Geomorphological Assessment of the Sedimentary Dynamics of the Sunday River, Quebec

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A Thesis
In
The Department
of
Geography, Planning and Environmental

Presented in Partial Fulfillment of the Requirements
for the Degree of Master of Sciences (Geography, Urban and Environmental Studies) at
Concordia University,
Montreal, Quebec, Canada

September 2012

CONCORDIA UNIVERSITY

School of Graduate Studies

This is to certify that the thesis prepared

By: Eric Lovi

Entitled: Geomorphological Assessment of the Sedimentary Dynamics of the Sunday River, Quebec

and submitted in partial fulfillment of the requirements for the degree of

Master of Science (Geography, Urban and Environmental Studies)

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Abstract

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of the Sunday River, Quebec

Eric Lovi

Many streams and rivers in agricultural areas have been straightened in order to enhance the drainage of cultivated land and facilitate crop management. This practice is now viewed as unsustainable as periodic re-straightening is often necessary to address the problems associated with bank erosion, compromising the ecological integrity of lotic and riparian ecosystems. This research aims to assess the current sediment dynamics, as well as directions of current and future channel morphology change, of a straightened upland gravel-bed river in order to provide guidelines for sustainable management schemes. The case study is the Sunday River (Quebec), located in the foothills of the Appalachian Mountains and regarded to contain prime trout habitat. The lowest reach has proved the most problematic as a mid-channel bar repeatedly establishes itself, resulting in considerable erosion of adjacent agricultural land. In response, stakeholders have sought to regularly intervene by extracting gravel and re-straightening the channel. The study methodology combines a GIS analysis of historical aerial photos, field data collection and hydraulic and sediment transport modeling. Topographic channel geometry, sediment grain size and discharge data were acquired over the span of 2 field seasons. Additionally, repeated terrestrial lidar scans of

eroding banks were acquired to aid in sediment budget evaluation. The 1D model HEC-RAS was employed to simulate current hydraulics and sediment transport, and to recreate pre-disturbance hydraulics by increasing cross-section spacing to mimic a longer, more sinuous channel.

Acknowledgements

This project would not have been possible without the help of many people and several organisations, all of whom I graciously thank for their contributions.

Financial support was provided by the Fondation de la Faune du Québec, the Municipalité de Saint-Jacques-de-Leeds, Concordia University and the Ministère des Ressources naturelles et de la Faune.

Luc Major and his team at the MRNF provided research equipment as well as several man hours of assistance in the field. Dr. Pascale Biron's NSERC grant provided for additional field expenses and equipment. Dr. Tom Buffin-Belanger at UQAR kindly allowed the use of ground lidar and DGPS equipment, while providing field assistance along with Sylvio Demers and Maxime Boivin.

Assistance in the field by Kelly Nugent, Larissa Holman, Lecia Mancini, Genevieve Layton-Cartier and Chris Ho was greatly appreciated.

Lastly, the guidance and assistance provided by Dr. Pascale Biron were invaluable, without which this study would not have been possible.

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1 INTRODUCTION

During the last century, many streams and rivers in agricultural areas were straightened in order to enhance the drainage of cultivated land and reduce the recurrence interval of over-bank flooding events. The process typically involved the removal of streamside vegetation, the removal of meanders and a re-shaping of the channel itself (Brookes 1998; Rhoads & Herricks, 1996; Talbot & Lapointe 2002). Channel linearization has resulted in fluvial systems being in a state of disequilibrium and is ultimately unsustainable: modified rivers will gradually return to their former state, as processes intrinsic to the fluvial system persevere, necessitating periodic dredging and/or re-straightening (Eaton & Lapointe 2001; Simon et al. 2007). The practice is detrimental to lotic and riparian ecosystems and can have several negative effects in downstream reaches, such as sedimentation, nutrient loading and flood wave magnification (Ashmore et al. 2000; Florsheim et al. 2008). In the early to mid 20th century, straightening projects were funded by the Quebec Government in order to promote rural agricultural development. Government bodies continue to be responsible for granting permits and funding, at least partially, maintenance (re-straightening) projects. This practice is unsustainable, both for financial and ecological reasons.

In this research project, the case study of a straightened upland gravel-bed river, the Sunday River, will be examined. The river is situated in the foothills of the Appalachian Mountains near the village of St. Jacques-de-Leeds, part of the MRC des Appalaches (Quebec). The river is recognized to provide prime brook trout habitat, and upstream reaches still preserve much of their ecological and morphological integrity. However, downstream sections are affected by continued manipulations (re-straightening and gravel extraction) which compromise ecosystem functioning, in particular for trout habitat. A pilot restoration project (MRNF, 2008) has been undertaken involving the Ministry of Natural Resources and the municipality of St-Jacques-de-Leeds. The project is based on the need to address the causes, as opposed to the effects, of sediment dynamics problems leading to regular channel manipulations, through the development of a sustainable management plan. Ultimately, the project aims to limit continued human interventions in the fluvial system and will hopefully generate solutions that are applicable to other comparable river systems.

2 LITERATURE REVIEW

2.1 River Equilibrium, Adjustment and Natural Processes

Rivers are major agents of change in the landscape. Fluvial processes are agents of landscape evolution as well as integral components in the natural functioning of ecosystems. For example, spring floods are known to mobilize or at least de-stabilize bed material, resulting in a more conducive environment for salmonid spawning activity three months later in the late summer – early fall (Payne & Lapointe 1997).

Rivers are also inherently complex natural systems which are expected, in natural or undisturbed states, to be in dynamic equilibrium (Knighton 1998). A river in dynamic equilibrium, also called a graded stream, "is one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and prevailing channel characteristics, just the velocity required for transportation of all of the load supplied from above" (Mackin 1948, p. 471). This means that, as rivers convey their sediment load, they will erode their bed and banks locally in space and time, migrate laterally across valley surfaces, but maintain average (equilibrium) forms unless a perturbation occurs (Richards 1982). Here, the concept of dynamic equilibrium is that of landscape-scale processes operating more or less continuously in a perceived equilibrium state resulting from several complex processes being in relative balance over time (Knighton 1998; Trenhaile 2007). In other words, rivers continually adjust themselves to maintain equilibrium with their environment (Richards 1982).

It is important to recognize that rivers carry both a liquid and a solid discharge. This acknowledgement is integral to the process of geomorphic analysis of any river. The liquid discharge is the rate of flow of water at a specific point. In most cases, discharge will remain relatively constant over the long term (decades or even centuries), with large variations occurring over shorter time periods, such as annually or seasonally. In most areas of Canada, spring floods, caused by concentrated periods of snow melt, constitute annual recurrences of larger magnitude discharges (Eaton & Lapointe 2001; Reid et al. 2007a).

In rivers, the solid discharge, or sediment load, can be transported either in solution, as suspended load, or through entrainment as bed load (Richards 1982). The proportion of suspended load to bed load will vary depending on the physical characteristics of the sediment in question along with the energy present in the flow. While very large amounts of sediment can be moved in solution or suspension, it has been determined that medium scale flood events, occurring only several times annually, are responsible for most sediment transport (Wolman & Miller 1960). More extreme flooding events associated with bankfull water levels, with recurrence intervals of around 1.5-2 years, define channel capacity and are thus responsible for creating the channel form (Wolman & Miller 1960; Leopold et al. 1964; Richards 1982). A river will adjust its channel through the processes of erosion and deposition to accommodate all flow stages up to the bankfull level. During events over bankfull level, water overflows onto the river floodplain.

There is an important link between liquid and solid discharges. The relationship can be quantifiably established through bed shear stress or stream power. A river's competence is given by bed shear stress (τ), which is the force per unit area responsible for the frictional pressure exerted on the bed by the flow based on the free body analysis of steady uniform flow and is defined as:

$$\tau = \rho\ g\ R\ S_0 \qquad \text{(eq. 2.1)}$$

where ρ is mass density (kg/m^3), g is acceleration due to gravity (m/s^2), R is hydraulic radius (m) and S_0 is the bed slope (m/m) (an approximation of the total energy line). Unit stream power (W/m^2) (stream power divided by channel width) is a measure of the sediment transport capacity of a river at a specific discharge, and is defined as:

$$\omega = \rho\ g\ Q\ So\ /\ w \qquad \text{(eq. 2.2)}$$

where Q is discharge (m^3/s) and w is width (m). The amount of sediment that is transported as bedload by a river depends on several factors, the most important ones being discharge, gradient, channel roughness and channel morphology (Knighton 1998). These variables are inter-related, as illustrated by classic equations relating velocity, gradient, depth (or hydraulic radius) and roughness, such as Manning's equation:

$$V = n^{-1}\ R^{3/2}\ S_o^{1/2} \qquad \text{(eq. 2.3)}$$

where V is average velocity (m/s) and n is Manning's roughness coefficient(Dust & Wohl 2012). Despite some known short-comings in the use of Manning's formula, such as when there are abrupt changes in the turbulence of the flow (e.g. Eaton & Lapointe 2001; McGahey & Samuels 2004), this is a widely used equation.

While a channel’s general morphology depends on several factors, its geometry will adjust itself to accommodate both the liquid and solid discharge (Knighton 1998). This can be viewed as a balance between discharge and sediment supply (Figure 2.1), as was first quantified by Lane (1955). Aggradation, i.e. sediment deposition, occurs when there is insufficient energy present in the flow to further transport the sediment load, whether suspended or entrained. Degradation is long-term erosion, and it occurs when the flow energy exceeds sediment supply. Long-term aggradation and degradation are often associated with base-level changes (e.g. Schumm 1993; Heine & Lant 2009). For example, sea level rise, creating shallower slopes in downstream reaches of rivers, results in aggradation, whereas degradation in a tributary can occur when the main channel incises its bed, for example following channelization (e.g. Simon 1989; Simon & Rinaldi 2006). Indeed, it is evident in Figure 2.1 that river straightening (or channelization), which results in increasing slope, and thus stream power, will tip the balance so that the arrow moves towards the left, resulting in degradation. In these cases, the capacity for sediment transport will exceed the sediment supply, resulting in channel incision and increased transport of sediment to the downstream reaches (e.g. Eaton & Lapointe 2001; Simon & Rinaldi 2006). This sediment will continue its path downstream until there is insufficient energy present in the flow to carry it further. The series of adjustments that follow river straightening are well documented, both from geomorphological (e.g. Simon 1989) and ecological (Hupp 1992) perspectives.

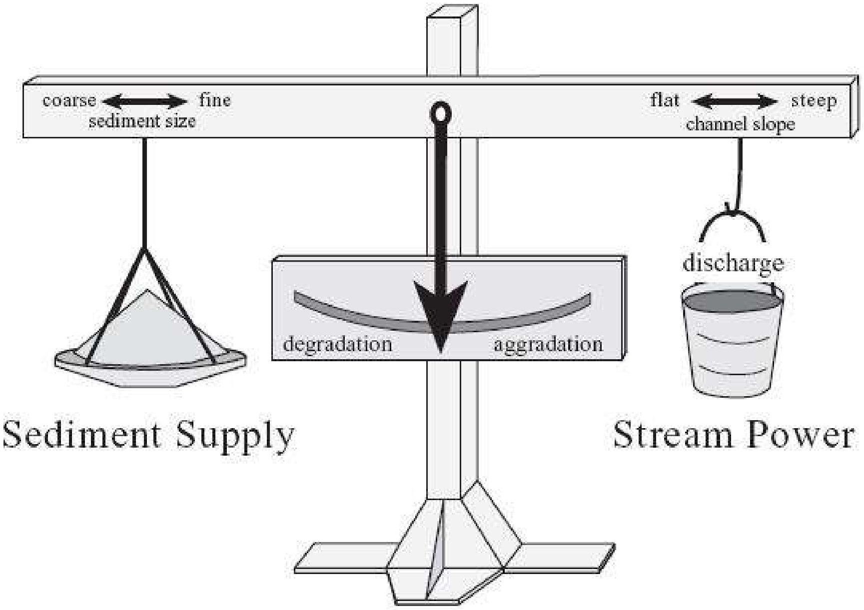
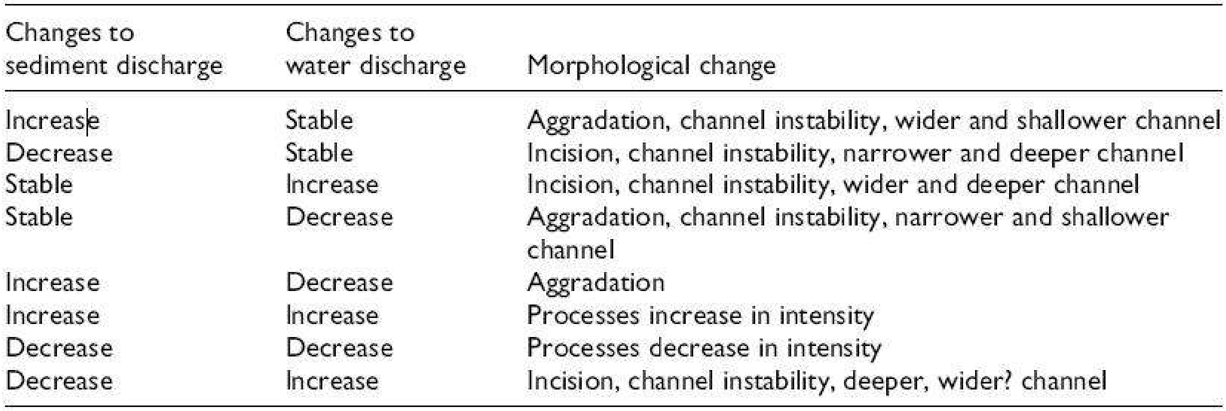


Figure 2.1 Balance model for aggradation and degradation of channels, emphasizing changes in the relationship between discharge and sediment supply. Redrawn from a widely circulated diagram that originated as an unpublished drawing by W. Borland of the USA Bureau of Reclamation, based on an equation by Lane (1955). From Blum and Törnqvist (2000).

Erosion and deposition are the results of entirely natural processes that allow a river to adjust its slope relative to physical conditions and sediment load (Simon et al. 2007). A river will always try to achieve the minimum slope needed to convey a specific mean discharge and sediment load in the most efficient way (Figure 2.1). According to Schumm (1977), readjustment of a stream's equilibrium profile (in order to rectify unit stream power imbalances) will result from changes to the sediment load or discharge. For example, an increase in discharge coupled with an increase in sediment load will lead to a widening of the channel and an increase in sinuosity. A decrease of both liquid and solid discharge will result in the narrowing and vertical incision of the channel coupled with a higher rate of meandering (to decrease slope). The key variables that are affected by these changes are width, depth, slope and sinuosity, with the direction of change sometimes being predictable, sometimes variable as there are several inter-dependencies between variables (Schumm 1977). Morphological changes resulting from these adjustments are summarized in Table 2.1.



Changes to sediment discharge	Changes to water discharge	Morphological change
Increase	Stable	Aggradation, channel instability, wider and shallower channel
Decrease	Stable	Incision, channel instability, narrower and deeper channel
Stable	Increase	Incision, channel instability, wider and deeper channel
Stable	Decrease	Aggradation, channel instability, narrower and shallower channel
Increase	Decrease	Aggradation
Increase	Increase	Processes increase in intensity
Decrease	Decrease	Processes decrease in intensity
Decrease	Increase	Incision, channel instability, deeper, wider? channel

Table 2.1 Morphological responses to changes in discharge and sediment supply. From Raven et al. (2010), based on Schumm (1977).

The mutual adjustments and variations between variables such as slope, sediment supply, discharge, grain size and bank stability lead to varying channel patterns which are adjusted to the characteristics of their physical environment and (local) climate. This results in identifiable ‘equilibrium’ channel patterns, several of which are represented in Figure 2.2.

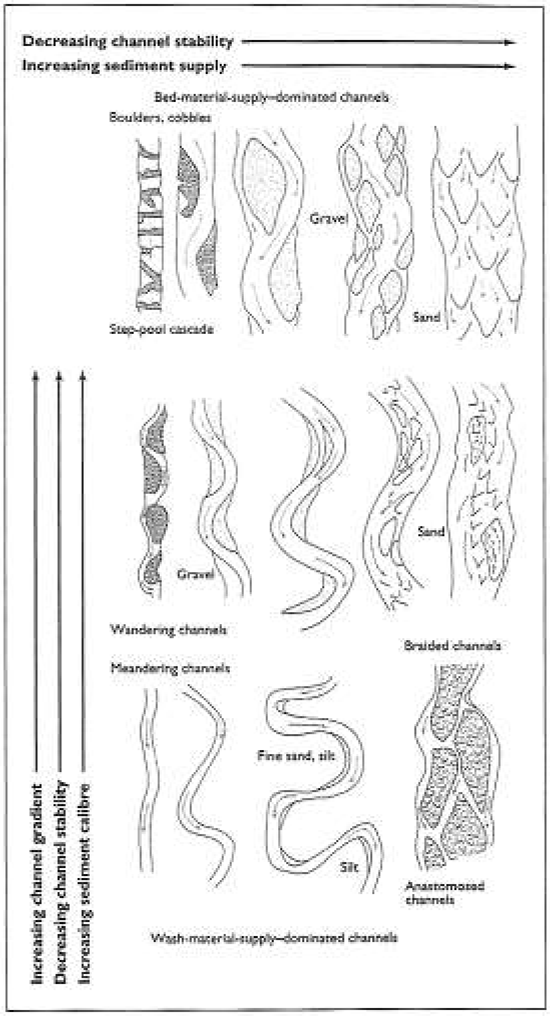


Figure 2.2 Channel patterns and their relations to slope, sediment size, sediment load and resulting stability. From Trenhaile (2007), based on Church (1992).

2.2 Sources of Sediment and Sediment Transport

2.2.1 Sources of Sediment

A river’s sediment load ultimately originates from the landscape of the drainage basin. Schumm (1977) has divided watersheds into three zones: the zone of sediment supply, corresponding to the upstream area, where sediments are usually coarse and banks are highly erodible, the zone of sediment transfer, in the middle sections, and the zone of sediment storage downstream (Figure 2.3). The Sunday River is located primarily in an upland region (Appalachian foothills) and is therefore thought to be in the zone of sediment delivery or supply, with downstream reaches situated in the zone of sediment transfer. In this section, both coarse sediment (bed load) and fine sediment will be discussed in turn.

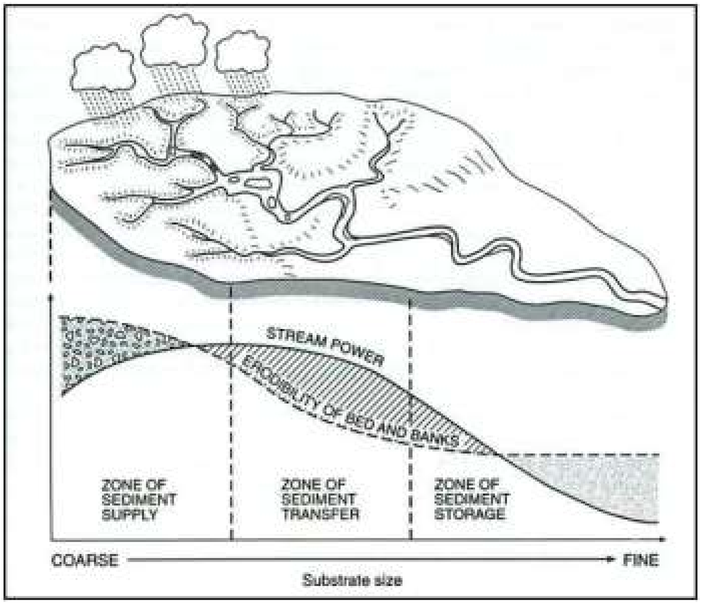


Figure 2.3 A simple classification of the watershed in terms of sediment dynamics. From Brookes and Sear (1996), based on Schumm (1977)

The majority of coarse sediment generally originates from headwater areas. Coarse sediment transfer within river channel networks is a four-stage process which involves (a) coarse-material delivery from hillslopes or river banks to a stream; (b) entrainment from the river bed at shear stress values exceeding a critical threshold; (c) transfer downstream; and (d) deposition in a temporary store or in a permanent sink (Reid et al. 2007a). The term ‘temporary store’ refers to sediment deposited in bars or on the channel bed, all or portions of which form the active layer. The active layer of a channel is the portion of the stream bed that is mobilized during high discharge events (floods) when critical shear stress is reached and entrainment ensues. Most coarse sediment moved as bedload will originate from the active layer (Haschenburger & Church 1998; Reid et al. 2007a).

In upland rivers and streams, valley hillslopes contribute a significantly higher amount of coarse sediment supply when compared to lowland fluvial systems. Raven et al. (2010) review the findings of three studies examining the relative contributions of hillslopes in upland fluvial systems. On average, they found that 22% of sediment originated from hillslopes while 78% originated from the river channel (Raven et al. 2010). Despite the fact that, in upland areas, channel reworking and bank erosion are the principal sources of sediment, that sediment must be replaced as it is conveyed downstream. This highlights the connectivity between valley slopes and the river system in terms of sediment supply. In upland areas the connectivity is high, whereas in flatter, lowland fluvial systems, the coupling is low (Reid et al. 2007a; Florsheim et al. 2008). However, it remains that the majority of coarse sediment originates from the channel bed and banks. Lawler (2005) highlights the importance of subaerial preparation processes that “ready” susceptible banks to erosion, such as hydration or freeze-thaw cycles. Such banks are often subject to mass movements or mass failure. The mechanisms of fluvial bank erosion, mass failure and subaerial processes often establish a positive feedback relationship, however the relative contribution of each mechanism generally varies along the river corridor.

The fact that banks are eroded is integral to the general functioning of fluvial systems and their dependent ecosystems: “Bank erosion from the headwater areas provides a source of (coarse) sediment… a size fraction that is necessary to form the physical structure of aquatic habitats” (Florsheim et al. 2008, p. 520). Unstable river reaches with high sediment mobility are often thought of as unsuitable for juvenile salmonids, but Payne and Lapointe (1997) found that these reaches provide rearing habitat for juveniles. This illustrates the need to properly conserve or rehabilitate all aspects and reaches of the fluvial system.

Fine sediment can originate from channel sources (a river’s bed and banks) and/or from soil erosion, often in the form of storm runoff from various catchment areas during precipitation events. More specifically, in-channel fine sediment originates from banks subject to high shear stresses (meander bends), mid-channel and point bars and bed material (empty spaces between larger particles) (Wood & Armitage 1997; Nelson & Booth 2002). Sediment sorting from headwaters through to lowland areas usually results in an overall reduction of average particle size from upstream reaches to those downstream (Figure 2.3). Because of this downstream trend, the erosion of banks in upland areas contributes a higher proportion of coarse sediment when compared to river banks in lowland areas (Florsheim et al. 2008).

Several studies have found that increases in fine sediment load (up to 2mm particle size) in gravel-bed rivers result in decreased salmonid embryo survival (Payne & Lapointe 1997; Evans et al. 2006). Furthermore, fine sediment carried in suspension increases turbidity, decreases light penetration, reduces primary productivity, impedes groundwater-surface water exchange and affects the feeding and respiration of invertebrates and fish. The end result is a general decrease in the ecological resilience of the lotic ecosystem coupled with lower diversity and abundance of lotic species. Fine sediments also contribute to heavy metal and nutrient loading of streams, sometimes resulting in the eutrophication of waterways (Payne & Lapointe 1997; Wood & Armitage 1997; Nelson & Booth 2002; Florsheim et al. 2008). The most widespread impacts of fine sedimentation result from the erosion of agricultural land (Wood & Armitage 1997). Soil erosion is exacerbated by several human activities that include the practices of agricultural drainage, soil tilling, channel modifications and access of livestock to streams and rivers. The long-term effects of mechanical equipment operation may also contribute to increased soil erosion (Evans et al. 2006).

2.2.2 Sediment Transport

Sediment transport has been found to be highly variable, both spatially and temporally (Lawler 2005; Reid et al. 2007a; Lane et al. 2008). Typically, rivers are conceived of as “jerky conveyor belts for alluvium moving intermittently seawards” (Ferguson 1981, p. 90). While fine sediments are most often transported in solution or suspension, bed load particles will be mobilized under high flow conditions. Under high flow conditions, bed load particles are usually moved downstream either to the next bar or erosion site but, under very high flow conditions, particles can be entrained as far downstream as adequate shear stress conditions exist for the particle size in question (Reid et al. 2007a).

As previously discussed, the active layer is the portion of the channel bed and banks that are mobilized during high discharge events. Depending on channel morphology, sediment size, bank stability and flow conditions, the depth of the active layer may be highly variable (Sear 1996). In a particle displacement study, Haschenburger and Church (1998) found that mean maximum active depth in a gravel bed stream is “about twice D90”, and active width is often significantly less than wetted width. This supports the theory that it is mainly superficial bed sediment that is entrained downstream and replaced thereafter; that the movement of bedload is through “cells” or zones of alternating scour and deposition dominating the transport process (Ashmore et al. 2000). While the active layer is the predominant source of mobilized sediment, sources can range from recent hillslope failures to significantly older deposits such as former river terraces.

While the entrainment of bed material is dependent upon the energy present in the flow (bed shear stress), it is not the only consideration in analysing the mobility of coarse sediments. The mobilization of particles on the channel bed is also dependent on the ‘intergranular’ geometry of the bed material, which is controlled by grain shape as well as sorting and packing (Buffington & Montgomery 1997). Bed surfaces typically undergo a natural ‘coarsening’ created when bed shear stress is less than the critical shear stress of the largest particles, resulting in the entrainment of smaller sized particles while larger ones remain in place (Klingerman & Emmett 1982; Gomez 1983; Vericat et al. 2006). This leads to armouring of the bed material as smaller particles come to rest on the lee side of larger ones. The degree of armouring has an influence on the bed grain size distribution, channel morphology, channel stability and bed load transport rates as both the size and volume of transported material is reduced (Vericat et al. 2006). Gomez (1983) reported that armoured surfaces are typically stable during low magnitude floods while their disturbance is common of higher magnitude floods. According to Buffington and Montgomery (1997, p. 1995), “it is well known that most gravel-bedded rivers are armoured”.

2.2.3 Estimating Sediment Transport

Measuring bedload transport is known to be a difficult task. Traditional, portable sediment traps may produce unreliable results (Haschenburger & Church 1998). Sterling and Church (2002) found that pit traps are more accurate than Helley-Smith samplers at collecting material larger than 2.8 mm. It has also been suggested that standard approaches to describing and predicting bedload transfer using traditional engineering methods (empirical formulas used in 1-D steady-state models) do not adequately consider the role played by channel morphology; as a result of precise quantitative measurement of actual transported sediment volumes, there is evidence that transport rates vary according to the morphology of the channel (Haschenburger & Church 1998; Eaton & Lapointe 2001; Lawler 2005). To properly account for differences in the “spatial variation in transport rate” due to morphology, several studies have investigated the ‘inverse’, ‘morphologic’ or ‘volumetric’ method for assessing bed load transport (Ashmore and Church 1998; Haschenburger & Church 1998). This method requires high resolution topographic data from directly before and after a high discharge event to determine net transport rates based on changes to sediment storage within the channel (Eaton & Lapointe 2001; Wheaton et al. 2010). The emphasis here is on measuring the volumes of sediment fluxes. Ashmore & Church (1998) and Haschenburger & Church (1998) argue that these methods are better for understanding the role that channel morphology plays on the heterogeneity of bed load transport rates. The process can also involve using the continuity equation alongside morphological evidence of channel changes, which can capitalize on the presence of historical information in estimating erosion and transfer rates.

The morphological technique has yet to be subject to extensive validation and testing, one of the reasons being that for field testing, a river with “discrete and persistent” zones of scour and deposition is needed (Haschenburger & Church 1998). Areas subject to both scour and fill during an event (resulting in no net channel bed change) produce no data for analysis. Furthermore, the morphologic technique examines only sediment entrained as bed load (Ashmore et al. 2000; Eaton and Lapointe 2001). However, in many cases the bed material fraction of the sediment load is significantly less than the hydraulic capacity would suggest (Ashmore & Church 1998). These findings corroborate those discussed earlier; high proportion of transported sediment is thought to originate from the banks as opposed to the upstream river bed.

There seems to be a general consensus that the development of theories that accurately describe and predict erosion and deposition is hindered due to a lack of high-resolution monitoring methodologies (Lawler 2005; Reid et al. 2007a). Furthermore, as Lawler (2005) points out, the study of the erosional and depositional processes operating in fluvial systems is challenging because of the episodic nature of relevant events coupled with the fact that many ‘competent’ events may have occurred in one measurement interval. Consequently, high temporal frequency observations produce more accurate observations and data compared to less frequent observations. This supports the use of highly sophisticated and expensive sediment volume measurement tools such as time sequences of very high resolution photogrammetry-based DEMs or terrestrial laser scanning (TLS). The hope is that the use of such technologies will shed light on the very dynamics of erosion and deposition.

TLS technology, or ground LIDAR (**Li**ght **D**etection **a**nd **R**anging), can be very useful in determining morphological change by precisely measuring volumes of bed material (Hodge et al. 2009; Wheaton et al. 2010). The technology may quickly become the standard in 3D measurement techniques for surveying and engineering applications because of its ability to acquire mass point cloud data in a relatively short time frame.

Traditional land survey methods are unable to compete in terms of spatial resolution and time required for data acquisition (Miller et al. 2008). While increasingly sophisticated surveying methods such as EDM theodolites, GPS and photogrammetry do generate high resolution DEMs and greatly aid in the study of morphological change, they are still limited by the trade-off between spatial resolution and detail captured (Heritage & Hetherington 2007). Oblique field-based LIDAR technology has the power to produce quick, high resolution point cloud data that is more accurate while having the potential for greater aerial coverage (Heritage & Hetherington 2007).

2.3 Human Disturbances in Fluvial Systems

As indicated above, the predominant view in fluvial geomorphology is that rivers adjust towards an equilibrium state. However, another approach is to perceive rivers as continually responding, in a dynamic way, to a range of catchment factors at a range of spatial and temporal scales (Raven et al. 2010). This view takes into account the fact that human disturbances in fluvial systems have been numerous and that their effects are far-reaching. Controls such as climate (Arnell & Reynard 1996) and land use (Kondolf et al. 2002) are known to affect the discharge and sediment supply in rivers. However, perturbations due to river engineering add complexities to a system that already has several linkages between variables, and result in an almost continual potential for channel instability (Raven et al. 2010). This is illustrated in Figure 2.4, which shows how human perturbations can directly or indirectly affect the three main controls on channel morphology, namely discharge, sediment transfer and the resisting forces of the channel boundary. For example, several studies examining the impacts of floods have documented how the severity of the impact on channel morphology was highest downstream of reaches where bank protection was in place (Payne & Lapointe 1997; Ashmore et al., 2000; Eaton & Lapointe 2001).

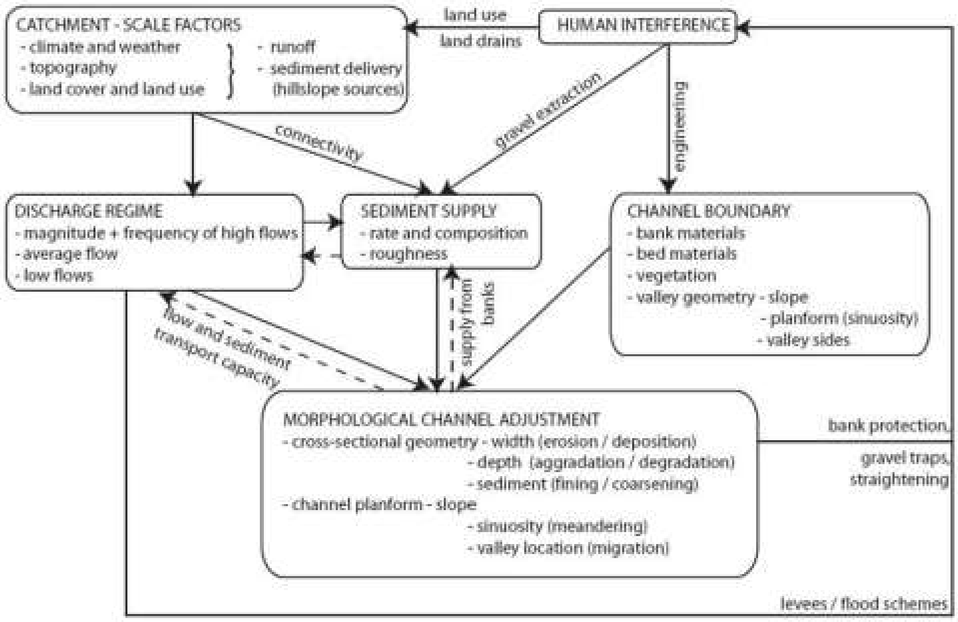


Figure 2.4 Linkages between factors influencing channel morphology showing the impact of human interference (from Raven et al. 2010).

Human disturbances include the straightening of channels, extraction of gravel, the building of dams, the design and installation of so-called “hard” engineering structures (energy dissipaters and grade control structures, bank armouring) as well as “soft” engineering structures (vegetation bank armouring). Both “hard” and “soft” engineering practices represent similar approaches to resolving issues such as bank erosion. For example, “hard” engineering involves the placement of rip-rap (boulders/cobbles with grain size too large to be entrained by maximum local shear stress values) while “soft” engineering (bioengineering) utilizes plants arranged in specific patterns to stabilize banks (Adams et al. 2008). The latter approach is regarded as more “ecologically friendly” but does not solve the problem of bank instability at scales larger than where it is installed. Furthermore, it does not allow for the re-adjustment of the sediment budget to natural levels leading to a propagation of the problem downstream (Brookes 1988; 1997; Simon et al. 2007). However, Lachat (1998) argues that the goal of bioengineering is to offer an alternative method to civil engineering approaches where human interests necessitate bank stabilizations.

During most of the last century, a popular practice in agricultural watersheds in South-Western Quebec (as with many agricultural areas in Europe and North America) was to straighten rivers and streams in order to have a greater degree of control on the hydrological regime as well as to simplify the shape of agricultural fields (Brookes 1998; Rhoads & Herricks, 1996; Talbot & Lapointe 2002). However, if a meandering or sinuous river is artificially straightened, the “natural balance” will inevitably be disturbed to some degree or another (Simon & Rinaldi 2006). As discussed previously, a river’s channel pattern is the result of careful adjustments to its slope in order to convey both liquid and solid discharges. Therefore, modifications to a stable channel pattern are essentially relatively rapid slope adjustments. If a channel pattern is modified but the sediment supply and discharge is not, the river will undoubtedly strive to re-establish its former equilibrium profile as “a channel must continue to carry its load of sediment with a given water discharge and this requires a given gradient that must be restored by [aggradation or degradation]" (Mackin 1948, p. 464). Because of these inevitable adjustments, frequent maintenance is needed following channel modifications where water and sediment supply remain constant (Simon et al. 2007).

Several studies have found evidence that channel instability and changes in channel pattern result from channel rectifications (Petit et al. 1996; Eaton & Lapointe, 2001; Surian & Rinaldi 2003; Simon et al. 2007; Raven et al. 2010). Talbot and Lapointe (2002) examined the effects of meander straightening on the Sainte Marguerite River in the Saguenay and found a re-profiling of the channel, resulting in a one meter incision upstream coupled with a two meter bed aggradation in downstream sections of the rectified rivers. Three meanders were found to be reactivated as well. Channel straightening often leads to channel incision due to elevated stream power producing higher shear stresses than normal (resulting in increased rates of degradation, sometimes the product of exceeding the cohesion of the substrate). The effects of incision can be numerous: increased sediment load, reduced water quality, lowering of the surrounding water table, damage to structures (e.g. bridges) and disturbance of coastal processes (Simon & Rinaldi, 2006; Heine & Lant 2009; Surian et al. 2009). Furthermore, in response to increases in channel slope and resultant stream power, pavement coarsening buffers the fluvial system from extreme degradation in upstream reaches of linearized streams (Talbot and Lapointe 2002). It therefore is not unreasonable to assume that in the upstream reaches of a rectified stream one would expect to find bed sediment that is coarser than it would be in an undisturbed state.

Similar effects result from sediment mining, dam construction, weir construction and bank armouring. All these disturbances will alter the sediment budget by restricting the volume of sediment available for solid discharge. Because channel morphology is a product of discharge and the transport and deposition of sediment, the removal or reduction of a river’s bed load will disrupt the sediment mass balance, resulting in adjustment to channel geometry (Leopold et al. 1964; Schumm 1977; Rinaldi et al. 2009; Raven et al. 2010).

Some perturbations such as dam construction and grade control structures also have the undesirable effect of longitudinal fragmentation, resulting in upstream river reaches being unattainable to transient fish (Simon & Darby 2002; Litvan et al. 2008). Fish habitat is also greatly affected by gravel extraction (Power 2001; Raven et al. 2010).

Structural modifications to channels have been developed and implemented with the aim of improving habitat for salmonids. Some examples include deflector structures and weirs meant to artificially create pools. However, few follow-up studies have been conducted on their effectiveness at generating habitat as well as their sustainability. A survey of 351 of these structures by Pattenden et al. (1998) found that more than a third were neither physically stable nor providers of the habitat they were designed to create. Furthermore, the study found that 81% of these structures were damaged or destroyed as a result of a major flood (Pattenden et al. 1998). These findings are corroborated by several other studies who argue that the solution lies in restoring the natural conditions and processes of rivers rather than in artificial in-channel structures (Miles 1998; Piégay et al. 2005a; Raven et al. 2010). These findings also highlight the need for more monitoring and study of these structures and suggest that the use of these structures might not be a sustainable solution to the problem of inadequate or scarce salmonid habitat.

2.4 Watershed Restoration and Management

It is clear that, whenever possible, simply removing structures that alter the liquid and solid flow regime (e.g. dams, weirs, bank fortifications), avoiding physical alterations to the channel and allowing the river to 'run its course' (adjust itself in order to re-establish an equilibrium profile) will, with adequate time, remedy the symptoms of a modified channel. However, the reality is that the very motivation for most alterations to fluvial systems is driven by human settlement within the watershed, often in valleys and low lying areas. Therefore, the problems and pressures that prompted manipulations and alterations to flow and sediment regimes still exist and must continue to be addressed (Brookes & Shields 1996; Shields et al. 2003).

Stream restoration or rehabilitation refers to the attempt at returning a stream and its lotic ecosystem to its historic (pre-degradation) state (National Research Council 1992). The implication is that we know, or can find out, what that natural, pre-modified state was. While exact information on the pre-degradation state of a stream or river network is hardly ever available, the “general direction and boundaries” can usually be established by combining existing historical data on the former state of the stream and comparing the stream to others that exist in similar physical and climatic environments (Shields et al. 2003; SER 2004).

Large scale, inter-disciplinary projects are typically those that offer the greatest potential for effective rehabilitation, although these are not always economically feasible. Project objectives should be set at the outset with input from all stakeholders. Hydraulic designers are then tasked with meeting these objectives. Sedimentation issues are, understandably, typically among the major issues to be dealt with, as sediment budgets are often neglected in civil engineering approaches to water management (the predominant historical form of employed management techniques) (Gilvear 1999; Shields et al. 2003; Simon et al. 2007; Raven et al. 2010). Most historical civil engineering projects were typically carried out on vulnerable, localised sites. It has become clear that the majority of these forms of interventions are unsustainable as they require constant maintenance (Brookes 1997; Shields et al. 2003; Florsheim et al. 2008). There is a growing consensus that geomorphological principles must be governing rehabilitation programs aimed at analyzing and addressing concerns at the watershed scale (Sear 1996; Piégay et al. 2005a; Spink et al. 2009). Restoring the dynamic equilibrium of a river or stream is often the best way to rehabilitate it but is not always feasible as it might represent a threat to infrastructure or human and natural resources in the floodplain. Consequently, benefits of rehabilitation must be weighed against risks to human interests, such as flooding and erosion (Shields et al. 2003; SER 2004).

Brookes and Sear (1996) outline a list of guiding principles for river restoration. At the onset of any restoration project, project planning and the setting up of realistic goals are crucial steps. In many agricultural watersheds pre-disturbance conditions may be unknowable, and it may in any case not be possible to restore ecosystems to their pre-degradation state (Wheaton et al. 2006). Catchment-scale considerations of water quality and the sediment delivery system must be properly evaluated, as the coupling between these and the river system is strong (Brookes & Sear 1996). Furthermore, the relationship between a river and its floodplain must be determined, as these interconnections are crucial in the fluvial system. Once restoration objectives are formulated, the evaluation of alternative methods for restoration can be undertaken, with ‘natural recovery’ (allowing a river to re-establish its intrinsic processes and features given enough time and space) representing one option for consideration. Proper project design and implementation are integral to success, along with post-project monitoring as adjustments and reiterations are often needed.

One possible method for stream restoration is the river corridor approach (Piégay et al. 2005a). This approach strives to re-establish the intrinsic functioning of the fluvial system. The river should be granted enough space to erode its banks and undergo meander evolution, to establish an ecologically functional riparian buffer zone and be allowed to overflow onto its floodplain (Brookes & Sear 1996; Brookes & Shields 1996; Brookes et al. 1996; Shields et al. 2003).

It is important to engage in close consultation with locals, or "typical users" of the river and/or watershed (McGahey & Samuels 2004; Piégay et al. 2005b). Firstly, they have a vested interest in cooperating and generating sustainable results; the research area is their home and could very well represent a portion of, or even their entire, livelihood. Secondly, because they spend a lot of time in the area, they probably have some form of knowledge (often historical) that may be beneficial to the project in some way or another. An informed and involved local population can prove to be the best custodians of the watershed (McGahey & Samuels 2004).

2.5 Numerical Modeling

Predicting changes in channel morphology over large temporal and spatial scales is quite challenging. Ideally, lessons learned from investigations of the generally small-scale processes and mechanisms responsible for turbulence, sediment entrainment, deposition and armouring (to name a few) should be integrated with open-channel hydraulic engineering principles in order to arrive at applicable results at appropriate scales (Reid et al. 2007b). Numerical models are powerful tools for doing so and represent an interesting and evolving component in the discipline of fluvial geomorphology. Several one-dimensional models developed in recent years constitute the majority of numerical models used in river engineering and morphological analyses, partly because the basic concepts have been in use for several decades (Pappenburger et al. 2005). These include models such as Mike 11, ISIS, SEDROUT and HEC-RAS (Pappenburger et al. 2005; Reid et al. 2007b; Aggett and Wilson 2009).

One-dimensional models require as input cross-sectional topographic data for channel geometry and estimates of surface roughness, such as Manning's n. However, as their name implies, they generate average values for this data so that each cross-section is considered one point along a longitudinal section (several linked cross-sections making up a channel reach). The output is also in this form; the program will generate a singular output value (e.g. shear stress) per cross-section. HEC-RAS, the model to be used in the case study of the Sunday River, can actually be thought of as three discrete 1D models running in parallel: over-bank sections on each side of the channel (i.e. the floodplain) are assigned their own estimates of surface roughness, yielding three discrete values for each cross-section (so long as the discharge is high enough as to produce a flow depth greater than zero on the surfaces beyond the banks) (Brunner 2010). The output of 1D models is more simplistic than those from 2D or 3D models, but the integration requires much simpler parameterization of channel characteristics.

Two-dimensional models allow for the lateral variability to be taken into account, with over-bank flow interacting with channel flow (Pappenburger et al. 2005). Three-dimensional models go one step further by allowing the vertical variability to be solved, yielding outputs in all three axes; longitudinal, transverse and vertical. This also requires more extensive input parameterization.

The applicability of models of different dimensionality and generality (model capability of handling different grain sizes, changes in width, graded beds) is usually dependent upon several considerations (Lane and Ferguson, 2005; Verhaar et al. 2008). Firstly, financial limitations will determine the feasibility of using different models: the code for the widely used 1D model HEC-RAS is public domain while most advanced 3D models are not. Second, because 3D models require extensive input parameterization and perform lengthy, demanding computations, they are consequently only suitable for modeling short reaches and time periods. Similar to 3D models (although to a lesser extent), 2D models require lengthier integration times and higher volumes of input data than 1D models, putting them out of reach for many practical applications. Recent research has found that complex 2D models based on high resolution DEMs may not exhibit better predictive abilities than 1D models when results are compared to field measurements (Pappenburger et al. 2005; Aggett & Wilson 2009). However, because 1D models provide bulk flow characteristics, “they fail to provide information regarding the flow field” (Chatterjee et al. 2008, p. 4695). To address this problem, attempts have been made at coupling 1D and 2D models, where flow in the channel is modelled in one dimension while 2D equations are used for flow occurring on the floodplain (Chatterjee et al. 2008).

3 OBJECTIVES AND RESEARCH QUESTIONS

The overall objective of this study is to improve our understanding of hydro-geomorphological processes and sediment dynamics in an upland gravel-bed river that has undergone human disturbances (channel straightening) in order to provide guidelines for sustainable management schemes that would limit interventions such as gravel extraction which are currently taking place. The case study is the Sunday River, near Thetford Mines (Qc), located in the upland part of the Bécancour watershed.

The specific research questions are:

1) What are the current sediment dynamics, channel morphology and longitudinal profile of the Sunday River and do they appear to be in relative equilibrium based on stream power?

2) Can some management solutions be suggested to remedy the erosion and deposition problems present in the Sunday River and possibly avoid the need for continued channel manipulations?

3) Can sediment transport be predicted for the downstream reaches of the Sunday River using numerical modelling? Is it possible to predict zones of erosion and deposition?

Although this project focuses on a case study, results drawn from this analysis are applicable to several other upland rivers in Quebec and elsewhere where sediment management is problematic. These rivers are typically of ecological importance as they provide very good quality fish habitat for salmonids. It is thus essential to provide management guidelines that will ensure that gravel is not removed and that fine sediments don’t clog up spawning areas.

4 METHODOLOGY

4.1 Study Area

The Sunday River watershed (46° 22" 17' N, 71° 22' 8" W) is located in the upland region of the Bécancour watershed in the province of Quebec (Figure 4.1). The area is characterized by the presence of the foothills of the Appalachian Mountains, a thin strip of weathered mountains composed of sedimentary rock along Quebec's southeast border. The Sunday River is a tributary of the Osgood River. It is a gravel-bed river approximately 12 km long with a catchment area of 45 km^2. Bankfull width ranges from 5-10 m, with average bankfull depth ranging from 0.5m to almost 2m in downstream portions. The average bed channel slope is approximately 0.5%. While the Sunday River is regarded as being a provider of high quality trout habitat, channel manipulations carried out in downstream reaches, and the regular maintenance of these, have compromised the integrity of this habitat. In particular, a mid-channel bar a few hundred meters upstream of the confluence of the Sunday and Osgood Rivers presents a challenge to river managers as dredging and gravel extraction are required on an annual basis to maintain both the linearized channel path and the desired channel width. Furthermore, a steep bank several hundred meters upstream appears to be eroding quite rapidly; the consequences of advanced bank recession are most likely to be quite severe as there exists a man-made pond situated within 10 m of the edge of the top of the bank (Figure 4.2).

Because this project was conducted in partnership with the MRNF, several GIS datasets were made available to us. In particular, a 10m resolution digital elevation model (DEM) (Figure 4.3) as well as an IRS satellite image were provided (Figure 4.4). Additional geographic information system (GIS) files, including DEMs, topographic maps as well as hydrological and road networks were obtained from GeoBase (www.geobase.ca).

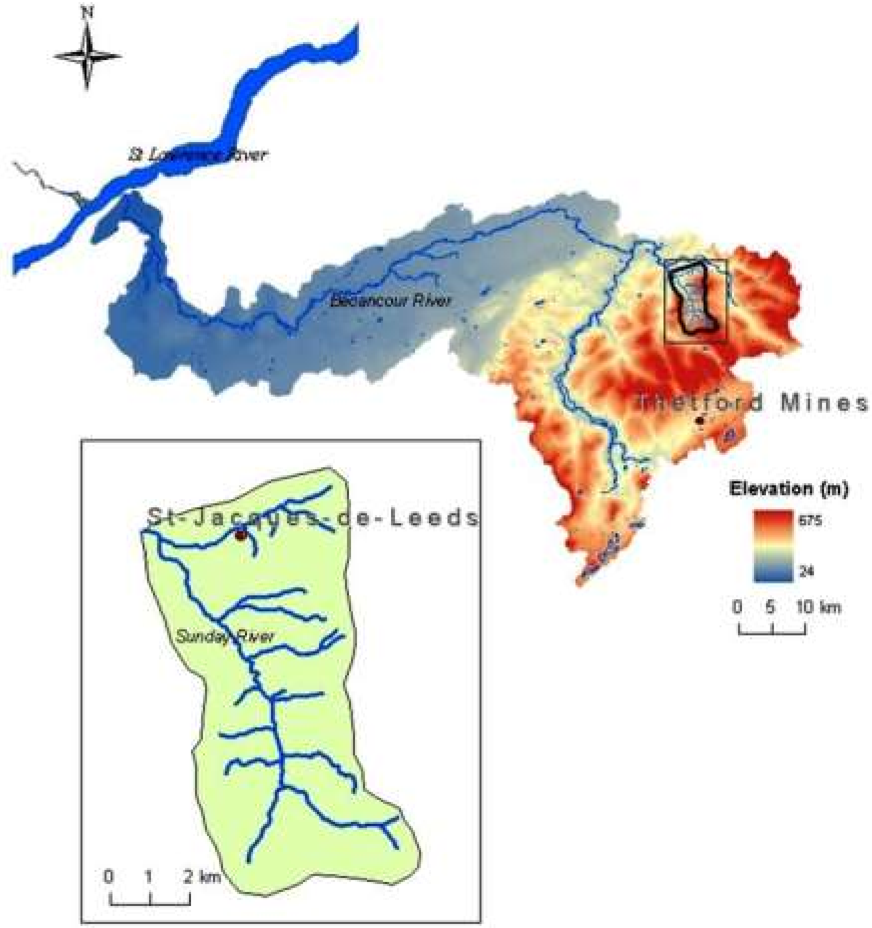


Figure 4.1 Location of the Sunday River watershed

Figure 4.2 Problematic mid-channel bar and eroding bank, downstream Sunday River

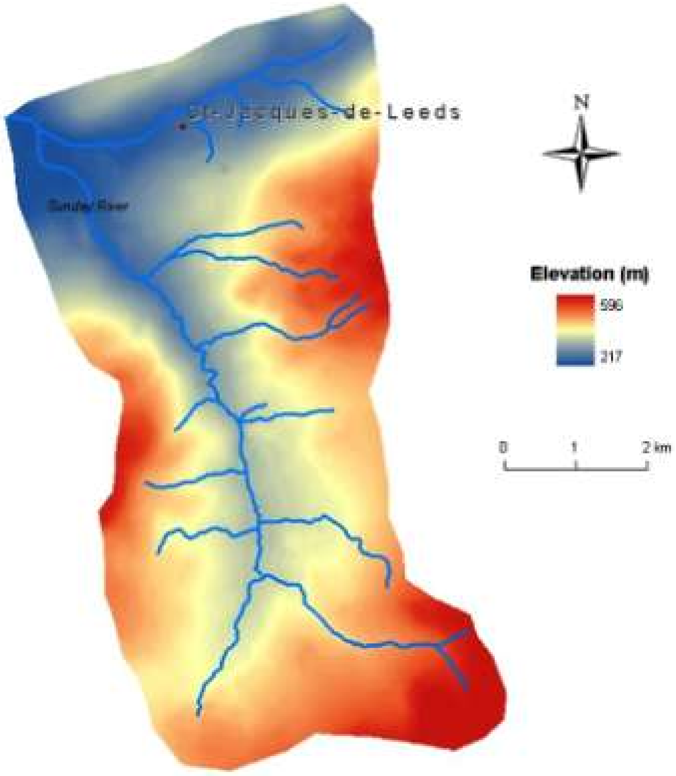


Figure 4.3 Digital Elevation Model (DEM) of the Sunday River watershed

4.2 Historical Analysis

The analysis of human disturbances in the watershed is based on ancient aerial photographs of the lower reaches of the Sunday River (where forest cover is less dense, making it possible to see the channel). They were obtained at the Université de Québec à Montréal Cartothèque as well as from Mr Mathieu Bussière from the Coop Forestière de St. Agathe. The aerial photos date from 1950, 1959, 1966, 1975, 1984 (UQAM), 1985, 1993, 1997, 1998, 2004 and 2007 (Coop St. Agathe). The photos were georeferenced and analyzed in a GIS software (ArcGIS, from ESRI), which allows for the determination of the extent, date and nature of channel rectification as well as former stream patterns. For the georeferencing process, roads that are known not to have changed layout over time were used (Figure 4.4) Assuming no major change in elevation in the valley, the historical planform geometry of the river can be used to reconstruct longitudinal profiles of the downstream section (Figure 4.4) at various times in the last 60 years. This information helped in determining the historical equilibrium profile of the river. A search for topographic maps dating back further than 1950 concluded without avail.

Figure 4.4 Aerial photographs from 1950 and 2004 showing georeferencing targets.

Historical documents of the various human interventions on the Sunday River were also available through various sources. Mr. Guy Brochu, from the Ministère du Développement Durable, de l'Environnement et des Parcs (MDDEP) provided a comprehensive list of intervention descriptions and dates from historical information conserved and compiled by the Ministère de l'Agriculture, de l'Alimentation et des Pêcheries (MAPAQ).

4.3 Field Data Collection and Analysis

In order to document hydro-geomorphological processes and sediment dynamics occurring in the Sunday watershed (research question #1), extensive field data was collected. The basic variables of interest (see Figure 2.1) consist of discharge, channel slope, grain size and sediment supply. Additionally, field data are required as input in the numerical model as well as to calibrate and validate the modeling results. In particular, detailed transects of bed and bank topography were needed at a large number of cross-sections in order to avoid instabilities in the model.

4.3.1 Water Level and discharge

There is no existing gauging station in the Sunday River watershed, nor are there any historical data available. During the summer of 2009, two pressure transducers (Solinst – Barologger & Levelogger; Global Water – Global Logger II) were installed in the Sunday River. The first installation, referred to as Station 1 and comprising a Global Logger II, was installed on the 17th of June 2009 in a river bank approximately 230m from the downstream limit of the Sunday River (Figure 4.5). The second installation, referred to as Station 2 and comprising both a Levelogger and Barologger, was installed on September 4th 2009 under a bridge about a quarter of the way between the headwaters and the lower limit of the river, approximately 5.25km upstream from station 1 (Figure 4.5). These transducers measure the hydrostatic pressure of the water column above them and are both set to take readings every 15 minutes.

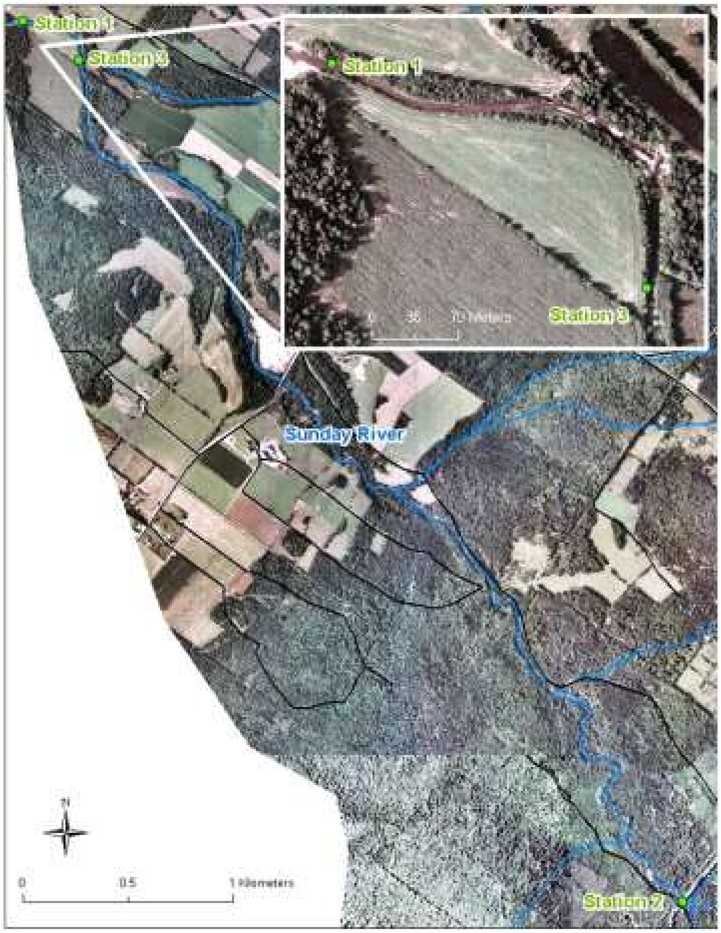
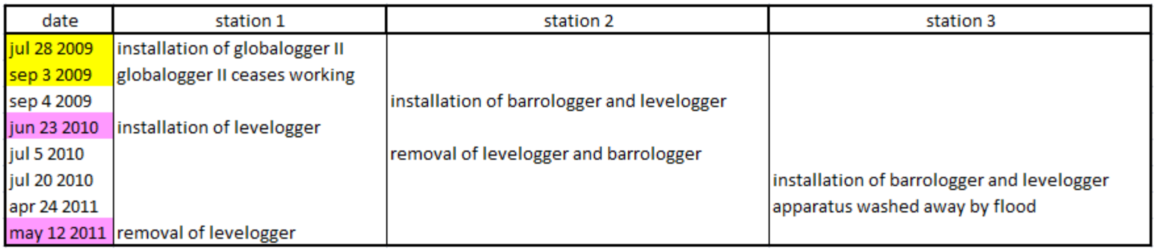


Figure 4.5 Location of pressure transducers

Unfortunately, several complications arose in the collection of water depth data (Table 4.1). Both pressure transducers installed in 2009 had to be dismantled and relocated in 2010, and in the spring of 2011 one of them was completely washed away in a large magnitude flooding event. The Global Logger II at station 1 ceased working on September 3rd 2009. Unfortunately, it was not known that the device had failed until the spring of 2010 when the logged data was to be retrieved. On June 23rd 2010 it was replaced with a Solinst Levelogger (at a position 3 meters downstream from the previous location). The Solinst Levelogger does not record atmospheric pressure and must therefore be installed in close proximity to a barometric pressure logging device if atmospheric pressure data is not already being acquired by other means (as water column pressure must be differentiated from barometric pressure). It was decided that the data from the upstream installation (Station 2) could be used for atmospheric compensation of the downstream data as this installation included a Barologger and was sufficiently close. Due to a difference in elevation of approximately 100 meters between the two installations, a slight correction was applied to the atmospheric pressure data to be used to compensate the data from the downstream Levelogger.



date	station 1	station 2	station 3
jul 28 2009	installation of globalogger II		
sep 3 2009	globalogger II ceases working		
sep 4 2009		installation of barrologger and levelogger	
jun 23 2010	installation of levelogger		
jul 5 2010		removal of levelogger and barrologger	
jul 20 2010			installation of barrologger and levelogger
apr 24 2011			apparatus washed away by flood
may 12 2011	removal of levelogger		

Table 4.1 Three different transducer locations and the installation and dismantling of the apparatuses, by date. The dates in yellow correspond to the beginning and ending of the period of data collection by the Globalogger, while those in pink correspond to the period of data collected by the Solinst levelogger.

The upstream Levelogger and Barologger located at Station 2 were removed on the 5th of July 2010. This was a result of road and bridge work being undertaken by the Minister of Transport on the very structure on which the transducer had been installed. Consequently, it was decided to relocate the transducer to the upstream end of the studied reach, approximately 400m upstream of Station 1. The transducer was installed on the 20th of July 2010 on the left bank (facing downstream) and was subsequently referred to as Station 3.

Upon returning to the study site in May of 2011, it was discovered that a very high magnitude flooding event that occurred in late April 2011 had completely washed away the Station 3 installation. This was unexpected since the 2-inch ABS piping installation was anchored to two trees on the bank, one of which was approximately 20 centimetres in diameter and appeared to be strongly rooted in the bank. During this flood event, a section of bank of at least 1.5 meters by 4 meters was dislocated and entrained, along with several mature, healthy trees. As a result of this loss (of both Levelogger and Barologger data), no atmospheric readings were available since the last survey of November 6th 2010. Atmospheric pressure data from the Thetford Mines weather station were used in lieu of the unavailable local data.

A Leica total station (TC805L) was used at repeated intervals to determine and monitor the height of the transducer above the bed and to determine the elevation of the water surface. Water depth and channel width measurements taken at regular intervals were used to obtain the cross-sectional area of the channel. The square counting method was employed to ensure a high degree of accuracy of computed discharge values. Throughout the 2009 and 2010 field seasons a current velocimeter (Swoffer model 2100) was used to acquire several cross-sectional measurements of velocity for a range of flow conditions. These included 5 measurements at the Station 1 location in 2009 and another 8 in 2010, 5 at the Station 3 installation in 2010 and another 3 at Station 2. The computed discharges were combined with the water level data to generate a rating curve. However, it remained difficult to obtain cross-sectional velocity measurements at very high discharges, mainly because of the difficulty of wading in the river at high flow stage with high velocity.

To supplement the dataset and thus increase the accuracy of the equation(s) linking stage to discharge, theoretical discharges were computed using Manning's equation:

$$Q = n^{-1} R^{3/2} S_o^{1/2} A \qquad \text{(eq. 4.1)}$$

where n is Manning's roughness coefficient (with a range from 0.013 to 0.03), Q is average discharge (m^3/s), R is hydraulic radius (m) and A is the cross sectional area (m^2). By comparing the theoretical discharges to the measured ones, it was determined that the value of n = 0.013 was indeed the most reasonable (Figure 4.6). A rating curve was computed based on best-fit parameters: then plotted and an equation generated using curve fitting software:

$$Q = 66.5254\, e^{(-1.6182/Y)} \qquad \text{(eq. 4.2)}$$

where Y is flow depth and Q is discharge (Figure 4.6)

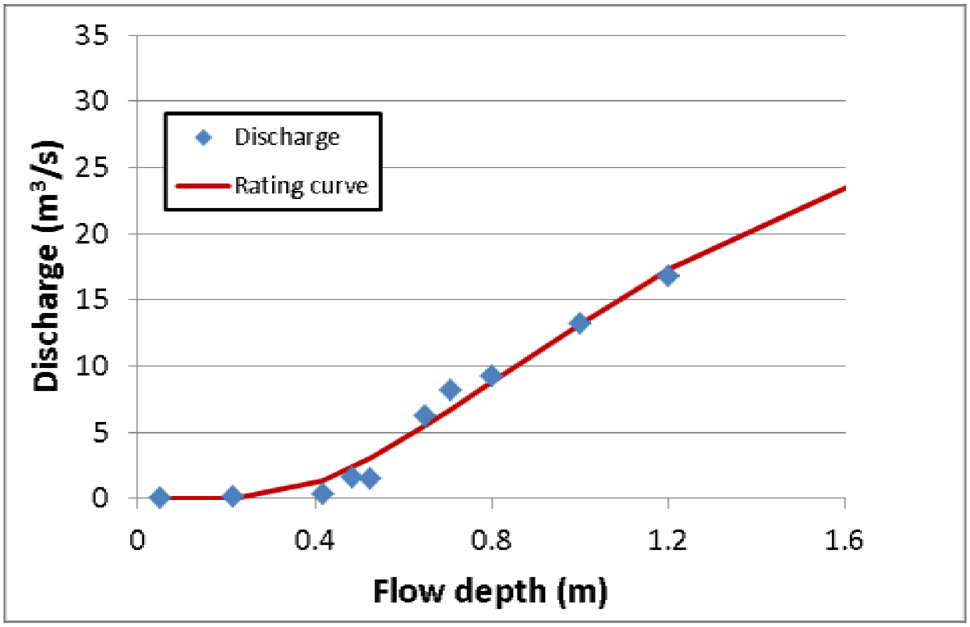


Figure 4.6. Rating curve at Station 1 on the Sunday River.

4.3.2 Long Profile

In early November of 2010, a Magellan Promark differential GPS unit was loaned from Dr. Thomas Buffin-Bélanger from Université du Québec a Rimouski (UQAR). The apparatus provides coordinate data (latitude, longitude and elevation) accurate to a few centimetres. The equipment was used on the 5th, 6th and 7th of November 2010. Data collected were used to generate a longitudinal profile of the river bed and water surface along a 500m section of the Sunday River at its downstream end. Point data were also used to increase the number of cross-sectional geometry transects to be used in one-dimensional modeling and to add locations of interest (such as areas of bank stabilization) and the exact geographic locations of the benchmarks used in total station survey in order to georeference previously acquired topographic data.

Raw point data were transformed into coordinates in UTM NAD83 using GNSS Solutions data treatment software and then integrated into an ArcGIS database.

4.3.3 Grain Size

The Wolman method (Wolman 1954) was employed with random sampling at evenly spaced cross-sections (spacing was determined using a standard GPS). Sediment samples were analyzed in each cross section by picking up whatever sediment happened to be directly under the big toe as one meter footsteps were taken perpendicular to the longitudinal axis of the channel. A total of 719 sediment samples were collected on the channel bed and bar surfaces of the Sunday River. Of these, 379 were collected in the 500m study reach; the data was grouped into 4 discrete zones to facilitate its use in the sediment modeling module of HEC-RAS (Figure 4.7).

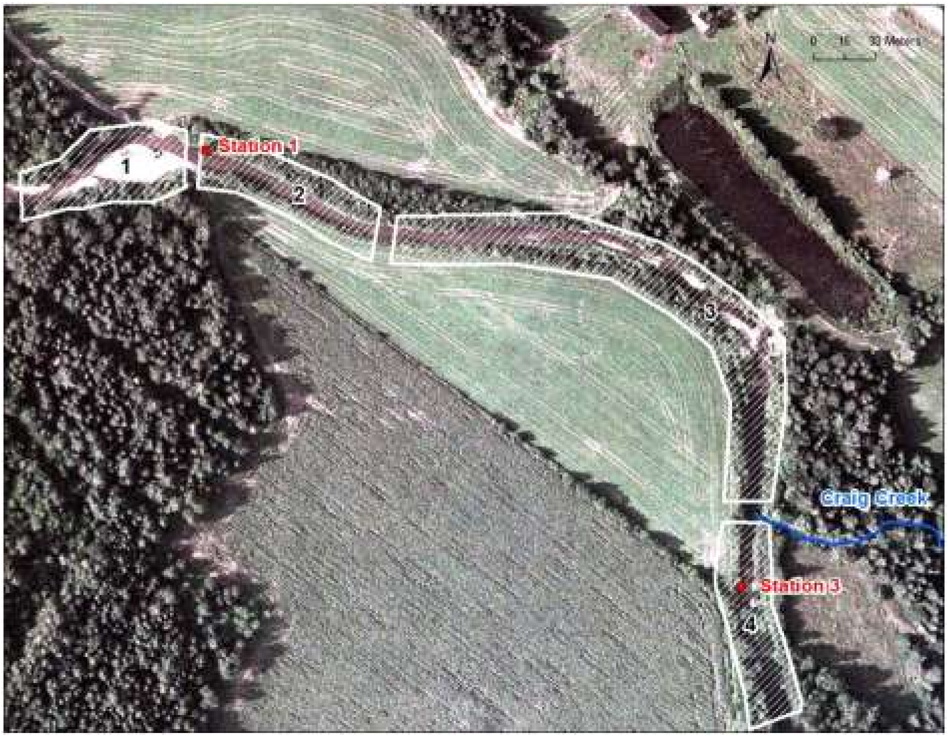


Figure 4.7 Sediment zones in model reach

Another 237 were collected from the surface of the mid-channel bar itself. Additionally, sediment samples of the sub-surface of the mid-channel bar were collected in order to analyze differences in sediment size distribution due to bed armouring. In total, 19.14 kg of sediment were acquired from 7 sections of the bar (Figure 4.8).

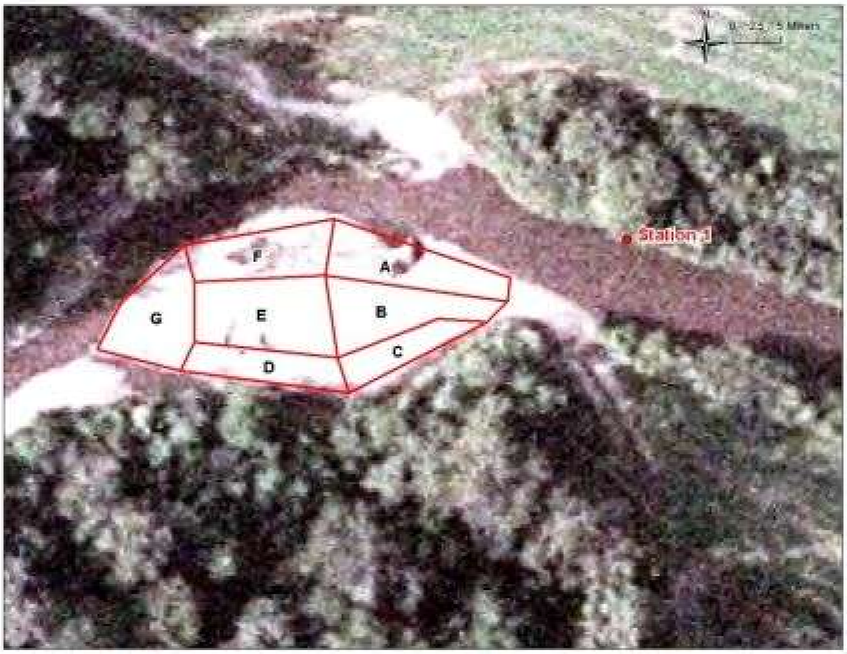


Figure 4.8 Mid-channel bar sediment zones

The bar was divided into these sections of approximately equal areas in order to be able to record variations in sediment size distribution both longitudinally and laterally. The subsurface sediment samples were sorted into size classes using the sieve analysis by weight method. All sediment data, both above and below surface, were plotted on the phi scale in order to determine size class distribution as well as the D_{16}, D_{50} and D_{84}, where D_{16} represents the grain size diameter where 16% of the grains are finer, D_{50} is the median diameter, and D_{84} is the diameter where 84% of the grains are finer.

4.3.4 Sources of Sediment and Sediment Transport Rates

Previous work situating and characterizing bank failure locations and sediment sources on the Sunday River was made available (Frederic Lewis, pers. comm.). This analysis also included the evaluation of bank stability, riparian zone presence, and livestock access to the river and its tributaries. At the outset, the measurement of erosion rates of the particularly problematic steep bank (bank angle well over 45°, Figure 4.2), which consists of relatively cohesive sediment and exhibits signs of water saturation (possibly because of the presence of a pond on top of the bank) was attempted using the technique of erosion pins. A total of ten 1.3 m pins were installed in the bank in the summer 2009. However, because of the cohesive nature of the bank material, bank failure events were too large in volume to be measured using this technique (Figure 4.9). For the technique to be effective the rods would presumably have to be inserted to a depth of at least 2 m, they would have to protrude from the bank at least 1 m, and would have to be of a sufficient diameter to resist large weight loads generated from bank material falling from above. Given the context and limitations of this research, using erosion pins in this study was unrealistic.

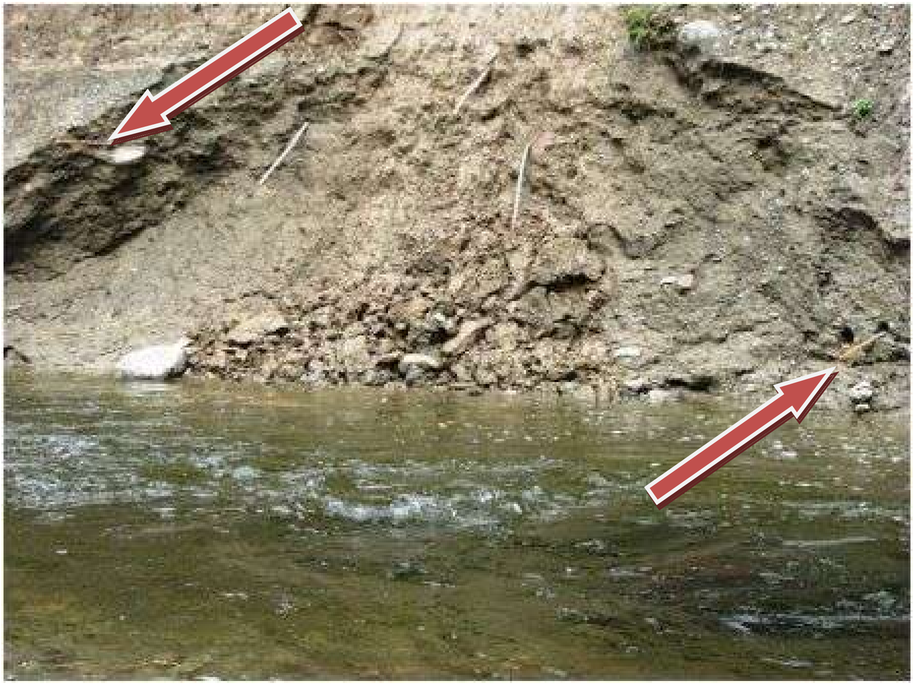


Figure 4.9 Erosion pins after one or more bank failures. Note the orange pins to the left and right of the 3 mangled pins in the center of the photograph. This photo is of a lower section of the bank in Figure 4.2.

This bank was ultimately analyzed using a Leica Scan Station 2 terrestrial laser scanner (TLS), otherwise known as ground LIDAR (Figure 4.10). A second site was also investigated using TLS. The second site is a series of two meanders (one wavelength) where the Sunday River borders a saw mill. Mill workers allege that the banks here erode an average of “a foot or two” per year. These banks are characterized by what is predominantly coarse sediment. The sites were surveyed twice in 2009, once in August and again in November. At the first site (Figures 4.2 & 4.9), another survey was also taken in June 2010.

Figure 4.10 Leica Scan Station 2 in operation on the Sunday River.

TLS scans generate point clouds which can be analyzed using either CAD software, proprietary software produced by the manufacturer (Leica Cyclone) or, as in this case, a combination of both. Point cloud data was treated in Cyclone to remove “noise” such as branches, debris, or anything that can be confused with actual bank values. Once this preliminary analysis is completed, a digital elevation model (DEM) was generated using Cyclone Topo software. ArcGIS was then used to overlay successive DEM datasets and to generate estimates of the volumes of sediment that had been eroded during the time intervals between LIDAR scans.

The problematic mid-channel bar at the downstream-most reach of the Sunday River was repeatedly surveyed using a total station in order to track its evolution and determine how sediments accumulate in the downstream Sunday River. During the summer 2009, 5 surveys were undertaken (July 14th, 23rd, 28th and August 5th, 12th). In

2010, 4 additional surveys of this reach were undertaken (June 4th, July 5th, August 20th, and November 7th). The data were analyzed in ArcGIS by generating DEMs and overlaying these in order to determine areas of degradation or aggradation.

4.4 Numerical Modelling

4.4.1 HEC-RAS

The one dimensional model HEC-RAS (Hydrologic Engineering Centers River Analysis System), version 4.1.0, was used in this research study. The model was developed by the US Army Corps of Engineers and is available free-of-charge: http://www.hec.usace.army.mil/software/hec-ras/. The software is able to perform four types of analysis: steady flow and unsteady flow simulations, sediment transport computations and water quality analyses. In the steady and unsteady flow components, the model performs back-water calculations to compute water surface profiles for different characterizations of the reach(es) being studied. Modifications can be made to geometry, flow and resistance characterization and saved as ‘plans’ in order to facilitate comparison studies. The recent development of HEC-GeoRAS (a tool for HEC-RAS parameter input as well as post-integration analysis in Arc GIS framework) has greatly improved the applicability of the model to fluvial geomorphological investigations by simplifying cross-sectional profile acquisition and input. One of the main benefits of

HEC-GeoRAS is the capability to use DEMs instead of cross-section topography for channel geometry input (Aggett & Wilson 2009).

HEC-RAS was used in this study to predict the water surface profile, measures of erosive potential such as stream power and shear stress, and sediment transport estimates along the problematic downstream section of the Sunday River (Figure 4.11). A 1D model such as HEC-RAS does not take into account the effect of lateral changes in channel geometry and roughness but instead uses average values of cross-sectional data for these. This leads to more simplistic results than 2D or 3D models, but also requires much simpler parameterization of channel reach characteristics (Brunner 2010). Input parameters for steady flow simulations are discharge, successive cross-sectional channel geometries, and roughness estimates of the channel and banks, characterized as Manning’s n values. Sediment transport analysis requires the additional input of grain size classes and their respective distribution at each cross section.

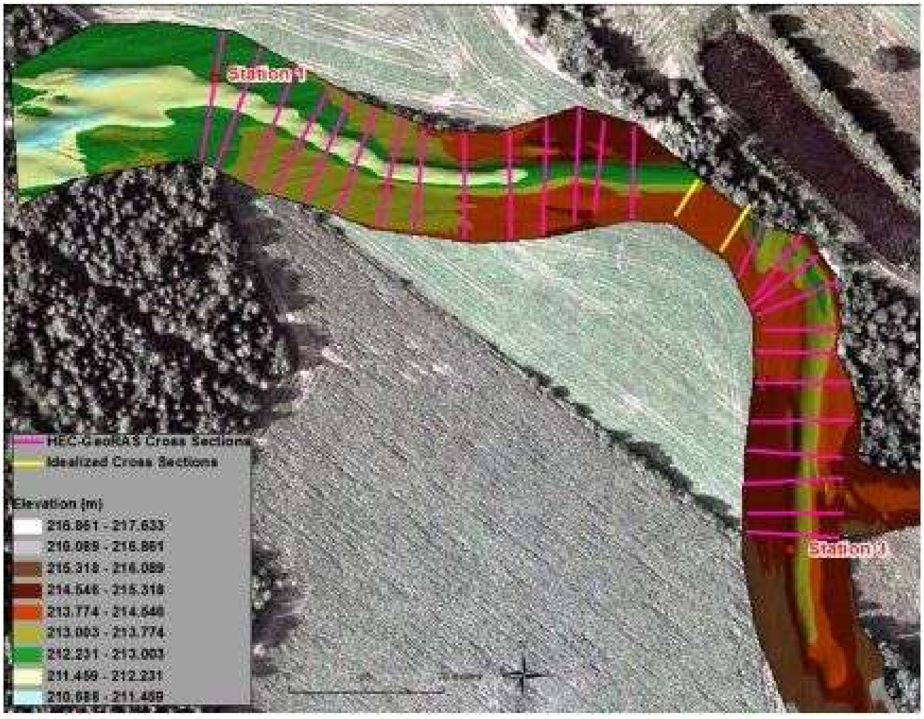


Figure 4.11 Model reach overlaid with TIN generated from total station and DGPS data and transects. Pink transects were generated by HEC-GeoRas extension for ArcGIS while yellow transects were supplemental transects input manually.

It is recommended to gather cross-sectional data both upstream and downstream of the reach to be studied in order to eliminate any user-defined boundary conditions that may lead to inaccurate results. However, cross sections at and downstream of the mid-channel bar (Figures 4.2 and 4.8) were not incorporated into the study as the area was deemed to be too dynamic over short time periods, resulting in difficult or impossible model validation and output verification. A total of 26 cross-sections were positioned to represent the changes in slope and roughness (Brunner, 2010).

A total station and DGPS unit were used to gather (X,Y,Z) points along the cross-sections which extended from the channel onto the adjacent banks (pink transects in Figure 4.12). As is evident in Figure 4.12, an area devoid of data was present just downstream of the left handed bend (looking downstream) below the artificial lake. The lack of point data was a result of vegetation in the area, which limited the field of view of the total station and interfered with the satellite signal reception of the DGPS unit. The model simulations produced water surface slopes in the area in question that were inconsistent with those measured in the field. In response, a temporary total station benchmark was installed in the area in order to supplement the dataset. Instead of generating a new TIN, the points themselves were incorporated into 2 supplemental cross sections directly in HEC-RAS (yellow transects in Figure 4.11).

Sediment transport potential is a measure of the volume or mass of a specific-sized sediment class a river is capable of transporting at specific stages. The sediment transport equations are applied separately to each grain class, e.g. D_{50}. The equations available in HEC-RAS are the following: Ackers and White (1973); Engelund and Hansen (1967); Laursen-Copeland (1958); Meyer-Peter Muller (1948); Toffaleti (1968); Yang (1979); Wilcock and Crowe (2003). The Wilcock and Crowe (2003) equation was used in this case as it is the only equation that is available in both HEC-RAS and BAGS. However, it is not ideal in this case due to its relatively high sensitivity to estimated sand content (precise estimates of sand proportions were not acquired). Once transport is computed for each grain class, a total volume is computed by summing the contribution of each class relative to its abundance (Brunner 2010).

If a high-enough resolution DEM of the watershed had been available, it would have been possible to extract some parameters such as unit stream power (equation 2.2) (e.g. Barker et al. 2009) which could have been compared to the output of the numerical modelling simulations. Unfortunately, the only DEM available for the Sunday watershed is that provided by the MRNF, which has a pixel resolution of 10 m, but which is built from contour interpolation and for which there exists no detailed error assessment. Preliminary tests running hydrology tools in ArcGIS revealed that it was not possible to use this DEM to extract any relevant information such as water surface slope or channel width, both of which are variables needed for the calculation of unit stream power (e.g. Ferencevic and Ashmore, 2012).

An important parameter in 1D modelling is channel roughness, quantified using the Manning roughness coefficient (n). Channel and floodplain roughness are assigned different values of composite roughness estimates as overbank areas are modelled as discrete channels (see section 2.5). Manning's n estimates were initially made for each transect based initially on the grain size distribution analysis (see section 4.3.3).

Modelled water surface slope was compared to actual slope as a calibration technique, and Manning's n was adjusted in accordance. Theoretical discharges using Manning's n values for the channel were compared to actual flow rates as a validation technique.

4.4.2 BAGS

BAGS (Bed load Assessment for Gravel bed Streams) is a software in the public domain developed by Peter Wilcock, John Pitlick and Yantao Cui (Wilcock et al. 2009) to calculate sediment transport rates in gravel bed streams. It is written as a macro for Microsoft Excel. Several bedload transport equations are available for use in BAGS, such as Parker (1990); Parker et al. (1982); Parker and Klingeman (1982); Wilcock (2001); Wilcock and Crowe (2003); and Bakke et al. (1999). The Wilcock and Crowe (2003) model was used in the simulations for this study to be more easily comparable to the simulation result generated by HEC-RAS. Input parameters required include channel geometry input as X-Y coordinates, channel slope, hydraulic roughness estimates, discharge, and bed material grain size distribution. The input values for the BAGS simulations were identical to those used in HEC-RAS. The purpose of using BAGS was to verify simulation integration and the results produced by the sediment transport module of HEC-RAS by duplicating them in BAGS.

5 RESULTS

5.1 Historical Analysis

The downstream section of the Sunday River between the route 226 bridge and its confluence with the Osgood River underwent significant straightening in the 1950s. Mr Guy Brochu, an engineer and analyst with the Ministère du Développement Durable, de l'Environnement et des Parcs, provided a document entitled “Consultation le 8 avril 2008 du dossier conservé par le ministère de l'Agriculture, de l'Alimentation et des Pêcheries (MAPAQ)” summarizing the historical records of work carried out in the Osgood and Sunday River watersheds (Brochu 2009). The records indicate that work being executed on the Sunday River was suspended on the 6th of December 1954, resumed on the 13 of July 1955 and finished on the 27th of August 1955. This is believed to be the initial large scale channel manipulation based on both the MAPAQ records and the analysis of historical aerial photographs (Figure 5.1). It resulted in an approximate decrease of channel length from 3.63 km to 2.72 km, which corresponds to an increase in slope of about 25%. The lower Sunday River was almost entirely linearized, save for 2 large wavelength meander loops in the downstream reach.

Historically the Sunday River had adjusted itself to the confines of the valley as well as its solid and liquid discharge regimes. However, following the initial channel manipulation of 1955, intermittent but continued re-straightening work had to be undertaken because the course of the river had been altered from its natural state. The MAPAQ records indicate that subsequent work was undertaken in the Sunday

Watershed in 1976-1977, that work along 1063 m of the Craig Creek (a tributary of the Sunday, Figure 4.7) was undertaken in 1984, and that “maintenance” of the Sunday River was undertaken in 1992, 1999, 2000, 2005 and again in 2007 (Table 5.1). These records include interventions that were executed in response to requests by either the municipality of Saint-Jacques-de-Leeds or the county (MRC des Appalaches, formerly known as MRC de l’Amiante and previously also as Conseil de comté de Mégantic). However, unsanctioned channel manipulations (dredging and re-straightening) in the area of the mid channel bar and in the downstream-most reach of the river (around zone 1, Figure 4.7) are alleged to have occurred on a 2-3 year basis, at least in recent times. It is believed that the last intervention was carried out in 2008.

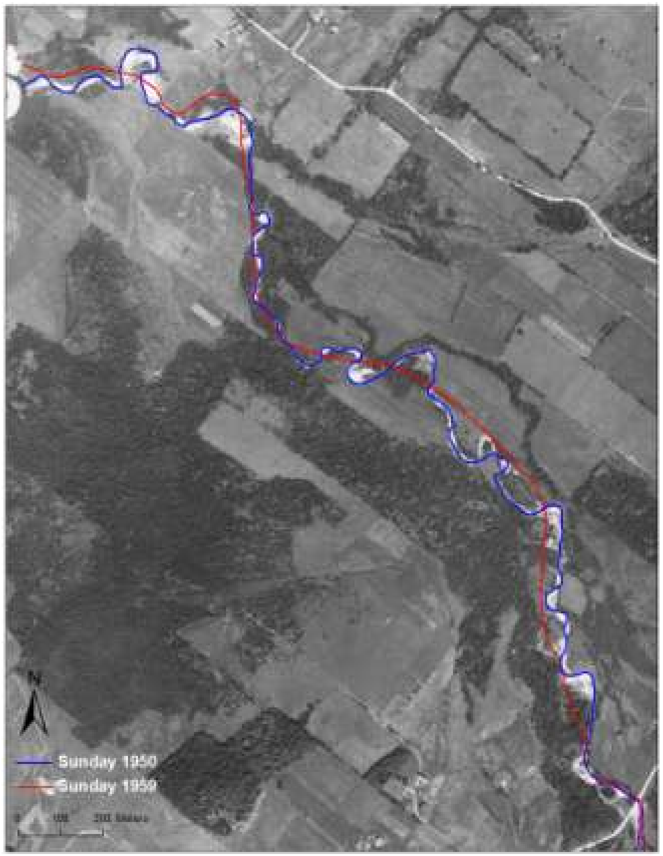


Figure 5.1 Historical paths of the lower Sunday River in 1950 and 1959 overlaid on an aerial photograph from 1950. The first and largest straightening effort occurred in 1954-55.

While the initial channel straightening that occurred in 1954-1955 was the most drastic, that which was carried out in 1976-1977 was also significant in terms of its impact on the downstream Sunday River. It was during this intervention that 2 large meander loops were eliminated from the downstream-most reach of the Sunday River (Figure 5.2). This reach is now characterized by significant problems of erosion and constitutes the reach of interest in this study.

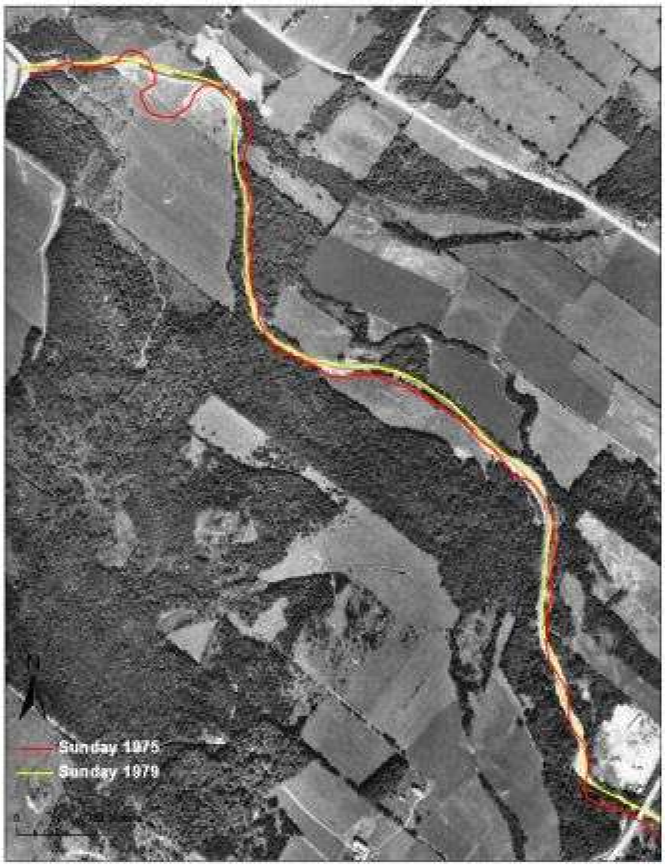


Figure 5.2 Channel paths in 1975 and 1979 overlaid on aerial photograph from 1979. The second most significant channel manipulation occurred in 1976. Two large meanders were removed from the area now characterized by the formation of a mid-channel bar.

Figure 5.3 shows the earliest (1950) and most recent (2007) channel paths measured from aerial images that were available for study. One can easily see the development of a meander bend around a mid-channel bar at the top of the image. According to the accounts of local farmers, the meander bend re-establishes itself within the span of 2-3 years after re-linearization by means of removal of the bar.

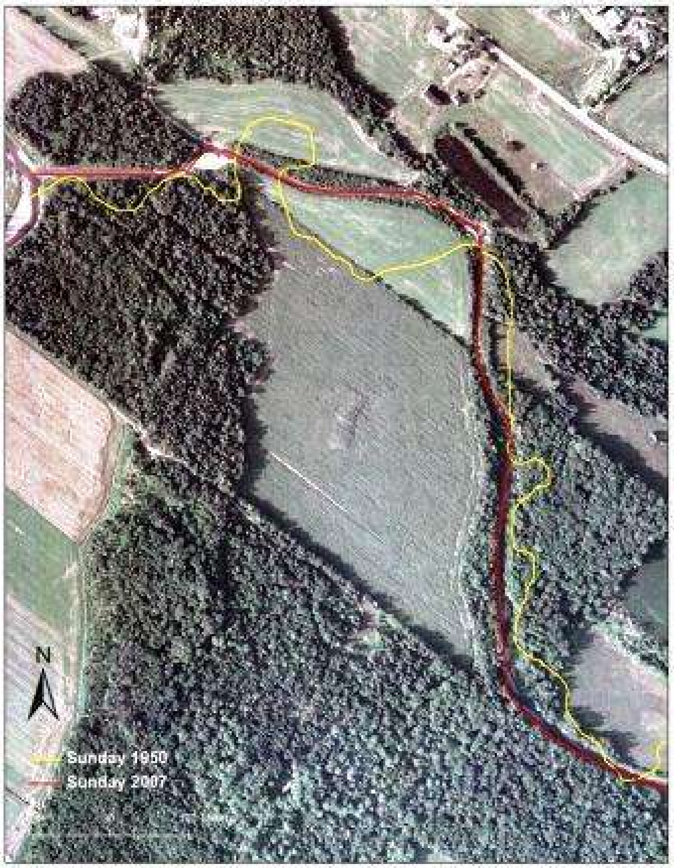
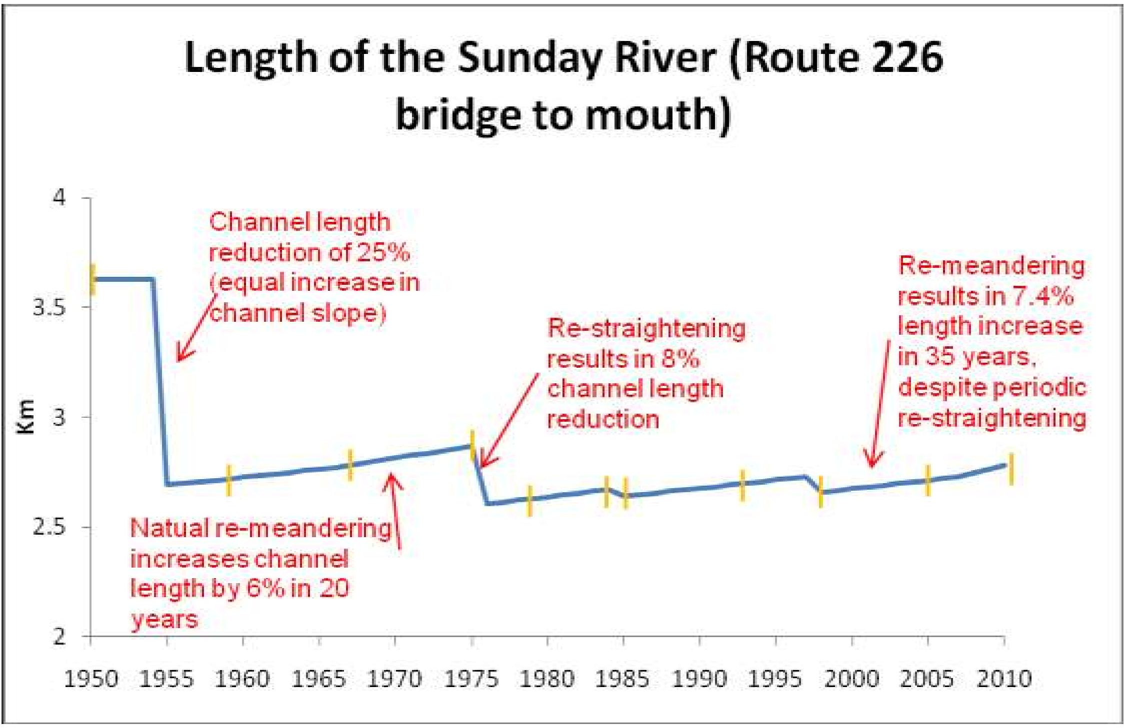


Figure 5.3 Channel paths in 1950 and 2007 overlaid on a satellite image from 2007. The channel has been displaced up to 100 meters in the downstream most reach.

GIS analysis of historical channel length shows that the average rate of re-meandering in the Sunday is relatively consistent, and is roughly equal to an increase in length of 8.5 meters per year between the Route 226 Bridge and the confluence with the Osgood. Table 5.1 summarizes channel length in each of the aerial photographs and satellite images obtained for the study. The re-straightening work that has occurred in 1954-55, 1976 and 1999 resulted in sharp decreases in channel length, and therefore in increases in channel slope (Table 5.1, Figure 5.4).

Year	Length: 226 Bridge – mouth (km)
1950	3.63
1959	2.72
1966	2.77
1975	2.87
1979	2.63
1984	2.67
1985	2.64
1993	2.7
1998	2.66
2007	2.66
2011	2.8

Table 5.1 Channel lengths as measured on 11 aerial images between 1950 and 2011.



a)

b)

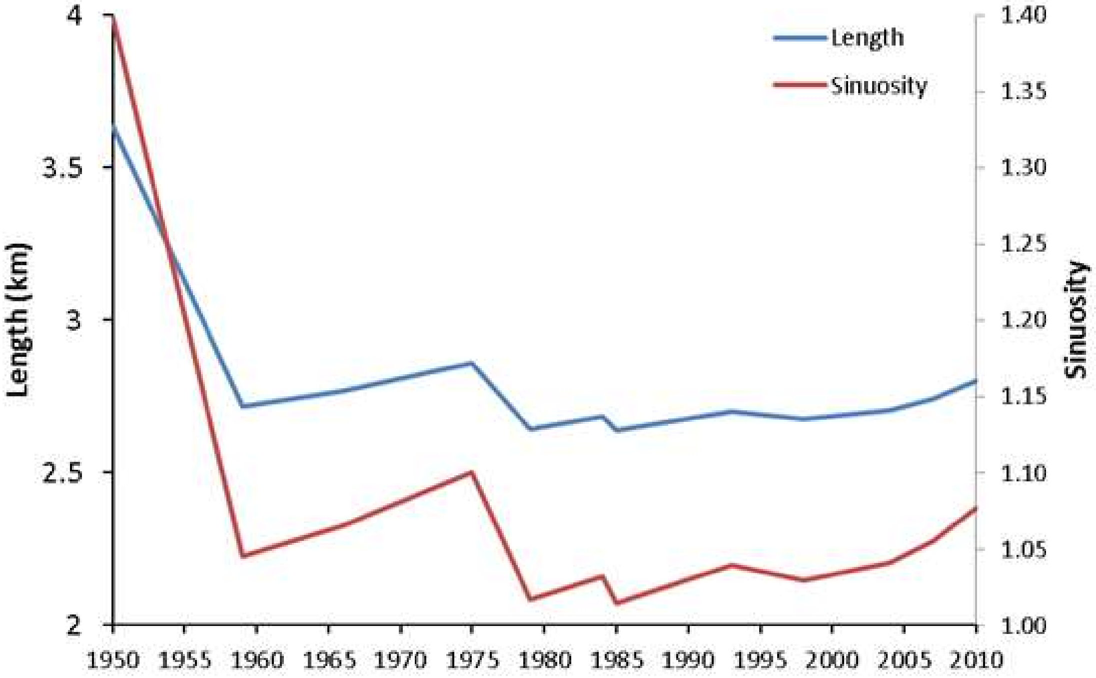


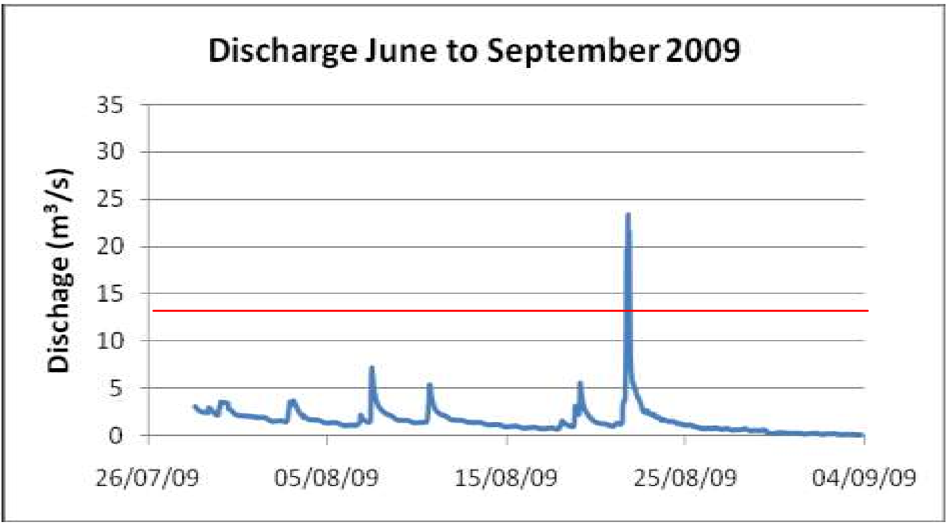
Figure 5.4 a) Channel length of the downstream Sunday River between 1950 and 2011. A relatively consistent rate of re-meandering was observed following river straightening. Orange marks indicate channel lengths measured from aerial images, with linear interpolation used between these dates, assuming a constant rate of re-meandering. Three significant straightening events (as documented in the MAPAQ records) are shown. 5.4 b) shows the sinuosity index over the same time scale

5.2 Field Data Collection and Analysis

5.2.1 Discharge

During the study period, discharge (as computed from the rating curve (equation 4.2)) varied between 0.02 m^3/s and 30.2 m^3/s (Figure 5.5). It should be noted that there is a higher level of uncertainty associated with estimated discharges above bankfull (approximately 14.7m^3/s) as this is the upper limit of the dataset used to generate the rating curve. The maximum discharge occurred on April 28, 2011 and corresponded to a water level at Station 1 of 2.1 m above the bed, approximately 0.9 m above bankfull level. Although no historical discharge data exist to confirm it, it is estimated, based on the recollections of local farmers, that the recurrence interval of a flood of this magnitude is approximately 50 years. The estimated bankfull discharge of 14.7 m^3/s, corresponding to a water surface elevation of 212.5m, was attained or exceeded once in August 2009 and three times during the spring of 2011 (once in March, twice in April). Thus, it is theorized that there were several events capable of transporting significant amounts of bedload sediments during the study period.

a)



b)

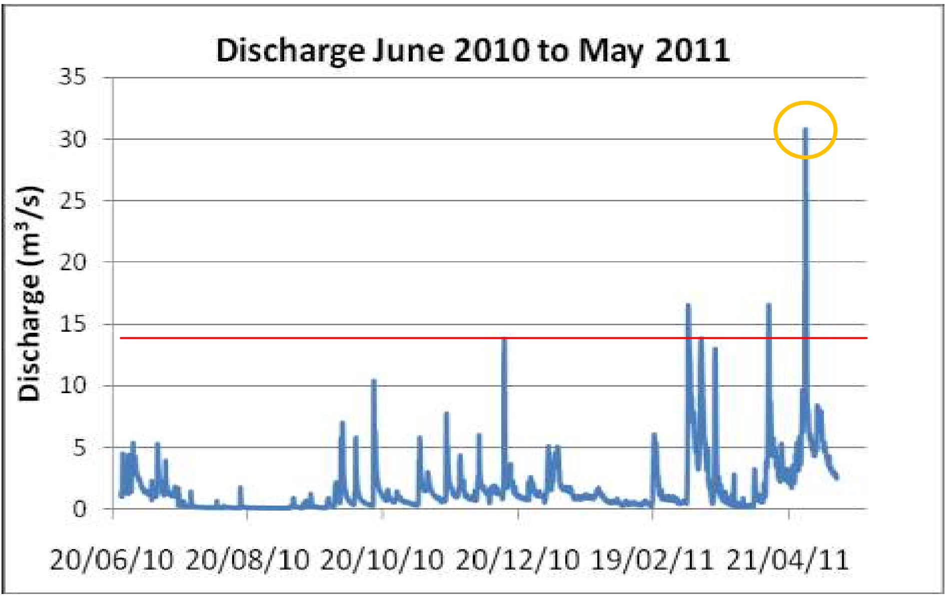


Figure 5.5 Hydrographs showing discharge measured at Station 1 for a) June through September 2009 and b) June 2010 through May 2011. The red lines indicate the bank full stage while the orange circle in b) demarks the estimated 50-year recurrence flood that occurred in late April 2011.

5.2.2 Long Profile

The longitudinal profile of the water surface of the lower Sunday River is presented in Figure 5.6

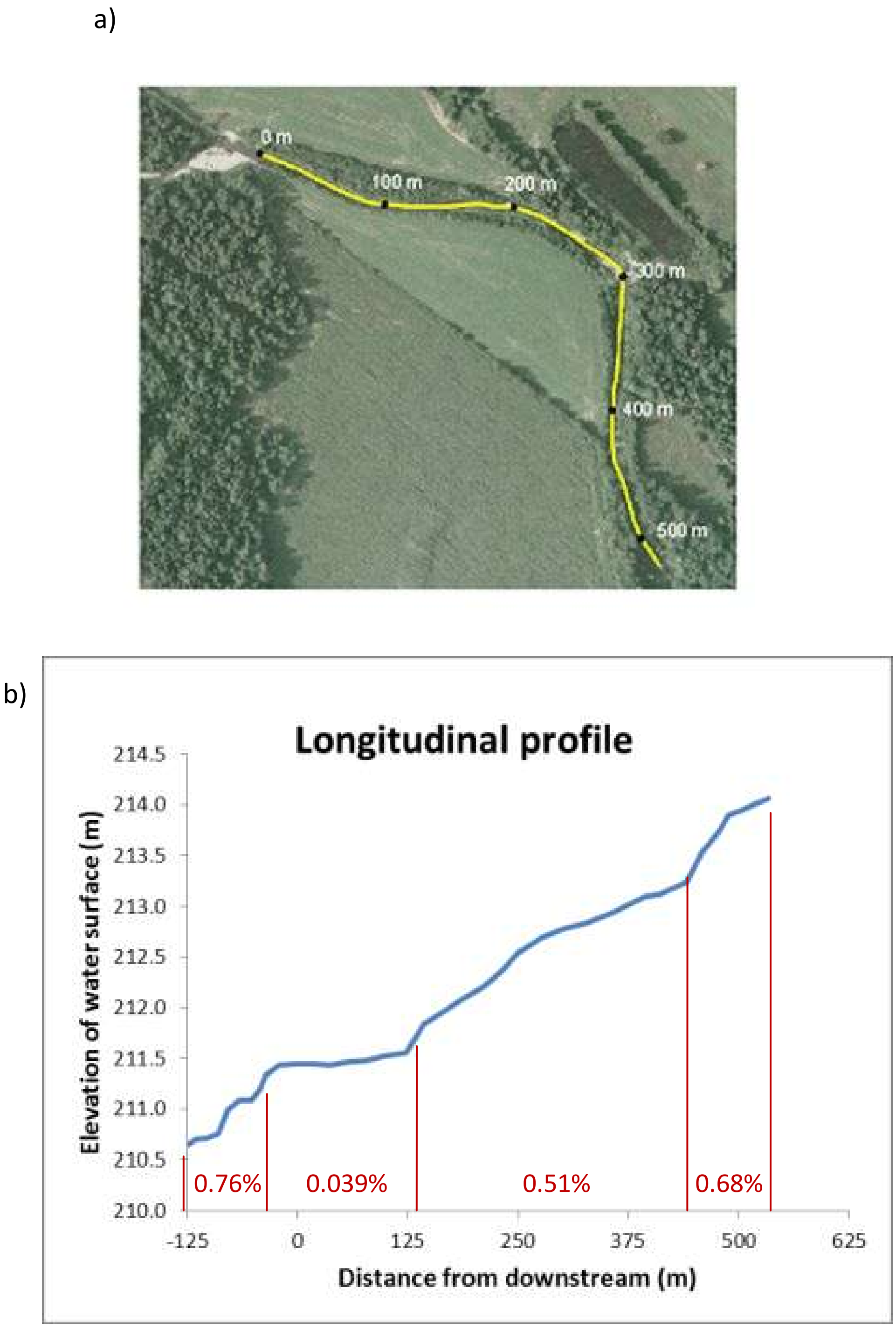


Figure 5.6 Longitudinal profile of the study reach of the Sunday River. Distance is measured from station 1 (which corresponds to 0 on Figure 5.6 a). The four slope zones in b) are presented in Figure 5.7.

Figure 5.7 Study reach with water surface elevation points measured November 7th 2010 (which corresponds to the medium discharge) for the four slope zones (see Figure 5.6).

There are clearly significant variations of the slope in the study reach, with markedly shallower slopes in the downstream section (both upstream and downstream of the mid-channel bar). The study reach can be divided into four discrete sections based on breaks in slope (Figures 5.6 and 5.7). The section immediately upstream of the Station 1 pressure transducer has a water surface slope that is lower than adjacent sections by a difference larger than one scale of magnitude (0.039% compared to 0.51% for the reach immediately upstream and 0.76% for the reach immediately downstream). Interestingly, slope zone 1 (that which is furthest downstream) is characterized as having the steepest slope. Water surface elevation data was acquired during relatively low flows, during which only one perennial channel weaves its way to the right (looking downstream) of the bar. The bar itself is thus more accurately defined as a point bar, during lower flows.

The upstream end of the point bar acts as a sort of damn, holding back water at its upstream limit. As the water flows around the bar, a narrow channel incises itself somewhat, creating the steep slope. However, as was observed in the field, it is theorized that at higher flows nearing bankfull level water flows around and over the bar, resulting in a lower and more uniform slope throughout the two downstream-most slope zones (Figure 5.6 and 5.7).

It is possible to calculate bed shear stress (τ) for these four zones using equation 2.1. Figure 5.8 presents bed shear stress for the four zones at low (Q = 0.03 m^3/s), medium (Q = 1.02 m^3/s) and bankfull flow (Q = 14.7 m^3/s) (medium flow corresponds to the median flow of the discharge record). The water surface slope used in the calculations was for the medium flow stage, which was very similar to the low flow stage water surface slope. At bankfull flow, it is probable that the water surface slope would change (see section 5.3). However, due to the difficulty of collecting data at higher flows, we have no field measurements of the water surface elevation at bankfull level and thus had to assume that only flow depth would change with flow stage. As is evident in Figure 5.8, bed shear stress is markedly lower in slope zone 2.

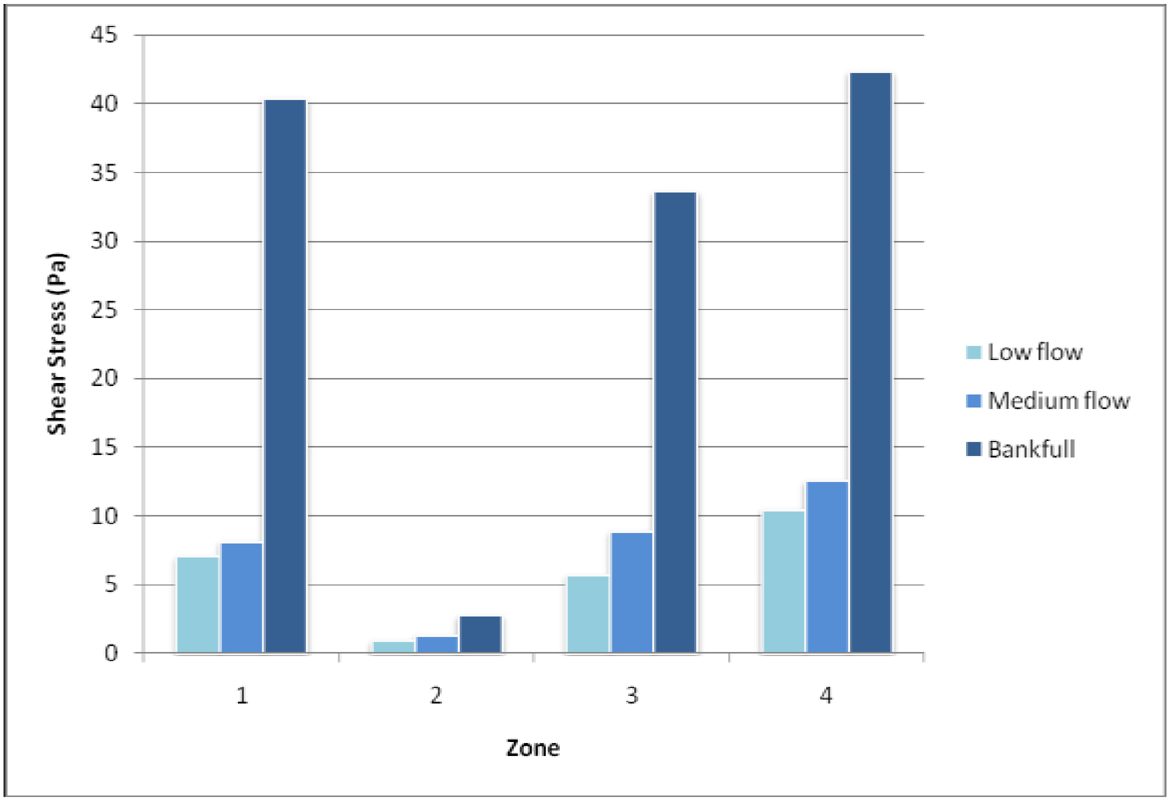


Figure 5.8 Bed shear stress computed from equation 5.1 for the four slope zones as delineated in Figure 5.7. Low, medium and bankfull flows correspond to discharges of 0.03, 1.02 and 14.7 m^3/s, respectively.

5.2.3 Grain Size

In order to analyze the shear stress results in terms of sediment transport, the grain size distribution in each zone had to be characterized. The calculated D_{16}, D_{50} and D_{84} are presented in Table 5.2 for the study reach.

	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)
Zone 1	3.1	18.4	38.1
Zone 2	2	16	90.5*
Zone 3	2.6	38.1	104
Zone 4	13.9	36.8	73.5
All Zones	3.3	23.4	64

Table 5.2 Grain size in the four sediment zones (Figure 4.8).
* Note that rip rap bank stabilization was put in place in this zone, which is likely the cause of the large difference between D_{50} and D_{84}. Sediment distribution curves are presented in Appendix A.

It is apparent that there is a certain degree of downstream fining in the study reach. Zone 1, which is furthest downstream, is characterized by somewhat finer grain sizes than the other zones, although they are not dissimilar to the grain size in zone 2. In fact, the grain sizes of zones 1 and 2 appears to be quite similar, as do those in zones 3 and 4. Nonetheless, a trend of downstream fining is evident. Zone 1 can be characterized by two distinct sections: a perennial channel and a large mid channel bar (Figures 4.8 and 4.9). The size of the sediment both on the surface of the bar and below was found to be significantly finer than the sediment in the channel. Furthermore, both longitudinal and lateral gradients in grain size were observed on the bar. The zones that are furthest downstream (Figure 4.9 and Figure 5.9) were found to display finer sediment while zones that are laterally further away from the main channel also display finer sediment. In other words, there is a trend of fining both downstream and laterally away from the main channel, towards the inside of the meander bend. Figure 5.9 illustrates the results of a sieve analysis of samples taken on and below the surface of the bar:

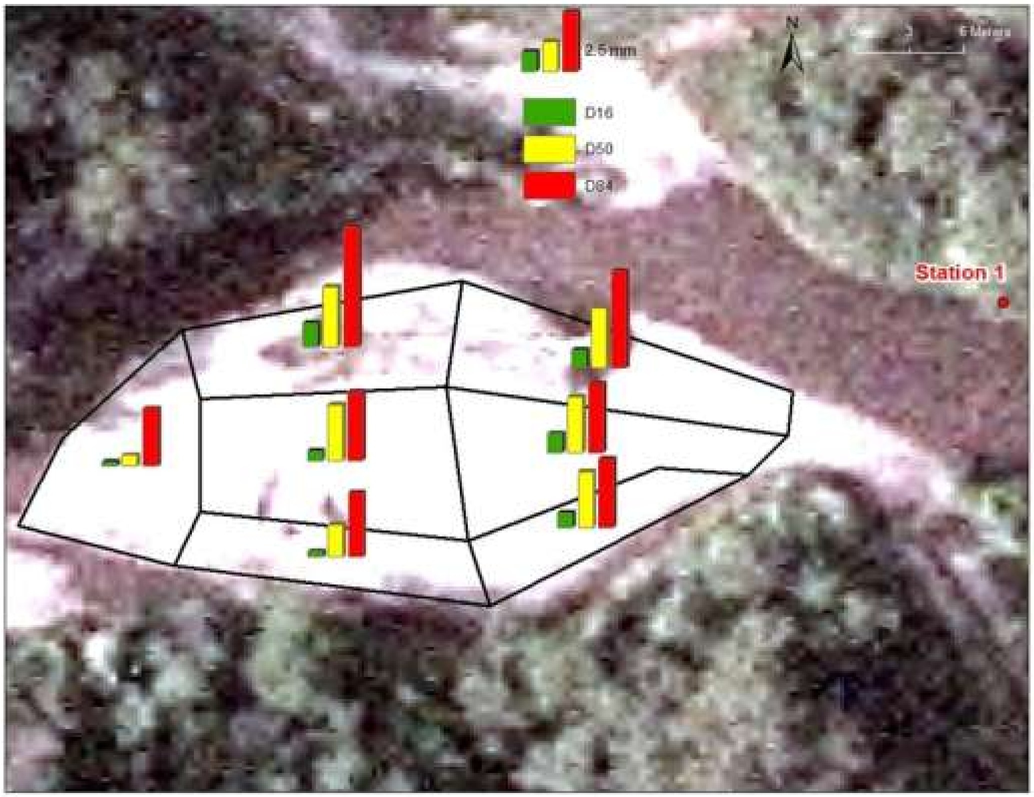


Figure 5.9 Mid channel bar sediment zones with D_{16} (green), D_{50} (yellow), and D_{84} (red) represented by proportionately sized bar charts.

Critical shear stress is defined as the minimum shear stress necessary to induce motion in a particle of a representative size (D_{50} or D_{84} – here D_{50} is used). Although in gravel-bed rivers with heterogeneous sediments the relationship between critical shear stress and mobilized particle size can be complex (Parker et al., 1982; Buffington and Montgomery, 1997; Lenzi et al., 2006), here the simple Shields approach is used (Shields, 1936):

$$\tau_c = \theta_{ec}\, g\, (\rho_s-\rho)\, D_{50} \qquad \text{(eq. 5.2)}$$

where τ_c is critical shear stress (in N/m^2 or Pa), θ_{ec} is Shields non-dimensional shear stress (taken here as 0.044), g is acceleration due to gravity (in m/s^2), ρ_s is mass density of sediment (using quartz, i.e. 2650 kg/m^3) ρ is mass density of water (1000 kg/m^3) and the D_{50} is in meters. Figure 5.10 shows how critical shear stress compares with estimated bed shear stress at three different flow stages for the four sediment zones delineated in Figure 4.7.

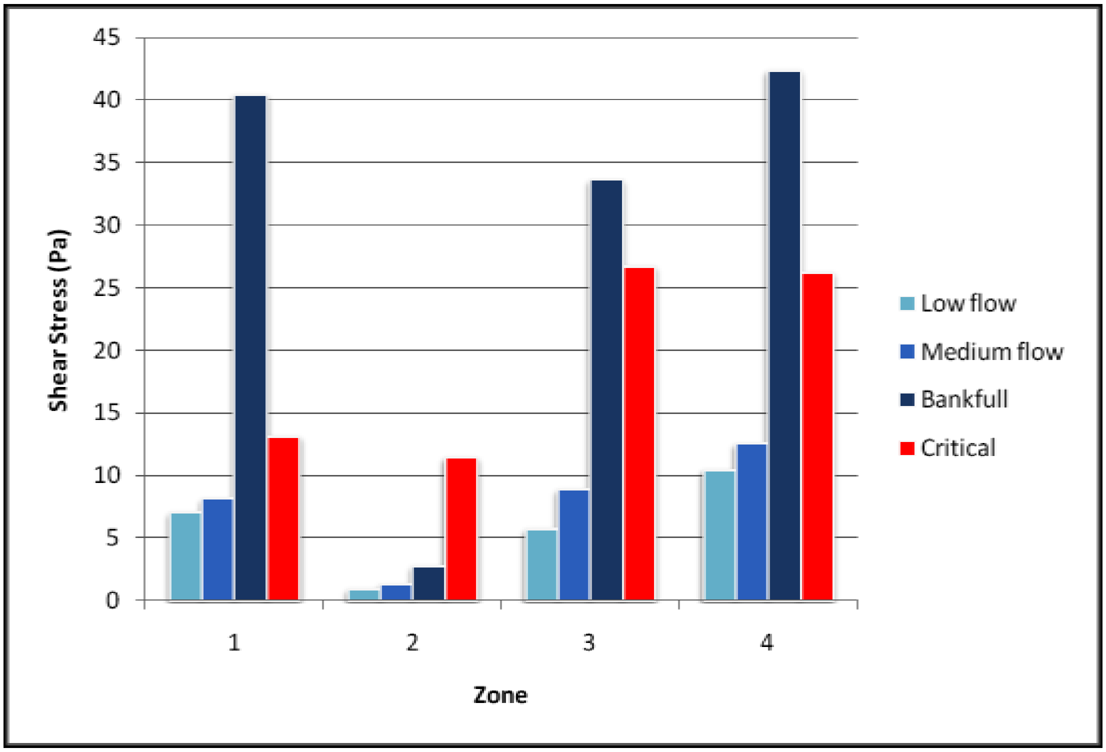


Figure 5.10 Critical shear stress for the four sediment zones (as per Figure 4.7) shown in blue. Bed shear stress for low (0.298 m^3/s), medium (1.02 m^3/s) and bankfull (14.7 m^3/s) discharges.

Overall, the relationship between critical shear stress and bed shear stress supports what has been observed in the field: sediment is conveyed through most of the upstream study reach and then deposited in the area that is delineated by the downstream end of zone 2 and the upstream portion of zone 1 where the mid-channel bar is formed. In the mid-part of zone 1, bed shear stress values increase again, leading to more erosion and a re-meandering of the channel downstream of the bar. In the field, it was observed that some finer sediment was deposited in the downstream half of zone 2. This sediment appeared to be re-mobilized during higher flows either to be carried out of the watershed or to be re-deposited on the mid channel bar or point bars further downstream.

Of note is the fact that while critical shear stress in zones 1 and 2 are essentially identical, bed shear stress values at bankfull are ten times higher in zone 1 than in zone 2 (Figure 5.10). This is due to the relatively small grain size in zone 1 that is a symptom of sampling that included the mid channel bar along with the perennial channel. The formula for critical shear stress uses grain size while that for bed shear stress uses slope. While the later solely uses the slope of the perennial channel, the former uses the grain size values of the said channel as well as the bar. Because the grain size values are artificially low for the channel in zone 1, critical shear stress in the perennial channel is believed to be underestimated. Oppositely, if water surface values had been obtained for higher flows (during which water flows over the mid channel bar and slope values are anticipated to be lower as there is a smaller break in slope between zones 1 and 2), bed shear stress in zone 1 would be smaller than those displayed in Figure 5.10. Nonetheless, zones where critical shear stress is surpassed by bed shear stress are believed to experience bed erosion, whereas zones where critical shear stress is surpassed by bed shear stress (at bankfull, in both cases) are believed to experience bed accumulation.

Additional factors are believed to have contributed to the specific location of the mid channel bar at the downstream end of zone 2. The left bank (looking downstream) throughout zone 2 is fortified with rip rap (Figure 5.11). This bank stabilization results in the effective depth in the channel increasing sharply with increase in stage, which may contribute to "flushing out" sediment that would have accumulated in this zone of low slope during lower flows.

Figure 5.11 Rip Rap as bank fortification on the left bank in zone 2.

Figure 5.12 Tractor crossing as seen from the right bank immediately upstream of the mid channel bar.

Furthermore, a tractor crossing (Figure 5.12) at the very upstream limit of zone 1 leads to a sudden and significant widening of the channel, and therefore to a decrease in depth, shear stress, unit stream power (equation 2.2) and overall sediment transport capacity.

At the upstream end of the mid channel bar, channel width was measured to be at least 25 m at bankfull level, resulting in a unit stream power of 2.25 W/m^2 at bankfull discharge. In comparison, at a location 10 m further upstream, channel width was measured to be 9 m, resulting in a unit stream power of 6.24 W/m^2 for the same discharge. Sediment transport capacity thus decreases dramatically at the tractor crossing. Calculations of unit stream power (Equation 2.2) for the model reach are presented in Figure 5.13.

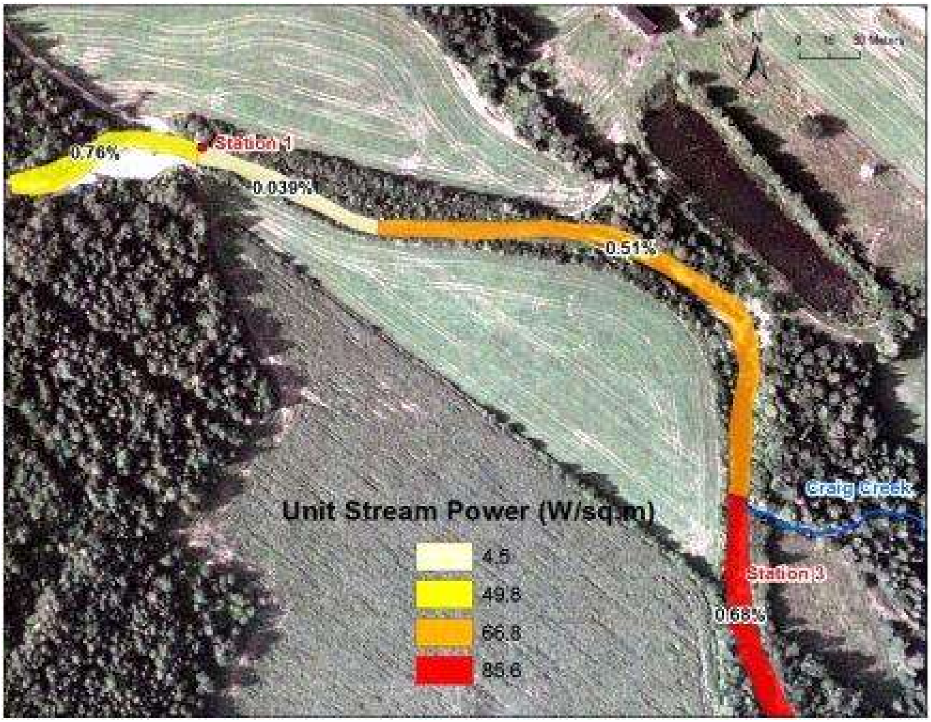


Figure 5.13 Unit stream power at bankfull stage (14.7 m^3/s) in the study reach, calculated using zone averaged width and water surface slope (indicated for each zone).

As the mid channel bar is formed, a positive feedback loop is likely to establish itself and contribute to further growth of the bar. Unit stream power and shear stress are higher along the side of the bar due to an increase in slope. As erosion of the bank continues, channel width increases as well, thus decreasing unit stream power and causing deposition along the edge of the bar and forcing more flow to be constrained on the side of the bar, with high erosive power when the bar is above the water surface. The existence of such a mechanism would have the effect of contributing to the growth of the bar.

Bank armouring in zone 2 and the presence of a tractor ford likely explain why the mid-channel bar forms in the specific location that it does. It remains, however, that the principle reason for the formation of the bar is the drop in slope in this area. Indeed, historical photographs show evidence of large meander loops forming in the very same area (Figure 5.1) as the course of the Sunday River had been naturally adjusted to the physical characteristics of its valley.

The most significant erosion in the study reach was observed at the downstream end of zone 1, where the channel is clearly in a re-meandering process and where the high slope generates sufficiently large shear stress and unit stream power for bank erosion to occur (Figure 5.14).

Figure 5.14 The mid-channel bar in the downstream portion of the study reach, sediment zone 1 (Figure 4.7). Note the re-meandering trend in the channel downstream of the bar. It is possible that the large boulders to the right of the riffle section were intentionally placed as rip rap.

5.2.4 Sources of Sediment and Sediment Transport Rates

Estimates of volume of eroded material were generated for the steep bank below the artificial lake (Figure 4.2). Figure 5.15 shows the extent of the erosion of this bank between 2009 and 2011.


a)

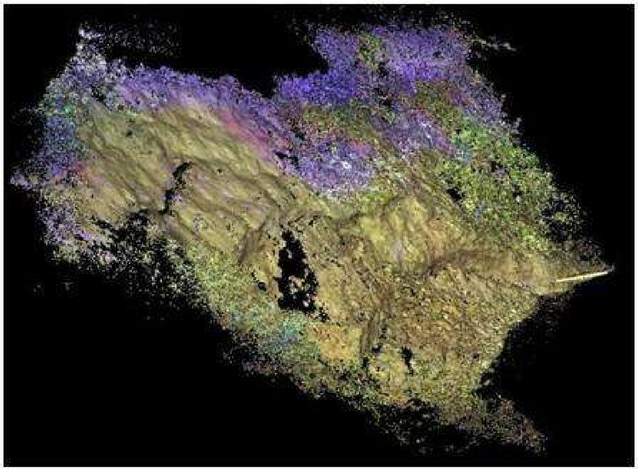

b)

c)

Figure 5.15 Photographs of the steep bank (Figure 4.2) in a) 2009, b) 2010 and c) 2011 illustrating rapid bank erosion. The red circles highlight the same tree in the three photographs, whereas the yellow circles call attention to the presence of coarser material present in the overall relatively fine matrix of the bank.

The terrestrial lidar data analysis (Figure 5.16) allowed for an estimation of the volume of eroded sediment from this bank.

a)



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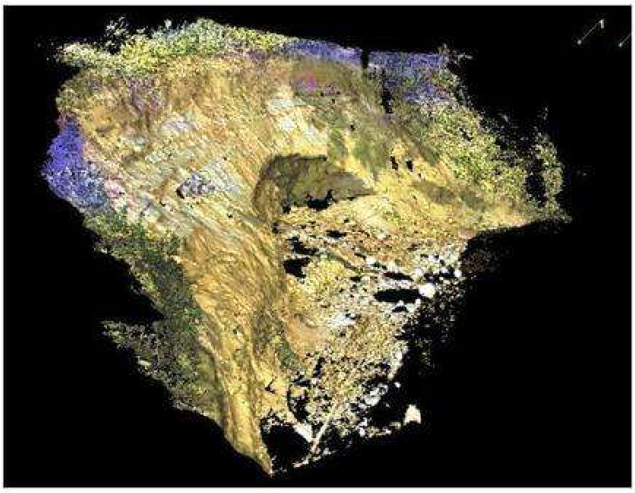


Figure 5.16 Side view of the lidar generated point cloud in a) 2009 and b)2010 of the bank in Figure 5.15 with vegetation removed, looking upstream from the right bank.

Figure 5.17 shows a schematized view of the regression of the bank shown in Figure 5.15. The volume of eroded material was calculated to be 319.2 m^3. This material can be estimated to weigh over 400 tons.

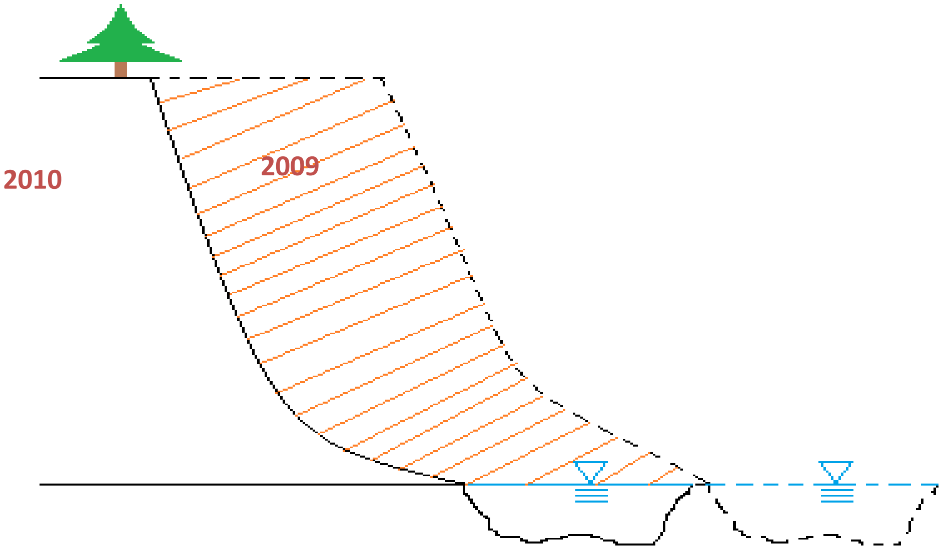


Figure 5.17 Schematic representation of the bank regression for the bank shown in Figure 5.15.

While the Sunday River is a gravel bed river (Table 5.2), the mid channel bar does contain finer sediment, especially below the armoured surface layer (Figure 5.9). The erosion of the steep bank in figure 5.15 is assumed to be predominantly a source of sand and clay sized particles, some of which may have contributed to the formation of the mid channel bar. However, as is evident in the areas demarked by yellow circles in Figure 5.15, while the matrix composing this bank is mostly fine particles, some coarse particles did originate from the bank and can also be assumed to have contributed to the mid channel bar formation.

Topographic analysis of the mid channel bar provides evidence that indeed the bar was growing in size during the study period. Figure 5.18 shows 4 DEMs of the bar generated from data collected between July 2009 and May 2011, using the same scale of elevation.

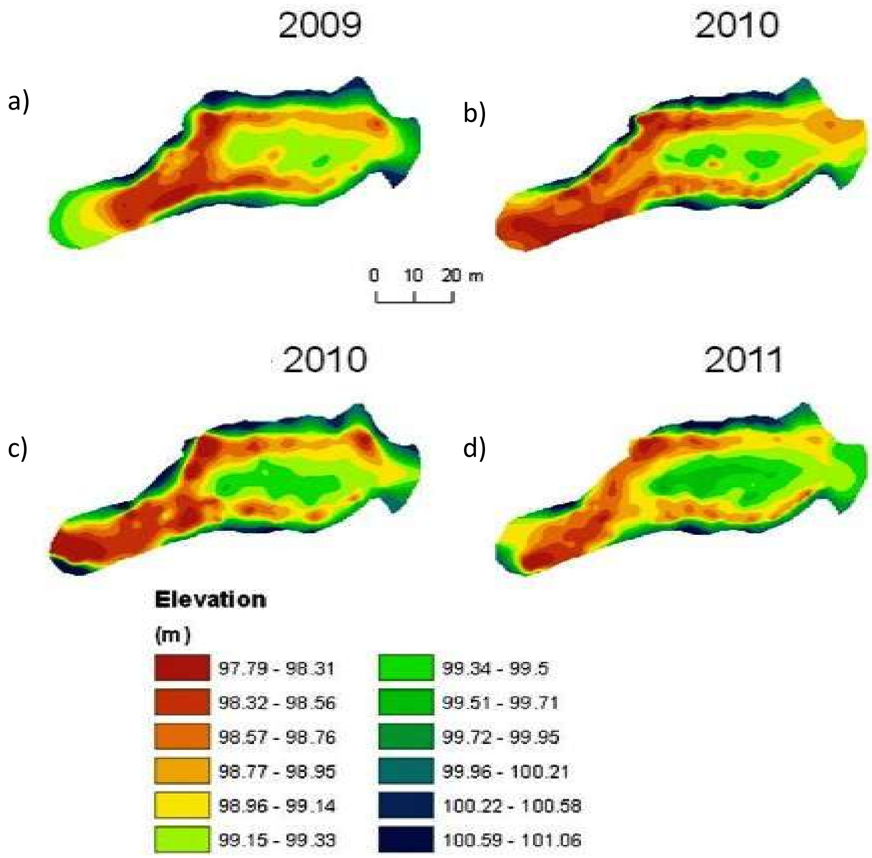


Figure 5.18 DEMs of the mid channel bar generated from topographic data acquired a) July 14 2009, b) June 4 2010, c) November 7 2010 and d) May 12 2011.

A GIS overlay of the first and last DEM allowed for zones of erosion and deposition to be identified (Figure 5.19). It is clear that the mid channel bar is in fact a dynamic feature in the Sunday River. Areas in dark blue indicate those where deposition of sediments resulted in vertical accretion equal to or above 0.5 m, while those in red indicate areas of scour of the same magnitude. These results reveal that the river is in fact re-establishing a higher sinuosity in this area.

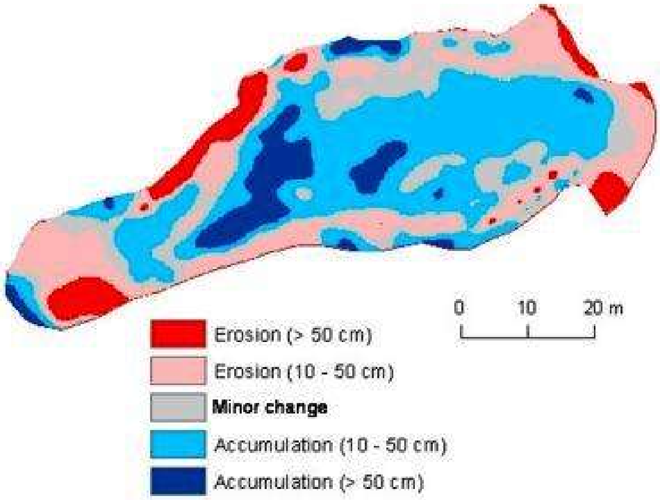


Figure 5.19 DEM of elevation change of the mid-channel bar between July 2009 and May 2011.

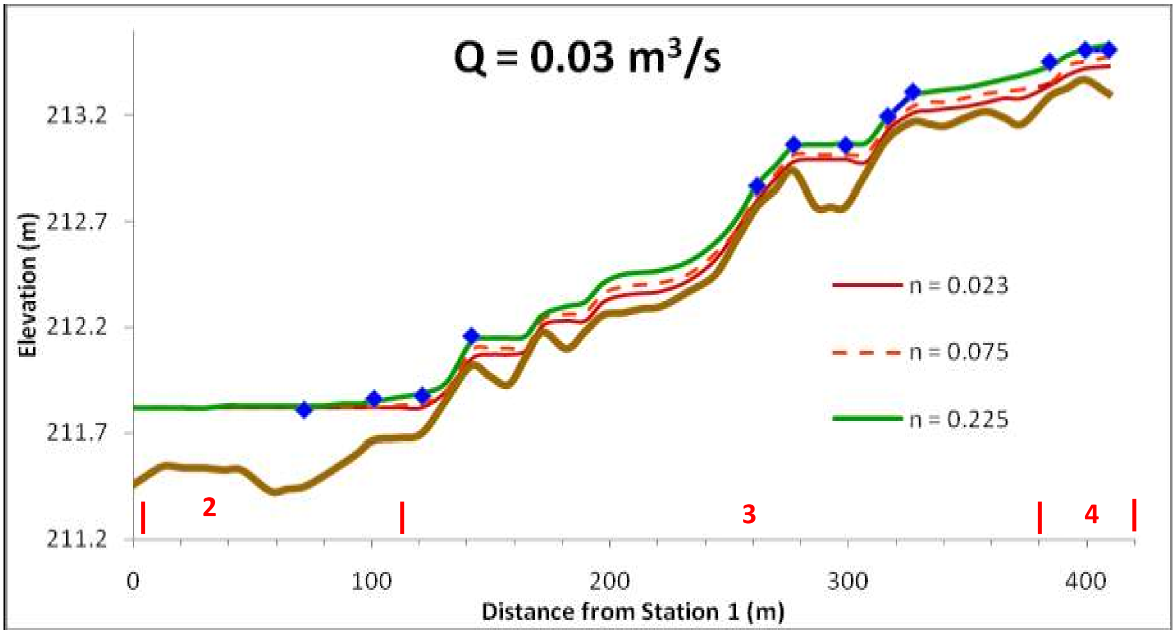
5.3 Numerical Modeling

5.3.1 HEC-RAS

Model Calibration

Model calibration was carried out using simulated and measured water surface slope through Manning's n parameterization. A comparison of water surface data acquired in the field with those generated by HEC-RAS for different Manning's n is presented in Figure 5.20 for a low and medium discharge.

a)



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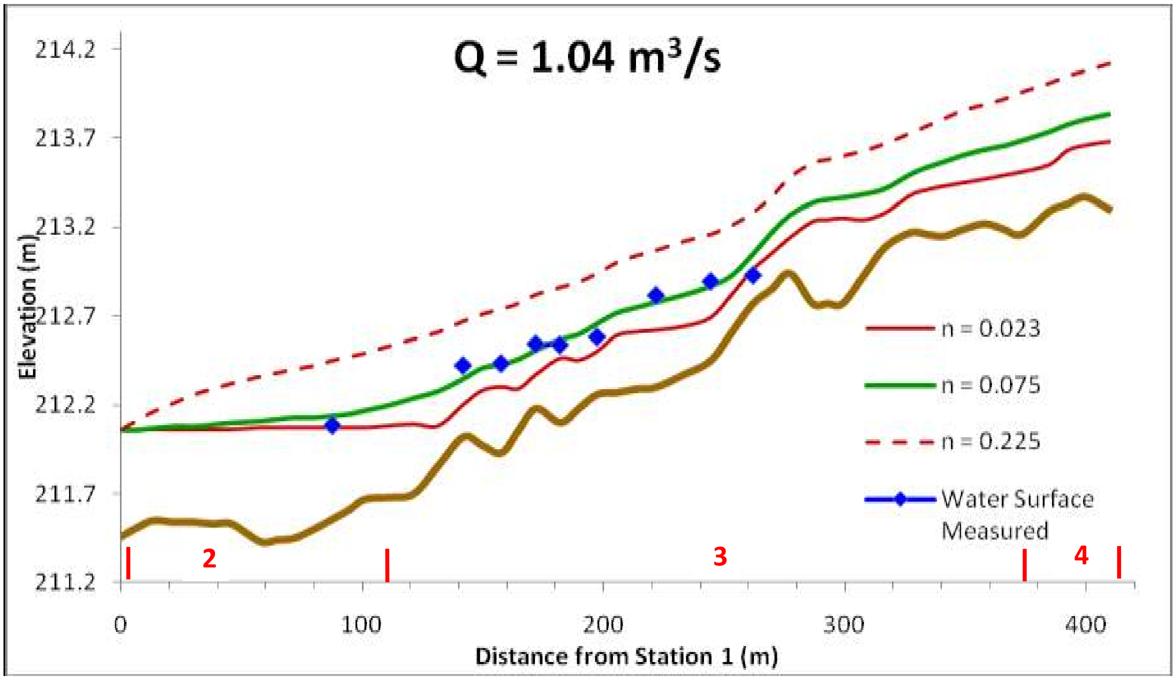
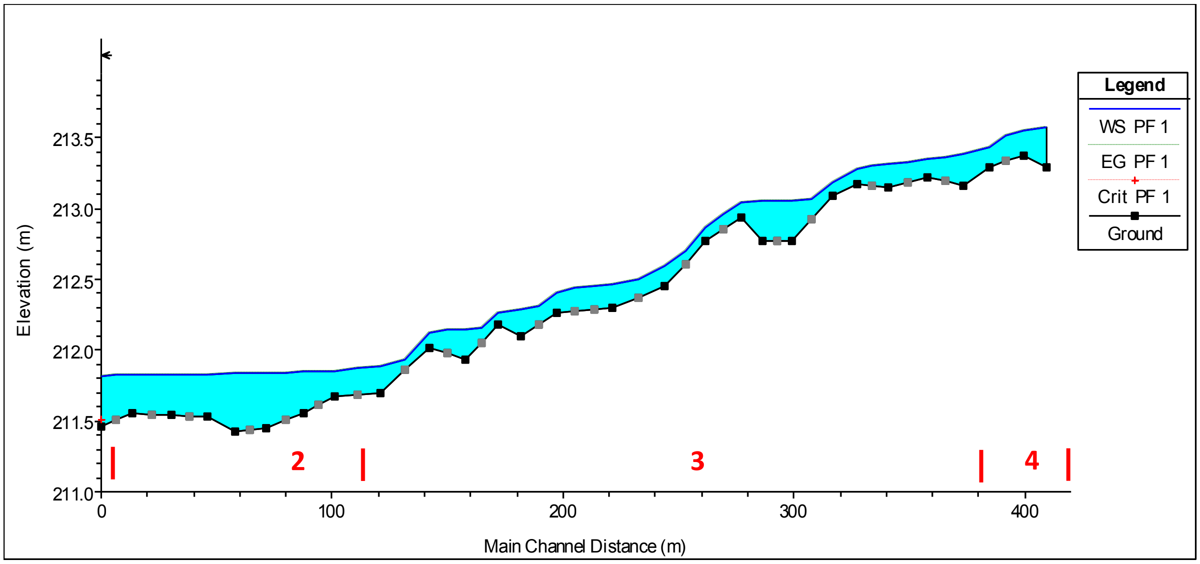


Figure 5.20 Comparison of water surface profiles as modelled by HEC-RAS for a) low flow as measured August 20 2010 and b) medium flow as measured May 12 2011, at varying Manning's n values. The n values which generate a water surface slope closest to the field measurements is indicated as a thick green line in each case. The zones (Figure 5.7) are represented in red at the bottom of the graphs.

Based on the comparison made in Figure 5.20, it is evident that Manning's n should be varied with discharge for the model to be able to reproduce water surface elevations as observed in the field. Indeed, the necessity to do so has been noted in other studies involving hydraulic models (Cao et al. 2003). Due to the difficulty in gathering water surface data at higher flows, parameterization of Manning's n was not possible for higher discharges, and the Manning's n that was best suited for the medium discharge was used in simulations of higher discharges.

Several water surface profiles of the Sunday River, as generated by HEC-RAS, are presented in Figure 5.21.

a)



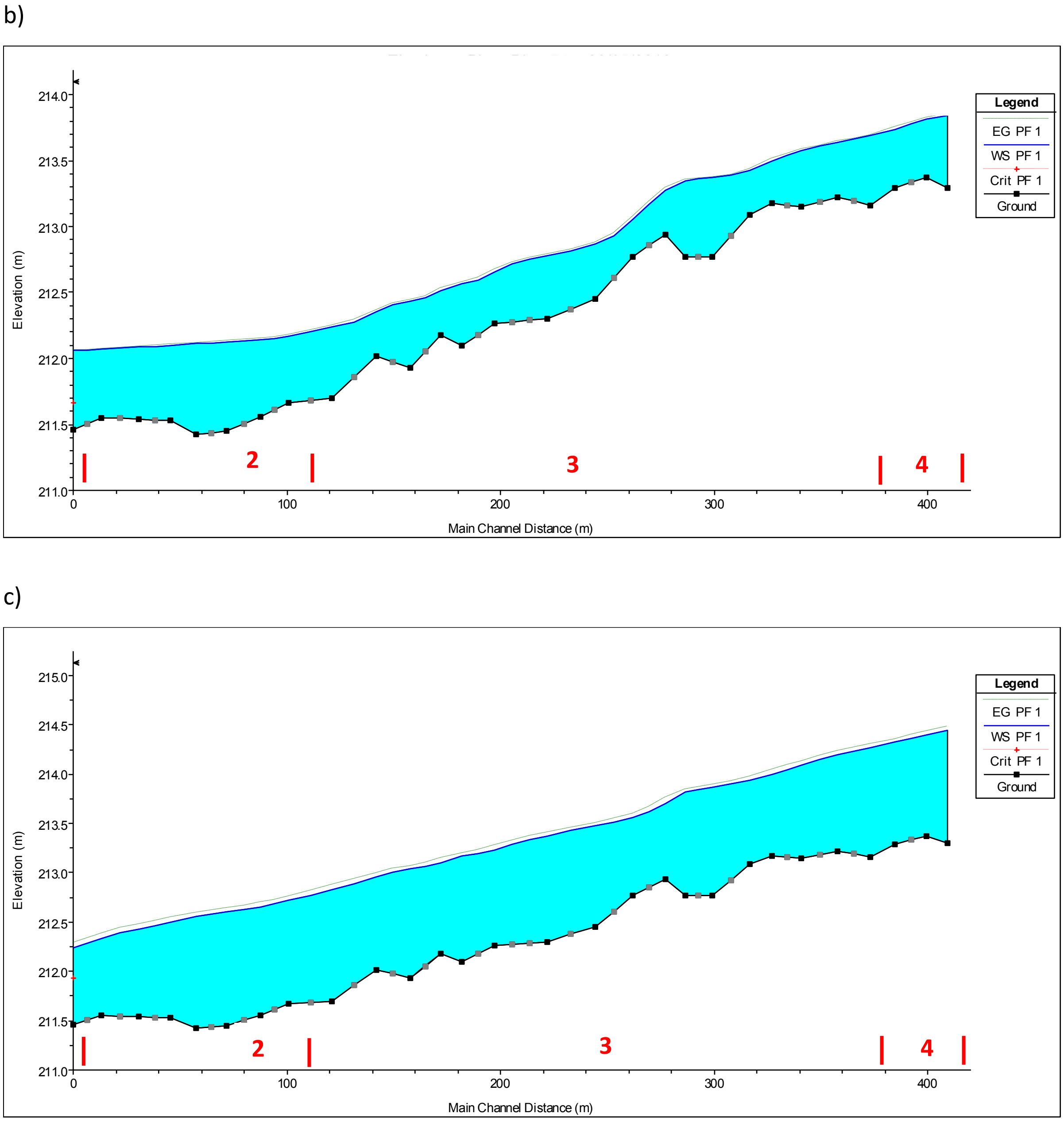


Figure 5.21 Water surface profiles generated by HEC-RAS for discharges recorded on a) August 20 2010 (0.03 m^3/s), b) May 12 2011 (1.04 m^3/s) and c) Nov 5 2010 (6.24 m^3/s). The extent of slope zones 2, 3 and 4, (Figure 5.7) are indicated in red above the x-axis. Main channel distance is measured from Station 1 (Figure 4.10).

The water surface profiles for low and medium flows matched well with water surface elevation data measured in the field, as well as with the water surface slopes measured in zones 2, 3 and 4 (Figure 5.7). In Figure 5.21c, the slope is essentially uniform along the study reach. As flow stage increases so will Manning's n since flow resistance is higher further up the banks. It is likely, however, that in reality the slope would be less uniform due to the increase in roughness.

Simulation with reach lengths similar to those in 1950

The length of the downstream reach of the Sunday River, from its confluence with the Osgood to the top of the HEC-RAS model reach, was approximately 941 meters in 1950, compared to 653 meters in 2007 (Figure 5.22). This represents a decrease of roughly 31% in channel length. To simulate pre-straightening conditions in HEC-RAS, the channel and bank lengths were increased by the same proportion, increasing the total length of the model study reach from 414 meters to 542 meters by adding equal portions to each reach length (distance between cross sections). HEC-RAS simulations were then carried out for the same discharges as previous. The resultant water surface profiles are presented in Figure 5.23.

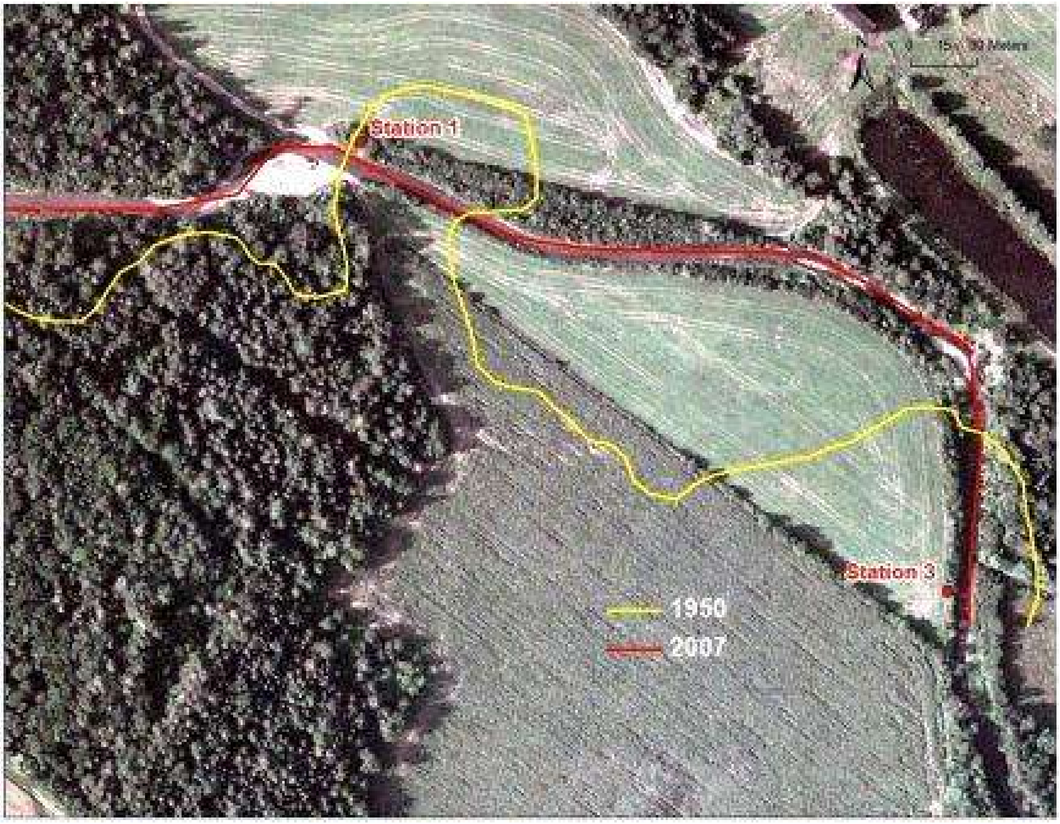


Figure 5.22 Model reach with channel path in 1950 and 2007.

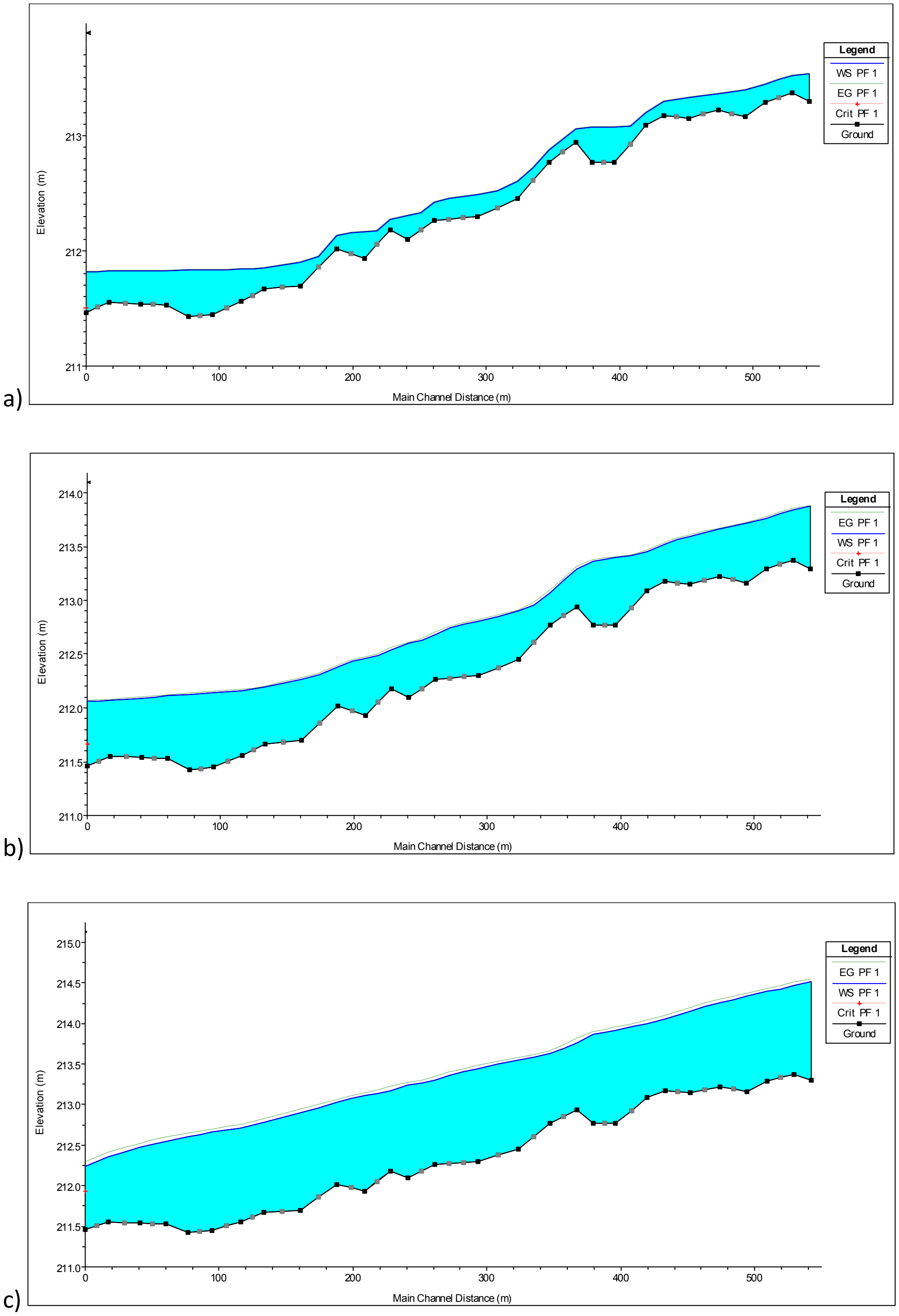
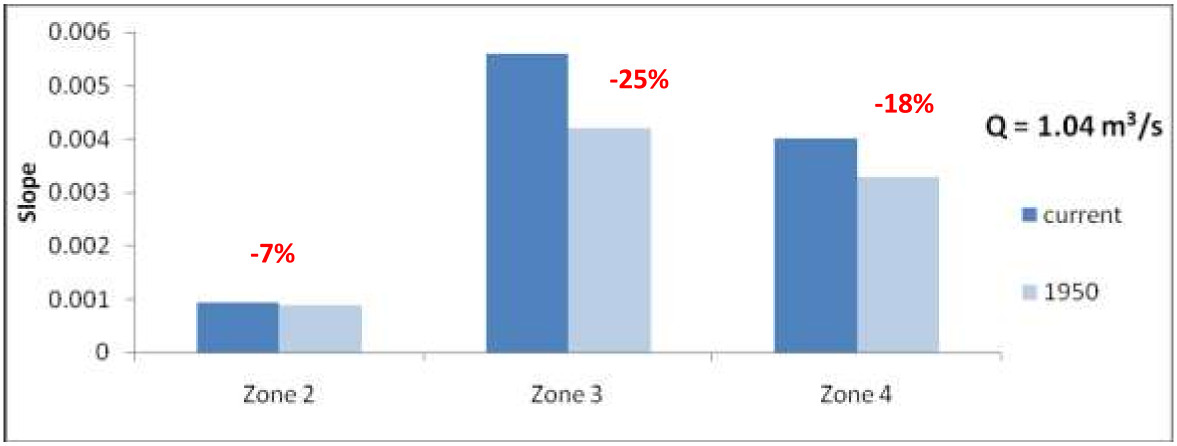


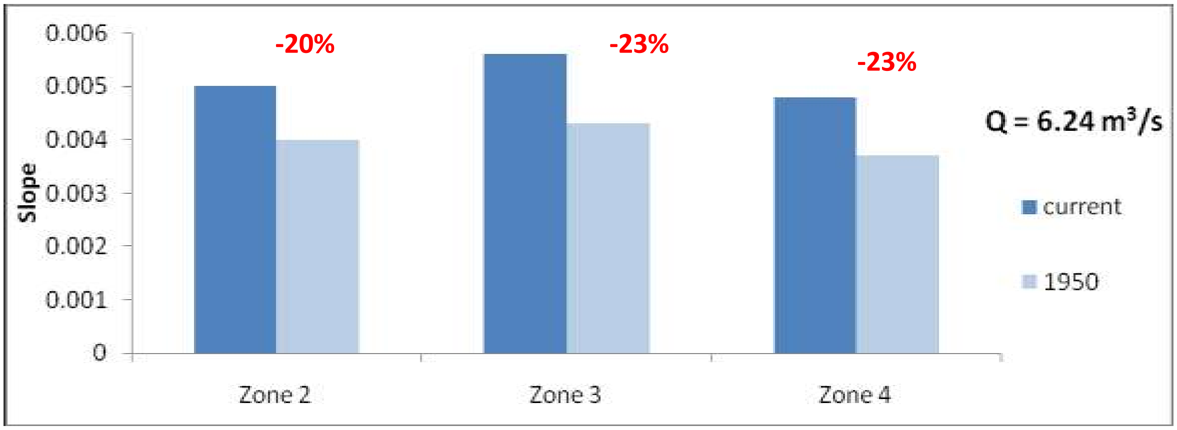
Figure 5.23 HEC-RAS profile plots for discharges of a) 0.03 m^3/s, b) 1.04 m^3/s and c) 6.24 m^3/s where channel length has been increased to approximate that from 1950.

Simulations of the Sunday River with a channel length similar to that in 1950 showed a decrease in water surface slope between 7% and 26% for a range of discharges. Similarly, model shear stress estimates decreased by between 7% and 22%. Figures 5.24 and 5.25 illustrate the effect of the increased channel length on water surface slope and shear stress, as computed by HEC-RAS, for three different discharges.

a)



b)



c)

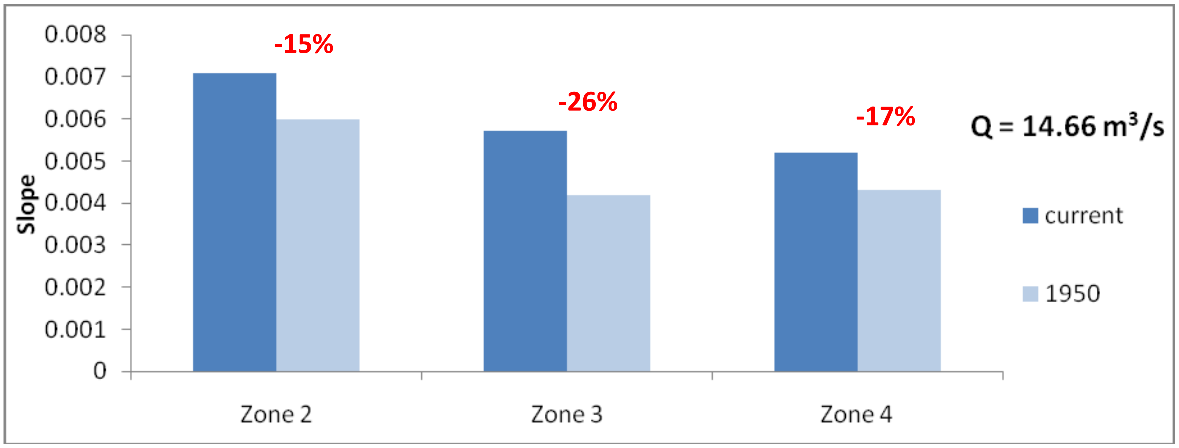
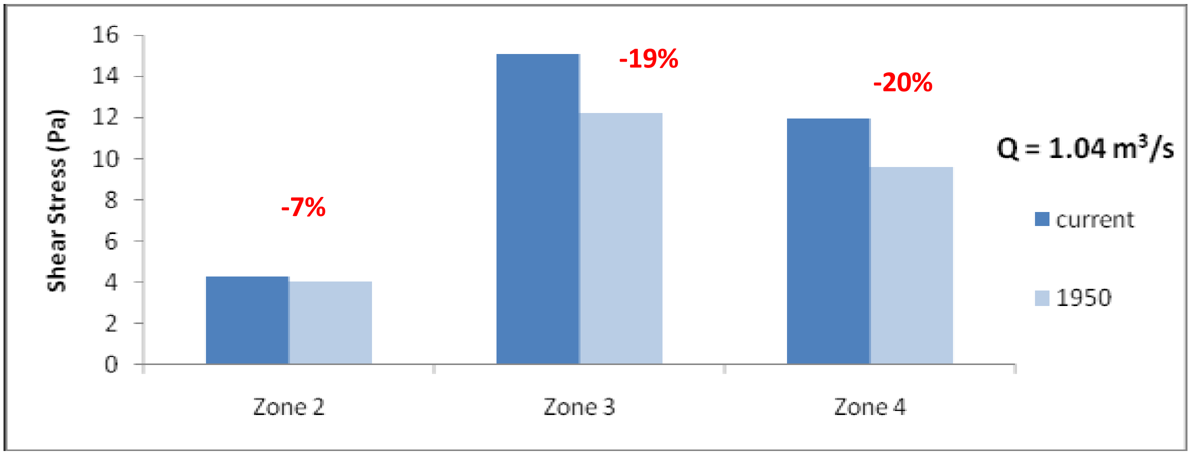
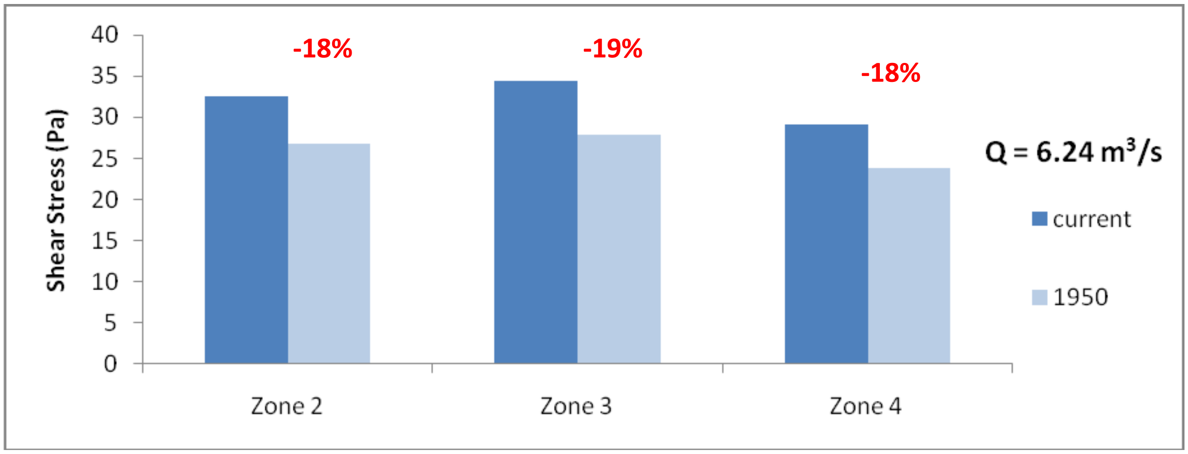


Figure 5.24 Relative change in slope in the 3 slope zones (Figure 5.7) for the current channel length of the Sunday River compared to one similar to that in 1950 (Figure 5.22). Slope values are given for three discharges: medium, high and bankfull.

a)



b)



c)

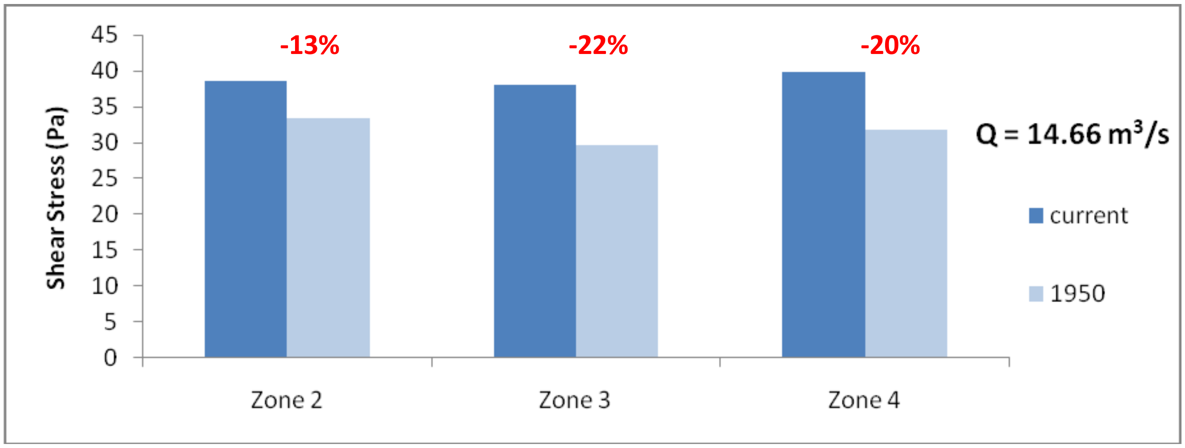
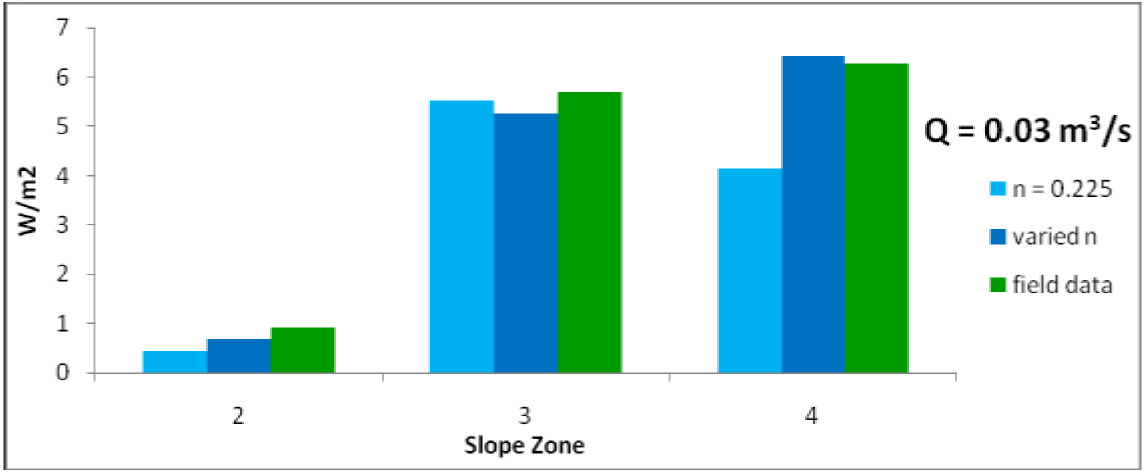


Figure 5.25 Relative change in shear stress in the 3 slope zones (Figure 5.7) for the current channel length of the Sunday River compared to one similar to that in 1950 (Figure 5.22). Shear stress values are given for three discharges: medium, high and bankfull.

Sensitivity Analysis

A sensitivity analysis was carried out by comparing shear stress values as calculated from field data (Figure 5.8) to those generated by HEC-RAS. As is evident in Figure 5.21, HEC-RAS predicts that water surface slope in each zone changes as discharge increases, becoming more uniform across the study reach, which is to be expected. The sensitivity analysis was thus carried out only for low and medium discharges since no field measurements of water surface were acquired at high flows. It was found that the shear stress values calculated from field data were quite similar to those produced by HEC-RAS for the low flow case, but less so for medium flow case. Fine tuning Manning's n in each zone made it possible for HEC-RAS to reproduce the shear stress values calculated from field data with a high degree of accuracy. However, these modified Manning's n values represented a considerable departure from those that yielded the most accurate water surface elevations (Figure 5.21), which illustrates the significant influence of Manning's n estimates on model output. The results of the analysis are presented in Figure 5.26.

a)



b)

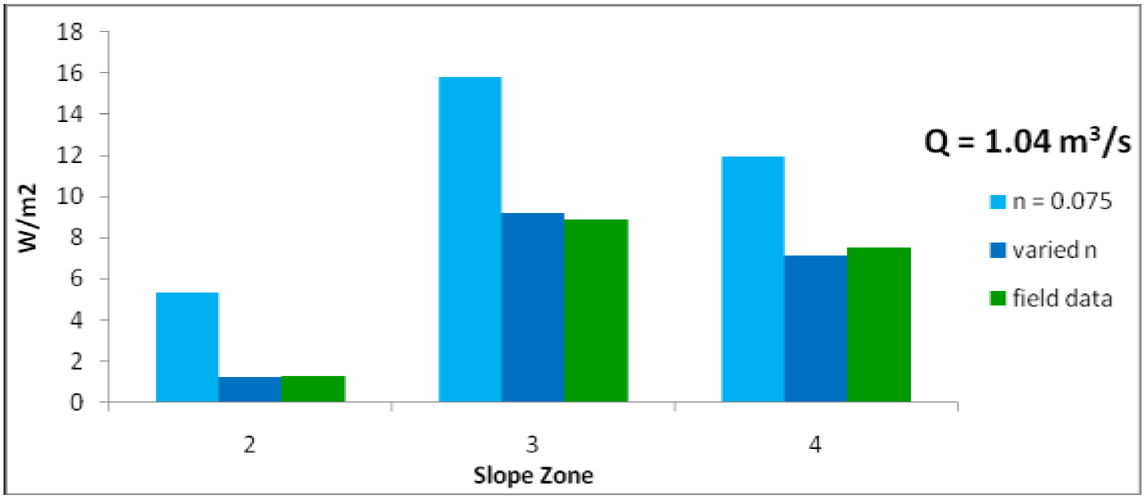


Figure 5.26 Shear stress for three slope zones in the model reach as calculated from simulation data versus field data. In the low flow case a), shear stress was better approximated in HEC-RAS by using a Manning's n of 0.3 in slope zone 2, 0.2 in zone 3 and 0.4 in zone 4. However, for the simulation using Manning's n of 0.225, the n that best reproduced water surface levels, did produce relatively close approximations of shear stress. This was not the case for the medium flow case b). Rather, it was found that the Manning's n value of 0.075 that produced the most accurate water surface levels resulted in overestimated shear stress values. A Manning's n of 0.035 in zone 2, 0.018 in zone 3 and 0.015 in zone 4 was found to be necessary in order to reproduce shear stress values as calculated from field data.

5.3.2 Sediment Transport

BAGS

BAGS was run for two discharges, high flow (6.24 m^3/s), as recorded November 5 2011, and bankfull flow (14.66 m^3/s), which was estimated using the rating curve (section 5.2.1). Four representational cross sections were modelled (Figure 5.27) along with their corresponding sediment size distributions (Table 5.2). A summary of the bedload transport rate for all grain sizes is presented in Table 5.3.

Figure 5.27 Four transects used in BAGS sediment modelling software. Transect numbers represent approximate distance in metres from station 1.

Discharge	cross-section number			
	4	146	331	404
6.24	4.19E-08	0.0145	0.0367	0.127
14.66	6.91E-07	1.34	1.57	8.37

Table 5.3 Rates of sediment transport as simulated by BAGS in kg/min. for all grain size classes at high and bankfull discharges (m^3/s).

HEC-RAS

Sediment modeling in HEC-RAS proved to be problematic. The process involves considerably more parameterization than BAGS, and seems to have a few bugs. Despite several efforts, sediment transport capacity estimates for the downstream section of the study reach were not successfully simulated. Table 5.4 Summarizes HEC-RAS results compared to those generated by BAGS. Although the overall trend is similar, with a decrease in transport rates from upstream to downstream, HEC-RAS predicted no bedload transport at cross-section 146 for high flow, when both our field observations and BAGS results indicate there is movement at that flow stage. Unfortunately, there was not enough time in this project to further investigate why HEC-RAS resulted in no transport predictions in that case.

Discharge (m3/s)	Model	cross-section number			
		4	146	301	404
6.24	HEC-RAS	0	0	1.25E-08	2.625
	BAGS	4.19E-08	0.0145	0.0367	0.127
14.66	HEC-RAS	0	0	0.00239	16.6
	BAGS	6.91E-07	1.34	1.57	8.37

Table 5.4 HEC-RAS sediment transport capacity simulation results compared to those generated by BAGS, in kg/min. Sediment transport capacity estimates for cross-sections 4 and 146, even at bankfull flow, were zero.

6 DISCUSSION

6.1 Steep Bank

It is clear from historical photos that the channel was not previously located near the steep, rapidly eroding bank (Figure 4.2). The relocation of the channel to the foot of the bank in 1959 (Figure 5.1) was presumably done to maximize agricultural land area, and most likely without the foresight that erosion would ensue and jeopardize the stability of the land on top of the bank. In fact, it is possible that before this area was subject to erosion by the river, the slope between higher and lower ground may have been more gradual. The resolution of the scans of the aerial photographs, in addition to the fact that they are taken from a virtually overhead vantage point, do not permit discerning if this was indeed the case. The pond appears to have been dug slightly before 1985, as it is the first aerial photo in which it appears. Bank erosion resulting in lateral channel migration is primarily responsible for the problem that now threatens the stability of the pond and the land on top of the bank, but the very presence of the relatively large, artificial body of water does compound the problem; it adds weight and saturates the soil composing the bank, making it more vulnerable to erosion and freeze thaw processes. It should also be noted that due to the relatively tall height of the bank, its erosion produces considerably higher sediment volumes than the shorter banks that characterize the rest of the study reach.

6.2 Mid-Channel Bar and Lower Sunday River

Spanning more than half a century, repeated re-straightening efforts aimed at eliminating the mid-channel bar in the lower reach of the Sunday River have proven unsuccessful in the long term. Furthermore, sustained dredging and rectifying adversely affect the lotic ecosystem of the Sunday River. This study has identified numerous factors that shed light on exactly why this mid-channel bar perpetually re-establishes itself, as well as several reasons as to why it establishes itself where it does.

Firstly, a marked drop in slope in the reach where the bar is located and immediately upstream of it (zone 2, Figure 5.6) was identified in both channel bed elevation data and low and medium discharge water surface elevation data. Hydraulic model simulations re-produced this break in slope, the result of which is a decrease in sediment transport potential, as documented in shear stress and unit stream power estimates. Additionally, historical aerial photographs show large meander loops in the area where the mid-channel bar forms, indicating a low valley slope in this area.

Secondly, the presence of a tractor crossing at the upstream limit of the area in which the mid-channel bar forms is theorized to significantly contribute to a widening of the channel and de-stabilization of the banks (Figure 6.1). Channel width increases by a factor of more than two within a distance of only a few meters, drastically reducing unit stream power.

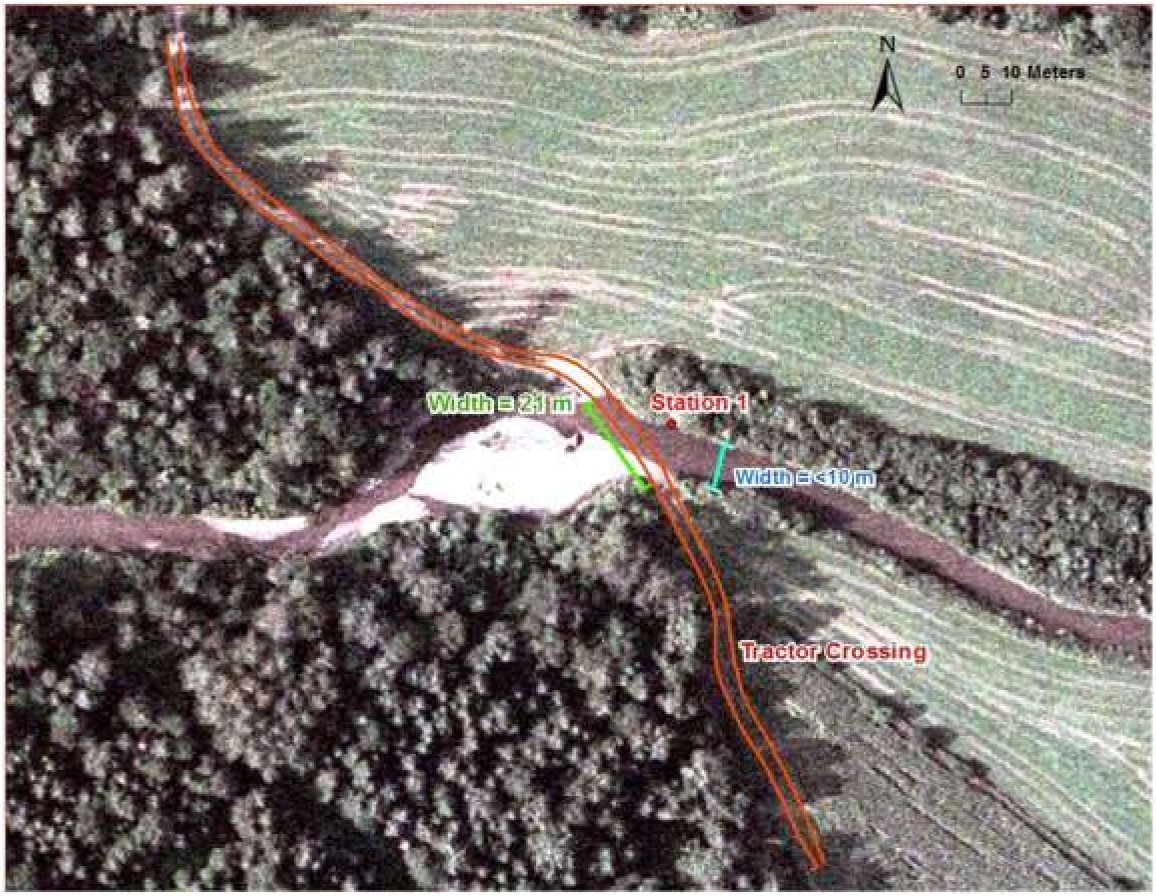


Figure 6.1 Tractor crossing in the downstream reach of the Sunday River, just upstream of the mid-channel bar.

Thirdly, channel straightening upstream of the bar has resulted in higher sediment transport capacity, contributing to a high rate of sediment deposition on the bar. Bank armouring on the left bank just upstream of the mid-channel bar and on the right bank further upstream has limited both lateral erosion and meander migration (Figure 6.2). Unit stream power values for bankfull discharge in the lower Sunday River (Figure 5.13) are significantly higher than the 35 w/m^2 threshold that is generally accepted as that which characterizes a dynamic river (Figure 6.3, Sear, 1996). Consequently, entrained sediment is eventually transported onto the bar. Furthermore, the fortification of the left bank immediately upstream of the mid channel bar might contribute to the erosion of the bank to the right of the bar, as the flow is deflected towards the opposite bank. Indeed, it has been well documented that bank stabilization efforts often lead to increased erosion upstream and downstream of the said bank (Downs & Gregory, 2004).

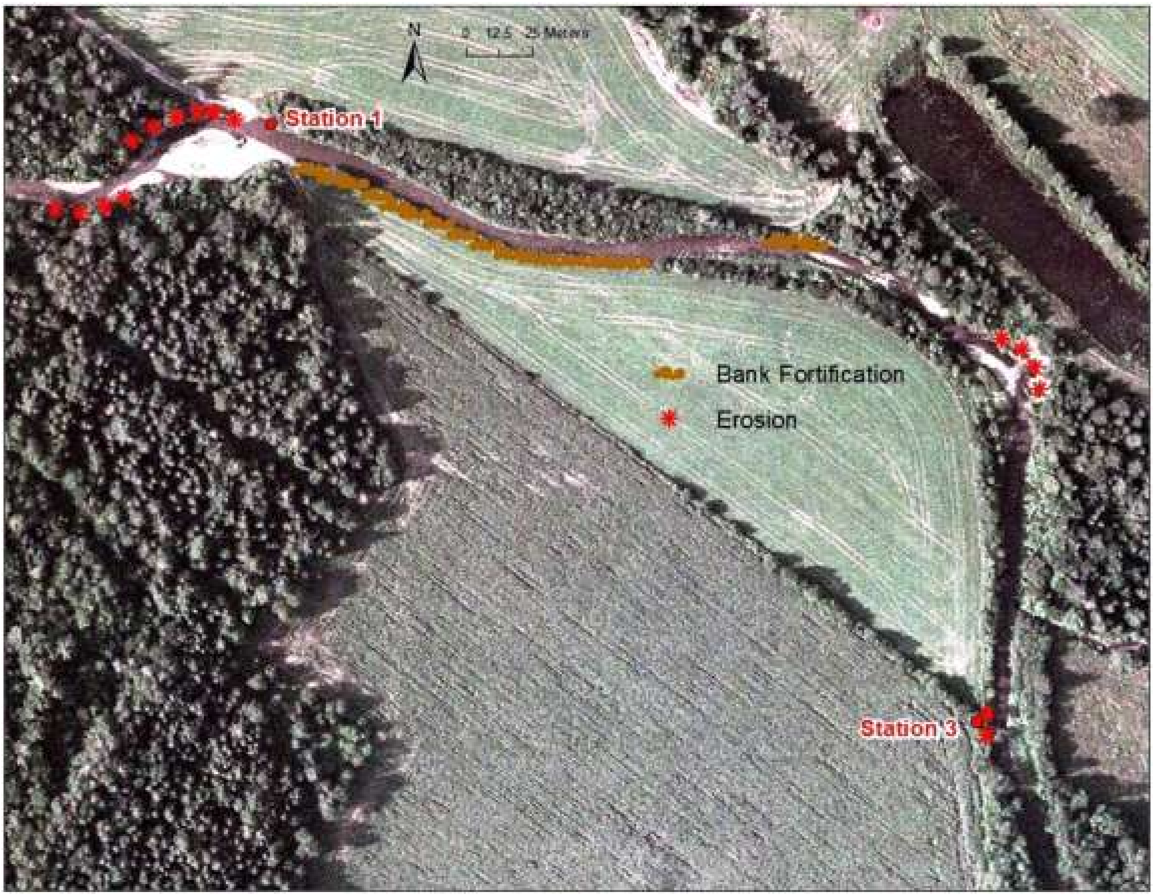


Figure 6.2 Locations of bank armouring with rip rap versus locations of documented erosion. It should be noted that rip rap was identified in outer meanders where erosive powers are relatively high, and due to bank vegetation the rip rap was not easily visible. Only once a few large concrete blocks were identified were the banks inspected for the extent of rip rap. It is possible that additional banks are fortified with material that is no longer easily recognizable. A few boulders that might constitute the remnants of unsuccessful bank fortification attempts on the right bank immediately downstream of station 1 were also identified.

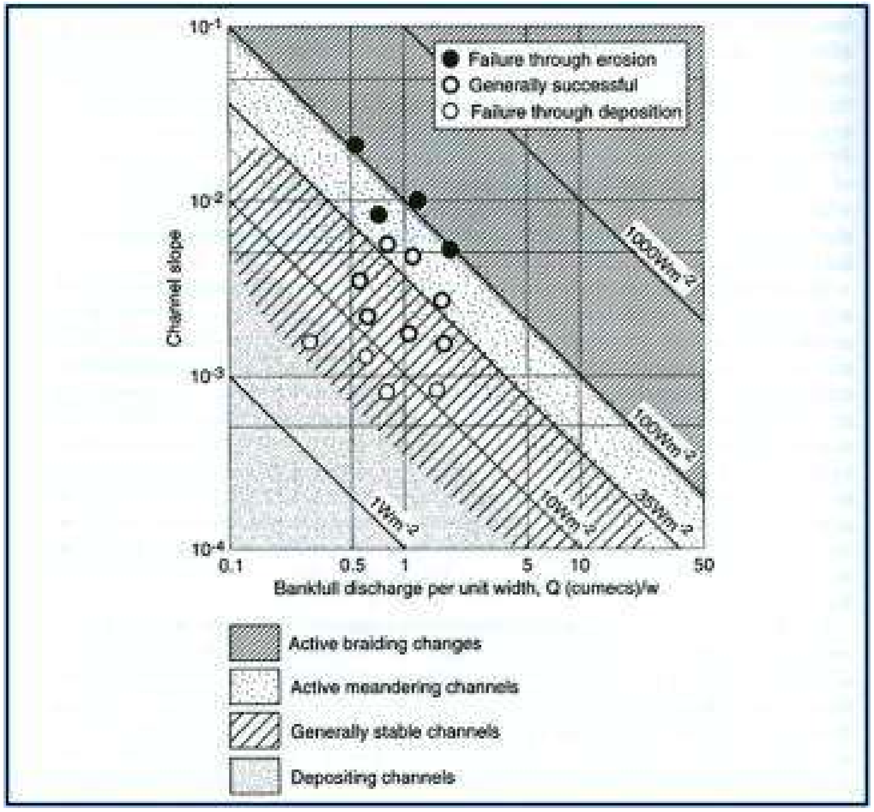


Figure 6.3 Approximate stream power thresholds of river channel adjustment (from Sear 1996). Estimates of unit stream power at bankfull stage (Figure 5.13) in zones 1, 3 and 4 are all above the 35 w/m^2 threshold that characterizes active meandering channels.

Fourthly, either as a result of vertical incision or dredging, or both, it is theorized that the lower Sunday River is in fact entrenched. Channel incision may have contributed to the break in slope between zones 2 and 3 (Figure 5.6) and further contributed to the growth of the mid-channel bar. With access to its floodplain only during very high magnitude flooding events, the energy present during any lesser magnitude discharges is not alleviated by overbank flow, thus furthering bank erosion and lateral meander migration downstream. Even following the flood of April 24th 2011 (Figure 5.5), an event estimated to have a recurrence interval of 50 years and to have had a discharge more than double that of bankfull, there was no evidence of fine sediment deposition on the floodplain upstream of the mid-channel bar. Furthermore, the presence of bank fortification in the reach prevents the river from re-establishing a more natural width, depth and terraced profile, as would otherwise be expected (Hupp, 1992). A reach characterized by the combination of a straightened, entrenched channel with fortified banks will undoubtedly result in highly unstable reaches further downstream.

The findings of this study constitute evidence that the lower Sunday River is in fact a significantly modified graded stream occupying the zone of sediment transfer. Indeed, the natural channel pattern of a river is based on environmental determinants including the physical environment and local climate (Schumm 1977). Thus, the re-meandering tendency of the lower Sunday River is an entirely natural process; all rivers will continually adjust themselves in order to achieve the minimum slope needed to convey a specific mean discharge and sediment load in the most efficient way (Figure 2.1). Furthermore, this process is an entirely desirable one in terms of ecosystem health and functionality (Payne and Lapointe 1997; Florsheim et al. 2008; Kondolf 2011). Lotic ecosystems established themselves and have evolved over the ages in undisturbed fluvial environments, and their survival depends on the preservation of these.

It is thus not surprising that the mid-channel bar forms where it does and forms so quickly. This is a product of natural fluvial processes, one that contributes to the quality and availability of trout habitat, and which should be allowed to operate.

6.3 Possible Solutions

Historically, issues of bank erosion and channel re-meandering have been addressed using “hard engineering” techniques, such as bank armouring. This approach, as discussed in section 2.4, has been shown to be largely ineffective and unsustainable, especially when considering the reach scale as opposed to individual meanders. Oppositely, contemporary river restoration efforts often focus on encouraging bank erosion and adding or re-creating meanders (Spink et al. 2009; Kristensen et al. 2011). Within the context of sustainable development, solutions to the problems plaguing the downstream Sunday River should be designed to be long lasting and to minimize the impact on trout habitat. Based on historical records, it is obvious that the Sunday River, in its downstream section, was characterized by the presence of large meanders. As this section is close to the Osgood (approximately 200m), to which the Sunday is a tributary, and which represents the ultimate base level of the river, there is a limited amount of space in which the river must adjust itself.

From the perspective of sustainable, long lasting solutions, that which is most effective is the river corridor approach, as outlined in section 2.4. In the lower Sunday River, there are several reaches where the riparian zone is nonexistent and the floodplain consists almost entirely of cultivated land. Ideally, a river corridor should be established, as per Figure 6.4, and a riparian zone should be re-established and left untouched so that plants and trees may be allowed to grow. In addition to stabilizing river banks, these provide cover and even sources of food for salmonids at certain life stages, and thus contribute to the quality and extent of trout habitat (Kondolf 2011). Floodplain access would improve as lateral migration of the channel would result in minimized vertical channel incision, thus contributing to more gradual flood wave propagation as well as a significant improvement in ecological integrity.

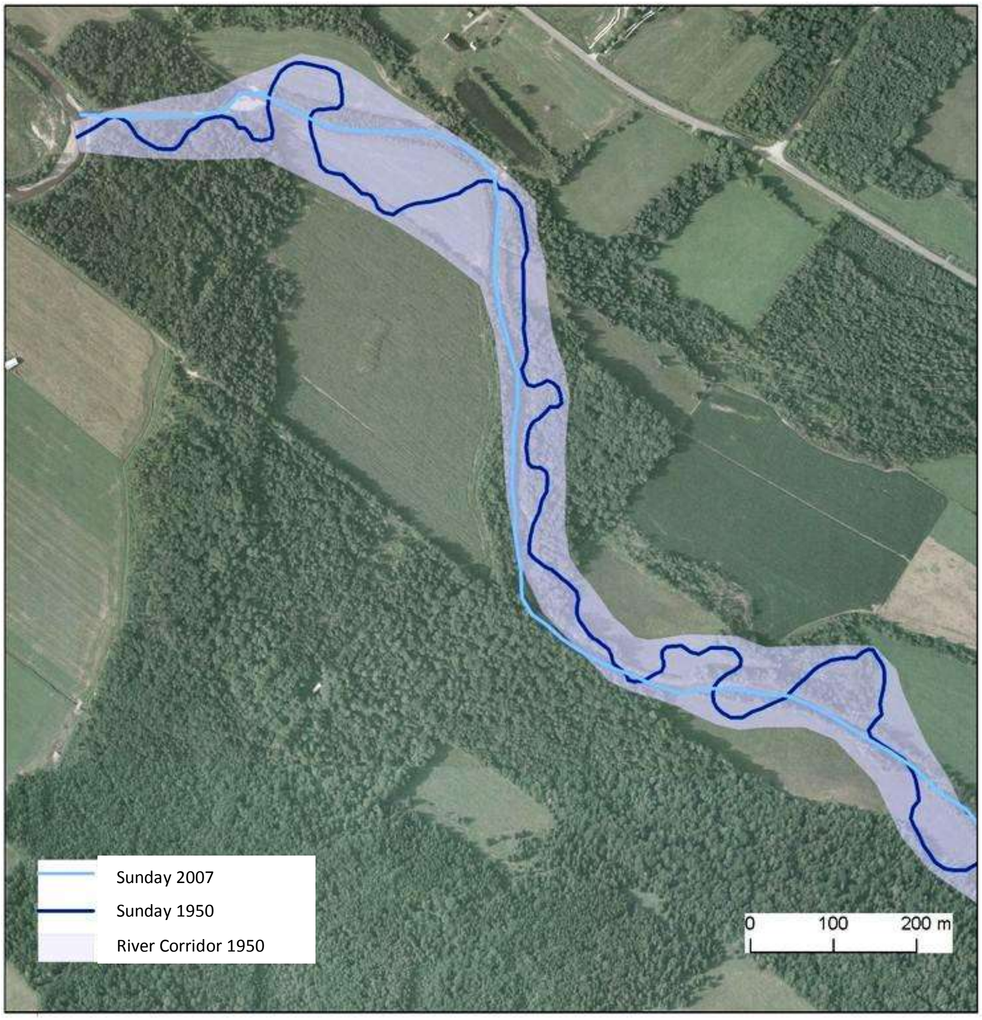


Figure 6.4 River corridor based on 1950 channel path.

However, without the acquisition of river-side land and the designation of conservation easements, the river corridor proposal is not realistic, seeing as the agricultural land adjacent to the Sunday River is the livelihood of local farmers. A more realistic solution would involve the abandonment of the use of the tractor crossing. The rip rap should also be removed from the banks upstream of the mid channel bar. Or, at the very least, further bank stabilization attempts should be avoided. However, leaving the rip rap in place will undoubtedly prevent lateral meander migration, floodplain access and progress towards remediation of the incised channel, all resulting in continued instability in the downstream reach. If the river upstream of the mid channel bar were allowed to meander as it would in a natural state, channel slope would decrease, resulting in a decrease in erosive energy and a relative stabilisation of the channel. Furthermore, the sediment eroded and entrained would be stored in point bars and remobilized (Figures 2.2 and 2.3). For this, some agricultural land will have to be sacrificed. The alternative to dedicating a portion of the land around the mid-channel bar to lateral migration of the Sunday River necessarily will entail regular interventions in order to prevent the river from returning to a natural form, as has been the case since the late 1950s (Figure 2.4).

To address the problem of the steep bank, although it also would entail the loss of agricultural land, a reorientation of the channel to its former path is recommended. The banks should not be armoured in this case, for reasons outlined above. However, the stability of the right bank upstream of the steep bank would be enhanced by the presence of wooden deflector-style installations that would orient the flow away from the problematic area. It must be considered that there is an imminent trade off looming

– if things carry on as they have, soon enough the bank will give way and the pond will empty into the valley below. This will render the land on top of the embankment unusable or in need of backfilling, but there is a chance that the agricultural land below would be “reconfigured” as a result, necessitating excavation work and adversely affecting trout habitat.

7 CONCLUSION

Channel modification efforts that aim to limit bank erosion are rarely viable on a long term basis, especially in dynamic rivers such as the Sunday (Downs and Gregory, 2004). Historically, efforts to deal with bank erosion have been based on “hard engineering” principles such as bank stabilization. More and more however, hydro-geomorphological principles are employed, in which the concept of river corridor plays and integral role (Piégay *et al.*, 2005).

The recommendations for management of the problems of erosion in the downstream Sunday River determined in this study are as follows:

- To stop using tractor crossing upstream of the mid-channel bar;
- To remove bank stabilisation material upstream of the mid-channel bar;
- Reconfigure channel to historical path near the steep bank.

The proposed solutions aim to return the Sunday River to a state where it is in relative equilibrium with the geomorphological and climatic variables present in the Sunday River watershed. It has been clearly demonstrated through field surveys, historical analysis and numerical modelling that the Sunday River is indeed a river possessing a dynamic sediment regime that is characterized by the regular transfer of sediments downstream (Figure 2.3). History has shown that regular maintenance is required to maintain a channel that has been modified from its natural state (Figure 5.4), as is usually the case following river channel straightening (Figure 2.4). This practice compromises the quality and availability of trout habitat. If interventions were to cease and all rip rap were to be removed from the banks, the Sunday River would eventually return to a channel pattern similar to that present in 1950.

While the recommendations outlined in this paper call for solutions that entail the loss of agricultural land, the value that a natural channel form and functional, healthy riparian zone bring to the fluvial system and the resulting cultural, recreational and environmental benefits afforded by a healthy river should be considered. It is essential to understand that if trout habitat is to be preserved (and certainly ameliorated), straightening interventions must be stopped. If interventions are stopped, the river will adjust itself to the slope of the valley and the liquid and solid discharges it must convey. This entirely natural process of adjustment will lead to the Sunday River re-establishing a meandering planform through the process of bank erosion and sediment deposition, and ultimately result in meander migration. A meandering river in a transfer zone, i.e. where banks are continuously reworked, must have a mobility corridor in order to exist. It is therefore only logical that if trout habitat is to be preserved, a mobility corridor in the low slope reach in and around the mid-channel bar must be established.

The Sunday River is a product of the physical environment (the valley and the sedimentary material of which it is composed; the water delivered by the hydrological cycle) being acted on by the forces of physics. If neither the physical environment nor the forces of physics are changed, then it is expected that a dynamic river will tend to return to its pre-modified layout, i.e. the 1950 sinuous pattern. Ultimately, a choice needs to be made by river managers: do we want to preserve the natural fluvial environment and reap the social, spiritual and economic benefit it provides, or do we want to sacrifice it for a relatively small gain in agricultural land. Compromise is possible – it is possible for both agricultural activity and a healthy river to coexist alongside one another, but priorities must be made clear, and certain sacrifices will be necessary. It is important that this choice be seriously contemplated by all stakeholders, for it is the very essence of the problematic issue of the downstream Sunday River.

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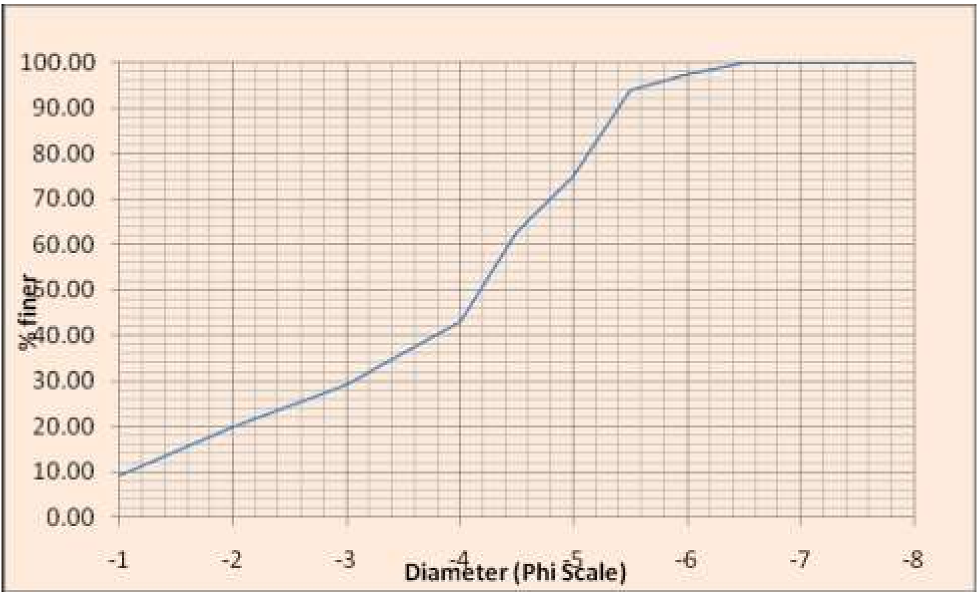
Appendix A

a)



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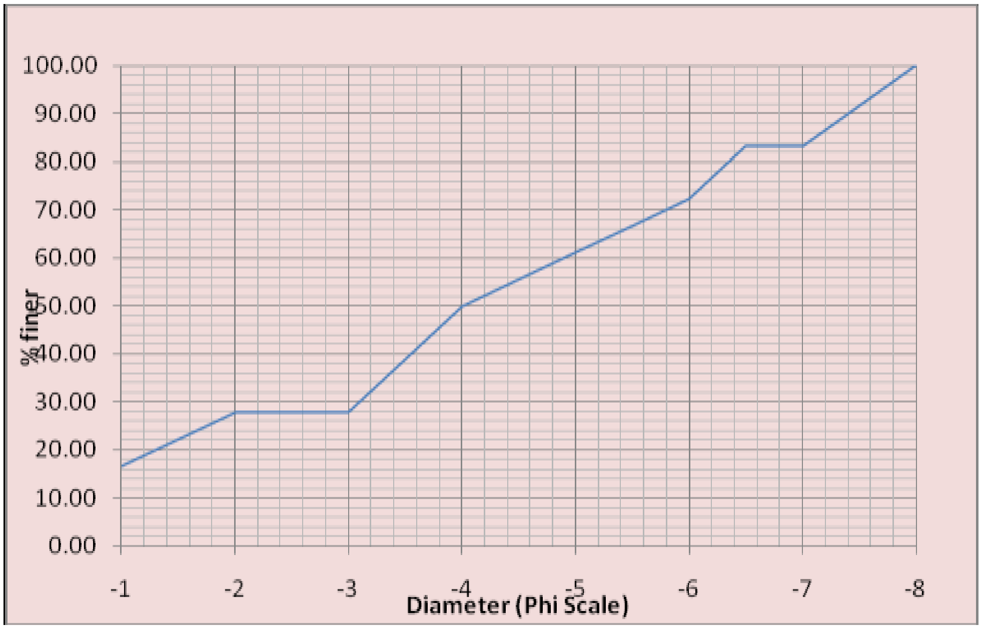
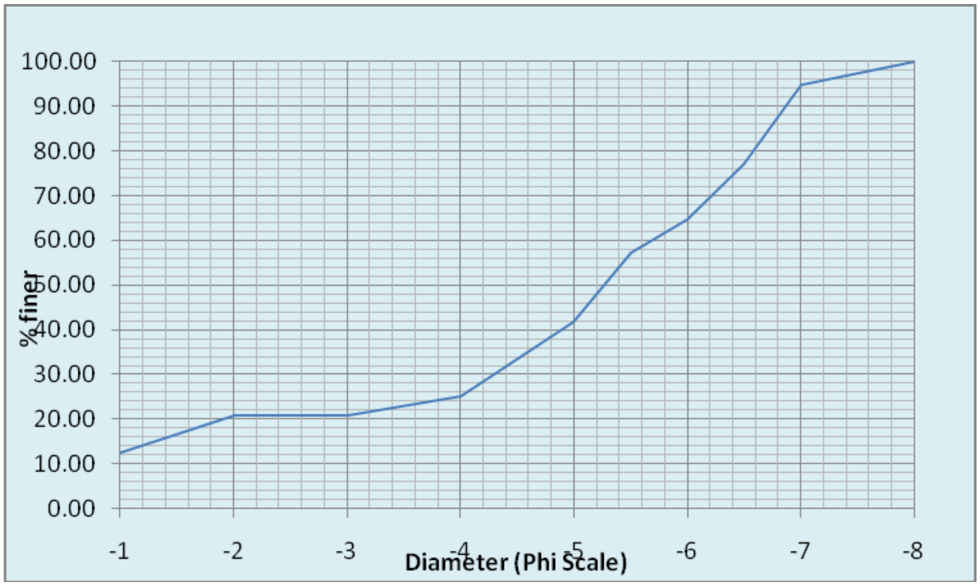


c) 
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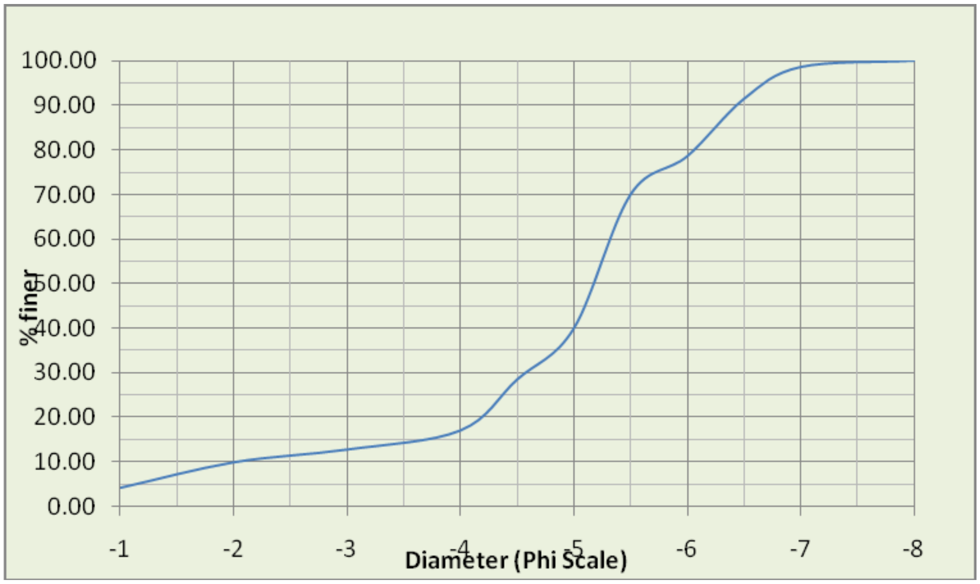
Diameter (Phi Scale)

d) 
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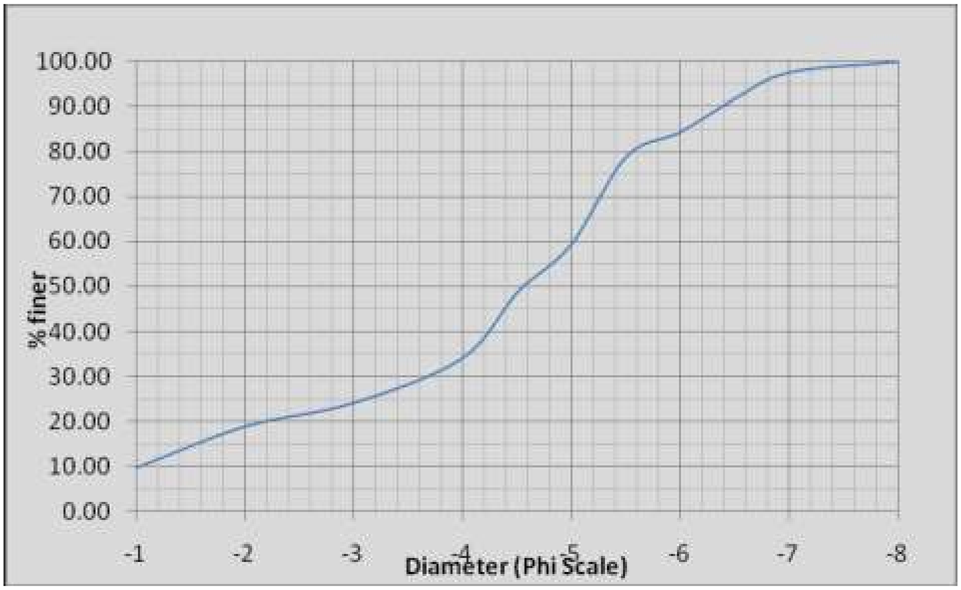
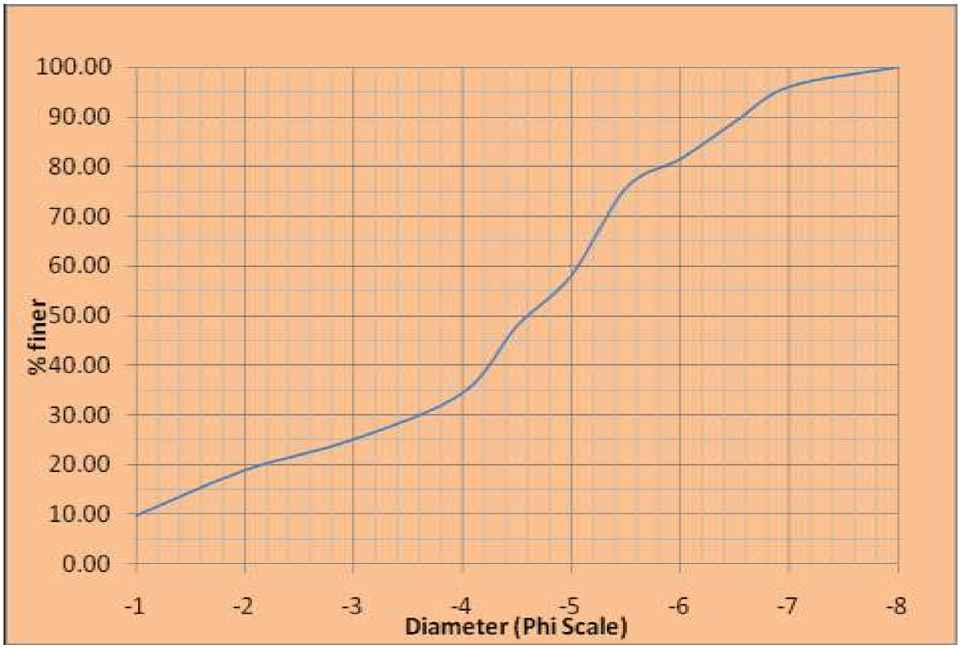
e) 

f) 

Sediment distribution curves:

a) Zone 1
b) Zone 2
c) Zone 3
d) Zone 4
e) Entire model reach (Zones 1-4)
f) Entire lower reach of Sunday river (Route 226 bridge to confluence with Osgood)