery practices that have been proposed for the Suncook River in light of our findings.

Chapter 2

Geographic and geologic setting

2.1. Regional Geology Overview

Bedrock in New Hampshire is composed of strongly deformed Paleozoic metamorphic rocks intruded by several generations of plutonism (Billings, 1956). The Paleozoic rocks form northeast-trending belts perpendicular to the direction of the middle to late Devonian Acadian Orogeny that formed the Appalachian Mountains (Marvinney and Thompson, 2000).

In southern New Hampshire, the bedrock is composed of Ordovician to Silurian metavolcanic and metasedimentary units. The lower member of the Rangeley Formation, a stratified, high-grade metapelite of Silurian age, underlies the study area. The eastern margin of the Suncook River valley is defined by the strike-slip Pinnacle Fault. The Suncook River runs along the strike of the fault as it joins the Merrimack River (Lyons et al., 1997).

During the Late Wisconsinan, the most recent glacial period that started 25 ka, the Suncook River valley was the site of an arm of glacial Lake Hooksett. Ice started retreating 17 ka, clearing New England by 12 ka. The general southeast-northwest trend of movement of these glaciers defined the orientation of glacial forms in the region (Flanagan et al., 1999). Glacial sands and clays from glacial outwash form most of the substrate in our study area.

2.2. Geographic Setting

The Merrimack River flows 254 km from its origin at the confluence of the Pimagewasset and Winnipesaukee rivers near the town of Franklin, New Hampshire, to the Atlantic Ocean at Newburyport, Massachusetts. Its basin covers a total area of 13,000 km^2 and forms the fourth largest watershed in New England (CDM, 2003).

The Suncook River in southern New Hampshire is a minor tributary to the Merrimack River (Figure 3). Its source at Crystal Lake, near the town of Gilmanton, New Hampshire, forms from drainages in the Belknap Mountains. The river flows southwest for 63 km to the town of Suncook, New Hampshire, where it joins the Merrimack River. Along its course the Suncook River receives only one major tributary, the Little Suncook River (Figure 4). The total area of the Suncook River watershed is 663 km^2.

Our study area is located between U.S Route 4 and Short Falls Road, east of Suncook Valley Highway and west of Black Hall Road in the town of Epsom, New Hampshire (Figure 5). Two areas are of special importance in this study: the site of the 2006 avulsion (box A in Figure 5) and the site of the 2007 meander cutoff (box B in Figure 5). The site of the 2006 avulsion is 15 km upstream of the confluence between the Suncook River and the Merrimack River. It can be accessed by traveling along the Suncook Valley Highway and turning onto Old Mill Road to reach the abandoned channel. The avulsion site is 700 meters northeast (upstream) walking along the dry channel. The site of the 2007 avulsion is located 12.5 km upstream of the confluence with the Merrimack River. It is accessed by traveling along Black Hall Road and turning west on Water Street, by the local high school. An unmarked dirt road branches to the south from Water Street. The end of this dirt road is across an area of tall grasses and bushes from the site of the 2007 avulsion.

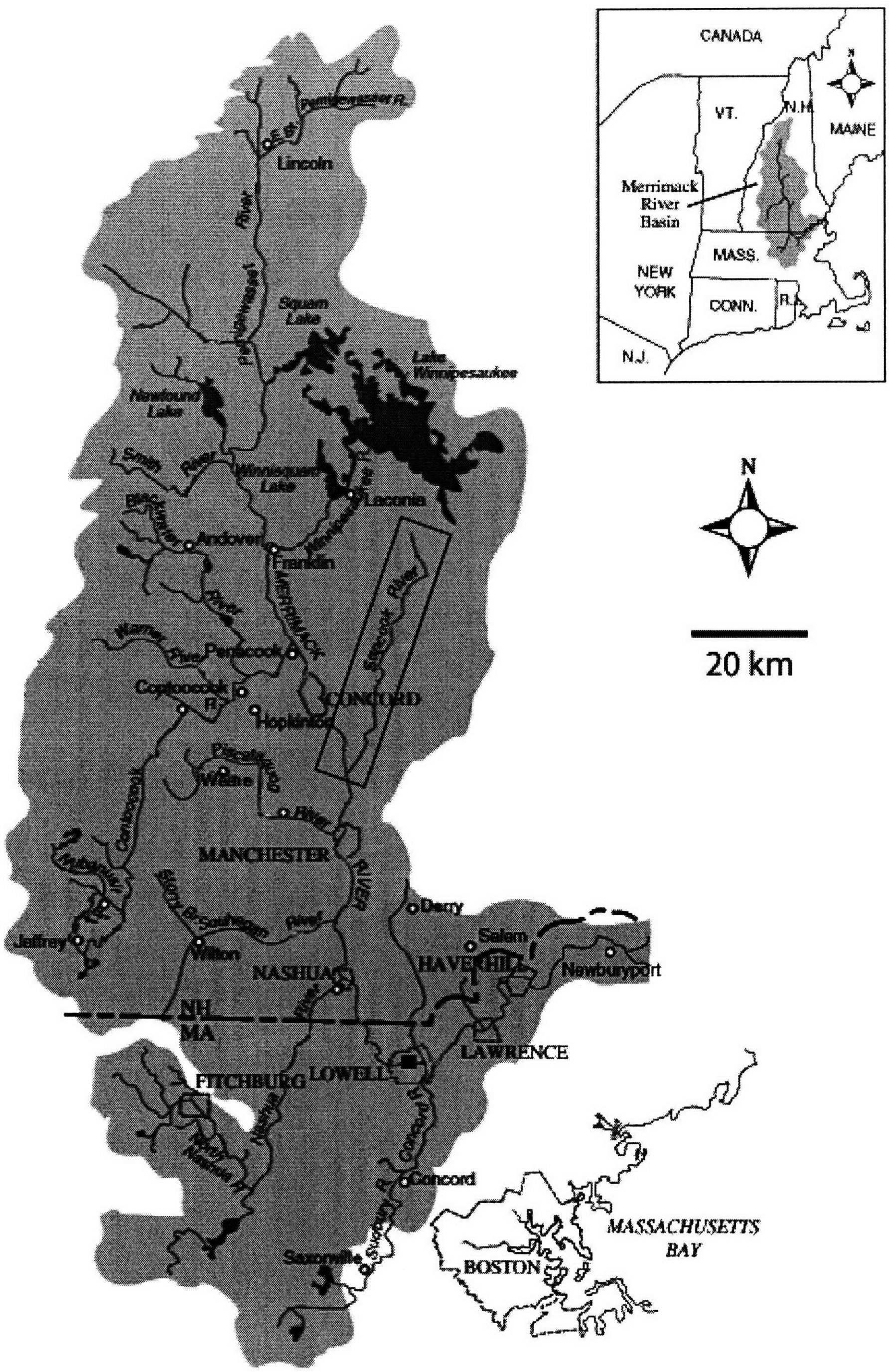


Figure 3. Merrimack River Basin showing the major tributaries to the Merrimack River and nearby towns. The box marks the location of the Suncook River (Modified from USACE).

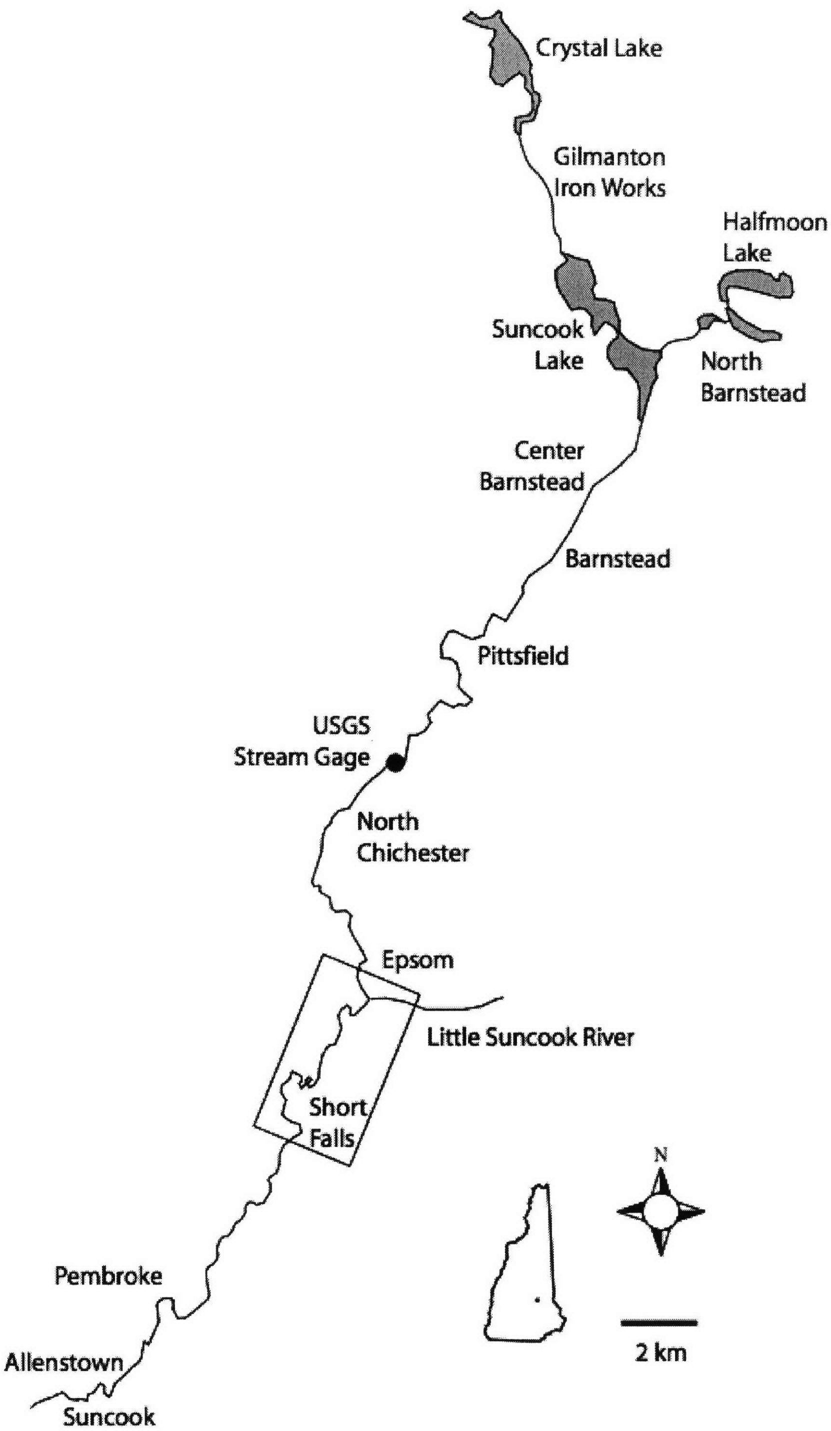


Figure 4. Map of the Suncook River and its tributary, the Little Suncook River. Labels show the townships the river crosses. Black circle denotes the location of the USGS stream gage.

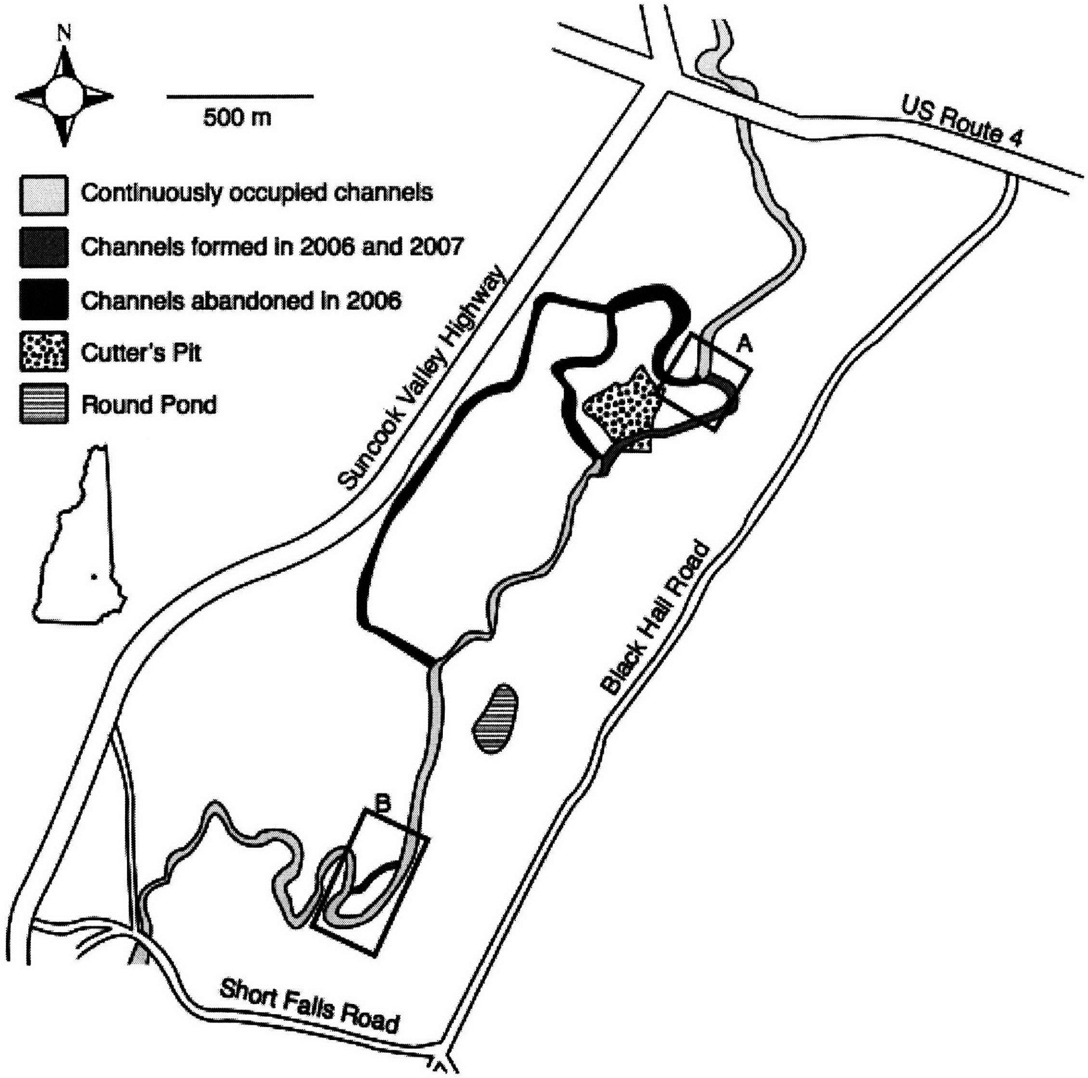


Figure 5. Map of the study area showing the pre-avulsion and newly formed channels. Box A marks the site of the 2006 avulsion; box B shows the location of the 2007 meander cutoff.

2.3. Geometry of the 2006 Avulsion Site

Before 2006, the Suncook River split into two branches as it flowed through the town of Epsom, New Hampshire (Figure 6). The westernmost, primary channel carried most of the flow, while a smaller, secondary channel flowed to the east to later rejoin the main Suncook River. The bifurcation of these two channels is located 30 m upstream of

Huckins Mill Dam, also known as Old Mill Dam. A smaller retention dam separated the main channel from the secondary channel. The area between these two channels is known as Bear Island and, until 2006, was the site of a privately owned campground. Bedrock is exposed only around Huckins Mill Dam and along the abandoned portions of the secondary channel, where it weathers into rounded shapes with well-formed potholes.

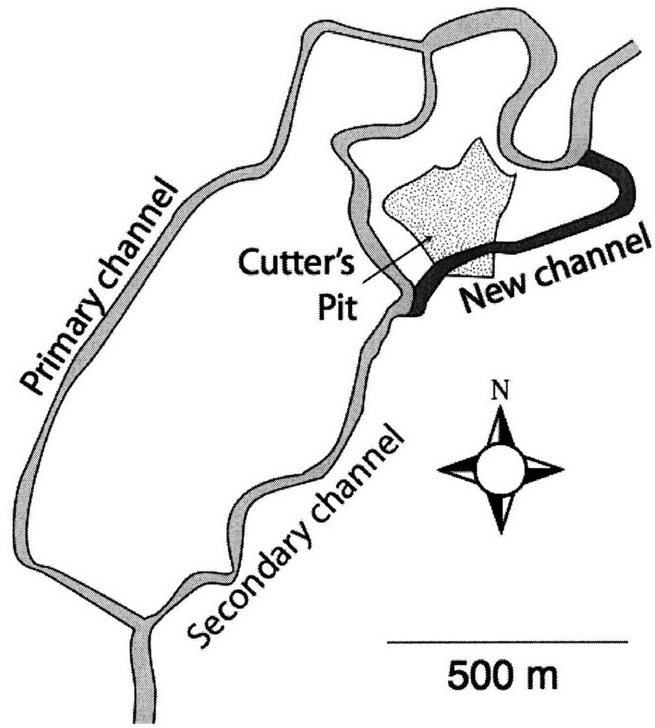


Figure 6. Geometry of the site of the 2006 avulsion. Before 2006, the Suncook River branched into a primary and a secondary channel. During the 2006 flood, a new channel formed through Cutter's Pit, a sand mining operation, and connected the main channel of the Suncook River to the secondary channel. This channel now captures all of the flow.

Upstream of the bifurcation, the Suncook River meanders across a wide floodplain before entering an area of high and steep banks. The area between the meanders and the secondary channel was the site of a sand mining operation, known as Cutter's Pit, that had been in operation since the 1960s (Concord Monitor, 2006). By 2006, these activities had removed at least 6 meters of material from this site. Although the flooding in 2006 dramatically modified the geometry of Cutter's Pit, remnant topography, as well as anecdotal evidence, suggest that there was a ridge that rose at least 10 m above the pit floor on the downstream end of the excavation. Area residents say that trucks and other heavy machinery commonly passed between the pit and an outside private road over the downstream ridge, reducing its height to 1.5 m above the pit floor. The ridge on the upstream end of the pit is estimated to have been approximately 1 m high.

Chapter 3

Overview of 2006 flooding event

In early May 2006, a low-pressure weather system formed over Scandinavia and migrated west. This slow-moving system was stationed over eastern Canada between 12 May and 15 May, allowing moist southeastly winds to create a circulating storm over New England (Climate Prediction Center, 2006). An average of 38 cm of rain fell in New Hampshire during that time, with an accumulation of 43 cm near the town of Epsom (Orff, 2006). Numerous New England rivers flooded during this storm, and many exceeded their expected discharge for a 100-year flood (USGS, 2006) (Figure 7).

Although the Suncook River was visibly flooded, no discharge was recorded for this event because the river had no gage in operation at the time. The Suncook River gage, located near Chichester, New Hampshire, was managed by the United States Geological Survey between 1918 and 1970, and was reactivated in November of 2007 (see location in Figure 4). Perignon (2007) scaled the discharge of the nearby Soucook River to the larger drainage area of the Suncook River watershed in order to estimate the flow for the Suncook River during the flood. The peak discharge for the Suncook River, which was reached between evening and midnight of May 14, 2006, was estimated to have been 277 m^3s^{-1} (9786 cfs).

Perignon (2007) developed a flood frequency analysis for the Suncook River using the available discharge record from 1918 to 1970 and the estimated discharges between 1971 and 2006. The recurrence interval for the May 2006 flood was calculated to be approximately 114 years (Figure 8). Only the a flood was ever recorded with a higher discharge in the Suncook River, with a measured peak discharge of 365 m^3s^{-1} (12,900 cfs) and an estimated recurrence interval of 200 years.

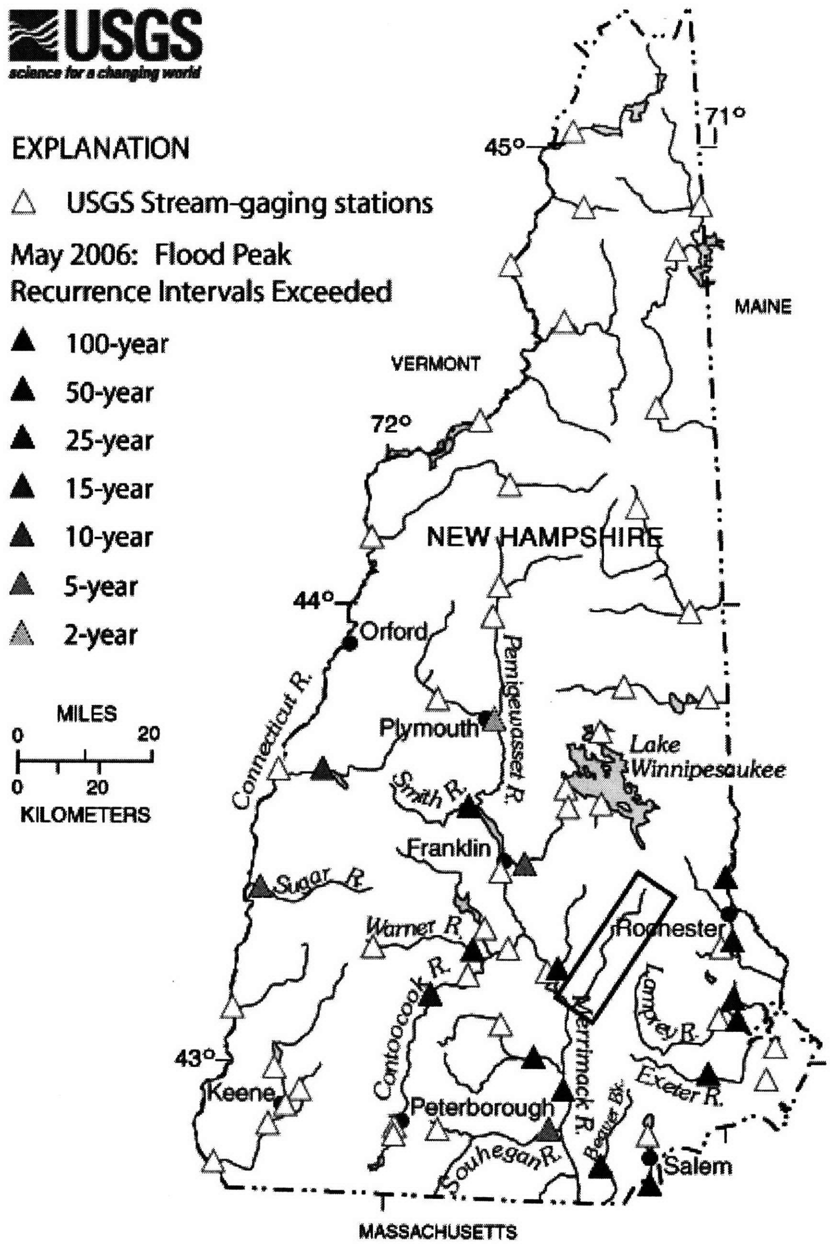


Figure 7. Exceeded recurrence intervals for discharges recorded by USGS gages in New Hampshire during the 2006 flood. The box marks the location of the Suncook River. (Modified from USGS, 2006).

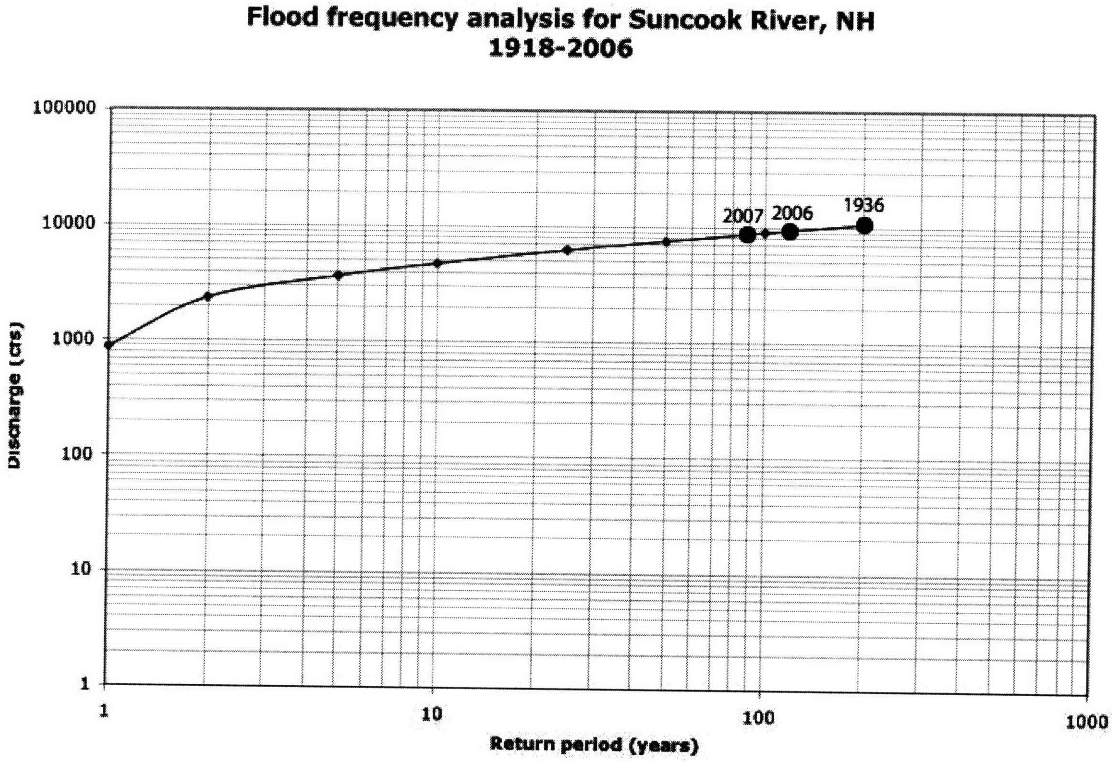


Figure 8. Flood frequency analysis for measured and estimated discharges in the Suncook River from 1918 to 2006. Circles mark the recurrence interval of the estimated discharge of the 2006 and 2007 floods, and the recorded discharge for the 1936 flood (Perignon, 2007).

3.1. Mechanism and Consequences of the 2006 Avulsion

Between 14 May and 15 May 2006, the rising floodwaters of the Suncook River entered Cutter's Pit by flowing over the low upstream ridge. Wittkop et al. (2007) found high-water marks in the weeks following the 2006 avulsion that suggest that the water pooled in the pit to a depth of 1.5 m. Once it reached this level, water flowed over the gap on the downstream ridge around Cutter's Pit and onto the downstream floodplain where it joined the secondary channel of the Suncook River.

The flowing water quickly eroded the ridge, leaving a steep drop between the floor of the pit and the downstream floodplain. This step migrated upstream by the episodic sectional collapse of its walls until it connected with the main channel of the Suncook River and captured all of its flow for the new, steeper path. Perignon (2007) calculated the migration rate of the knickpoint during the 2006 avulsion to have been between 25 and 50 m/hr. Eyewitnesses reported water flowing upstream from Huckins Mill Dam as water drained from the primary channel and into the new channel (Orff, 2006). During the time that the water level remained high, water continued to pool on the floodplain and in the pre-existing channels of the Suncook River, but as the discharge returned to normal levels this water drained and the only remaining active channel was the newly formed section and the downstream end of the secondary channel. The creation of the new channel also carved terraces into the floor of Cutter's Pit (Figure 9) and deposited thick layers of the eroded sediment on the downstream floodplains.

After the 2006 avulsion, the Suncook River flowed through the study site in a single channel. The new section of the channel is outside of both the 100-year and 500-year flood zones as defined by the FEMA flood insurance rate maps of 1978 (Figure 10). New flood insurance maps are being developed by FEMA in response to the changes in flooding patterns brought on by the new position of the river and the sedimentation in the channel downstream of the avulsion site.

The knickpoint or step did not stop migrating when it intercepted the main channel of the Suncook River. After the flood ended, it continued traveling upstream, steepening the channel, and accommodating the profile to the new slope and shorter path of the river. The substrate changes upstream of the avulsion site from sand and gravel to

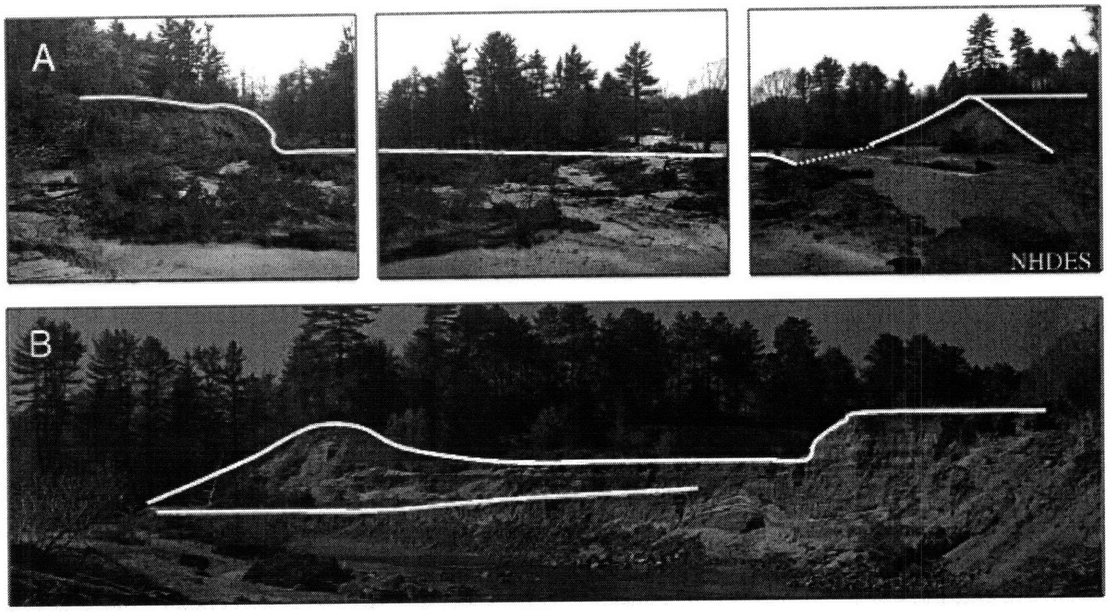
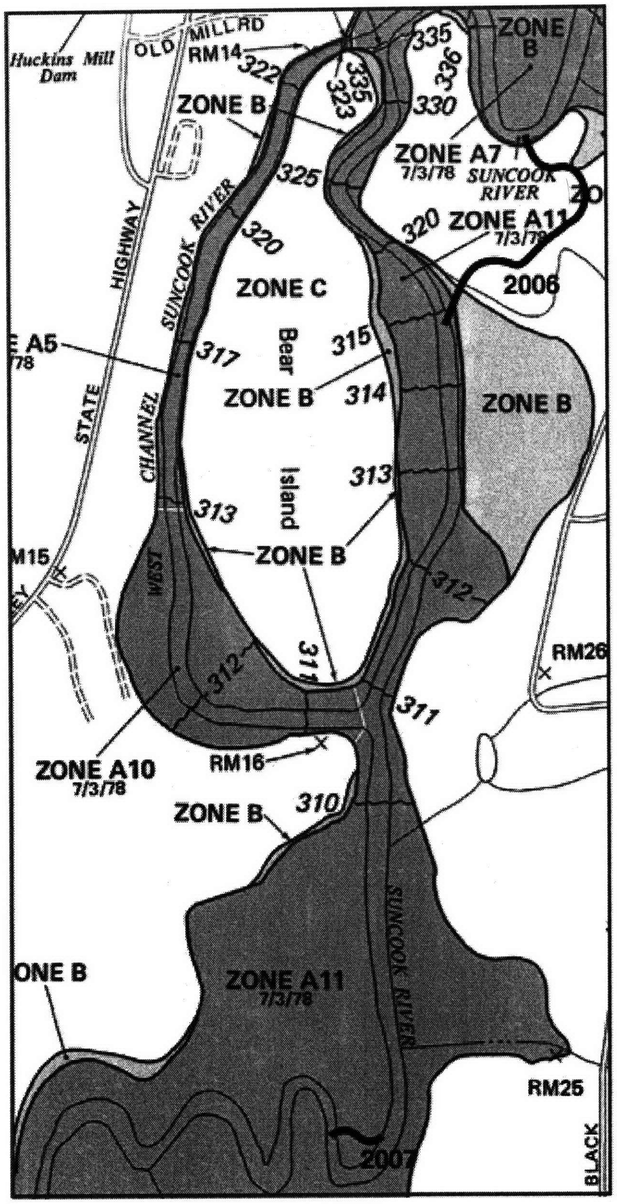


Figure 9. View of Cutter's Pit after the 2006 avulsion. Composite image A looks downstream from the left bank of the Suncook River. White lines mark the remnants of the downstream ridge around the mining excavation (Modified from images courtesy of NHDES). Image B shows a cross section of Cutter's Pit. The upper white line shows the profile of the downstream ridge (left) and floor of the quarry. The lower white line marks a terrace carved by the flow during the avulsion.

sands interbedded with cobbles and boulders. This slowed the migration of the knickpoint as material was harder to transport. Likewise, the sediment transport capacity of the flow decreased as discharges reached non-flood conditions.

Field surveys performed in late November and early December of 2006 (Perignon, 2007) place the knickpoint approximately 100 m upstream of the avulsion site. Aerial photographs from June 2007 show that the knickpoint had migrated an additional 300 m. This position is visible in aerial photographs as a sudden widening of the channel and the appearance of fallen trees in the channel from the collapsed banks. There is also an increase in water-surface turbulence from the steeper slope of the channel and the debris.



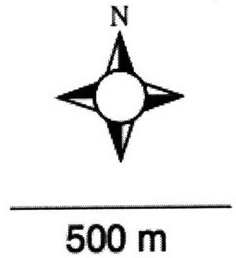


Figure 10. Modified FEMA Flood Insurance Map from 1978 showing the channels formed in 2006 and 2007. The dark gray areas mark the floodplains that are expected to be occupied during a 100-year storm. The light gray areas show the 500-year floodplain. Note that the 2006 avulsion channel falls outside of both of these areas (Modified from FEMA, 1978).

Figure 11 shows the recorded positions of the knickpoint through time as well as the location of the U.S. Route 4 Bridge that crosses the Suncook River upstream of the avulsion site. The foundations of this bridge will probably be affected by the migration of the knickpoint, and its stability represents an immediate challenge for the management of the river.

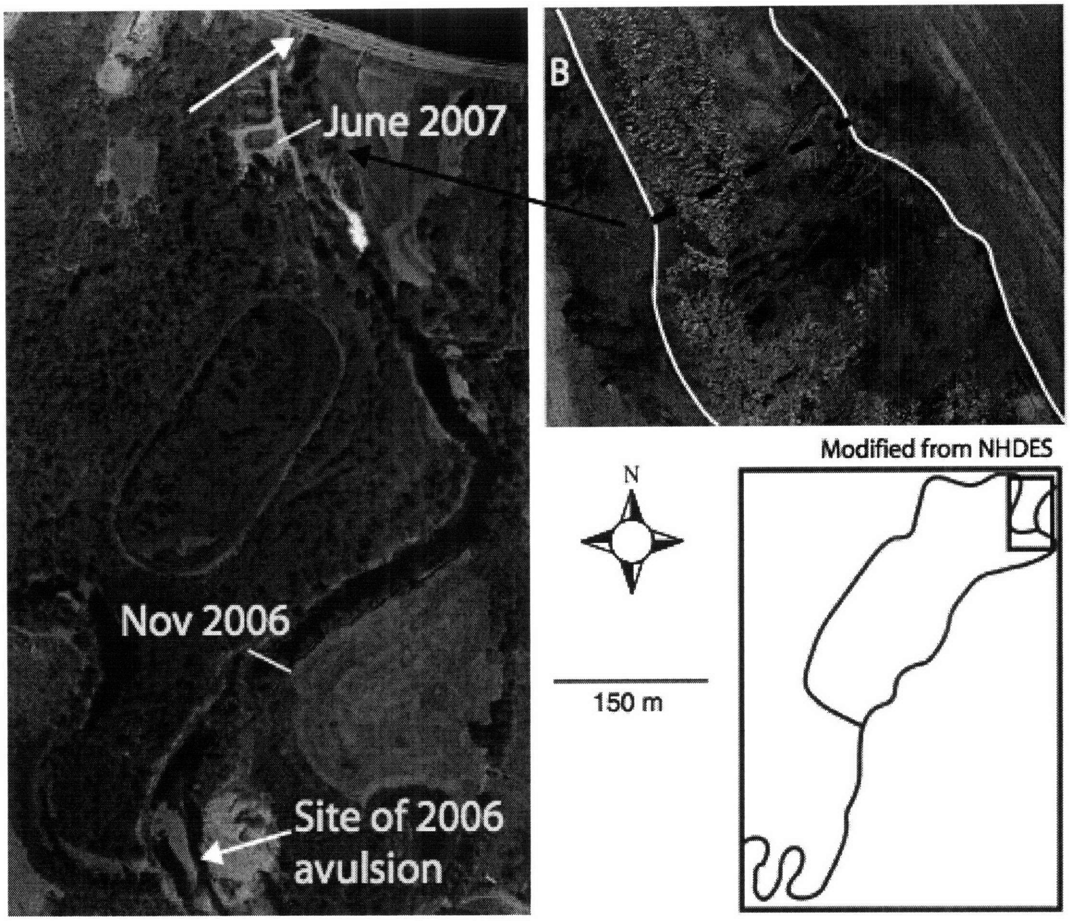


Figure 11. Aerial photo of the Suncook River taken June 2007 showing (A) the locations of the knickpoint upstream of the site of the 2006 avulsion. The November 2006 location for the knickpoint was obtained through field surveys (in Perignon, 2007). The June 2007 location was observed in the field and compared to the location in this image. Note the proximity of the US Route 4 bridge. (B) Close view of the knickpoint in June 2007 from the aerial photograph. Note the widening of the channel and the appearance of debris. White lines mark the banks of the river. Dashed black line shows the approximate location of the upper end of the knickpoint (Aerial photograph courtesy of NHDES).

Perignon (2007) suggests that particular conditions at the study site permitted the avulsion of the Suncook River during the 2006 flood. By that time, mining at Cutter's Pit had removed a large volume of material from the site and lowered the topography by at least 6 meters from its original elevation. Likewise, the lowering of the downstream ridge by the passage of heavy machinery gave the floodwaters a path to the downstream floodplain. The local surficial geology was also favorable for the creation of the new channel. The channel that is now abandoned is lined by glacial boulders that armored the bed against incision. The new channel, however, cut through fine sands and clays. This material was easily erodible and transportable and facilitated the rapid formation of a new path. If the knickpoint had encountered boulders or a bedrock reach as it migrated upstream, it could have slowed down or stopped migrating, possibly not capturing the flow of the Suncook River before the flood levels dropped. Finally, the low slope of ponded water behind Huckins Mill Dam could have made the new path of the water favorable for an avulsion. Following the Slingerland and Smith (1998, 2004) model for avulsions, a high water-surface slope ratio between the newly formed channel and the pre-existing channel determines that an avulsion could occur. In the absence of pooling behind the dam, their model suggests that only a partial avulsion would have formed, capturing only some of the flow of the Suncook River and not abandoning the pre-existing channel.

The avulsion of the Suncook River in 2006 mobilized between 90,000 m^3 and 115,000 m^3 of sediment in 12 to 24 hours (Perignon, 2007; Wittkop et al., 2007). The flood transported the finest of these sediments as suspended load far downstream. It also deposited a large volume of material on the floodplains surrounding the Suncook River. Several grazing and agricultural fields were destroyed, as well as the yards of residents of Epsom and the downstream towns of Allenstown and Pembroke. The area around Round Pond in Epsom was also severely affected. During the flood, water flowed directly into Round Pond through a breach in the levees created by sand mining. The floodwaters deposited sediment in the pond and formed an outlet channel that flows back into the river. These channels continue to be active during periods of high flow (Figure 12). The sediment also buried one of the two wells from which the town of Epsom obtained its drinking water.

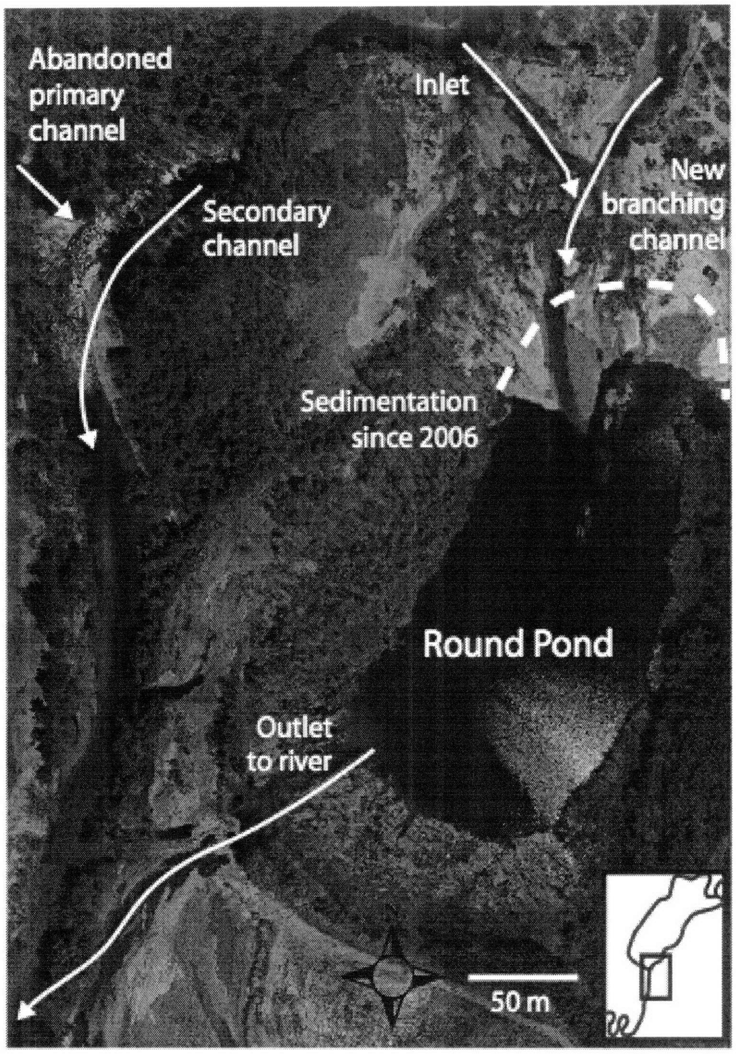


Figure 12. Aerial photograph of Round Pond taken in June 2007 showing widespread sedimentation (light gray). The white arrows mark the flow direction of channels, including the newly formed inlet and outlet channels for Round Pond. The dashed white line shows the extent of Round Pond before it was partially filled with sediments during the 2006 event (Dryer et al., 2007) (Aerial photograph courtesy of NHDES).

Chapter 4

2007 Flooding Event

The largest flood in the Suncook River in 2007 occurred between 15 April and 16 April, when a powerful extratropical cyclone brought heavy precipitation to eastern United States and Canada. This storm started on 13 April as a low-pressure system over southwestern United States. Moving east, it gathered strength as it encountered the warm waters of the Gulf Stream. The storm stalled offshore of New York on 15 April, causing rain to fall throughout New England. The accumulated precipitation for April 16 near the town of Epsom, New Hampshire, approached 70 mm. The storm then drifted southeast onto the Atlantic Ocean, where it dissipated (NOAA, 2007).

Several rivers in southern New Hampshire exceeded their expected 100-year flood discharges during this event (Figure 13). Since no discharge gage was active in the Suncook River at the time, there is no information about the magnitude of this flood in that watershed. Using the Soucook River as a proxy for the discharge of the Suncook River, Perignon (2007) estimated that discharge for the 2007 flood approximated 8500 cfs (240 m^3/s), which is close to a 90-year recurrence interval (Figure 8).

The decreased channel depth due to sediment deposition downstream of the 2006 avulsion site caused flooding at a much larger scale than expected for a flood of this magnitude (Concord Monitor, 2007b). Houses and mobile homes were flooded in the towns of Epsom, Allenstown, and Pembroke, New Hampshire (Concord Monitor, 2007b), and others in the same region reported sedimentation on the floodplains where they were built (Concord Monitor, 2007a). Many residents also reported flooding in areas that were not affected by the larger 2006 event, pointing to a dramatic change in the extent of the active floodplain for the Suncook River.

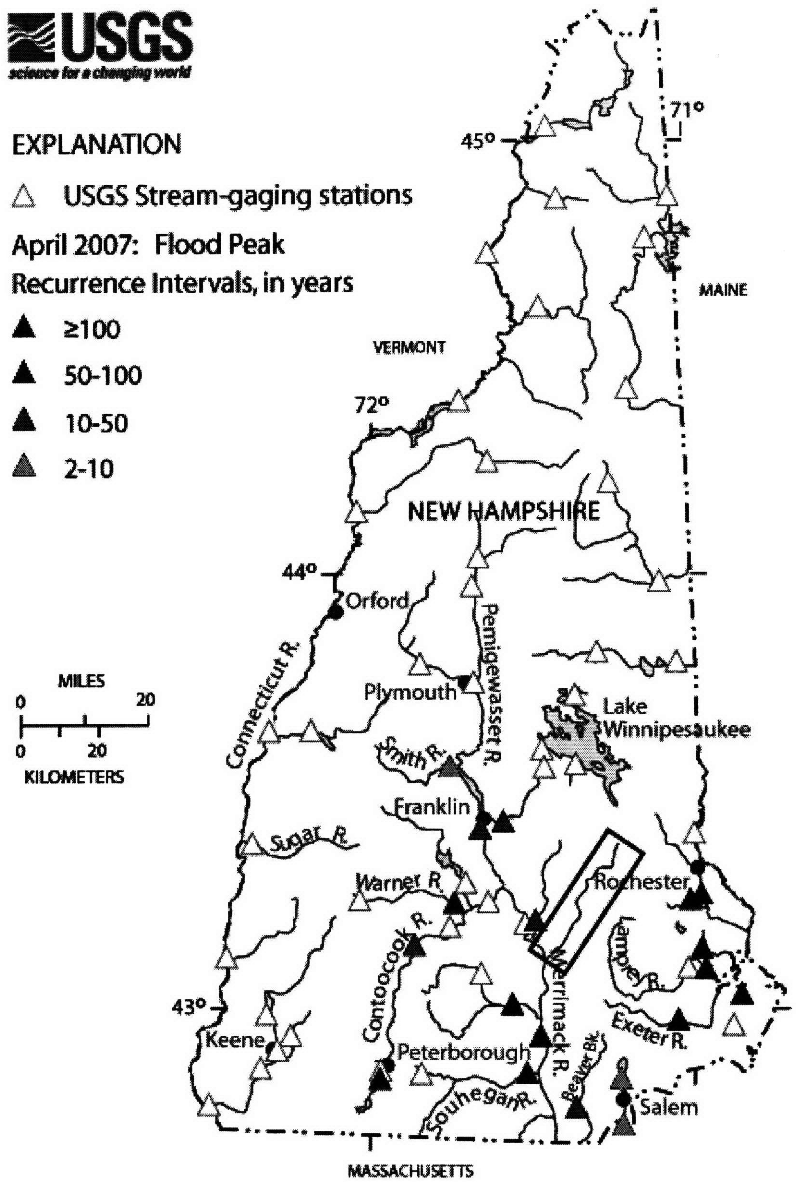


Figure 13. Recurrence intervals for discharges recorded in USGS gages in New Hampshire during the 2007 flood. Box marks the location of the Suncook River. (Modified from USGS, 2007).

On 16 April 2007, the flooding Suncook River cut a chute through a meander bend neareast to Round Pond, creating a new path for the water while still routing most of the flow through the pre-existing channel (Figure 14). The new channel is approximately 215 m in length, while the path along the meander measures about 520 m (Dryer et al., 2007). The chute formed through fields that belong to the Epsom Fire Chief, Stewart Yeaton, who had used them as grazing land for cattle and abandoned them after the 2006 flood.

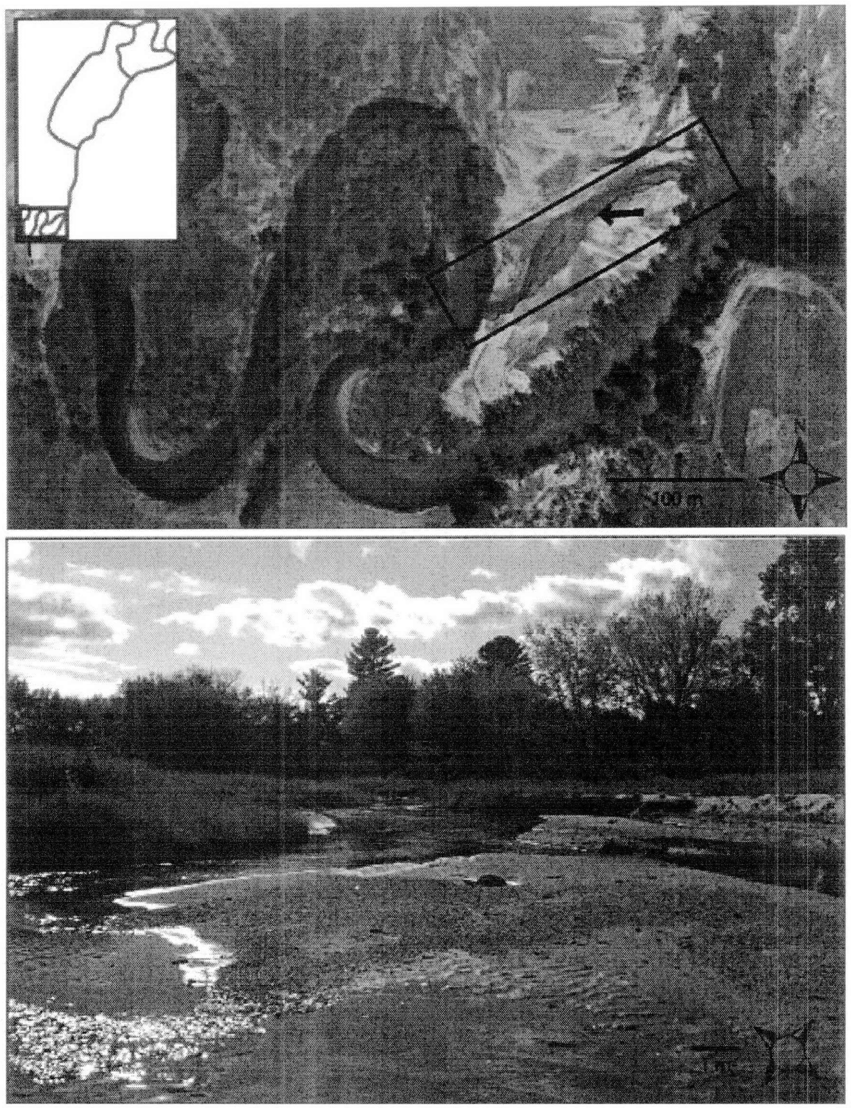


Figure 14. (Top) Aerial photograph taken in June 2007 of the meander bends downstream of Round Pond. The box marks the location of the new channel. The black arrow points to the location from which the bottom image was taken. (Bottom) Downstream view of the new channel. This image was taken in November 2007, with very low flow conditions (Aerial photograph courtesy of NHDES).

Measurements in July 2007 showed that natural levees approximately 50 cm high had been built along the left bank of the river, burying the bases of trees. The elevation of the channel bed was observed to be very similar to the elevation of the left floodplain. The elevation of the bed of the river was measured 1 m below the elevation of the surface of the meander bend through which the chute was cut.

Subsequent observations in September 2007 showed that the elevation of the bed of the main channel immediately upstream of the meander cutoff appeared to be approximately 10 cm lower than during the June observations. In addition, the new channel cut through the Yeaton fields had widened and deepened, and appeared to carry a larger proportion of the flow.

4.1. Evidence for sedimentation from the 2006 flood

4.1.1. Sedimentation on the floodplains

The meander cutoff that formed during the 2007 flood revealed the sedimentary profile of the floodplain (location shown in Figure 15). Three layers stand out in the section because of their light color, indicative of a lack of organic material. We believe that these correspond to sediments that were quickly deposited on the surface of the floodplain by large floods. They are separated by dark, organic-rich layers that were probably formed through the gradual accumulation of material on the floodplain during small floods (Figure 16).

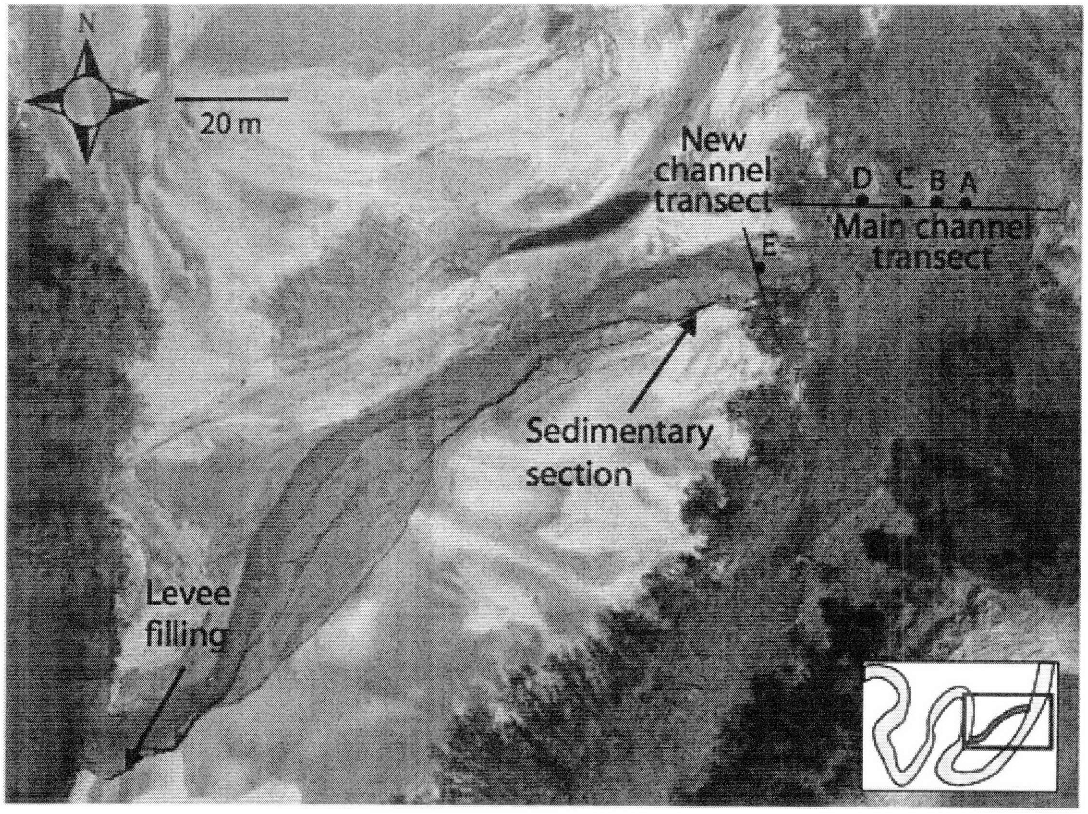


Figure 15. Aerial photo of the new channel marking the location where measurements were made. Sites A-E show the sites from where cores were extracted (Aerial photograph courtesy of NHDES).

The lack of a developed soil layer on the surface of the inner bank of the meander bend suggests that the uppermost flood layer, labeled Layer A, is very recent. Close observation shows that this 45-cm-thick layer is formed by two beds separated by a sharp unconformity with no developed soil. One possible interpretation is that the uppermost bed (labeled A1) is the product of the 2007 flood, while the thinner lowermost bed of Layer A (labeled A2) corresponds to deposits from the 2006 flood. The widespread sediment deposits from the 2006 flood, however, suggest that the volume of material transported during that event was much greater than during the 2007 flood, which caused flooding but little sedimentation around this site. We believe that that all of Layer A was

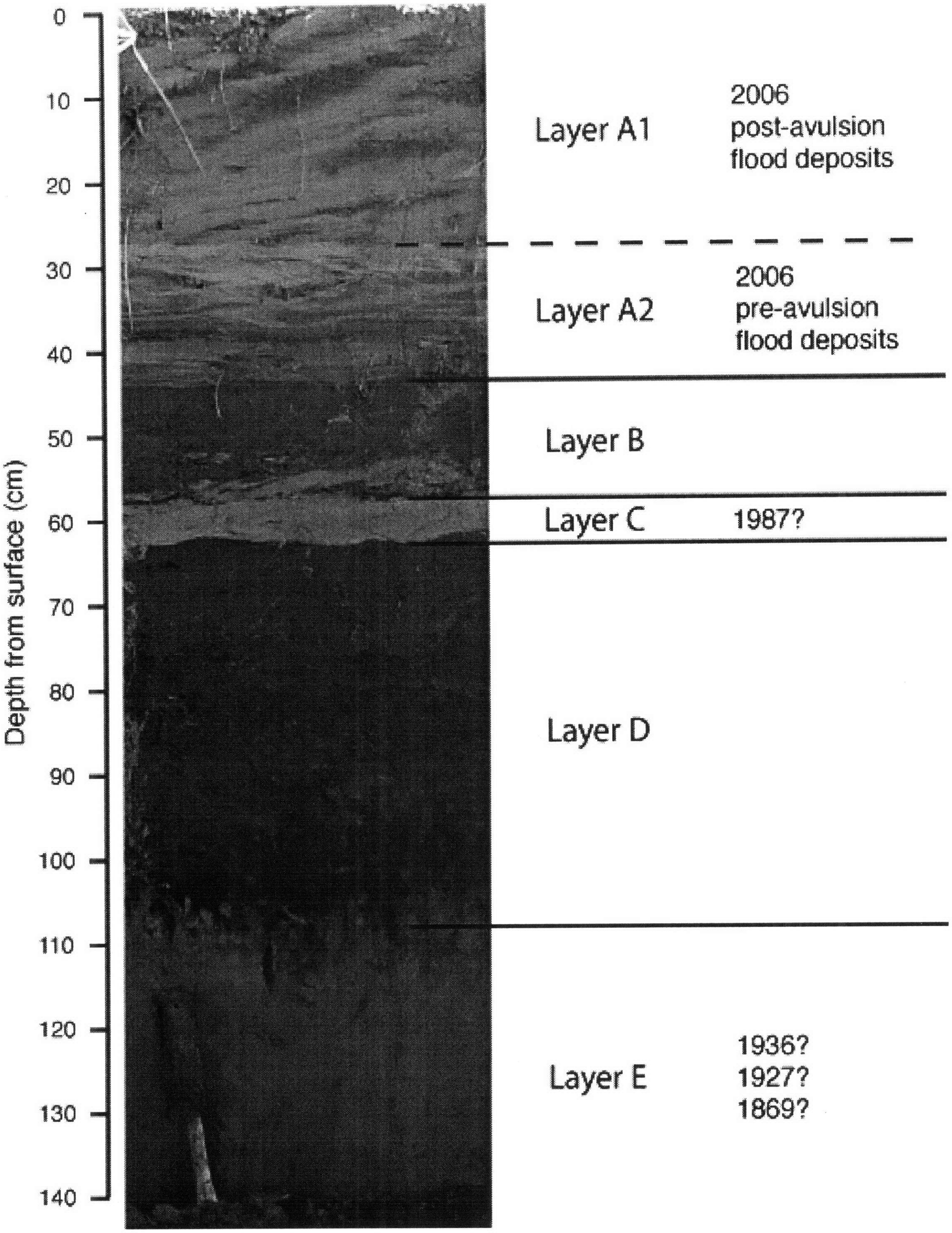


Figure 16. Sedimentary profile of the floodplain exposed in the channel of the 2007 meander cutoff. Light layers represent flood deposits; darker layers correspond to soil horizons. Top of section corresponds to sparsely vegetated surface of the floodplain. Solid lines mark transitions between depositional rates and separate the layers. These are labeled youngest (A) to oldest (E). Dashed black line marks the inferred initiation of the 2006 avulsion and a change in sediment load of the river.

deposited in 2006 and that the boundary between the two beds corresponds to the initiation of the avulsion. A thin veneer of unconsolidated sediments on the surface of the inner bank of the meander bend probably corresponds to the extent of the 2007 deposits.

Upon close examination, A2 shows an upward progression of bedforms from planar bed to climbing ripples marked by beds of very fine white sediments, characteristic of the material in Cutter's Pit, and organic-rich darker material carried by the flow. The bottom of bed A1 marks the sudden appearance of coarser material with the same general characteristics of bed A1 forming larger climbing ripples. The sediment load of the river markedly increased when erosion of the avulsion channel started, creating the morphology of bed A1.

Layer A is observed to lens out towards the river on the downstream end of the cutoff (marked in Figure 15), where the soil layer below raises to the surface (Figure 17).

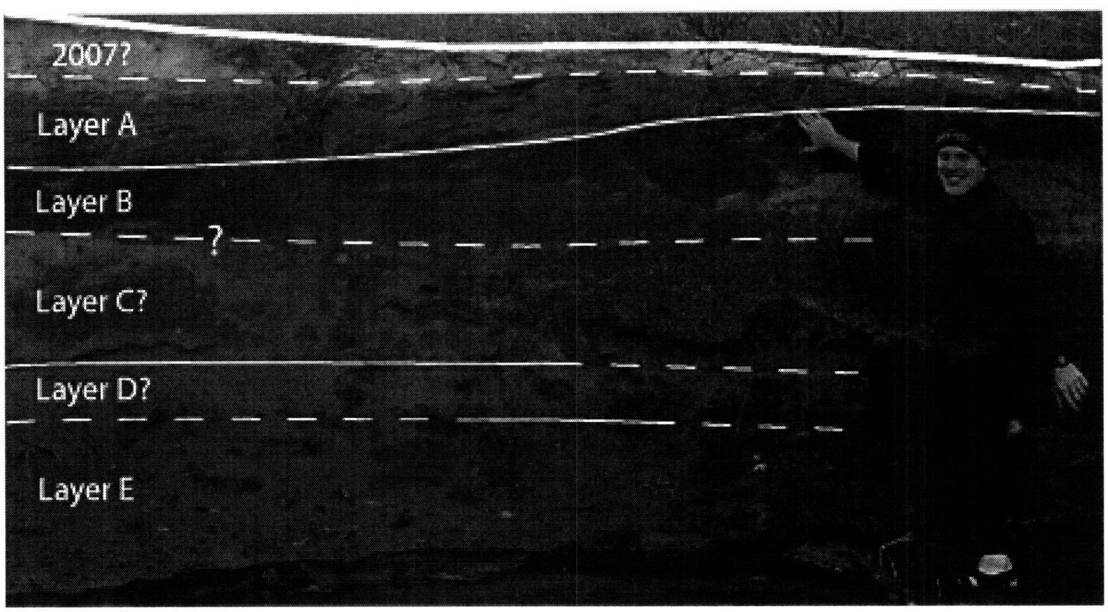


Figure 17. Sediment section at the downstream end of the meander cutoff channel showing that material released during the 2006 avulsion (Layer A) fills the depression created by the natural levees on the floodplain. The location of the contact between layers B and C is uncertain. The layer marked as 2007(?) could be part of Layer A.

This pattern preserves the structure of the natural floodplain levees, approximately 30 cm tall, which had formed along the banks of the river. The 2006 flood deposited sediments in the depression contained by those levees and formed a higher surface.

Below Layer A is Layer B, a 15-cm-thick bed of organic-rich material that we believe contains the sediments deposited by minor floods between 2006 and the previous large event. It lies over Layer C, which we believe is a flood deposit. The lower section of Layer B contains coherent fragments of Layer C, which could have been incorporated into the upper layer by roots.

Layer C is a thin deposit composed of fine yellow sediments that probably corresponds to another major flood in the Suncook River. In late March and early April 1987, a flood with measured recurrence intervals between 25 and >50 years affected many New Hampshire watersheds, including the Merrimack basin (New Hampshire Department of Safety Natural Hazard Mitigation Plan). While we do not know if this flood impacted the Suncook River, it is likely that Layer C corresponds to this event.

A 40-cm-thick layer of soil, labeled Layer D, separates Layer C from the lowest flood deposit. The contact between Layers D and E is diffuse, probably as a result of the action of roots.

Layer E is a layer of unknown thickness composed of fine yellow sediments and believed to correspond to a major flooding event. Three events appear in the historic record as severely affecting the Merrimack River basin, and possibly the Suncook River. One of those events occurred in March 1936 and was recorded by the Suncook River gage. It was caused by heavy rains that triggered snowmelt, and lasted 10 days. Perignon (2007) calculated this flood corresponded to a 200-year flood in the Suncook River.

Layer E could also have been caused by a flood in November 1927, which was less severe than the 1936 flood for the Merrimack basin (New Hampshire Department of Safety Natural Hazard Mitigation Plan). The oldest flood in the historical record occurred due to a tropical storm in October 1869 and could have also deposited these sediments.

4.1.2. Sedimentation in the channel

There is limited direct evidence for the depth of sediments that remain in the channel following the 2006 avulsion. Many local residents describe that the elevation of the bed has increased such that sections of the river that were passable in motor boats are now too shallow for them. We believe that sedimentation in the Suncook River by Yeaton's fields allowed the meander cutoff of 2007, so measuring the depth of these sediments is vital to understand the evolution of the channel and a possible increase of the risk of avulsions.

We obtained four sediment cores along a transect in the Suncook River immediately upstream of the inlet of the 2007 meander cutoff, as well as one core in the new channel (locations shows in Figure 15, labeled A to E). We used a 230-cm-long PVC pipe with an inner diameter of 5 cm outfitted with four L-shaped brackets attached with screws 53 cm from the top of the pipe. This apparatus was driven into the ground using a 13.6 kg post driver, a commercially-available steel tube with a capped end and with handles intended to install posts for fences (Figure 18). Once the L-brackets reached the bed of the channel, a PVC cap was placed on the end of the PVC pipe to create a seal. The pipe was then pulled out of the ground by the handles and transported horizontally to the bank, where the cap was removed and the collected sediment cores were extruded, measured, and photographed.

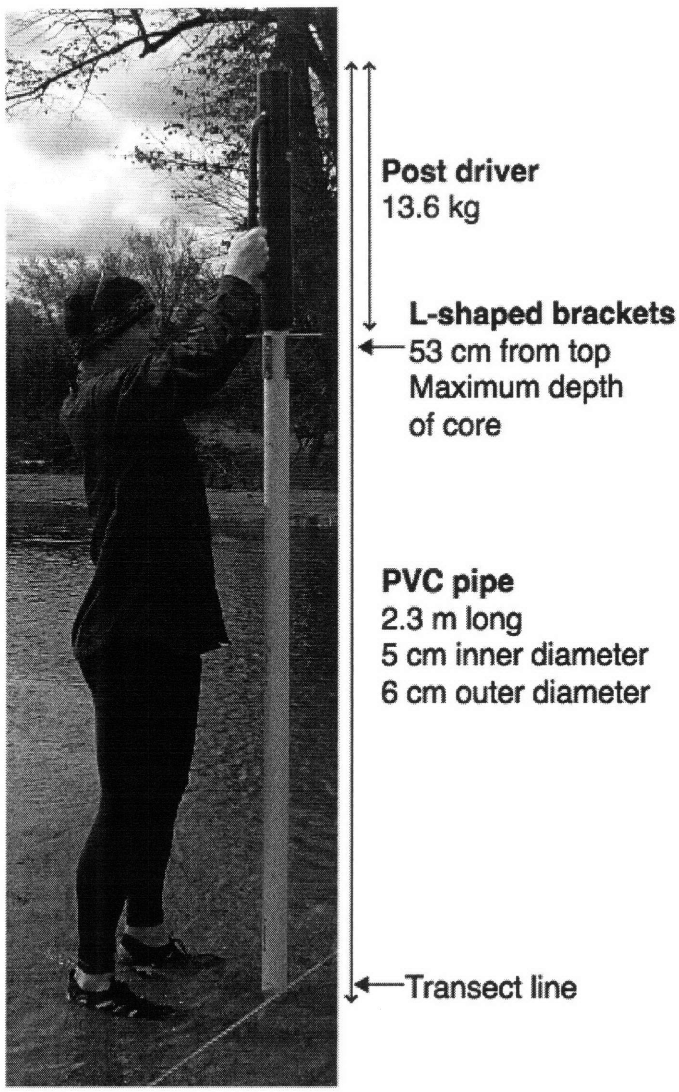


Figure 18. Device used for obtaining sediment cores in the river. PVC pipe was outfitted with L brackets as handles. It was driven vertically into the bed at pre-determined distances across the channel using a post driver until the handles reached the bed. The free end of the pipe was then covered with a PVC cap and the device was pulled up by the handles and carried horizontally to the bank, where the cap was removed and the sediments extruded.

Four distinct layers (labeled 1, 2, 3, and 4) were found to repeat in all cores in the main channel. Figure 19 shows the depth of the transitions between these layers in each of the cores.

The uppermost layer, labeled 1, is composed of quartz-rich sand with a median grain size of 1 mm. The quartz grains are well rounded, and the layer includes flakes of muscovite and an unidentified black mineral. Layer 2 shows a bimodal distribution of grain sizes, with a matrix similar to Layer 1 and larger granitic clasts with a median diameter of 10 mm. Layer 3 shows the same characteristics as Layer 1. It lies sharply over Layer 4, which is formed of fine-grained, well-rounded and well-sorted sand that is composed mostly of quartz and includes biotite flakes. This layer is characteristically very cohesive when wet.

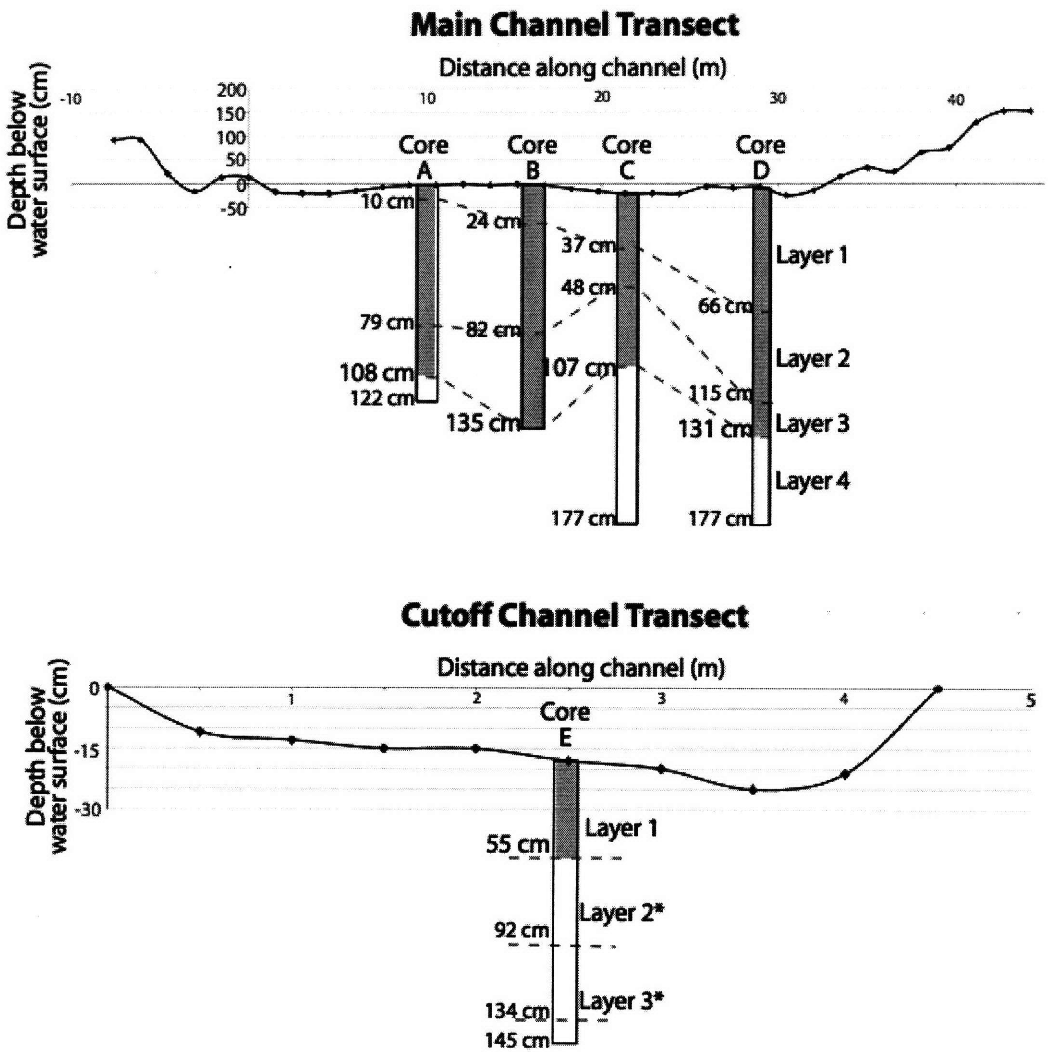


Figure 19. Transects of the main channel and the cutoff channel at the site of the 2007 avulsion showing the locations and profiles of the shallow sediment cores. Gray horizontal line shows water depth at the time the measurements were taken (30

September 2007). The average discharge for this day was calculated as 1.4 m^3/s (49 cfs) using data for the nearby Soucook River and the discharge estimation method of Perignon (2007).

The core obtained from the meander cutoff channel shows the same upper layer (Layer 1). Beneath this layer we observed a gravel bed (Layer 2*) with a wide distribution of sizes (from sand to clasts up to 5 cm) over a layer of sand and gravel (Layer 3*). The coring apparatus recovered a section of woody debris underneath Layer 3*. The state of decay of this woody debris suggests that it had been buried for decades.

We suggest that Layers 1 to 3 correspond to layers deposited during the 2006 flood. These layers show the same sandy matrix characteristic of material in Cutter's Pit, which is different from the morphology in Layer 4. Material similar to Layer 1 continues into the cutoff channel. We believe that it migrated during high flows in 2007 after the new channel formed. Layers 2* and 3* do not appear to be related to the material from the 2006 flood because they are different from the sediments observed in the channel. These beds could be part of a widespread layer beneath the floodplain composed of the substrate of a previous channel buried by the migration of the meanders.

Chapter 5

Sediment waves as drivers for avulsions

Although there are no measurements of the bed elevation in the channel next to Yeaton fields before the 2007 flood, the widespread sedimentation observed throughout the Round Pond area during the winter of 2006 and the evidence for sedimentation on the bed of the channel suggest that this meander cutoff occurred as a result of the increase in bed elevation in the channel. The channel of the Suncook River at the site of the 2007 meander cutoff was observed to be near superelevation (bed elevation level with floodplain elevation) with the left floodplain in July 2007. The bed, however, was lower than the inside of the meander bend, where the meander cutoff occurred. Complete superelevation of the channel would not have been necessary for an avulsion to occur — even a moderate increase in the elevation of the bed would have allowed the floodwaters to leave the channel and flow over the meander bend, allowing the creation of a steeper and shorter path.

We suggest that the sediments released during the 2006 avulsion are traveling down the Suncook River channel as a sediment wave, which both translates and diffuses as it moves gradually downstream. Sediment waves are transient zones of accumulation of sediment that exceed the transport capacity of the channel and locally increase the elevation of the bed (Gilbert, 1917; Hoey, 1992; Nicholas et al., 1995; Bartley and Rutherford, 2005). Sediment waves have been observed in other systems where sudden events released pulses of sediment into rivers. We propose that, in the case of the Suncook River, the sediment wave elevated the bed at the site of the 2007 avulsion, allowing the new channel to form. We want to understand how the diffusion and translation of this sediment wave down the channel will change the flooding patterns and risk of avulsions along the river.

5.1. What is a sediment wave?

The continuous sediment load of a river is the result of constant erosion of the upstream channel and runoff from surrounding lands. The sediment load, however, can occasionally increase from large, sudden inputs of material (of natural or human origin) into the channel. When these pulses of sediment exceed the transport capacity of the channel and cannot be immediately carried away by the flow, they are known as sediment waves (Gilbert, 1917; Hoey, 1992; Nicholas et al., 1995; Bartley and Rutherford, 2005). Sediment waves are areas of sediment accumulation and increased bed elevation in a channel that evolve over time as a result of their interaction with the flow (Sutherland et al., 2002). The term "wave" is used because these sediment accumulations can be described in terms of amplitude, wavelength, and the celerity of their migration (Lisle et al., 1997). The length of sediment waves ranges from hundreds to thousands of meters, and their height has been measured from tens of centimeters to several meters (Miller and Benda, 2000).

The channel conditions for sediment transport determine how much a sediment wave translates and/or disperses over time. The impact that a sediment wave has on its channel depends on its evolution: a diffusive wave reduces the intensity but prolongs the impact for downstream environments, whereas a translational wave causes sections to rapidly degrade and recover, but continues to affect areas downstream with greater force

(Sutherland et al., 2002). A very low Froude number, corresponding to deep, low-gradient channels with fine-grained beds, facilitates the translation of sediment waves that do not diffuse (Meade, 1985; Lisle et al., 2001), while Lisle et al. (2001) found that waves in steep channels with coarser material on their beds and Froude numbers of 1 only disperse but do not translate. It is therefore appropriate to assume that sediment waves generally exhibit both translation and diffusion at varying degrees for all cases between these two endmembers.

5.2. Mathematical description of a sediment wave

As we stated above, the purpose of this study is not to develop a mathematical model to describe the movement of sediment waves but instead to use previously developed equations to describe the movement of the sediment wave that we propose was formed during the 2006 avulsion of the Suncook River. Our two-dimensional model is a first approximation to the behavior of a sediment wave in the Suncook River, and while it cannot explain the detailed interaction of the wave and the geometry of the natural system, it provides us with an approximation for the behavior of the wave in the system.

Mathematical models for sediment waves use equations derived from first principles to describe their evolution. While different authors differ on the details of the equations, they all reach similar conclusions on the governing mechanisms for the evolution of sediment waves. Since we are only interested in the large-scale evolution of the wave in our model channel, we selected a published mathematical model based only on the ease by which we could use it to reproduce the conditions in the Suncook River. We chose the equation developed by Lisle et al. (1997) because we can readily measure or estimate the parameters that this equation uses to describe sediment waves, and because its form facilitates the distinction between diffusion and translation (Figure 20).

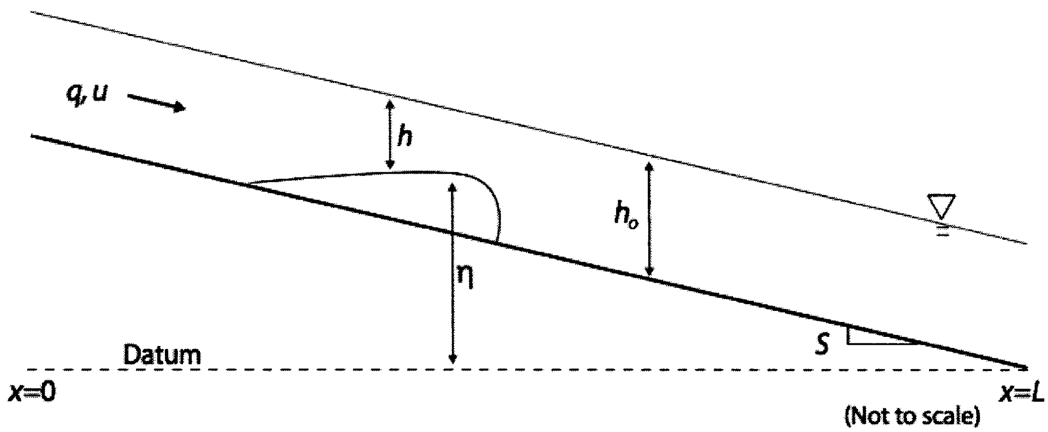


Figure 20. Schematic diagram of the model channel showing variables in use.

Lisle et al. (1997) state that the evolution of the topography of a sediment wave in a channel can be described by (Equation 13 in Lisle et al., 1997)

$$\frac{\partial \eta}{\partial t} = \frac{KqS^{1/2}}{R_s(1-p)Fr_o} \frac{\partial^2 H}{\partial x^2} \tag{1}$$

where η is the bed elevation, S is the plane bed slope for the equilibrium profile, and p is the porosity of sediment. R_s is the submerged specific gravity for sediment given by

$$R_s = \frac{\rho_{se\dim ent} - \rho_{fluid}}{\rho_{fluid}} \tag{2}$$

where $\rho_{se\dim ent}$ is the density of the sediment and ρ_{fluid} is the density of the moving fluid, in this case, water. Fr_o is the Froude number for uniform flow before the addition of a sediment wave, given by the equation

$$Fr_o = \frac{u_o}{\sqrt{gh_o}} \tag{3}$$

where u_o and h_o are the vertically averaged velocity for uniform flow and the water depth before the addition of a sediment wave respectively, and g is the acceleration due to gravity. K is an empirical constant in the Meyer-Peter–Müller equation (Sinha and Parker, 1996). The discharge per unit width q is defined as (Equation 4 in Lisle et al., 1997)

$$q = uh \tag{4}$$

where u is the vertically averaged fluid velocity and h is the water depth. H is the total mechanical energy of the fluid per unit weight, and is given by the sum of the velocity, elevation above a datum, and pressure heads with the equation

$$H = \frac{u^2}{2g} + \eta + h \tag{5}$$

Lisle et al. (1997) should be consulted for the detailed derivation of these equations.

Lisle et al. (2001) show that Equation 1 is similar to a form proposed by Dodd (1998) that separates the diffusion and translation components of the evolution of the wave. Dodd (1998) combined one-dimensional conservation equations with the Meyer-Peter–Müller (MPM) bed-load equation and a constant friction coefficient to show that (Equation 6 in Lisle et al., 2001)

$$\frac{\partial \eta}{\partial t} = \frac{KqC_f^{\ 1/2}}{R_s(1-p)}\left[\frac{\partial^2 \eta}{\partial x^2} + \left(\frac{\partial}{\partial x}(1-Fr^2)\frac{\partial h}{\partial x}\right) + \ldots\right] \tag{6}$$

where Fr is the Froude number

$$Fr = \frac{u}{\sqrt{gh}} \tag{7}$$

C_f, the dimensionless friction coefficient, can be related to flow velocity using the relationship (Equation 4 from Lisle et al., 2001)

$$C_f = \frac{u}{\sqrt{\tau/\rho}} \qquad (8)$$

where ρ is the fluid density and τ is the boundary shear stress for steady uniform flow

$$\tau = \rho g h S \qquad (9)$$

The unspecified terms inside the brackets in Equation 6 are relevant only to unsteady flow terms, and can be disregarded for flows where $Fr < 1$. The term outside the brackets relates wave evolution to bed-load transport rate. The first term inside the brackets states the rate of wave diffusion, showing aggradation at the concave-upwards extremities of the wave when the term is positive and degradation of the convex-upwards crest of the wave when the term is negative. The second term inside the brackets expresses the rate of translation of the wave. For $Fr < 1$, waves translate downstream, but become stationary as the flow becomes critical (Fr approaches 1). For $Fr > 1$, sediment waves travel upstream (Lisle et al., 2001).

5.3. Simplifying the modeling equations

Equation 6 must be solved for bed elevation (η) as a function of distance (x) and time (t) before it can be successfully modeled. However, several variables must be simplified before a solution can be obtained.

In steady, uniform flows, the slope of the water surface is equal to the slope of the equilibrium bed. Steady flows are those where the discharge does not change in time, while channel depth and water velocity are the same with distance down the channel at any point in time. While these conditions rarely occur in nature, most lowland rivers can be approximated as having steady, uniform flow when observed over long timescales and distances.

Assuming steady, uniform flow, we can state that the water surface slope is equal to S, the bed slope for the equilibrium profile. This is the slope of the channel that is, at any point in time, unaffected by the sediment wave and can be observed upstream and downstream of the perturbation. A more realistic solution to the water surface elevation would reflect the interaction of the flow with the geometry of the bed. For subcritical flow ($Fr < 1$), as in most natural rivers, the water surface is drawn down over the bed perturbation. While it is possible to solve for the water elevation using backwater computations (see French, 1985; Sturm, 2001), we chose to ignore this variation in water elevation because it is closely approximated by a flat surface.

From this assumption of equal water surface slope and bed equilibrium slope, we can calculate the depth of water (h) as a function of bed elevation (η) using geometric arguments (Figure 21). The water depth (h) at any point along the channel can be written as

$$h_x = h_o - [\eta - (L - x)S] \tag{10}$$

where h_o is the characteristic water depth in an unaffected reach, L is the total length of the model channel, and x is the position along the channel measured from the upstream end. We can rewrite Equation 10 as

$$h_x = h_o + LS - \eta - xS \tag{11}$$

Using Equation 10, we can express the vertically averaged fluid velocity (u) and the Froude number (*Fr*) as a function of bed elevation (η).

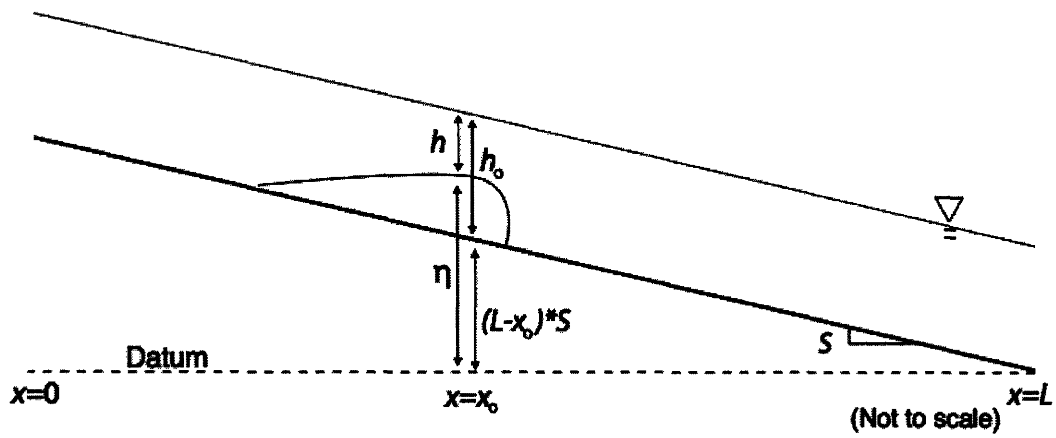


Figure 21. Model channel geometry showing the derivation of the equation for water depth.

The friction factor (C_f) is expressed in Equation 7 as a function of u, and thus of bed elevation (*h*). We can simplify the equation by observing that the shear stress on the bed is a combination of the shear stress on individual grains and the shear stress on bed undulations

$$\tau = \tau_G + \tau_B \tag{12}$$

Lisle et al. (1997) found that the τ_G constituted close to 90% of the boundary shear stress in their system, and thus chose to ignore form roughness. Following this assumption, we can calculate the friction coefficient for particles (C_G) using a form of the law of the wall

$$C_G = \kappa^2 \left(ln \frac{z}{z_o} \right)^{-2} \tag{13}$$

where κ is von Kármán's constant, z is the elevation of mean velocity $z = 0.368h$ and $z_o = 0.1d_{84}$ (Whiting and Dietrich, 1990). The approximation $\tau \approx \tau_G$ allows us to estimate C_f as approximately equal to C_G.

The value of C_G does not change very much with variations in water depth. We will therefore assume that the value of C_G calculated for the characteristic water depth (h_o) is constant everywhere in the channel for all bed elevations

$$C_f \approx C_G = \kappa^2 \left(ln \frac{0.368h_o}{0.1d_{84}} \right)^{-2} \qquad (14)$$

5.4. Values of specific terms in the modeling equations

The initial geometry of the sediment wave in the model channel is determined from the estimated volume of sediment released during the 2006 avulsion and the geometry of the new channel. From field surveys and geometric calculations, Perignon (2007) and Wittkop et al. (2007) estimated the volume of sediment that was mobilized during the 2006 avulsion was approximately 100,000 m^3. In this model, we assume that half of those sediments were deposited on the floodplain and removed from the system, and thus do not need to be included in our calculations. The section of channel that formed in 2006 cut through layers of fine sands and clays, which are easily transported by high flows as suspended load. We therefore also assume that half of the sediments that remained in the channel were transported far downstream during the flood as suspended sediment and are not part of the initial sediment wave. Based on these assumptions, the final sediment volume that is incorporated into our sediment wave model is 1/4 of the total initial volume, or an estimated 25,000 m^3 of sediment.

While we are modeling the evolution of a sediment wave in two dimensions, we need to use the width of the channel to transform three-dimensional values, such as total water discharge, into two-dimensional values, water discharge per unit width. While the width of the Suncook River channel varies downstream of the avulsion site, we use the average bankfull width as a characteristic width to which we normalize all values. We chose this width because it corresponds to the conditions in which the channel most effectively transports sediments. While bankfull flows are floods with an approximate recurrence interval of 1.5 years (Dunne and Leopold, 1978) and do not reflect the normal flow conditions of the Suncook River, this assumption serves as an approximate average of all flow conditions and allows us to ignore the high flood discharges that have occurred between 2006 and 2007. Parish Geomorphic (2008) measured the width of the Suncook River at the confluence of the old channel and newly occupied channel to be 37.73 m (123.8 feet). We selected 40 m as the characteristic width of our model channel. Using this width, we can define the sediment volume per unit width as 625 m^2.

We selected the characteristic depth of the channel in our model (h_o) to be the bankfull depth of the channel without the sediment wave. We cannot directly measure the bankfull depth from current cross-sectional profiles of the river because the bed is already elevated by the sediment wave. Sediment cores from the main channel near the 2007 avulsion show approximately 1 m of sediment in the channel above the pre-avulsion sediments. Since the bankfull elevation at that location is 1 m above the bed, we assume for our model that the bankfull depth, and thus the characteristic depth, is 2 m.

Because we are using bankfull depth and width, we chose to use the bankfull discharge for a channel without a sediment wave as the characteristic discharge in our model. We estimate that the characteristic discharge (Q) is approximately 113 m^3/s (4,000 cfs), based on bankfull characteristics for the reference reach of the Suncook River in Parish Geomorphic (2008) and their calculations for the affected sections of the river. The water discharge per unit width is thus calculated as 2.8 m^2/s.

The size of the bed material for the Suncook River channel is used in our model to calculate the dimensionless friction factor (C_f). The sediment mobilized by the 2006 flood, which is the major constituent of the sediment wave, is characteristically bright white quartz-rich sand with a median size (d_{50}) of 1 mm, and 84th percentile (d_{84}) of 96 mm (Parish Geomorphic, 2008).

For the area of the confluence of the abandoned and newly active channels in the Suncook River, Parish Geomorphic (2008) calculated the channel grade as 0.30% from aerial photographs and topographic maps. This value gives a bed slope for the equilibrium profile (S) of 0.0030.

The porosity of sediment (p) is estimated as 0.4 (Lisle et al., 1997). K is an empirical constant for the Meyer-Peter–Müller equation set as $K = 8$ by Lisle et al. (1997) following Sinha and Parker (1996). The acceleration due to gravity g is 9.8 m^2/s, and $\kappa = 0.407$ is von Kármán's constant. The density of water is ρ_{water} = 1000 kg/m^3, and the density of quartz sand is $\rho_{se\dim ents}$ = 2650 kg/m^3. These values make R_s, the submerged specific gravity of sediments, equal to 1.65.

The total length for the model channel (L) was set to 5000 m, a distance that, along the Suncook River, reaches from the downstream end of the newly formed channel to the Short Falls pond downstream of the 2007 avulsion site. Bed elevations were calculated every 5 meters down the channel.

Table 1 summarizes the values for all constants used in our model of a sediment wave. While some of these values are not realistic for the real river at any one point in space and time, our simplifications average the high flow conditions that have occurred in the Suncook River between 2006 and 2007.

Table 1 – Constants used in the sediment wave evolution model.

Constant term	Symbol	Value
Characteristic width		40 m
Characteristic depth	h_o	2 m
Sediment volume per unit width		625 m^2
Water discharge per unit width	q	2.8 m^2/s
84th-percentile sediment size	d_{84}	0.096 m
Bed slope for equilibrium channel	S	0.003
Porosity of sediment	p	0.4
Dimensionless constant	K	8
von Kármán's constant	κ	0.407
Acceleration due to gravity	g	9.8 m^2/s
Water density	ρ_{water}	1000 kg/m^3
Sediment density	$\rho_{sediment}$	2650 kg/m^3
Submerged specific gravity of sediments	R_s	1.65
Model channel length	L	5000 m
Lengthstep	ΔL	5 m

5.5. Initial Geometry of the Sediment Wave

The initial conditions for mathematical models of sediment waves are defined by the user. Lisle et al. (1997) chose a tall, rounded triangle of height $0.5h_o$ as the initial geometry of their model. This geometry is more suited for material placed in the channel by instantaneous releases such as landslides. Sediments mobilized into the Suncook River during the 2006 flood over a period of 12 to 24 hours. We chose a broad Gaussian distribution of height $0.5h_o$ as the initial geometry of the sediment wave in our model because the wide base better reflects the release of sediment over time. Gaussian functions are of the form

$$f(x) = a exp\left(\frac{-(x-b)^2}{2c^2}\right) \tag{15}$$

where *a, b,* and *c* are real constants and $a > 0$ and $c > 0$. Variable *a* corresponds to the maximum height of the curve, *b* is the position of the center of the peak, and *c* controls the width of the curve.

We chose $a = 0.5h_o$ to reflect our measurements for the thickness of the deposited sediments near the site of the 2007 avulsion. The values of *b* and *c* were selected to reflect the volume of sediment in the channel, which we calculated by integrating the

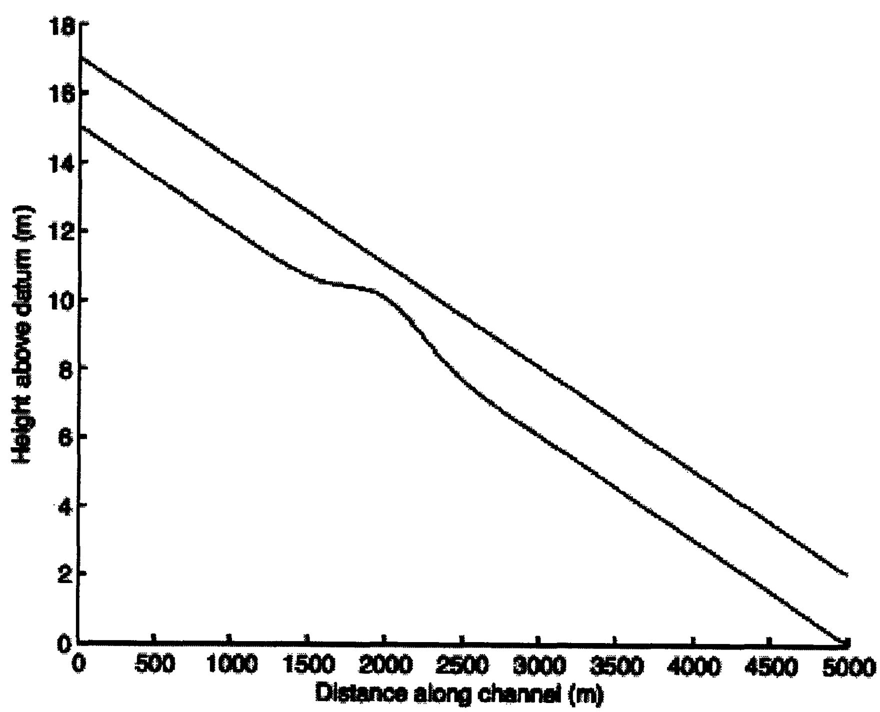


Figure 22. Initial geometry of the sediment wave and water surface. Vertical exaggeration is 1:50.

function along the total length of the channel to find the area under the curve. The unit volume of sediment that we assume would exist in a sediment wave was 625 m^2. A value of $c = 250$ defined a wave with an area of 626.6 m^2.

We believe that the center of mass of the sediment wave is located near the site of the 2007 avulsion because this site has suffered widespread flooding and sedimentation during the last two years. Likewise, our measurements of the recent increase in bed elevation near Round Pond, as well as the observation of shallow flow in high-resolution aerial photographs, confirm our hypothesis. We therefore centered the wave at $b = 2000$, which places the center of mass of the wave near Round Pond (Figure 22).

5.6. Modeling the sediment wave

We developed a simple numerical experiment for the evolution of a sediment wave in the Suncook River using MATLAB. Length steps of 5 m were set in order to obtain a detailed profile of the sediment wave, while time steps of were kept short (1 second) for numerical stability. The program used in this simulation is included in Appendix A.

We discretized Equation 6 using an explicit finite difference approximation and solved for the bed elevation ($\eta_{x_o t_o}$) for every length step at every time step.

$$\frac{\partial \eta}{\partial t} \rightarrow \frac{\eta_{x_o,t_o} - \eta_{x_o,t_o-\Delta t}}{\Delta t} \tag{16}$$

$$\frac{\partial^2 \eta}{\partial x^2} \rightarrow \frac{(\eta_{x_o,t_o} - \eta_{x_o-\Delta x,t_o}) - (\eta_{x_o-\Delta x,t_o} - \eta_{x_o-2\Delta x,t_o})}{\Delta x^2} = \frac{\eta_{x_o,t_o} - 2\eta_{x_o-\Delta x,t_o} + \eta_{x_o-2\Delta x,t_o}}{\Delta x^2} \tag{17}$$

where x_o and t_o represent the current position along the channel and time step for which the bed elevation is calculated, and Δx and Δt represent the length of steps in space and time in the model.

The term outside the brackets in Equation 6 is constant and can be written as a single term.

$$C = \frac{KqC_f^{1/2}}{R_s(1-p)} \qquad (18)$$

Solving the advection term of Equation 6 requires the calculation of the depth of flow at a given point before bed elevation can be calculated for that same point. Lisle et al. (1997) solved for the depth of water before each point using step-backwater computations found in French (1985). In setting the slope of the water surface equal to the slope of the equilibrium bed, we ignored backwater effects. We simplified the calculation of bed elevation by assuming that the water depth of the previous length step remained constant. After obtaining the bed elevation, we calculated water depth using the assumed flat water surface and used that water depth for the next length step. This simplifying assumption can be made because the calculations are performed on a broad sediment wave and use short length and time steps. This makes the bed elevation, and thus the water depth, very similar between any two consecutive points in the model.

This assumption allows us to write the advection term in Equation 6 as a constant that is recalculated at every time step.

$$B_{x_o,t_o} = C\left[\frac{\partial}{\partial x}(1-Fr^2)\frac{\partial h}{\partial x}\right]_{x_o,t_o-\Delta t} \qquad (19)$$

We can then solve Equation 6 for bed elevation at a given time step and length step.

$$\eta_{x_o,t_o} = \frac{\frac{\eta_{x_o,t_o-\Delta t}}{\Delta t} - \frac{2\eta_{x_o-\Delta x,t_o}}{\Delta x^2} + \frac{\eta_{x_o-2\Delta x,t_o}}{\Delta x^2} + B_{x_o,t_o}}{\left(\frac{1}{\Delta t} - \frac{C}{\Delta x^2}\right)} \tag{20}$$

The model was run for a total of 25,000 seconds (6.94 hours) with timesteps of 1 second. Time steps were short for numerical stability (Lisle et al., 1997). The model was stopped before the edges of the wave reached the ends of our channel.

5.7. Results and Discussion

Our mathematical model shows that a sediment wave under bankfull conditions for the Suncook River diffuses rapidly over time but shows little to no translation down the channel. Figure 23 shows the evolution of the wave as calculated by our model.

To understand the behavior of a sediment wave in the Suncook River, we can analyze the diffusion and translation terms of Equation 6 separately. Because Equation 6 is a linear second-order parabolic partial differential equation, we can separate the equation into a diffusive part and a translative part.

Diffusion

$$\frac{\partial \eta}{\partial t} = \frac{KqC_f^{1/2}}{R_s(1-p)} \frac{\partial^2 \eta}{\partial x^2} \tag{21}$$

Translation

$$\frac{\partial \eta}{\partial t} = \frac{KqC_f^{1/2}}{R_s(1-p)} \left(\frac{\partial}{\partial x}(1-Fr^2)\frac{\partial h}{\partial x} \right) \tag{22}$$

5.7.1. Diffusion of the sediment wave in the Suncook River

The diffusion equation is a partial differential equation that is used to describe the diffusive movement of materials. It can be used to describe the distribution of heat

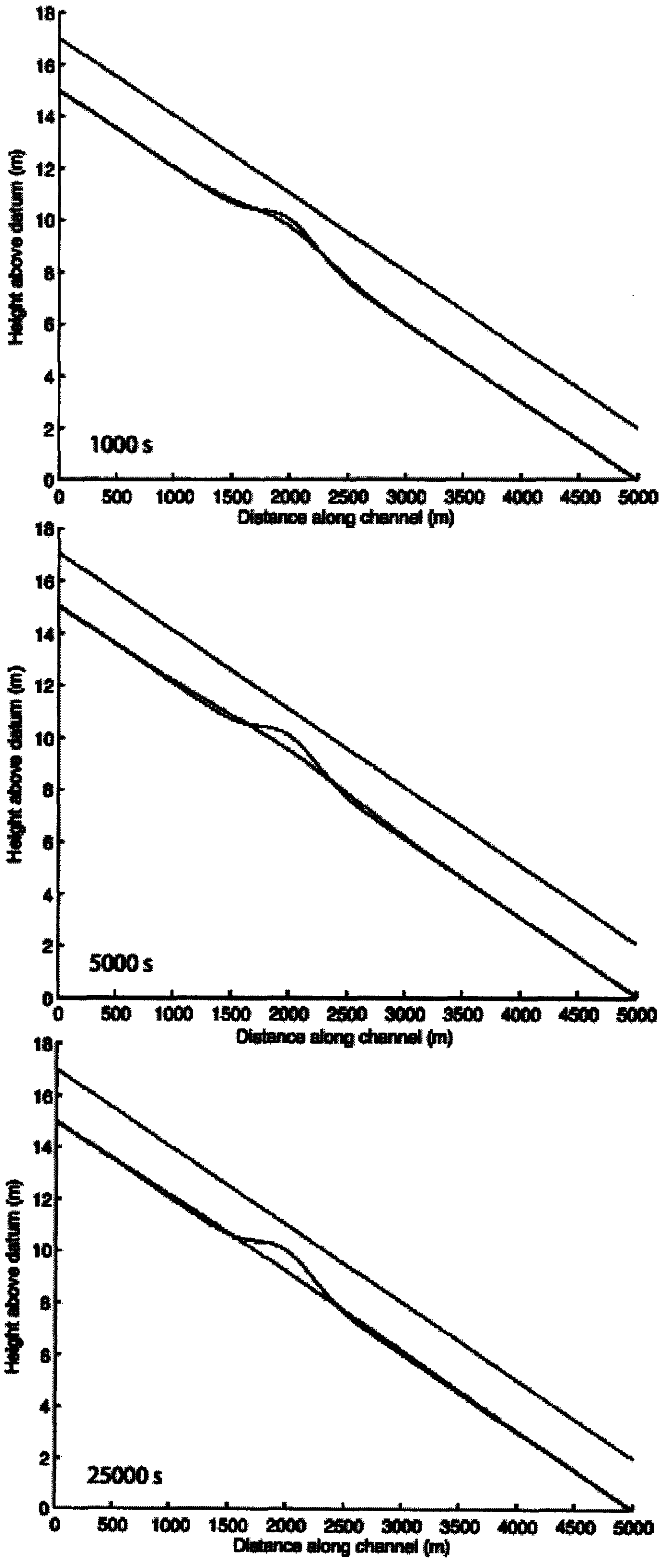


Figure 23. Results of the model for evolution of the sediment wave, showing the initial geometry of the wave, the water surface, and, respectively, timestep (A) 1000 s, (B) 5000s, and (C) 25000 s. The rapid diffusion is evident, and advection can be seen in the asymmetry of the curves in (A). Vertical exaggeration is 1:50.

through a medium over time, the changes in concentration over time of elements in solution, as well as the diffusion of particles. The general form of the diffusion equation with anisotropic diffusion is

$$\frac{\partial \Phi(\vec{r},t)}{\partial t} = D\nabla^2 \Phi(\vec{r},t) \tag{23}$$

where $\Phi(\vec{r},t)$ is the concentration of an element as a function of space and time, and D is the diffusion coefficient or diffusivity with units of [length^{2}time^{-1}].

Equation 21 is a sediment diffusion equation. From Equations 21 and 23, we can determine that the diffusivity of the wave is

$$D = C = \frac{KqC_f^{\ 1/2}}{R_s(1-p)} \tag{24}$$

The curvature of the surface $\nabla^2 \eta(x,t)$ determines that material will be removed from the crest of the sediment wave and added to the edges at a rate that is proportional to the diffusivity. Our mathematical model mirrors this behavior, with the apex of the wave decreasing in elevation at a rate that decreases exponentially with time (Figure 24).

5.7.2. Translation of the sediment wave

Translation is the movement of material across a certain distance in a certain direction. The second term in the brackets in Equation 6, separated in Equation 22 and defined as B in Equation 19, describes the translation of a sediment wave down a channel. The rate of translation of a wave in a channel depends on differences in Froude number and water depth between two consecutive length steps.

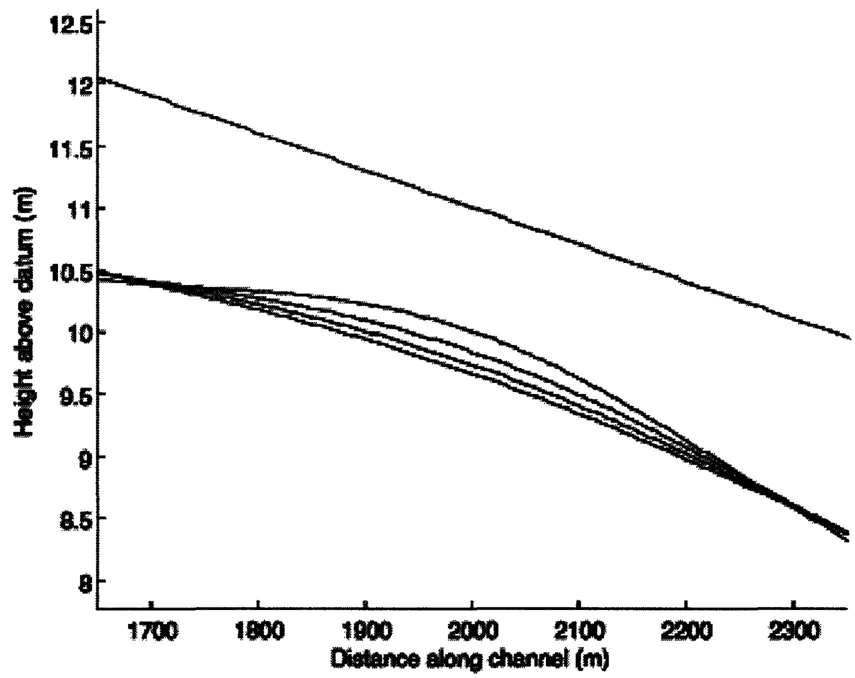


Figure 24. Apex of the sediment wave showing initial conditions (top), and timesteps 500 s, 1000 s, 1500 s (bottom). Straight line shows the water surface. Notice how the diffusion rate decreases over time. Vertical exaggeration is 1:20.

The Froude number for the flow in our model ranged between 0.32 for sections of the channel not affected by the sediment wave to 0.90 over the apex of the sediment wave with the initial geometry. The Froude number never exceeded 1, and thus the flow never reached critical conditions. Flow depth ranged between 2 m in an unaffected reach to 1 m over the apex of the wave. Because of the broad initial sediment wave, the Froude number and the depth of water did not significantly change between length steps.

We calculated the rate of translation of the wave by comparing the position of the wave at the initial and final timesteps. The position of the center of mass of the initial wave was set at x = 2,000 m. From the output of the model, we calculated that the center of the wave at t = 25,000 s was located at x = 2604 m. The total translation of the wave over the model running time was 103 m and a rate of 14.83 m/hour.

The dominance of translation over diffusion in the evolution a sediment wave can be quantified by calculating the dimensionless Pèclet number

$$Pe = \frac{v\lambda}{D} \tag{25}$$

where v is the velocity of the center of mass of the sediment wave in m/s, λ is a characteristic lengthscale, here defined as the width of the initial sediment wave, and D is the diffusivity. A Pèclet number much higher than 1 implies that the evolution of the wave is dominated by translation, while a Pèclet number much lower than 1 implies that it was dominated by diffusion.

The diffusivity D is defined from Equation 24 and the model variables as D = 2.1221. The value of λ can be calculated from Figure 22, which shows the initial conditions for the wave, as λ = 1,500 m. The velocity of the sediment wave v was measured by observing the position of the center of mass of the wave between two distant time steps, resulting in v = 0.00412 m/s. The Pèclet number for a sediment wave in the Suncook River, based on these values, is 2.91, indicating that diffusion dominates the evolution of the wave but translation is still present.

The dominance of diffusion over advection in the evolution of the sediment wave suggests that the risk of avulsions at the location of the center of mass of the sediment wave will decrease over time as material dissipates. The risk for avulsions along the flanks of the wave, however, will initially increase as the base of the wave widens but will then decrease as material diffuses. Because the wave shows only minor advection, the zones of increased risk of avulsions will not translate downstream over time but will remain near their present location.

5.8. Analysis of model assumptions

The results from our mathematical model show that diffusion dominates the evolution of the sediment wave in the Suncook River. Our model correctly reflects the expected behavior of the wave described by Equation 6 from Lisle et al. (2001). It is important to remember, however, that there are other mathematical models for the evolution of sediment waves (Cao and Carling, 2003; Lanzoni et al., 2006) that do not agree with the equations proposed by Lisle et al. (1997, 2001). Our model should therefore be considered only as a first approximation to the behavior of sediment waves under the conditions of the Suncook River, but other studies should be done to confirm our results.

Our model ran under constant bankfull conditions, when sediment transport is most efficient. Constant bankfull depths and discharges are unrealistic for any fluvial system. The high efficiency of sediment transport during bankfull flow implies that the timescales of wave evolution observed in our models are higher than those that occur in the natural system. The real time for diffusion and advection of a sediment wave in the Suncook River depends on the magnitude of floods that occur, and thus cannot be predicted. We can realistically expect decades to pass in order to observe the evolution of a sediment wave in the Suncook River as it was shown in this model.

A total model running time of 6.94 hours for the complete diffusion of a sediment wave, even at bankfull conditions, is unrealistic for a natural system. The short time scale of the evolution of the wave might be a result of the uniformity of the channel geometry and wave material. The meandering planform of a natural channel allows for the accumulation of sediment in point bars, creating reservoirs of material that are released slowly through time. Likewise, bankfull conditions could incorporate material into the channel that could lengthen the sediment wave. These parameters have not been taken into account during our simulation.

Chapter 6

Restoration of the Suncook River

Changes in the pattern of rivers that flow through populated areas can affect infrastructure and land practices. To prevent these changes, floods are often controlled by dams, rivers are contained in their channels by artificial levees, and migration of meanders is prevented by lining channels with resistant materials. When rivers catastrophically modify their planform, as the Suncook River did in 2006 and 2007, care is often taken to restore the river to a position where it does cannot affect human settlements along its path.

The management or restoration of a river must take into account the expected natural evolution of the channel. Our observations from the 2006 and 2007 avulsions, coupled with our findings from the mathematical model of a sediment wave, provide insight into the future geometry and behavior of the Suncook River system.

6.1. Effects of the sediment wave on the longitudinal profile of the Suncook River

The classification of a system as "recovered" from the effects of a sediment wave varies between studies. Bartley and Rutherford (2005) include the following criteria that have been used to define channel recovery:

(i) Return of the bed to previous levels (Gilbert, 1917; Madej and Ozaki, 1996);

(ii) Return to previous sediment loads (James, 1989);

(iii) The formation of stable, large-scale features in the channel (Erskine, 1996);

(iv) Return to an equilibrium channel profile (Hoey, 1992; Pitlick, 1993);

(v) When the features created by the sediment wave are considered to be valuable (for example, new habitats) or when the recovery time for the system is measured in tens of thousands of years because of low sediment transport rates (Brooks and Brierley, 2004).

The long-term stability of a river depends mostly on the return to an equilibrium profile where sedimentation balances erosion in the system. Alluvial channels in equilibrium show a smooth concave-up longitudinal profile with a linearly decreasing slope that optimizes the transport of sediment down the system. Natural rivers rarely show a perfect equilibrium profile, but long-lived systems show the general parabolic profile in individual reaches. The shape of that profile can be roughly determined from the elevation of the inlet upstream and the base level downstream, and the distance that the channel travels between those two points. All disturbances to the profile affect the balance of erosion and deposition of the system, and this feedback mechanism allows the channel to reach an approximate equilibrium profile again.

The recovery of an equilibrium longitudinal profile in a river that has had a large input of material but has suffered no significant changes in planform involves either the diffusion of the sediment wave until it is no longer a significant perturbation to the flow, or the translation of that wave out of the system. The formation of a new channel during the 2006 avulsion of the Suncook River, however, not only introduced a sediment slug into the system but it also shortened the distance that the channel traveled between its inlet and outlet, further disturbing the longitudinal profile of the river.

Figure 25 is a schematic diagram that shows the evolution of the longitudinal profile of the Suncook River in response to the 2006 avulsion. Before this event, the profile of the river was in equilibrium with the longer primary channel (Image A in Figure 25). At the time of the avulsion, the profile upstream of the avulsion site preserved the slope of the pre-existing profile, while the newly formed channel had a steeper slope (B in Figure 25). The knickpoint that now migrates upstream of the avulsion site is accommodating the channel to the steeper equilibrium slope of the now-shorter longitudinal profile. The sediment that was mobilized during the 2006 avulsion is contributing to the recovery of the longitudinal profile of the river by aggrading the bed downstream of the avulsion site (C in Figure 25). Even as the wave evolves over time, material will remain in the channel to steepen the bed and accommodate the new geometry of the river.

In response to the 2006 avulsion, the Town of Epsom, in conjunction with the New Hampshire Department of Environmental Services (NHDES), contracted an environmental consulting group to develop proposals for the management of the Suncook River. Parish Geomorphic presented a report in January 2008 on the geomorphology of the Suncook River and VHB/Vanasse Hangen Brustin, Inc. followed this evaluation with a proposal for restoration alternatives for this river. Their plans for the restoration of the Suncook River range from minimal control of the channel with the intention of protecting upstream infrastructure from headcut and reducing flooding downstream, to the

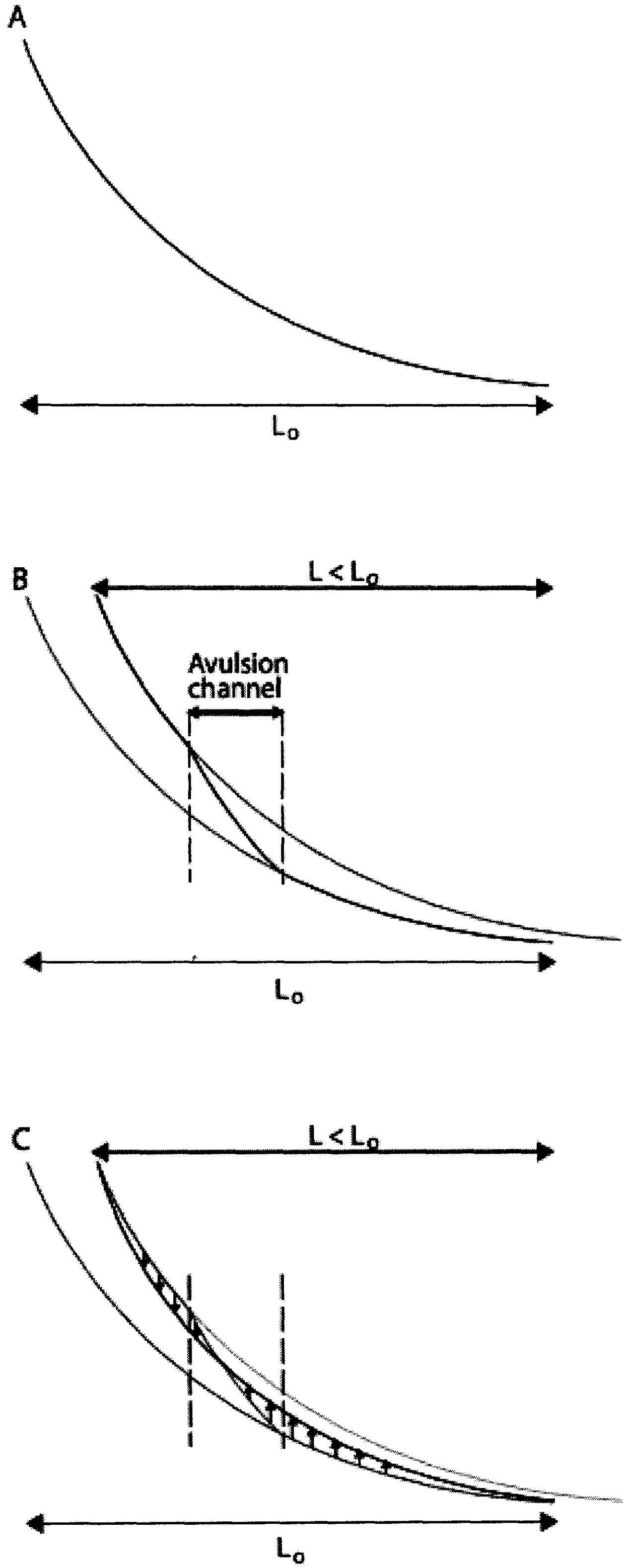


Figure 25. Schematic diagrams of the evolution of the longitudinal profile of the Suncook River following the 2006 avulsion. (A) Before the avulsion, the river had an equilibrium profile between a fixed inlet and a fixed outlet. The length of the channel is denoted L_o. (B) The 2006 avulsion shortened the channel ($L < L_o$) and created a steeper path connecting two sections of the river. The inlet and outlet remain fixed in elevation. (C) Incision upstream and deposition downstream of the avulsion site (marked by the arrows) restore the now shorter channel to an equilibrium longitudinal profile.

construction of a large diversion structure to restore the flow of the river to the primary channel.

Suggested plans for the restoration of the downstream reaches of the Suncook River involve the removal of sediment from the channel to return it to its previous depth. This would immediately decrease the flooding risk of that area to that before 2006, but it would cause incision upstream as the channel attempts deposit sediments in downstream reaches and form a new equilibrium profile.

Based on the results from our mathematical model for the evolution of the sediment wave, the removal of material from the channel might not be necessary. Our experiment shows that the hypothesized sediment wave in the Suncook River evolves mostly through diffusion, and does not significantly translate down the channel. Diffusive waves concentrate their effects on the reach of the river where their center of mass is located, but their effects decrease rapidly over time and eventually disappear (Lisle et al, 2001).

The area near Round Pond, where the center of mass of the sediment wave appears to be located, is not as densely inhabited as downstream reaches of the Suncook. The floodplain in this area has seen flooding and sedimentation during the 2006 and 2007 floods that, statistically, should not occur again in several decades. Therefore, no significant further damage should occur in this area during floods smaller than the 2007 event. Over time, the amplitude of the wave will decrease and the magnitude of the flooding should reduce. Based on these findings, it is possible that not removing sediments from the downstream reaches but instead allowing the sediment wave to evolve and restore the equilibrium profile of the channels over time is the easiest and cheapest alternative that would provide long-term benefits.

6.2. Proposed future studies

Parish Geomorphic surveyed numerous cross sections along the active and abandoned channels of the Suncook River during the summer of 2007. Few surveys were performed, however, between Round Pond and Short Falls, where the 2007 meander cutoff occurred and where we believe the sediment wave is located. Likewise, few surveys were done near the US Route 4 bridge, where the upstream end of the knickpoint was located at the time of their study.

We propose that a detailed field survey take place to determine the extent and location of the sediment wave in the Suncook River. This survey should include measurements of bed elevation as well as of sediment thickness measurements where possible. More sophisticated mathematical models must then be developed to understand the possible evolution of this wave, specifying the real geometry of the river and varying flow conditions. The results from these models would provide us with a better understanding of the current and future effects of a sediment wave in the Suncook River. These studies should be used to evaluate the risk of avulsions as a consequence of the sediment wave and to make further predictions for the evolution of the sediment wave.

We propose that, regardless of the restoration activities that the Town of Epsom and NHDES decide to implement, a monitoring system be put in place for the Suncook River that concentrates on the region between the confluence of the principal and new channels and Short Falls. This area should be monitored for variations in bed elevation that could show the migration of sediment, as well as for changes in the profile of the channel that could suggest an increased risk for avulsions. Likewise, upstream of the site of the 2006 avulsion, the rate of retreat of the knickpoint should be monitored by field observations and aerial photography. This monitoring system should include profiles taken at least once a year or after every major storm at a set of fixed locations. Long-term observations of bed elevation throughout the Suncook River would provide insight both into the movement of sediment waves and into the evolution of the longitudinal profiles of disturbed channels.

Any environmental restoration work in a river that, like the Suncook, has been affected by an event that causes a major change in its longitudinal profile must consider what the final equilibrium profile of the river would naturally be. Preserving the profile of a river out of equilibrium requires river control structures that are costly and can further exacerbate problems of sediment transport. We believe that an environmental management strategy that gradually returns the river to an equilibrium profile with minimal engineering would provide the largest long-term benefits for the environment of the Suncook River and the people living around it.

Chapter 7

Conclusions

River channels are ephemeral features in the landscape. They gradually but continuously migrate from side to side in a balance of erosion and deposition. Sometimes rivers abruptly abandon their channels and create new paths, redesigning their drainage patterns and dispersing sediments on the surface. This process is known as avulsion, and can occur at all scales from replacement of single meander bends by new channels to migration of entire deltas.

Avulsions can release large volumes of sediment into channels that do not have the capacity to transport them. This material locally increases the bed elevation of the channel, and increases the risk of avulsions for the surrounding areas. Gilbert (1917) and others have described cases of catastrophic releases of sediment into rivers where the material travels down the channel as a wave of sand and gravel. These sediment waves increase the elevation of the bed of the river and decrease the transport capacity of the channel. They can translate and diffuse over time, shifting the intensity and locus of their effects.

We propose that a sediment wave formed in the Suncook River in Epsom, New Hampshire, from the material released during a major avulsion in May 2006. In April 2007, a cutoff channel formed through a meander bend in an area downstream of the site of the first avulsion near where we believe the center of mass of the wave to be located. This small partial avulsion probably occurred because the sediment wave had locally decreased the transport capacity of the channel and elevated the bed to an elevation close to that of the floodplain. The purpose of this study is to determine the possible evolution of this sediment wave under flow conditions in the Suncook River.

We present measurements of widespread sedimentation on the floodplain and channel near the site of the 2007 avulsion. We obtained shallow sediment cores at this location that revealed that approximately one meter of sediment had been deposited in the channel. Those sediments have continued migrating as part of the sediment wave and now also occupy the new channel. We also measured the thickness of flood sediment deposits on the floodplain and obtained a possible record for deposition during previous floods.

The purpose of this study was not to develop a new set of equations to describe sediment waves, but rather to use previously developed equations to observe the evolution of a sediment wave in the Suncook River. We chose the equations presented by Lisle et al. (1997, 2001) to develop our mathematical model because we could readily measure the terms necessary for the calculation and we could easily study the diffusion and translation terms separately.

We simplified these equations to ignore backwater effects and assumed a constant water surface slope equal to the bed equilibrium slope. The initial geometry of the wave was a normal distribution of material with an amplitude of half of the total flow depth and an area under the curve equal to one quarter of the total volume of material mobilized during the 2006 flood. Our model ran under bankfull conditions to maximize the transport capacity of the flow.

Our mathematical model shows that a sediment wave in a model Suncook River diffuses quickly but shows minimal translation downstream. A wave that is mostly diffusive will concentrate its effects near the site of its center of mass, but the magnitude of those effects will decrease rapidly.

Proposals for the restoration of the Suncook River include the removal of material from downstream reaches. Based on the results of our model, we suggest that it might not be necessary to remove those sediments from the channel. The diffusive nature of the sediment wave prevents it from further affecting downstream reaches, and causes its effects to decrease quickly over time. The preservation of those sediments in the channel is also necessary to allow the river to reach a new equilibrium profile. Removal of sediments downstream of the 2006 avulsion site might cause further incision upstream as erosion increases to balance necessary deposition. Any restoration activities that take place in the Suncook River should attempt to bring the river to an equilibrium profile while minimizing human intervention in order to achieve a long-term solution.

We propose that other models for the evolution of a sediment wave in the Suncook River be performed to confirm our results. We also suggest that, regardless of the restoration activities that are implemented, a monitoring system be put in place that concentrates on the region between the confluence of the principal and new channels and Short Falls. These surveys should observe the evolution of the bed to determine the evolution of the sediment wave and warn of an increased risk of avulsions from an increase in bed elevation.

We must understand the nature of the rapid changes that are occurring in the Suncook River as a consequence of the 2006 avulsion before any restoration activities take place. Our work is a first approach at understanding the behavior and evolution of the sediment released by that event, and its consequences for the evolution and stability of the river.

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Appendix A

MATLAB code of the sediment wave evolution model

```
clear all;
close all;

% This is the final version of the sediment wave mathematical model
% presented in Perignon (2008), based on the equations of
% Lisle et al. (1997, 2001).


%%%%%%%%%%%%%% INPUT %%%%%%%%%%%%%%%%%%

%%%%% Constants %%%%%
K=8; %Dimensionless constant for MPM equation from Sinha & Parker
% (1996)
p=0.4; %Porosity of the bed Lisle et al., (1997)
g=9.8; %Gravitational acceleration (m/s2)
rho_water=1000; %Water density (Kg/cu. m)
rho_sed=2650; %Sediment density (Kg/cu. m)
kappa=0.407; %Von Karman's constant
d84=0.096; %84th percentile sediment size (m)

%%%%% Modifiable variables %%%%%
q=2.8; %Unit discharge (m2/s)
h_o=2; %Uniform water depth (m)
S=0.003; %Equilibrium slope (unitless)

%%% Variables calculated from other variables %%%
R_s=(rho_sed-rho_water)/rho_water; %Submerged specific gravity of
% sediment
Cf=abs(((kappa^2)*(log(0.368*h_o/(0.1*d84)))^(-2))^(1/2));
% Square root of dimensionless friction coefficient

%%% Combined constants %%%
C=K*q*Cf/(R_s*(1-p));

%%%%% Model specifics %%%%%
delta_t=1; %Timestep (year)
delta_l=5; %Length step (m)
L=5000; %Total length channel in model (m) - multiple of delta_l
totaltime=25000; %Duration of model - multiple of delta_t

lengthsteps=L/delta_l; %Number of lengthsteps in profile
timesteps=totaltime/delta_t; %number of timesteps in model


%%%%%%%%%%%%%% BED SLOPES %%%%%%%%%%%%%%%%%%

%%%%% Empty arrays %%%%%
bedelev=zeros(timesteps,lengthsteps); % Bed elevation array

%%%% Original bed elevation %%%%
bedelev_plane=zeros(1,lengthsteps); % Flat slope bed empty array
```

```
for position=(1:1:lengthsteps) % Loop to create slope
   ex=position*delta_l;
   bedelev_plane(1,position)=(L-ex)*S;
end

for row=(1:1:timesteps) % Slope bed at every timestep
   bedelev(row,:)=bedelev_plane(1,:);
end

%%% Water surface elevation for plotting later %%%
waterheight=zeros(timesteps,lengthsteps);
waterheight(1,:)=bedelev_plane(1,:)+h_o;

% Gaussian distribution of sediments with height 0.5*h_o for initial
% coditions
bedelev_o=zeros(1,lengthsteps); % Empty array of initial conditions
bedelev_o(1,:)=bedelev_plane(1,:); % Flat sloping initial conditions

for pos=(1:1:lengthsteps) % Create gaussian curve
    bedelev_o(1,pos)=roundn(bedelev_o(1,pos)+0.5*h_o*exp((-(pos-...
    (2000/delta_l))^2)/(2*(250/delta_l)^2)),-8);
end


bedelev(1,:)=bedelev_o(1,:); % Set initial conditions slope in bed
                             % elevation array


%%% Water depth array %%%
depth=zeros(timesteps,lengthsteps);
for loc=(1:1:lengthsteps)
depth(1,loc)=h_o-(bedelev(1,loc)-bedelev_plane(1,loc));
end

%%% Froude number array %%%
froude=zeros(timesteps,lengthsteps);

for each=(1:1:lengthsteps)
froude(1,each)=roundn(q/((g^(1/2))*((depth(1,each))^(3/2))),-10);
end


%%%%%%%%%%%%%% MODEL %%%%%%%%%%%%%%%%%

for time=(2:1:timesteps)
B=0;
for x=(3:1:lengthsteps)

% Discretized equation of Lisle et al. (2001)

    eta=((C*bedelev(time,x-2)/(delta_l^2))-(C*2*bedelev(time,x-1)/...
     (delta_l^2))+(bedelev(time-1,x)/delta_t)+B)/((1/delta_t)-...
     (C/(delta_l^2)));

     bedelev(time,x)=eta;

      % Calculate depth for next step %
      depth(time,x)=roundn(h_o-bedelev(time,x)+(L-(x*delta_l))*S,-10);
```

```
      deltadepth=roundn((depth(time,x)-depth(time,x-1))/delta_l,-10);

      % Calculate Froude number for next step %
      froude(time,x)=roundn(q/((g^(1/2))*((depth(time,x))^(3/2))),-10);
      deltafroude=roundn(((1-(froude(time,x)^2))-(1-...
          (froude(time,x-1) ^2)))/delta_l,-10);

      % Calculate second term for next step %
      B=roundn(C*deltafroude*deltadepth,-10);
end

% Smooth the curve at the end of each timestep to remove noise
bedelev(time,:)=smooth(bedelev(time,:));

end


%%%%%%%%%%%%%% PLOTTING %%%%%%%%%%%%%%

figure
title('Evolution of a sediment wave')
xlabel('Distance along channel (lengthsteps)')
ylabel('Height above datum (m)')
hold on
plot(waterheight(1,:),'-k')
plot(bedelev(5000,:), '-k')
plot(bedelev(10000,:),'--k')
plot(bedelev(15000,:),':k')
plot(bedelev(25000,:), '-k')
```