CATASTROPHIC VALLEY ENTRENCHMENT AND DEBRIS FAN FORMATION IN THE BLUEFIELDS RIVER, WESTMORELAND JAMAICA

A Masters Thesis

Presented to

The Graduate College of

Missouri State University

In Partial Fulfillment

Of the Requirements for the Degree

Master of Science, Geospatial Sciences in Geography and Geology

By

William Patrick Dryer

July 2010

CATASTROPHIC VALLEY ENTRENCHMENT AND DEBRIS FAN FORMATION IN THE BLUEFIELDS RIVER, WESTMORELAND JAMAICA

Geography, Geology, and Planning

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ABSTRACT

Little is known about the geomorphic response of Jamaican rivers to climate, geology, and human disturbance. The southwestern coast of Jamaica received a record of 32 cm of rain on June 12, 1979. Reports indicated that valley areas formed temporary lakes, overtopped small dams, and produced debris flows. This study investigates the effects of this extreme flooding on the geomorphology of the present-day Bluefields River near Belmont, Westmoreland Jamaica. The river drains 4.9 km^2 of limestone uplands and mountain slopes. This study evaluates evidence from longitudinal profiles, multiple cross-sections, Colonial maps, historical aerial photographs, oral histories, and sedimentological analysis to identify previous channel bed elevations and evaluate current channel morphology. The Bluefields River was entrenched by nearly 9 meters along its middle and lower reaches. In addition, Goat Gulley, its major tributary, was also incised along its lower and upper segments. Debris flows formed a large debris fan extending over 150 m out into Bluefields Bay. About 70% of the 1979 fan volume still remains today. While Colonial maps indicate that a delta fan always existed at the river mouth, the shoreline configuration was similar from the late 1700s to before the flood with little expression of the debris fan as now present. Therefore, the return period for this type of hydro-geomorphic event is >300 years. While causes are mostly related to climate and geology factors, human modification of the landscape may have contributed to increased rates and extent of channel incision, thus increasing sediment delivery. Bluefields Bay is now a fish sanctuary and further studies of sediment inputs to the bay over different timescales may be important for maintaining a healthy fishery.

KEYWORDS: Jamaica, rivers, channel morphology, debris flows, floods

This abstract is approved as to form and content

Robert T. Pavlowsky
Chairperson, Advisory Committee
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ACKNOWLEDGEMENTS

I wish to thank everyone who was involved in this project. There were many that supported my work and provided invaluable assistance in the field and laboratory. Conducting field work out of the United States is challenging and I would especially like to thank Wolde Kristos and the team at Reliable Adventures Jamaica (Decita Turner, Michael Grant, and Veda Tate) for their generous hospitality and insights into the Jamaican lifestyle. I would also like to thank field workers Jackie Ebert, Derek Martin, Erin Hutchinson, Patrick Womble, and Dave Speer for traveling to Jamaica to help me.

Most importantly, I would like to thank my advisor Robert T. Pavlowsky and committee members William A. Wedenoja and Melida Gutiérrez for their academic guidance over the last few years. This project would not have been possible without funding from two Missouri State University Latin American Caribbean and Hispanic Studies grants, one to Drs. Pavlowsky and Wedenoja and the other to me. In addition, partial funding was also provided by the Ozarks Environmental and Water Resources Institute and a thesis research grant from the Missouri State University Graduate College.

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CHAPTER 1

INTRODUCTION

It is important to be able to recognize the influence of infrequent, large floods on channel form within the constraints of longer-term watershed disturbances to better understand stream channel form and response. Rivers can adjust their form and behavior in response to changes in sediment yields and runoff over periods of decades to centuries or longer (Clark and Wilcock, 2000). There are four main variables that control the erosion and supply sediments in a watershed: precipitation and runoff (climate), soil erodibility, basin relief (geologic), and vegetation (Knighton, 1998). Climatic changes affect precipitation and runoff which influence flood frequency and discharge volume in a stream (Knighton, 1998) and also can alter vegetation cover which directly influences soil erosion and river sedimentation (Ritter et al, 2002).

Sediment supply to river systems can be a direct result of geologic constraints such as faulting, uplift, weathering, and soil composition (Knighton, 1998). However, land use changes that disturb soil, reduce vegetation cover, and increase runoff can increase soil erosion and sediment delivery to the river (Knox, 1987). Large magnitude floods can drastically alter channel morphology and mobilize large volumes of sediment. In general, sediment transport increases during floods with runoff duration and peak stage (Wolman and Miller, 1960). During flooding, geomorphic thresholds are exceeded, causing major changes in river planform and geometry (Ritter et al, 2002; Gupta, 1975, 1983). Changes in channel morphology due to extreme flooding can be short-term due to frequent smaller flows and the anchoring influence of vegetation to help restore channel geometry to previous or more stable conditions (Gupta, 1983).

Extreme Flooding in Jamaica

Little is known about the geomorphic response of Jamaican rivers to climate, geology, and historical human disturbance. Flood hydroclimatology as well as geologic setting varies regionally in Jamaica (Donaldson and Walters, 1981). The Bluefields River in Bluefields Bay, Jamaica provides a great opportunity to study channel change and stream response to a large magnitude flood. It has been documented on several occasions by the Jamaican government that heavy rains combined with low infiltration rates on upland soils and karst topography leads to periodic flooding in Jamaica and (Donaldson and Walters, 1979). However, on June 12, 1979 a severe tropical depression caused major flooding in southwestern Jamaica. This flood resulted in destruction of property, 41 deaths, and substantial changes to the form of the Bluefields River. Geomorphic effects of the 1979 flood include extensive incision into underlying residuum and colluvial soils, bedrock block transport, and formation of a large debris fan at the mouth.

This study investigates the effects of extreme rainfall and flooding on the geomorphology of the present-day Bluefields River near Belmont, Westmoreland, Jamaica (Figure 1). The Bluefields River drains 4.9 km^2 of limestone uplands, heads in coastal mountains at a top elevation of 760 m, and flows 4.7 km to the sea (Figure 2). The upper 3.5 km of the river is ephemeral, while the lower 1.2 km is perennial and used by local residents for bathing and washing (Figure 2). The spring-head of the Bluefields River provides a public source of drinking water with treatment to nearby towns. There are questions about the influence of nutrients, bacteria, and sediment from the Bluefields River on human health and marine life. It is hypothesized that sand and mud deposits originating from the 1979 flood are still found along the shoreline near the river mouth and may provide substrate for sea grass beds that support the local fishery.

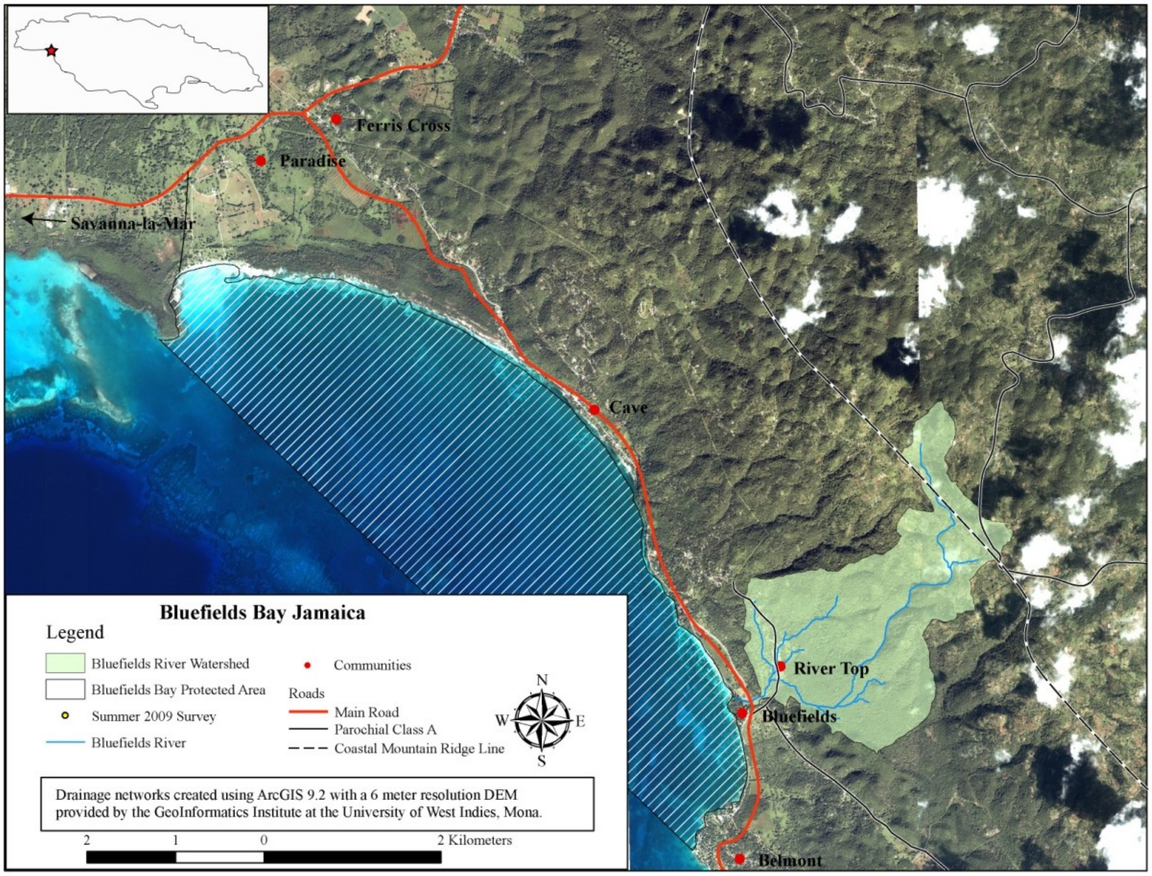


Figure 1. Bluefields Bay located on the south west coast in the parish of Westmoreland, Jamaica.

Bluefields Bay has a rich cultural history starting with the aboriginal villages of the Taíno, followed by Spanish settlement in the 1519, and the British settlement of 1655. Historically maps depict streams in Bluefields Bay during colonial times as a source for clean drinking water for Spanish and British ships anchored in Bluefields Bay. The historical maps also depict the land use of Bluefields Bay by the British for agricultural production of fruit, timber, and cattle grazing. Although most of Jamaica was cleared for sugar cane production during European settlement, there is little evidence that sugar cane cultivation existed in the Bluefields River watershed.

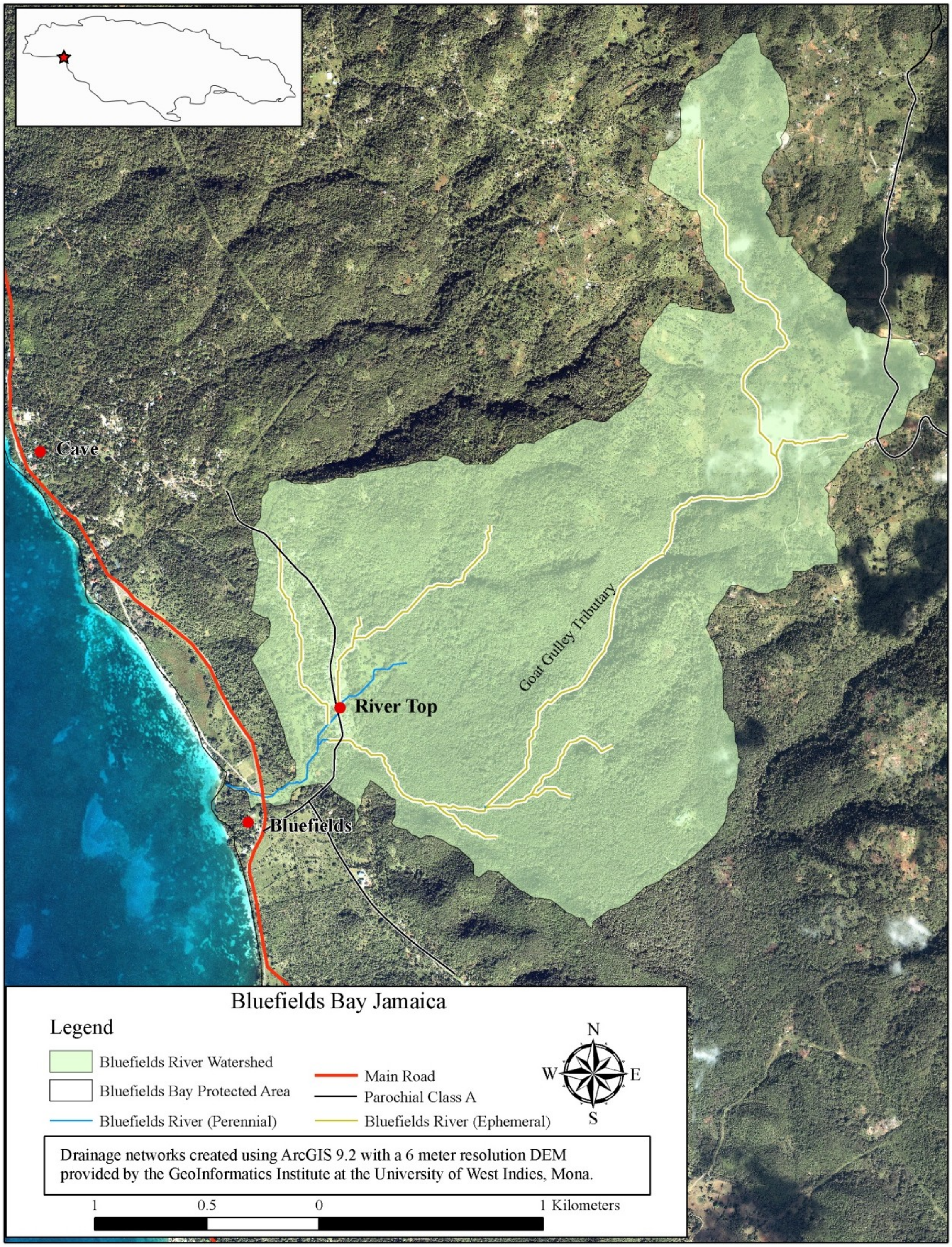


Figure 2. Location Map of the Bluefields River. (Year 2006)

Intense precipitation onto already saturated soils on June 12, 1979 led to catastrophic flooding and debris flows in western Jamaica (Donaldson and Walters, 1981). Nearly 32 cm of rain on the Bluefields River watershed lead to flooding and a debris flow (Donaldson and Walters, 1981). The amount of sediment that was eroded and transported during the flooding of 1979 is unknown. However, there is a lasting oral history from residents who witnessed the event as well as geomorphic indicators still present on the landscape that can be used to reconstruct the flooding and debris flow patterns. Several factors contributed to the catastrophic channel and valley changes along the Bluefields River including geology, climate, and human modifications to the landscape. The degree to which each factor influenced the debris flow and subsequent incision is investigated in this study. The understanding of why the event happened will give insight into the future and the possibility of a similar event occurring.

Sediment Delivery Processes

Studies of stream response following a debris flow are not well represented in the literature. However, historical land clearing and expansion of row-crop agriculture resulting in surface soil erosion and gulley formation have been documented (Knox, 1987; Faulker, 1998; Leece and Pavlowsky, 2001; James, 2006; Trimble, 1970). The large influx of sediment can be a result of human modifications of the landscape, mining operations (Knox, 1987; Faulkner 1998; Lecce and Pavlowsky, 2001; James, 2006), agricultural changes (Knox, 1977, 1987; Trimble, 1970), and urbanization (Ebisemiju, 1989). Longer term influence of land use change on channel sedimentation is a type of watershed “event” that operates over decades to centuries. Nevertheless, vast quantities of sediments can also be introduced by a single catastrophic event such as a debris flow (Benda et al, 2005).

Hurricanes frequent the Caribbean causing landslides, debris flows and flooding which all effect channel morphology (Ahman and Gupta, 1993). In upper watershed areas, coarse bedload materials are introduced to streams by episodic events such as landslides and debris flows (Osterkamp, 2001; Gupta, 1988; Benda et al 2005). Landslides and debris flows are common sources of sediment to upper watersheds in mountains and tropical environments (Benda et al, 2005). During the wet season, landslides occur periodically in Jamaica (Jamaica Gleaner, 2002). Debris flows in Jamaica occur on steep slopes that have intensely weathered colluvium or residuum with preexisting gullies.

Objectives

The Bluefields River offers a great opportunity to study river behavior and channel morphology in response to a large magnitude event due to the availability of land use history, access to the river, and the importance of water supply and quality to the community and bay fishery managers. Recently, Bluefields bay was declared a fish sanctuary to protect fish and fish habitat. It is unknown how infrequent episodic sediment inputs to Bluefields Bay will affect bay conditions, and habitat such as sea grass beds and coral reefs. The objectives of this study are to: (i) describe the geomorphic effects of a catastrophic flood in 1979; (ii) calculate sediment delivery to the debris fan from valley incision; and (iii) evaluate the potential role of colonial land disturbance and soil erosion leading to the destabilization of the Bluefields River in 1979. There is little known about the previous geometry, composition, or sediment loads of the Bluefields River prior to

1979. This makes it difficult to assess the current state of the river. However there are several ways to investigate the geomorphic history of the Bluefields River. It is important to understand the geomorphic history of the Bluefields River prior to the June 12th, 1979 flood to determine effects and give a basis for estimating future channel morphology changes and sediment transport. Historical channel conditions can be determined by investigating the stratigraphic record of floodplain deposits and trends in present channel morphology.

CHAPTER 2

FLUVIAL PROCESSES

Fluvial Geomorphology

Fluvial geomorphology is the study of river form, behavior, and changes over time. Rivers are very complex, dynamic systems that have many factors that control stream behavior. Alluvial streams are open systems that adjust to altered inputs of energy and materials (Simon et al, 2007). Flooding, sediment delivery, climate, and vegetation all influence stream behavior (Knighton, 1998). To understand why streams alter their channel morphology it is important to understand basic concepts of fluvial geomorphology.

Fluvial systems are controlled by two main factors, force and resistance (Lane, 1955). The force exerted by the stream on its bed is a function of the slope of the channel and the depth of flow (Lane, 1955). Resistance counters the effect of force on increased flow velocity in the channel and is a function of sediment supply, channel substrate, bedrock controls, and vegetation (Ritter et al, 2002). The balance between force and resistance will ultimately determine channel form, location, and sediment yield (Ritter et al, 2002). Changes over time to the distribution of force and resistance along the channel network will produce changes in channel form and sediment yields (Ritter et al, 2002).

Discharge and sediment loading of a stream are a function of climate, geology, and tectonics (Ritter et al, 2002). Climate and geology are liked by watershed surface conditions such as soils, vegetation, and stream networks (Knighton, 1998). The soils and vegetation act as a geomorphic filter or layer of resistance. The layer of resistance can vary and change due to human disturbances reducing surface resistance. Gradually streams can alter their geometry to convey changes in discharge or sediment yields (Ritter et al, 2002).

Eventually an event will exceed the stable limits of the original channel morphology, prompting a change in channel pattern (Ritter et al, 2002). During threshold exceedance the excess force leads to adjustments to increase resistance causing major changes in channel form (Ritter et al, 2002; Gupta, 1983). This major change in channel form happened in the Bluefields River. On June 12th, 1979 a large flood and debris flow lead to catastrophic valley incision in the Bluefields River.

Discharge and sediment loading of a stream are a function of climate, geology, and tectonics (Ritter et al, 2002). Climate and geology are liked by watershed surface conditions such as soils, vegetation, and stream networks (Knighton, 1998). The soils and vegetation act as a geomorphic filter or layer of resistance. The layer of resistance can vary and change due to human disturbances reducing surface resistance. Gradually streams can alter their geometry to convey changes in discharge or sediment yields (Ritter et al, 2002).

Causes of Incision and Head Cutting

Stream incision is a result of an imbalance between slope and resistance (Lane, 1955). High bed slopes result in increased stream power. If the force exerted on the channel bed exceeds the resistance of the bed material erosion and incision will occur (Ritter et al, 2002). A knickpoint is a stable outcropping of bedrock or other stable structure that locally increases bed slope. Knickpoints indicate locations of channel adjustment occurring over geologic time scales of thousands of years or more (Schuum and Lichty, 1965). Bed elevation and slope adjustments occur slowly in relatively resistant materiel such as bedrock. Increased erosive power or dramatic decrease in bed resistance allows for the undercutting of the kickpoint which can initiate a headcut (Benda et al, 2005). A headcut is the point of active headward erosion and incision of the channel bed at a knickpoint (Benda et al, 2005). A headcut is also referred to as the leading edge of a gulley (Bennett, 1999). The overall effect of headcutting is to reduce bed slope through the reach (Ritter et al, 2002).

Stream incision can be a result of flooding, climatic changes, and human activities. Climatic changes can alter the flood regime which can cause changes in sediment delivery to a watershed resulting in stream incision. Human activities such as land use changes can also alter sediment delivery to a watershed resulting in stream incision.

Flooding. Floods are a natural phenomenon and changes in a flood regime can cause floodplain and channel changes over time. Different magnitude flows have varying morphological significance to the channel. Magnitude (stage or discharge) and frequency (RI) are two very important factors when determining geomorphic effectiveness (Wolman and Miller, 1960). Most rivers in flood stage transport sediment. However, the importance of the event in terms of sediment transport is dependent on the magnitude of the event (Wolman and Miller, 1960). Large magnitude events have a larger impact on channel geometry than smaller more frequent events (Wolman and Miller, 1960; Gupta, 1988). The bankfull flood is often referred to as the channel-forming discharge (Simon et al, 2007; Rosgen, 1994). The bankfull discharge or the flow that occurs on average every 1.5 years is considered to have the most morphological significance because it is the discharge at which the in-channel processes at their maximum (Simon et al, 2004; Wolman and Miller, 1960). Overbank floods can exceed the bankfull discharge extending beyond the channel margins and into adjacent floodplain areas. When overbank flooding occurs the velocity of the water decreases and sedimentation on the floodplain occurs (Ritter et al, 2002). The bankfull discharge is important for sediment transport and maintaining stable channel patterns. At the bankfull stage streams have adequate stream power to transport coarse bedload sediment and maintain channel bars (Copeland et al, 2000).

Floods that occur every 1-2 years or more can transport coarse bed sediment (Trush et al 2000). However, during relatively large magnitude floods (>20 years) geomorphic thresholds are exceeded and processes that may take long periods of time naturally are greatly accelerated, leading to drastic changes in the landscape (Gupta, 1975, 1988). Large floods are a geomorphic agent that can drastically alter the channel morphology and surrounding landforms by threshold exceedance. Threshold exceedance may occur where the strength of the bed and/or banks of a river are overcome by the force of the flood flow causing a rapid change in channel form over a short period of time (Gupta, 1983). In the Bluefields River a geomorphic threshold was exceed by the debris flow or flooding that allowed for the rapid erosion of the channel bed. The rapid erosion could be a result of climatic changes (sea level rise), human induced changes (land use history), and geologic constraints (faulting).

Climate Change. Sea level has been gradually rising over the Holocene (past 12,000 years) in Jamaica. Sea level rise over the Holocene could directly influence the Bluefields River. Sea level is the base level for the Bluefields River. A change in base level would promote a response in channel morphology to accommodate the new base level in an attempt to maintain channel slope or grade. The gradual sea level rise would have over steepened the lower reaches of the Bluefields River as a result of coastal erosion shorting channel length and/or shoreline transgression. Over steepened segments near the mouth could have triggered incision and headcut initiation in the lower Bluefields River.

Human Activities. Effects of land use changes on stream channels have been well documented in North America (e.g. Knox, 1972, 1977, 1987; Trimble, 1970) but less is known about tropical regions. In response to land use changes, streams change their geometry (bed morphology) and storage to transport the sediment with the water available (Clark and Wilcock, 2000). Changes in sediment input from land use changes can occur from mining operations (James, 2006), agricultural changes (Knox, 1977, 1987; Trimble, 1970), and urbanization (Ebisemiju, 1989). Because of the lag between land use change and channel response it is difficult to isolate changes to specific land use modifications and the end result usually involves the interaction of multiple land use changes. Geomorphic lag involves a time gap of 10 years or more between disturbance "causes" and geomorphic "effects" due to periods of threshold exceedance and downstream transport of bed sediment. In the Bluefields River land use changes during colonial settlement would have altered natural vegetation cover that may have led to changes in sediment delivery to the Bluefields River. Human modifications to the vegetation cover and landscape would lead to increased runoff and erosion rates from steep hill slopes. The increased sediment supply would have led to increased sedimentation in the valleys. This excess sediment now stored along the river and within floodplain areas could be released episodically at some later date.

Give that land use changes during colonial settlement may have increased sediment delivery to the Bluefields River and increased storage of sediment in valley areas grade control structures such as bridges would have locally influenced sediment transport. The decreased slope upstream would have promoted sedimentation above the bridges and culverts thus forming sediment traps and conditionally stable knickpoints in channel bed elevation. With the destruction of the bridges during the debris flow, headcuts would have initiated at the bridge locations and worked upstream following the flooding.

Sediment Sources

Understanding sediment loading and bank stability is important when studying sediment transport and erosion potential. Sediment is the leading cause of water quality impairment in fluvial systems (Wynn, 2006). Suspended sediments in streams can be linked to phosphorus, bacteria, heavy metals, and pesticides which negatively affect water quality (Wynn, 2006).

The sediment supply to Bluefields Bay may influence the health of the sea grass in the bay. Changes in river morphology and sediment transport can have drastic impacts on biota and the habitat created by a stream (Wynn, 2006). The Bluefields River supplies sediment to Bluefields Bay which may supply nutrients and substrate for the growth of sea grass (Williams, 1990). Sea grass is important habitat for juvenile fish within the bay. On July 28, 2009 the ministry of Agriculture and Fishers declared Bluefields Bay as a fish sanctuary.

Generally the source of sediments to a stream depends on the location in the watershed. Hillslope processes such as debris flows and landslides dominate upper watershed areas (Benda et al, 2005). In the lower reaches, stream bank erosion is the main source of sediment to a stream (Wynn, 2006). In ephemeral rivers, sediment can be released from the channel bed or colluvial storage by incision.

Bank Erosion. Sediment sources can vary from system to system but up to 80% of the sediment input can be derived from erosion of the stream banks (Simon et al, 2000; Wynn, 2006). There are many ways that stream banks can fail introducing sediment into the system. Stable stream banks can be destabilized during prolonged rainfall events by increasing soil bulk density, changes in soil pore pressure, and changes in cohesion of soil particles (Simon et al, 2000). Stream bank retreat occurs by a combination of processes including subaerial, fluvial entrainment, and mass wasting. Fluvial erosion also introduces sediments into a stream. During higher flows the force exerted on the banks is increased along the stream banks, allowing for the erosion of banks and possible undercutting. The undercutting of banks can lead to the mass wasting of the banks directly delivering sediments to the stream (Wynn, 2006). Threshold exceedance can also deliver sediment directly to the stream channel. Threshold exceedance occurs when the force of soil cohesion is exceeded by gravity and banks fail by collapse (Simon and Rinaldi, 2000).

Debris Flows. A debris flow is the mobilization and flow of soil and rock down slope (Jibson, 1989; Benda et al, 2005). Debris flows can range from highly viscous flows and mudflows to flows that resemble typical fluvial transport, depending on the lithology and degree of weathering of the drainage basin and source materials (Ritter et al, 2002). Gullies and pre-existing channels act as a conduit for debris follows channeling the debris down slope (Benda et al, 2005). The high viscosity of a debris flow influences deposits that are formed during the flow. The dense viscous flows of sediment only allow for the deposition of the largest clasts during the flow (Ritter et al, 2002). The high viscosity of the flow allows for the transportation of large clasts as large as bedrock boulders and blocks (Ritter et al, 2002). Debris flow deposits are poorly sorted with boulders and cobbles embedded in a fine-grained sediment matrix (Ritter et al, 2002). Debris flows commonly occur in "colluvial channels" as defined by Montgomery and Buffington (1997). A colluvial channel is a stream channel that has ephemeral fluvial transport (Montgomery and Buffington, 1997). The majority of the sediments introduced to the colluvial channel are a result of hill slope processes. Hill slope processes include mass wasting, debris flows, landslides, soil creep and surface erosion (Knighton, 1998). Because fluvial transport is ephemeral colluvium can be stored in the upper watershed areas until it is released episodic by a debris flow (Benda et al, 2005).

Stream Recovery

A system that is severely degraded as a result of a large magnitude event takes time to recover and there are several steps in stream recovery. Recovering streams alter their sediment transport, floodplain formation, and geometry to their current regime (Simon and Rinaldi, 2000). Studying the floodplain formation, bank stability, and sediment transport of a stream can determine the current state of the stream and what implications that may have for the future (Simon and Rinaldi, 2000).

Simon and Rinaldi (2000) present a six stage channel recovery model for disturbed alluvial channels (Figure 3). The six stage model describes the channel before modifications, immediately after modification, and recovery phases. The first step in the stream recovery model is a perturbation to the system (either natural or human induced) that increases channel slope or shear stress on the bed. If the sediment supply cannot match the stream power available for transport, the stream will begin to incise (Lane, 1955). Channel incision creates steeper and unstable banks that allow the channel to widen laterally and allow the recovery of active floodplains. Bank erosion can produce sediment "slugs" for deposition downstream in recovering channels. Climatic changes such as increased rainfall or drought can lead to decreased sediment delivery to the stream starting the incision phase. Climatic changes can also affect the vegetation communities that will ultimately influence the amount of sediment derived from the hill slopes and transported to the stream channel (Knighton, 1998).

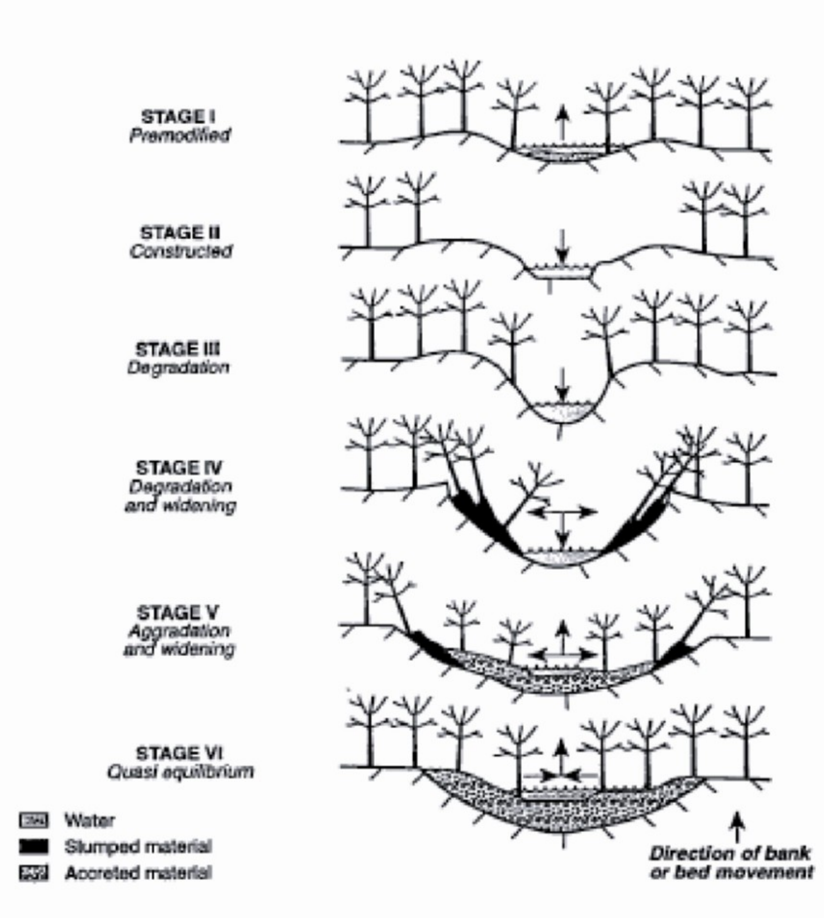


Figure 3. Stream Recovery Model from Simon and Rinaldi (2000).

CHAPTER 3

STUDY AREA

Location of the Bluefields River

The Bluefields River is located on the south coast of Jamaica in the parish of Westmoreland (Figures 1 & 2). The Bluefields River drains 4.9 km^2 of limestone uplands, heads in coastal mountains at an elevation of 760 masl, and flows 1.2 km to the sea (Figure 2). The Water Resources Authority (WRA) of Jamaica website states the Bluefields River originates from a limestone aquifer. The connectivity of the underground karst aquifers is unknown. The population of the surrounding communities of the Bluefields River was 3,133 counted by the 2001 census completed by the Jamaican government. There are several small communities within the Bluefields River watershed. The larger communities are Bluefields and River Top (Figure 2).

Geology

Jamaica is a mountainous island approximately 225 km long and 97 km wide and is the third largest island of the Greater Antilles (Figure 4) (Mitchell, 2004). The Cayman Trench separates Jamaica from Cuba and the rest of the Greater Antilles (Ahmad, 1993). A series of uplifting and faulting in the Eocene to Miocene era has led to both volcanic and sedimentary rock formations (Mitchell, 2004). In western Jamaica the surficial geology is dominated by post-Eocene carbonates. Locally the carbonates are divided in the Yellow (middle Eocene) and White (middle Eocene to late Miocene) Limestone

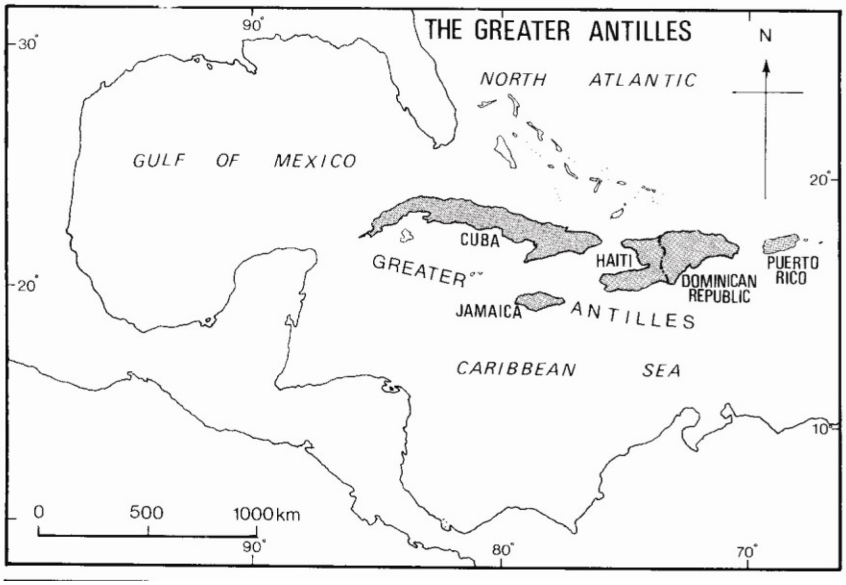


Figure 4. Locational Map of Jamaica. Jamaica is the third largest and most southern island of the Greater Antilles. Figure modified from Ahmad, 1993.

groups (Mitchell, 2004). The White Limestone group represents 60-70% of the islands surficial geology (Mitchell, 2004). The Bonny Gate formation, part of the Montpelier Group is extensively mined by the construction industry as an aggregate (Mitchell, 2004). The Bony Gate formation is the primary host rock for the freshwater aquifer on the island (Mitchell, 2004). The geology within the Bluefields watershed is composed of the Bonny Gate formation of the White Limestone group (Figure 5). Western Jamaica is dominated by extensive dissected karst limestone plateau (Garret et al., 2004).

There are several major faults in Bluefields Bay (Figure 6). Two normal faults run parallel to Bluefields Bay (Mitchell, 2004). The faults were active in Eocene to Miocene (Mitchell, 2004**)**. The Montpelier-Newmarket fault is the major fault in southwest Jamaica but is not within the study area boundaries. There are several faults that control valley orientation the Bluefields Bay watershed (Figure 5). The faults identified by the geologic map of Jamaica are orientated north-west to south-east direction (Figure 5).

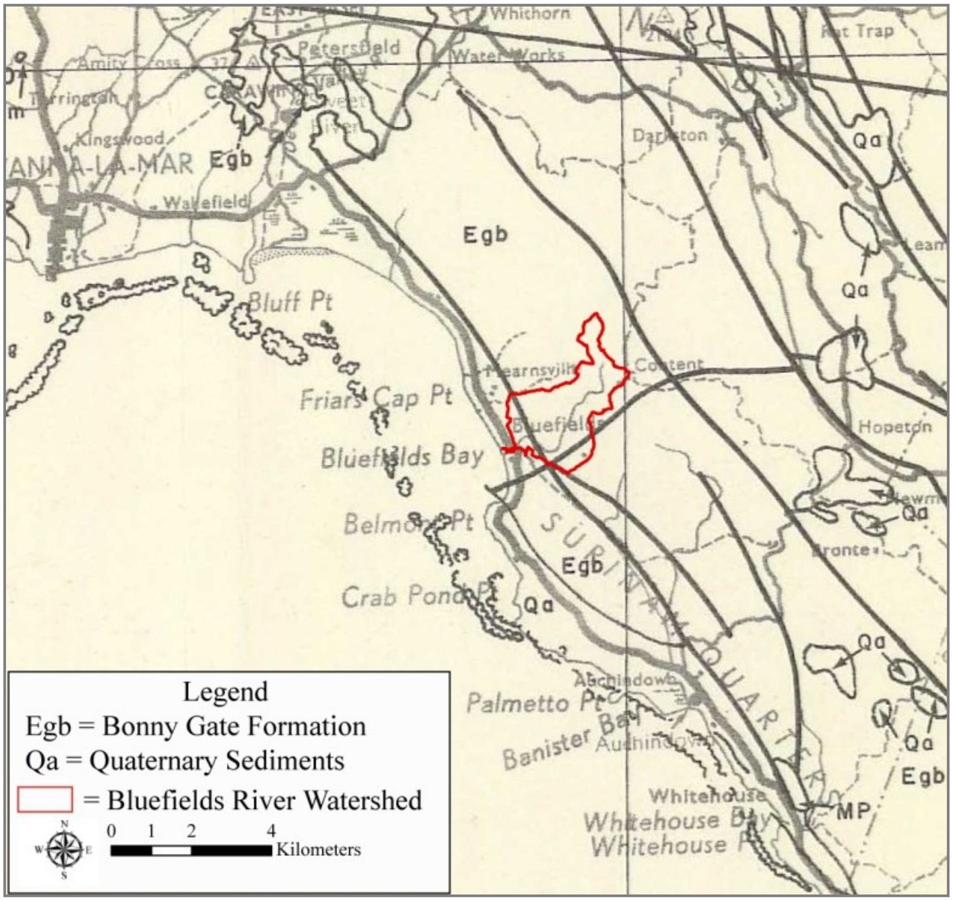


Figure 5. Geologic Map of the Bluefields River.

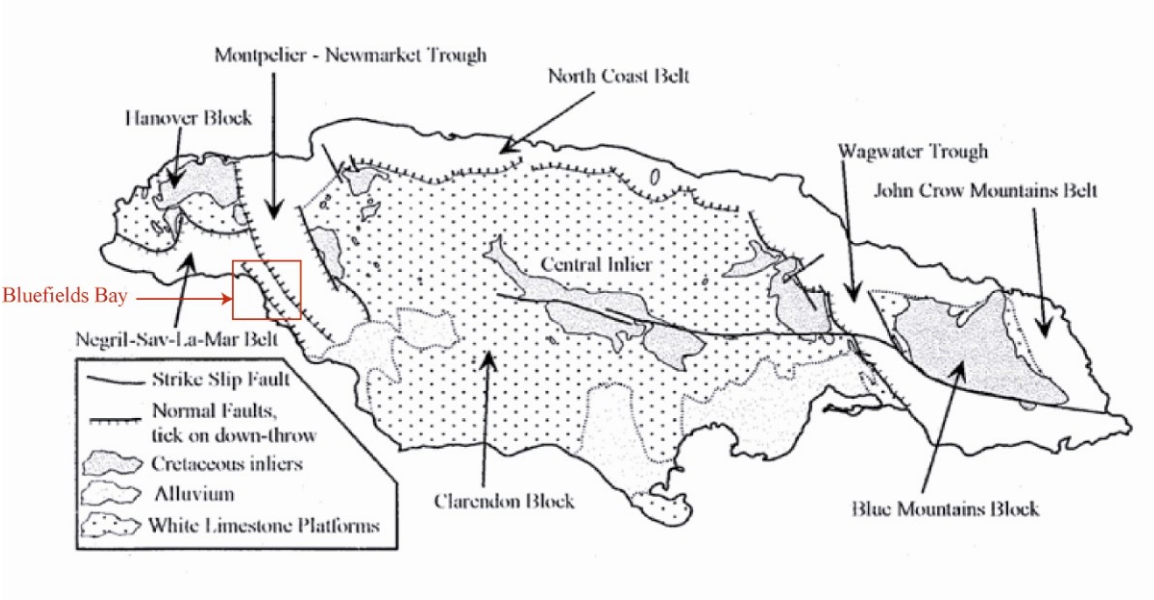


Figure 6. Major Faults in Jamaica. Figure modified from Garrett et al, 2004.

Climate Change

Throughout the Holocene (past 12,000 years) sea level has been rising in the Caribbean. Cores extracted from wetlands in Jamaica were analyzed with radio carbon dating techniques to reconstruct the Holocene sea level rise in Jamaica. The sea level curves created for Negril and Black River (Bluefields River is located between Negril and Black River) shows a sea level rise of about 13 meters over the Holocene (Figure 7) (Digerfeldt and Hendry, 1987).

Sea level rise in Jamaica was episodic throughout the Holocene. At the start of the Holocene sea level was about 12 m below the current mean sea level (Digerfeldt and Hendry, 1987). There was a rapid rise in sea level until about 5,000 years before present. About 3,000 years before present sea level was moderate with the mean sea level one meter lower than the current mean sea level. Sea level rise was gradual 2,000 years before present with the mean sea level only a half meter lower than current mean sea level. Oxygen isotope records indicate the Caribbean sea region underwent a gradual reduction in rainfall, relative to evaporation, over the past 900 years (Clark and Wilcock, 2000).

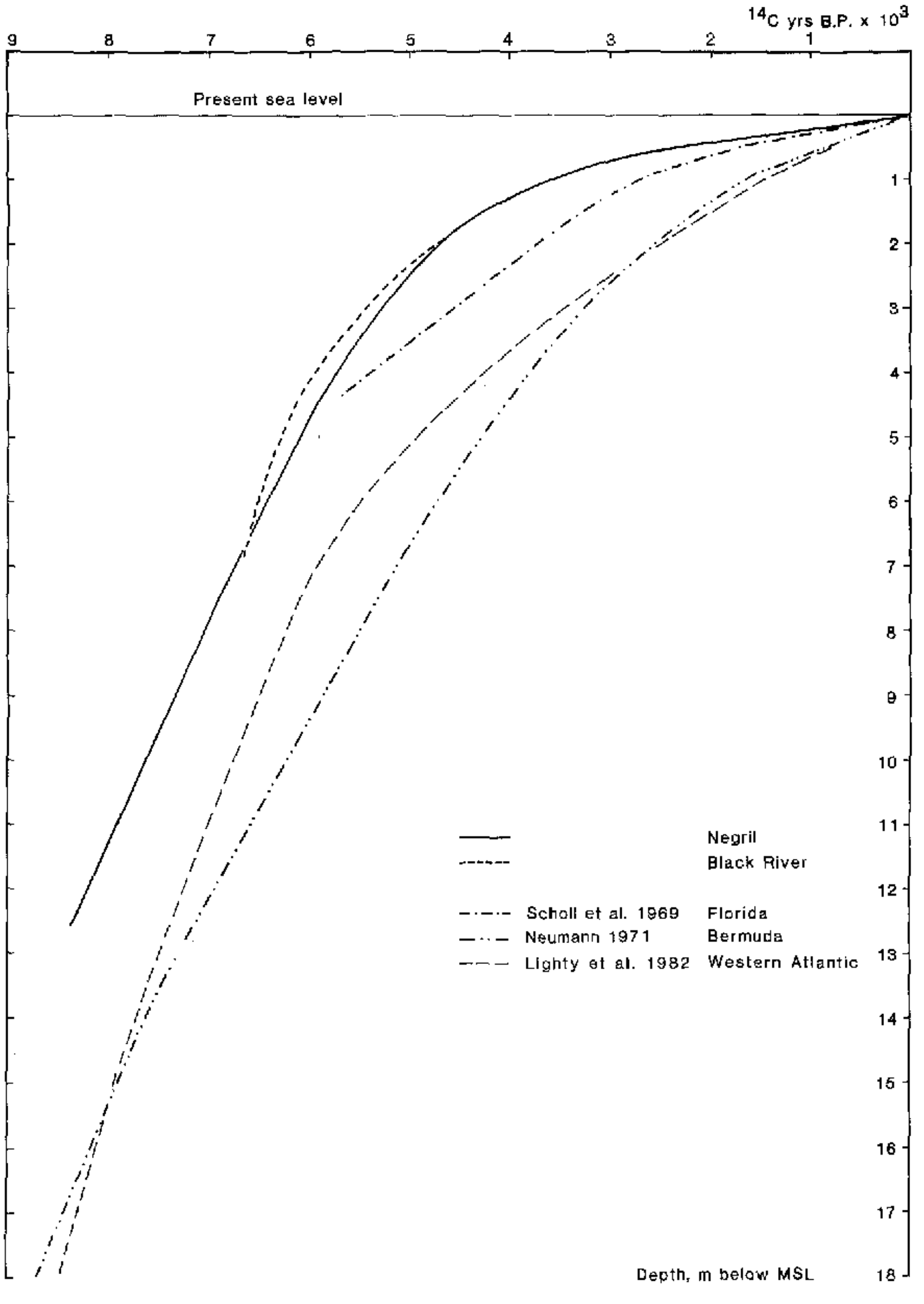


Figure 7. Holocene Seal Level Rise in Jamaica. Sea level rise curves in the Holocene for Negril and Black River, Jamaica. The curves for Jamaica are compared with previously published sea level curves for other Caribbean locations. Modified from Digerfeldt and Hendry 1987.

Present-Day Climate

Jamaica has a humid maritime climate influenced by local oragraphic effects, tropical depressions, and hurricanes (Gupta, 1988). The average temperature is Jamaica is 28°C (Water Resources Authority). Average rainfall in Jamaica is 1980 mm but varies greatly due to orographic lifting. The heaviest rainfall is concentrated in eastern Jamaica in the Blue Mountains. The rainfall is seasonal with the wet season from June through September and the highest rainfall occurring May-June and August- October (Figure 8).

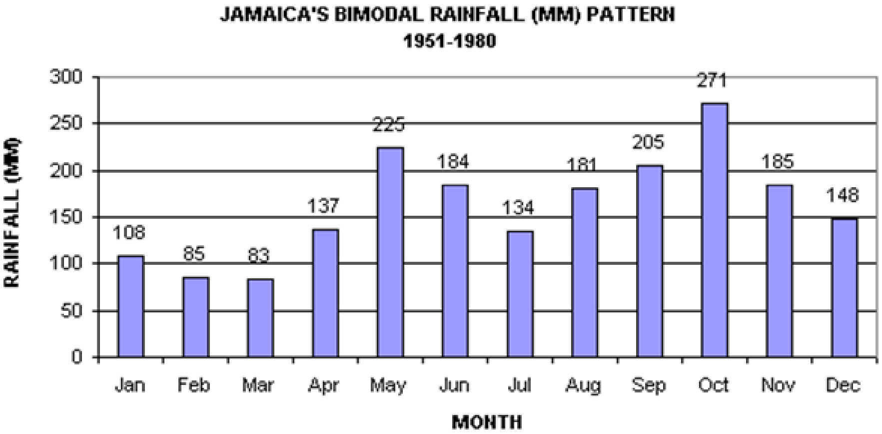


Figure 8. Average Monthly Rainfall. Average monthly rainfall in Jamaica (Jamaica Water Resources Authority Website).

Hydrology. Jamaica is divided into eight hydrological basins. The Bluefields River is located in the Cabarita Basin (VI) in southwestern Jamaica (Figure 9). The Water Resources Authority (WRA) of Jamaica has been recording daily discharge measurement since the 1970's for most of the major rives within the Cabarita basin. This data is available from the WRA on the online WRAMIS hydrologic database. Flow frequency for the Bluefields River was determined using data collected from the WRA.

Annual Discharge Records. To calculate flow frequency for Bluefields River data all years of record (1970-2008) was obtained from the WRAMIS online database.

The gauge on the Bluefields River is monitored two times per day by a local resident. For each year, a single maximum discharge record was used to determine the relationship between mean high water and channel morphology. However, the twice daily recording of river stage method of monitoring may miss flood peaks that occur overnight or in-between site visits. The minimum annual flow, median flow, mean flow, and maximum flow for the period of record at the Bluefields River gauge are listed in Table 1.

Figure 9. Hydrologic Basins of Jamaica modified from the Water Resources Authority of Jamaica.

Table 1. Range of flows (in cubic meters/second) for the Bluefields River.

Range of Flows	Discharge (m^3/s)	Depth at Gauge (m)
Minimum Flow	0.02	0.04
Median Flow	0.31	0.10
Mean Flow	0.34	0.11
Maximum Flow	1.81	0.22

June 12, 1979

The Bluefields River generally experiences similar annual rainfall patterns as the rest of the island. However, on June 12th, 1979 a severe tropical depression stalled over western Jamaica. Between 4:00 pm and 12:00 am June 12th, 31.2 cm of rain fell across western Jamaica. The total rainfall from June 10th to June 25th was 86 cm (Porter, 1981). The torrential rains on already saturated soils lead to catastrophic flooding, standing water in karst depressions, expansion of gulley systems, new sediment deltas, and floodplain deposition throughout western Jamaica (Jones, 1981) (Figure 10). Reports from June 12, 1979 indicate that valley areas and karst depressions collected water and formed temporary lakes in upper watershed areas.

Torrential rainfall is not uncommon in western Jamaica. The maximum 24 hr rainfall event on record is 44.7 cm in 1951 (Donaldson, 1981). The 24 hr maximum rainfall on June 12th 1971 was 31.9 cm. Although more rain fell in 24 hours in 1959 the torrential rains of did not cause severe flooding. In the days proceeding June 12th, 1979, western Jamaica had several moderate to heavy rainfall events (Donaldson, 1981). Therefore, antecedent conditions were wet and soil moisture levels were already high prior to the storm. Jones (1981) documented the gulling and debris fan formation along the entire southwestern coast following the 1979 flood. The WRA of Jamaica intensively studied the ponding of water in the New Market basin but did not study the flooding of the Bluefields River.

Soils

The Bluefields River watershed is composed of four different soil series: the Bonny Gate, Carron Hall, Chudleigh, and Union Hill. The Chudleigh and Union Hill

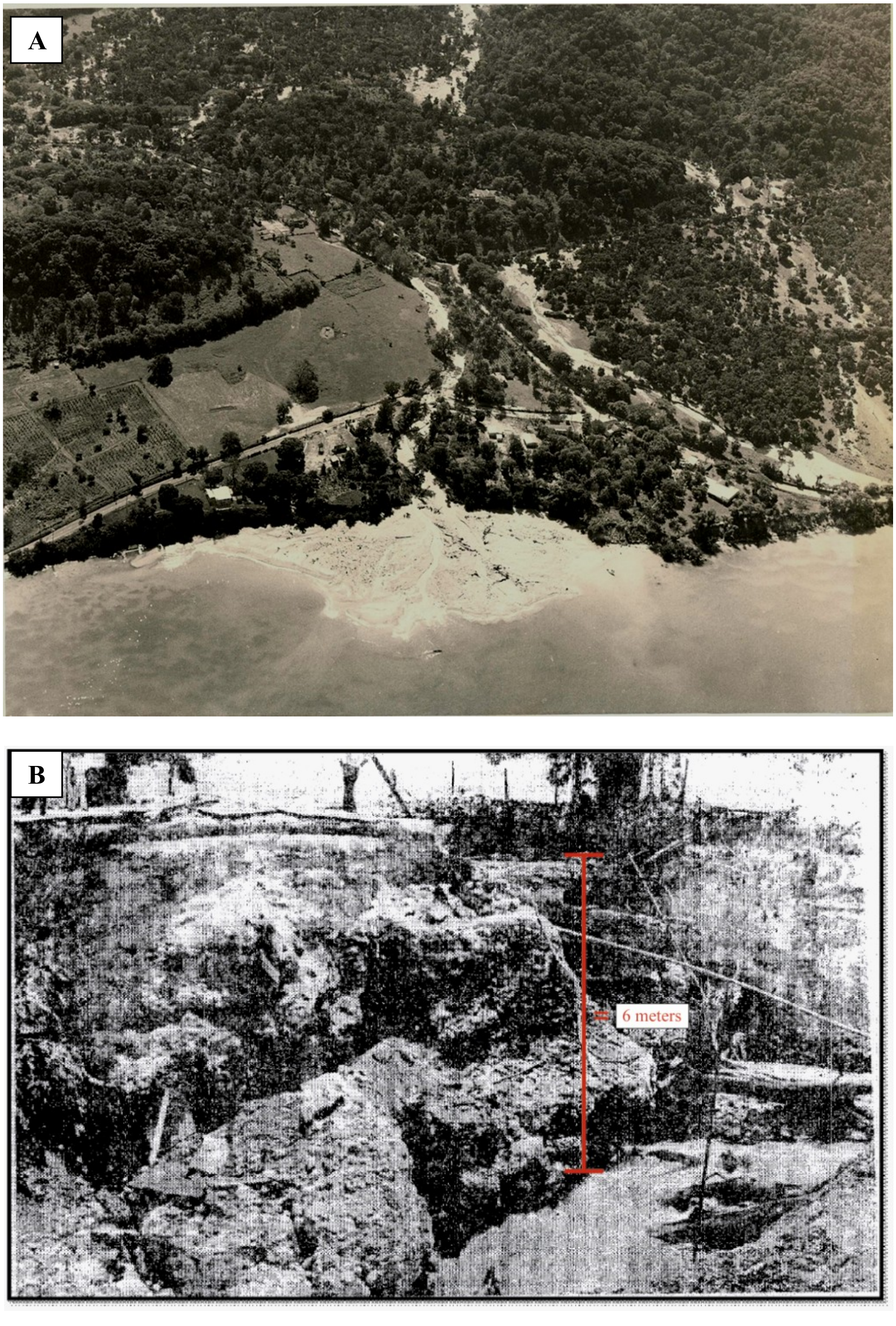


Figure 10. Flood Effects. The debris fan deposited at the mouth of the Bluefields River on 12, 1979 (A) and incision within 7 days following the debris flow (B) (Jones, 1981.)

formations are only found in upper watershed and are intensely weathered clay soils (Figure 11). The Bluefields River watershed generally contains two different soil series, with on the valley floor (Bonny Gate) and the other occupying valley side wall or hillslope positions (Carron Hall) (Figure 11). The Bonny Gate series is a stony loam consisting of large bedrock clasts and residuum (Jamaica Ministry of Agriculture, 1998). Over long periods of erosion or after mass failures, the Bonny Gate soil materials can release large bedrock blocks and cobbles to the Bluefields River (Figure 11). The Carron Hall series is old weathered colluvium that overlies residuum and bedrock (Ministry of Agriculture, 1998). These soils represent fine-grained depositional areas on the valley floor and supply silt and clay materials to the river when eroded. The infiltration capacities of the soils of the Bluefields River watershed are relatively low (Jamaica Ministry of Agriculture, 1998). Intense rainfall on low infiltration capacity soils leads to overland flow and standing water in depressions. The low infiltration combined with ponded water increases the potential for flooding.

Settlement History of Bluefield Bay Jamaica

Human impacts on channel morphology in the Bluefields River can be divided into three distinct time periods (Figure 12). The first time period (prior to European settlement) was characterized by large tracts of undisturbed forest and small areas of agricultural production by Taíno natives. The second time period was characterized by British settlement and land clearing. The third time period is post European settlement dominated by subsistence farming, cattle grazing, and reforestation.

Pre-European Settlement. The archaeological record for Jamaica is poor, due to lack of research, but there is evidence that the island was heavily inhabited by aboriginal

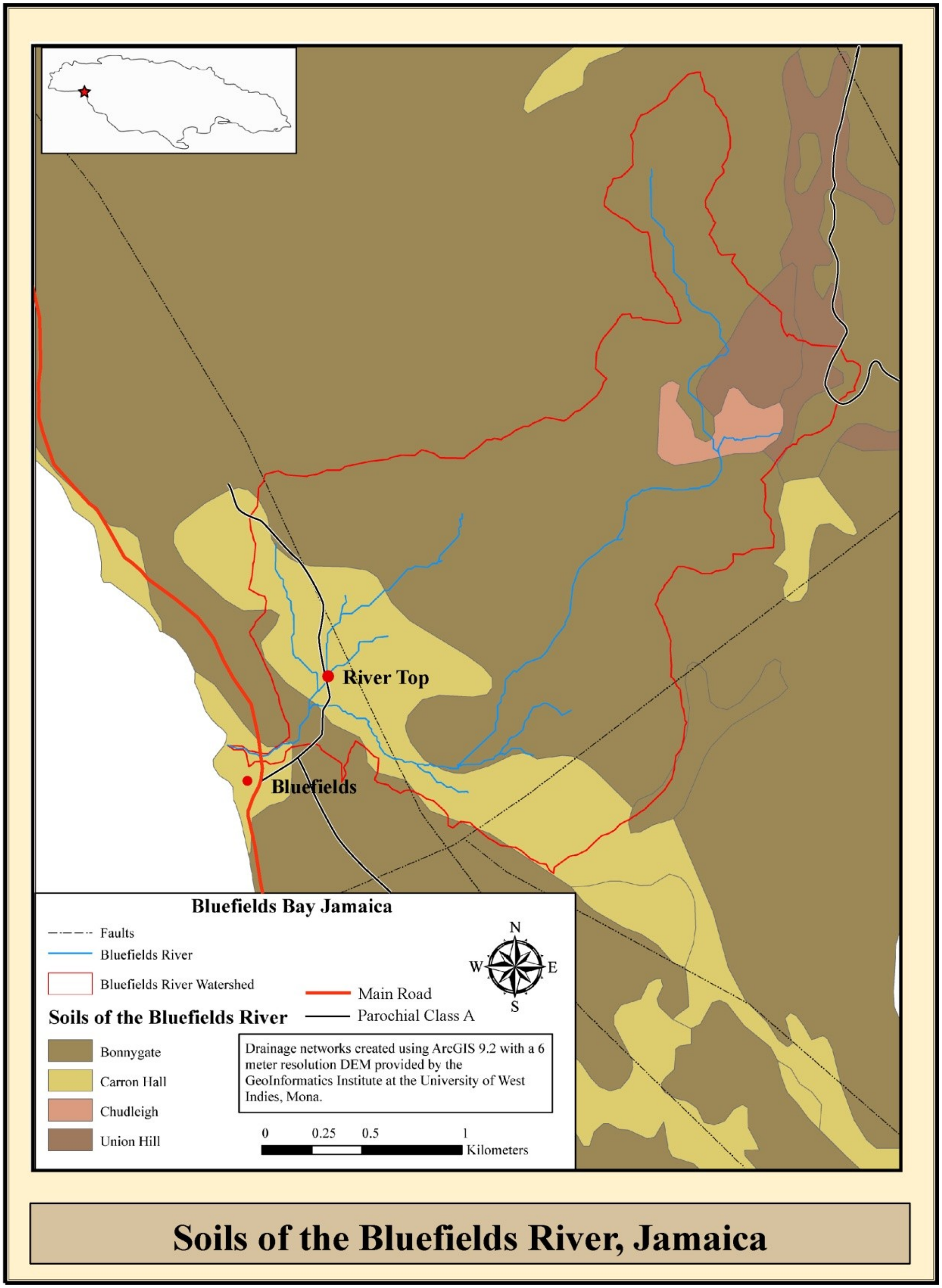


Figure 11. Soils Map of the Bluefields River. Notice the fault location and the resulting soil series relationships.

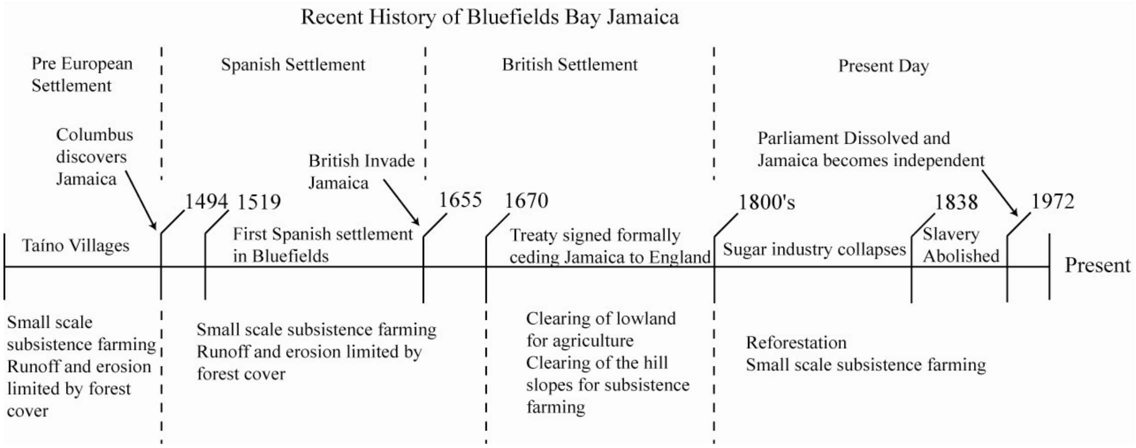


Figure 12. Recent History of Bluefields Bay, Jamaica.

people. There were large aboriginal villages along the coast, possibly consisting of thousands of people. The Taíno (aboriginal people) were heavily adapted to the sea, but they also practiced substantial agriculture known as Conuco cultivation. Conuco cultivation involves creating large mounds of soil to grow crops such as sweet potatoes. The Taíno also grew cotton, tobacco, and other fruit crops. Recent archeological digs have found pottery and artifacts from the Taíno people in the alluvial plains of the Bluefields River. The Taíno most likely limited agricultural practices to the easily farmed lowlands therefore having little effect on the sediment yield to the Bluefields River (Clark and Wilcock, 2000). During the pre-European settlement of Bluefields the runoff was limited by the dense vegetation. Sediment supply to the Bluefields River was a result of natural soil erosion, minor field disturbances, and climtate-geology controlled landslides or debris flows that are common in the steep hill slopes in Jamaica (Gupta, 1988).

Spanish Settlement. Columbus discovered Jamaica in 1494, but the island was not settled by the Spanish until 1509 (Figure 12). The first Spanish settlement was on the north coast, west of Ocho Rios. The Spanish settlement near Bluefields occurred in 1519.

The exact location of the settlement is not known but it was believed to be near the existing Taíno village along the lower Bluefields River. The Spanish settled near Taíno villages because they enslaved the Taíno. The Spanish settlement at Bluefields is an indication that the Taíno village in Bluefields was large. The Spanish likely had very little impact on the landscape. There is no evidence of large scale land clearing for agriculture during the Spanish settlement.

British Settlement. The British invaded Jamaica in 1655, forcing the Spanish to retreat to Cuba (Figure 12). A guerilla war followed until about 1660 when a treaty was signed formally ceding Jamaica to England in 1670. A fort was built by the British in Bluefields around 1656 for a defense structure. Land around the fort was divided into large lots for agricultural purposes. Because of the construction of the fort some of the earliest plantations on the island were probably established in Bluefields. Oristano great house dates to 1720 and there is also a nearby tavern that dates to 1750. Although most of the island was being cleared for sugar cane there is little evidence of the sugar monoculture in Bluefields (Figure 13). The estates grew a wide variety of crops including timber (logwood and pimento) pasture for cattle, ackee, coconut, guinea grass, and para grass (Figure 13). The British also used Bluefields Bay as a safe harbor for their ships and to replenish their ships with drinking water. The harbor at Bluefields is well documented in hand drawn maps. The steep hillsides were also cleared for small scale subsistence farming. This land clearing is recorded in historical maps of Bluefields Bay (Figure 13). Land clearing during the second time period (British settlement) around the 1700's would have dramatically increased water and sediment supply to the Bluefields River. The lack of permanent vegetation and increased runoff would have led to increased soil erosion (Clark and Wilcock, 2000). The historical maps can be used to

Figure 13. Historic Map of Bluefields Bay. Late 1700's. Map courtesy of National Library of Jamaica, author and exact date unknown.

document land use changes during the 1700's (Figure 14).

Present Day Bluefields. The third period is the modern period characterized by the conversion of cropland to pasture, forest, and small scale subsistence practices. The conversion of cropland to pasture and forest would decrease the sediment yield to the Bluefields River. Although the sugar monoculture did not overtake Bluefields, the area was cultivated in the 18th century. After the collapse of the sugar industry in the early 19th century, and Emancipation of slavery in 1838, the area changed dramatically. Some of the estates such as Belmont and Beston Springs were subdivided and sold to former slaves. Other estates such as Bluefields and Shafston were not subdivided but crops were not cultivated on the cleared land. This would have allowed for the re-growth of forests. The current land use is composed of small scale subsistence and grazing agriculture (Figure 15). The land cover data was obtained from the GeoInformatics Institute at the University of West Indies at Mona. Within the Bluefields River watershed the land cover is mapped as Disturbed Broadleaf Forest and Fields, Fields Tall Open Dry, and Fields and Disturbed Broadleaf Forest (Figure 15). There is no significant urbanization of the watershed. The primary infrastructure is comprised of small single family housing and small scale subsistence farming.

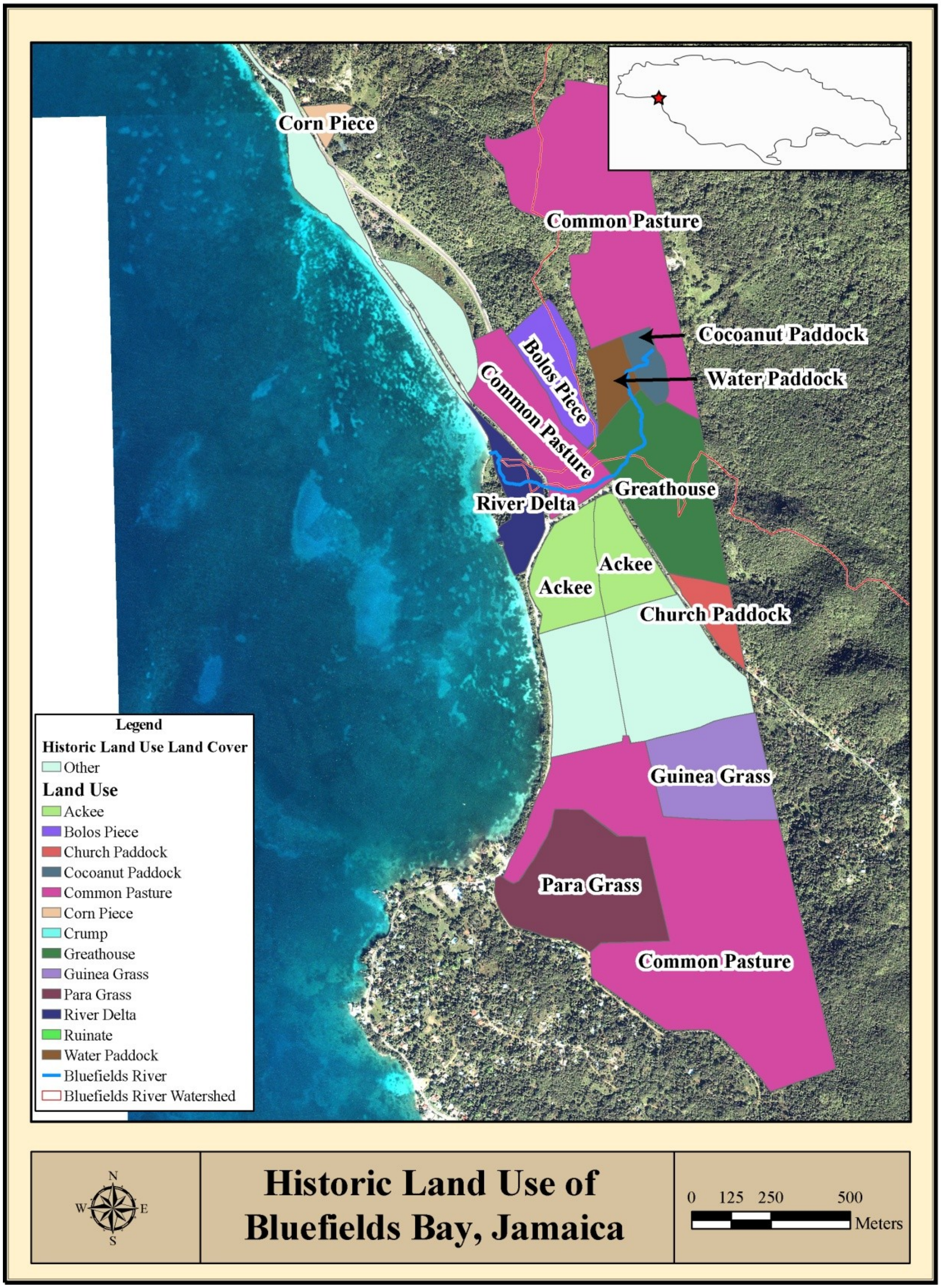


Figure 14. Historic Land Use of Bluefields Bay in the Late 1700's. The extent of the land use information is limited to the extent of the historical maps.

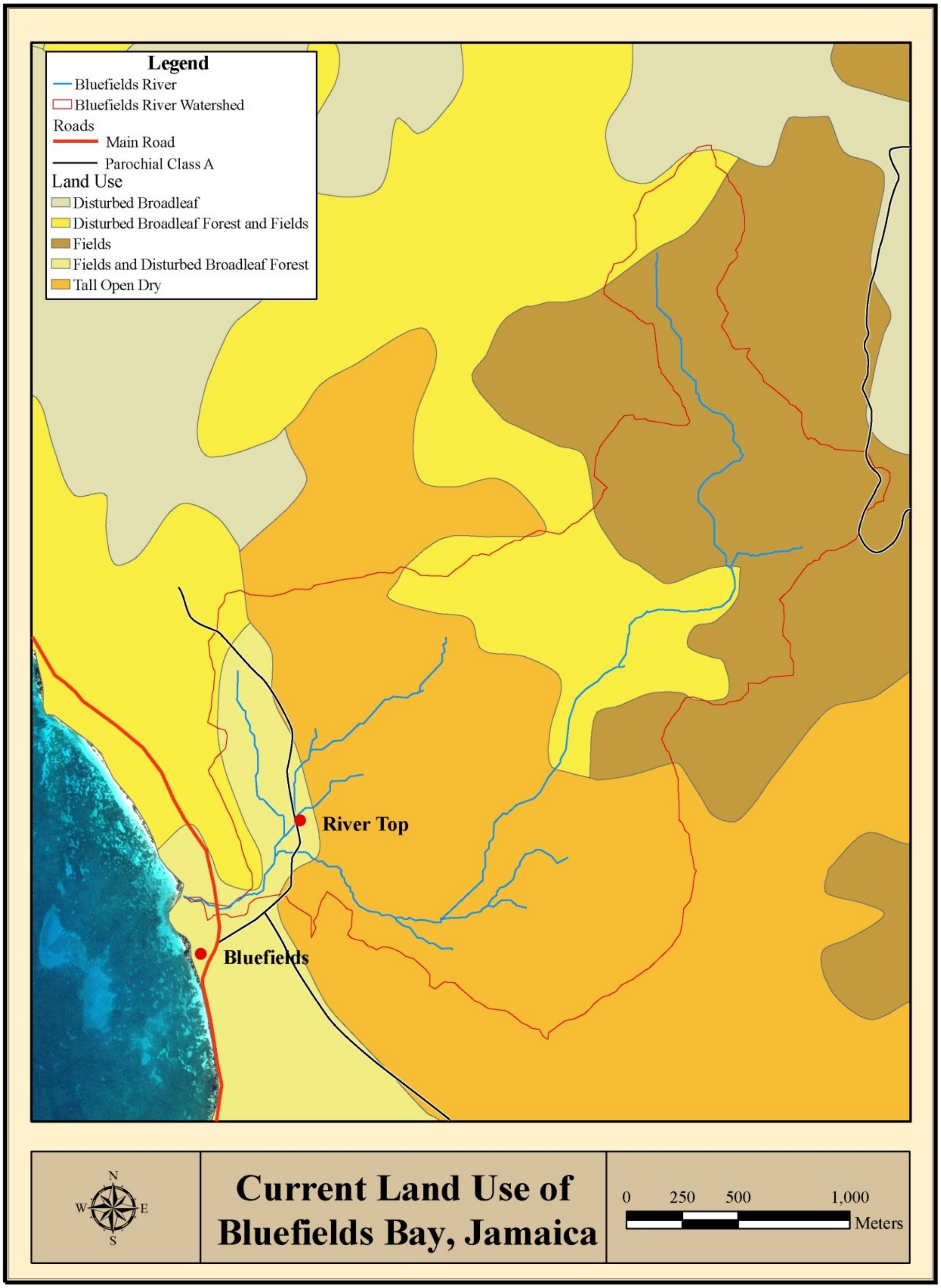


Figure 15. Current Land Use of Bluefields Bay (Forestry Department of Jamaica, 1998).

CHAPTER 4

METHODS

This study documents the current state of the Bluefields River and how it was affected by episodic events (flooding), sea level changes, climatic patterns, and intense historical land use. To investigate these relationships, the Bluefields River was surveyed using a total station to collect longitudinal and cross sectional data. Geomorphic assessment was used to determine channel bed profiles and hydraulics. The debris fan created during the 1979 flood is mapped to determine volume and extent. The data obtained from surveying will be used to determine sediment delivery to the debris fan during the 1979 flooding event.

Stream Surveying

The relationships between climate change, tectonics, and human modifications to the landscape can be investigated using a variety of methods. A longitudinal profile can be used to determine reaches that are actively eroding and unstable. The evolution of the longitudinal profile can provide insight to past conditions (Hack, 1957). Cross sections can provide detailed documentation of channel geometry and bank height elevations. The bank height relative to the active channel bed can be used as an indicator of stream morphology and recovery. Generally narrow and deep channels are typical of disturbed systems while wide and shallow channels are typical of natural systems.

Longitudinal Profile. The Bluefields River was surveyed using a Topcon total station from the River Top Bridge to the Ocean (Figure 16). River Top Bridge was chosen as a starting point because the bridge was unaffected by the 1979 flood. A

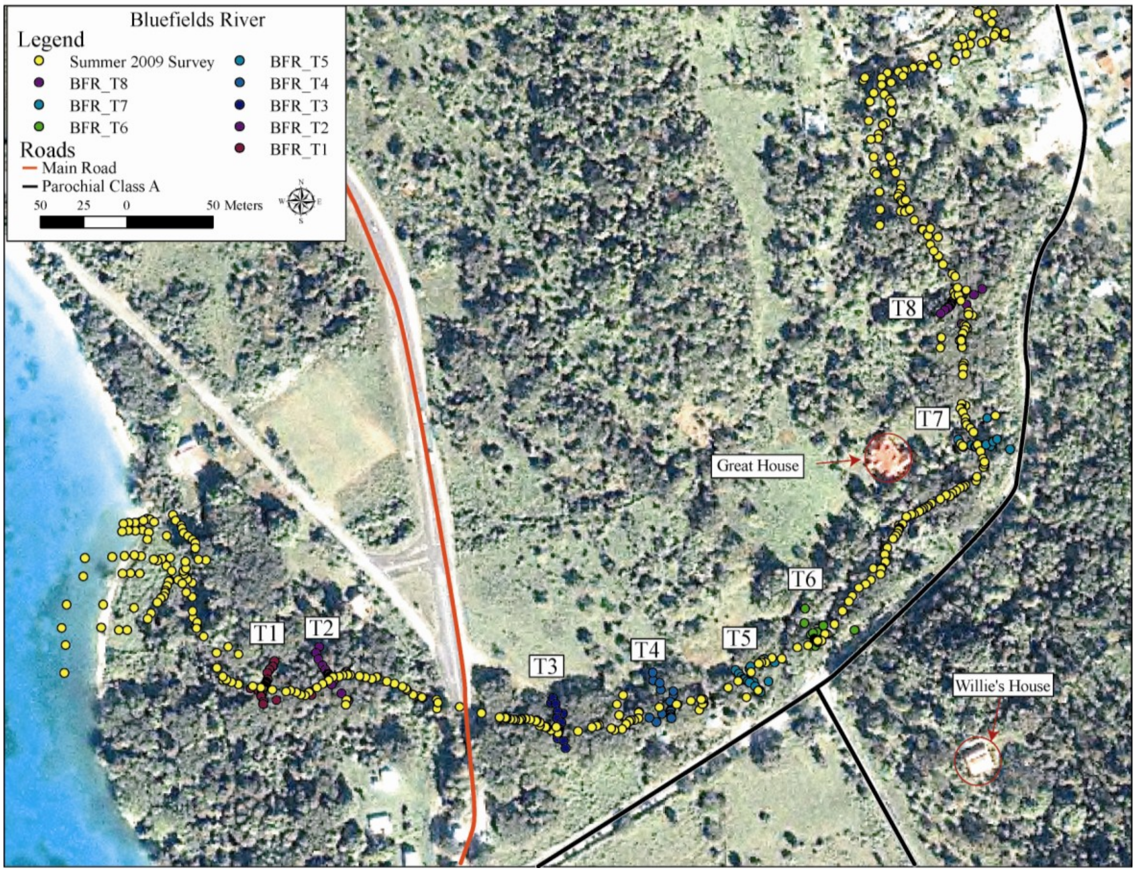


Figure 16. Longitudinal and Cross Section Surveys of the Bluefields River.

longitudinal survey is a survey of the thalweg or deepest part of the channel. The elevation of the thalweg is plotted over downstream distance (longitudinal profile) to obtain slope for specific reaches or an average slope of the stream (Rosgen, 1996). The longitudinal profile is used to locate knickpoints, slope, trends, and reaches that are actively eroding.

Cross Sections. Cross sections were also surveyed using a Topcon total station at typical cross sections along the main stem of the Bluefields River. Eight cross sections were surveyed from where the Bluefields River reaches the ocean to the confluence of the Goat Gulley Tributary (Appendix A and B). Bank height and channel width were also measured every 20 meters of the entire study reach. Pictures were also taken periodically along the main stem of the Bluefields River to create a photo log of the Bluefields River (Appendix C). The cross-sections were used to determine cross sectional area of the Bluefields River. The surveys were post processed after return from the field using TDS Foresight® software. The surveys were georeferenced using handheld Trimble Geo XH GPS units (Appendix D). After post processing the georeferenced surveys were converted to shapefiles for further geospatial analysis in ArcGIS software. The following geomorphic variables were used to describe present-day (2009) channel and incised valley dimensions:

Channel Width. The width of the active channel was measured at each cross section in the Bluefields River. The active channel occurs where the stream bed is actively eroding or transporting sediment. The channel width was measured as the wetted width perpendicular to flow.

Low Bank Height. The low bank height was measured using a stadia rod, folding rule, or total station. The low bank height is measured at the top of the lowest stream bank feature formed since the 1979 flood and represents the stage of the lowest bankfull indicator. The low bank feature was not observed at all cross sections such as where steeper valley walls or bedrock obstacles confined the channel or steeper channel gradients did not allow floodplain or bar deposition.

Floodplain Height. The present floodplain height was measured using a stadia rod or total station survey. This measurement indicated the stage of the new valley floor after the incision event. The elevation of the floodplain was higher than that of the bankfull channel and thus represents the maximum bank height of the present channel, possibly a low terrace. Differences between low bank and floodplain heights reflect the range of channel bank stages present along the channel.

Valley Width. The horizontal distance between the high banks is referred to as the valley width for this study. High bank elevations were measured on both the right and left sides of valley on the edge of the valley slope walls. These points probable occur on the pre-1979 floodplain, however they were stranded vertically by incision. The valley width was measured using a total station survey.

Valley Depth. The valley depth was also measured using a total station survey. The valley depth was measured as the vertical distance from the top of the high bank (valley bank) to the present thalweg. This is an approximate indicator of maximum incision depth since 1979. If desired, the average depth of incision could be approximated by the difference between valley height and floodplain height.

Two ratios were used to study the morphology of the incised valley. The valley entrenchment ratio is calculated by dividing valley width by valley depth. Smaller values indicate a relative narrow valley and steeper valley walls. The channel incision ratio is calculated by dividing the valley depth by the floodplain height. Larger values indicate relatively deep incision by the channel in 1979.

Sediment Sampling

Soil sampling was conducted on various alluvial surfaces to date and characterize landforms. The alluvial stratigraphy, terrace profiles, and the textural and geochemical analysis of the sediment were used to evaluate the impacts of historical sedimentation on the Bluefields River. A permit from the United States Department of Agriculture (USDA) was required to bring any type of soil into the USA. A Permit to Move Live Plant Pests, Noxious Weeds, and Soil (PPQ 526) was obtained from the USDA to import sediment samples from Jamaica to the USA. Sediment samples were taken at six sites along the main stem of the Bluefields River (Appendix E). Near Shore marine sediment samples were taken from three sites in Bluefields Bay. Marine samples were collected by swimming offshore and collecting the samples by hand from the ocean floor. The marine samples were collected offshore from Sunset Cottages, the Fishing Beach at the Bluefields Peoples Community Association (BPCA), and offshore from the Bluefields River debris fan.

Descriptions of the alluvial deposits included color, structure, organic debris, and anthropogenic deposits if possible. Sediment samples were prepped for geochemical analysis by sieving to isolate specific size classes. Samples were sieved to <250 µm, 250 µm-1 mm, and 1-2 mm fractions. All sediment >2 mm fractions were noted for composition and then disposed of in Jamaica to reduce weight of samples shipped to the USA. The geochemical analysis of the soils was used to determine mineralogy and heavy metal concentrations. Soil samples were analyzed with a handheld X-ray Fluorescence (XRF) analyzer in the laboratory to determine metal concentrations of the <250 µm fraction (Appendix F). The results from the sediment sampling will be presented in a future study with Dr. Pavlowsky.

Determining Pre-flooding Channel Geometry

To calculate the amount of sediment removed from the Bluefields River by incision following the 1979 debris flow and flooding, cross sections were used as a typical channel profiles for each reach. The channel geometry of the Bluefields River above the River Top bridge (obtained by measuring the active channel width and bank heights) was used as a reference reach of the pre-flooding channel geometry (Figure 17). After the surveys were rectified they were exported to Hydraflow® to determine cross


Figure 17. Upstream from River Top Bridge.

sectional area of the total channel (Figure 18). The cross sectional area of the total channel was calculated at each surveyed cross section. The calculated cross sectional area of the reference reach was assumed to be constant throughout the entire perennial reach of the Bluefields River because the lack of information to prove otherwise. The survey cross sections were then used as a typical channel profile for reaches along the Bluefields River. The crosses sectional areas of the surveyed cross sections were then multiplied by the distance of the representative reach to obtain a distance-weighted volume estimate. The cross sectional area and volume of the pre-flooding channel geometry was then subtracted from the volume estimates to give a total eroded sediment estimate (Figure 18).

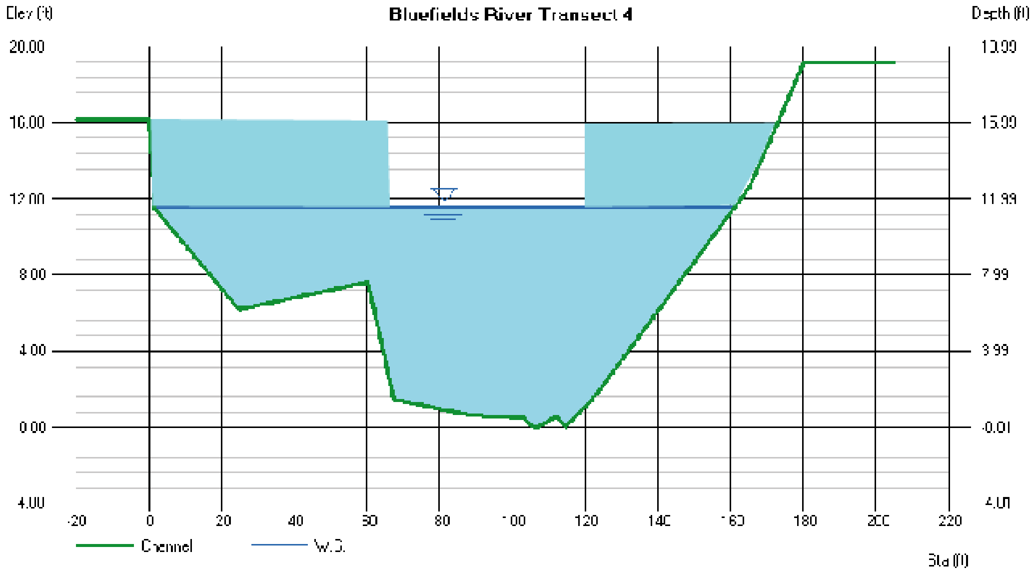


Figure 18. Determining Pre-flooding Channel Geometry. The blue shaded areas represent sediment that was removed from incision immediately following the debris flow of 1979. The pre-flooding channel geometry was estimated using areas upstream of the River Top Bridge that were unaffected by the 1979 floods.

Calculating Debris Fan Volume

The thickness of the fan deposit was determined from a contour map based on a total station survey in 2009 (Figure 19). The fan survey included the fan head, mid area, and toe. The seaward limit of the fan survey was along the outside edge of boulders believed to be originally deposited by the 1979 flood. Beyond the boulder line the bottom became smooth with mixed hard and soft bottom. At the time of the field survey, the boulder edge was at a depth of 1 to 1.5 meters below sea level. The surface area of the 1979 and 2006 debris fan was determined from aerial photography. The 1979 debris fan was separated into three sections (head, mid, toe) with graduated thickness to more accurately estimate its volume based on natural variations in the 2009 field map (Figure 20). Volume determinations were made based on the multiplication of the fan surface area by the average thickness of the deposit estimated at one half the maximum depth of accumulation for the respective fan area.

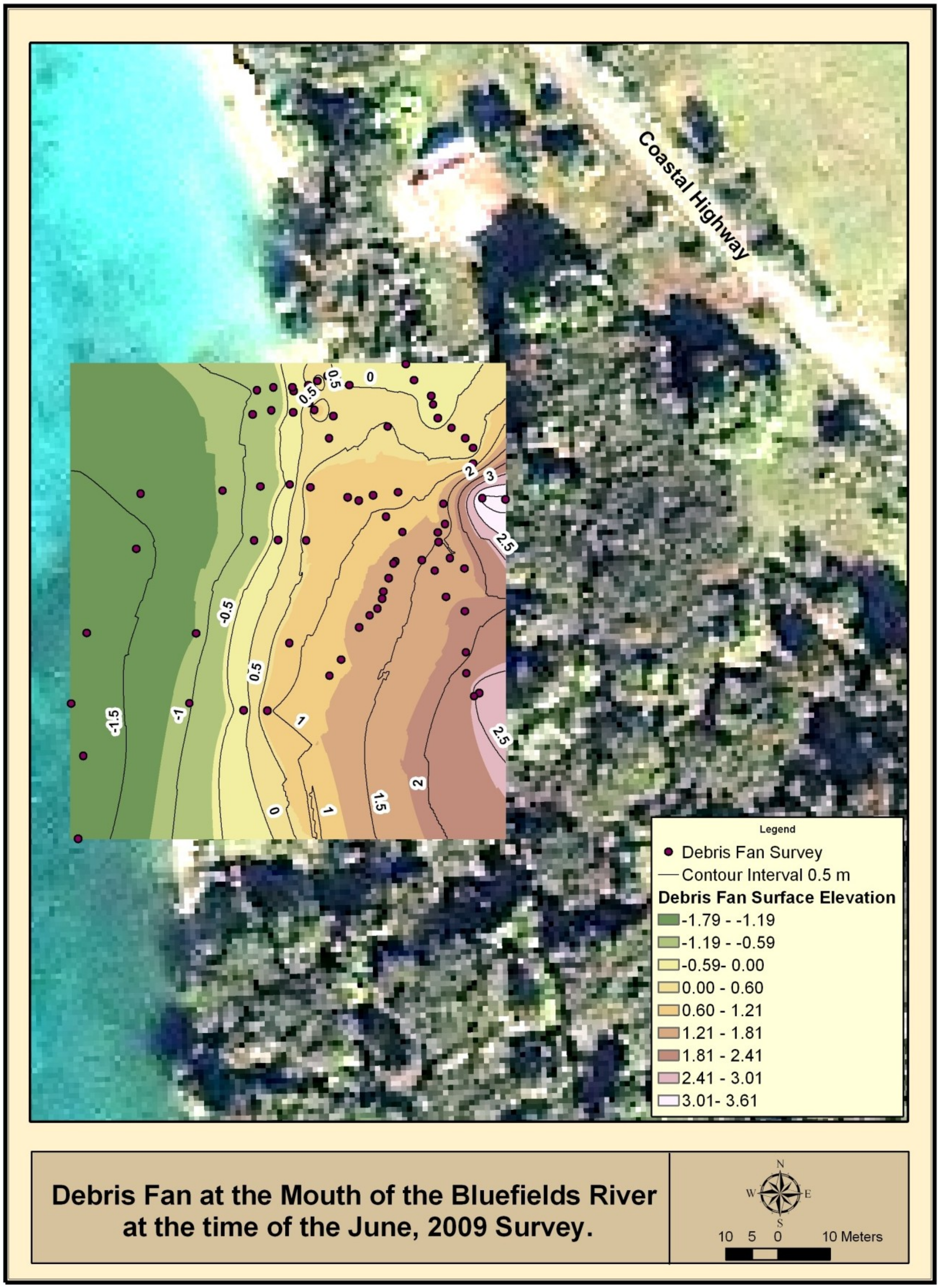


Figure 19. Calculating Debris Fan Volume: 2009 Fan Survey. Note: contour interval is 0.5 m.

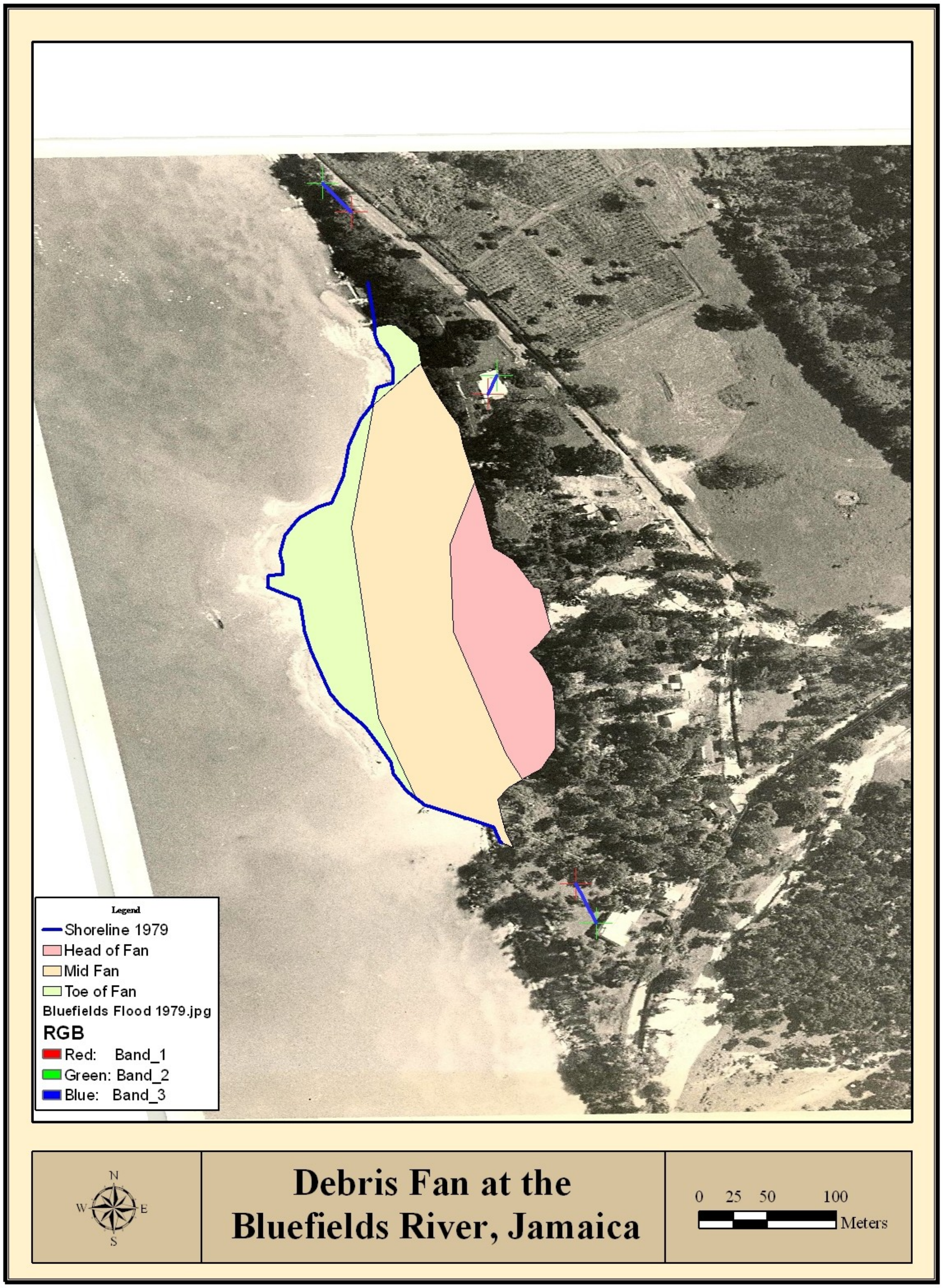


Figure 20. Calculating Debris Fan Volume: Fan Areas. Aerial extent of 1979 fan deposition after the flood. Head (pink) and middle (tan) fan areas indicate the extent of the 2006 fan.

Geospatial Data

Watershed areas were created from GIS data obtained from the GeoInformatics institute at the University of the West Indies, Mona. Initial analysis of the data in ArcGIS found some of the data to be inaccurate. There were discrepancies between the naming and locations of the streams. Therefore stream locations and watershed areas obtained from the GeoInformatics institute could not be used to accurately locate the Bluefields River. Stream channels were digitized from survey data and aerial photographs to more accurately locate the present location of the Bluefields River. Aerial photographs of Bluefields Bay in 1961, 1968, and 1993 were rectified to determine changes in land use and land cover (Appendix G). Rectification error was determined by measuring the largest point to point error in the aerial photographs. The debris fan was digitized to determine the extent of the debris fan prior to flooding in 1979.

CHAPTER 5

RESULTS: VALLEY INCISION OF THE BLUEFIELDS RIVER

Present-Day Channel Conditions

Longitudinal Profile. Present-day channel conditions were determined using the surveyed longitudinal profile of the Bluefields River. The longitudinal survey from the River Top bridge to the ocean is used to determine active headcut and current knickpoint locations (Figure 21). These inflections indicate the influence of resistant bedrock out-cropping along the channel and/or probable zones of catastrophic bed failure during the 1979 flood.

The shape of the longitudinal profile is used to classify the Bluefields River by sub-reach. The sub-reaches were determined based on entrenchment ratios, total valley width, and slope. The Bluefields River was divided into four sub-reaches to identify areas of differing channel geometry and from; (i) stalled head-cut above Goat Gulley to River-Top, (ii) catastrophic incision, valley wall failure, and valley widening in the middle reaches, (iii) incision, bed scour, and fan deposition below the coastal highway bridge (Figure 21). The area upstream of the River Top bridge was not included in the sub-reach classification because the reach upstream of the bridge was unaffected by the active head-cutting during and after the flood. Generally, slopes ranged from 1-5% and locally increased to 10% in step-pool reaches that are influenced by bedrock knickpoints (Table 2). There is a bedrock kinckpoint that is present upstream from the coastal highway bridge and upstream of the confluence of the Goat Gulley tributary (Figure 21).

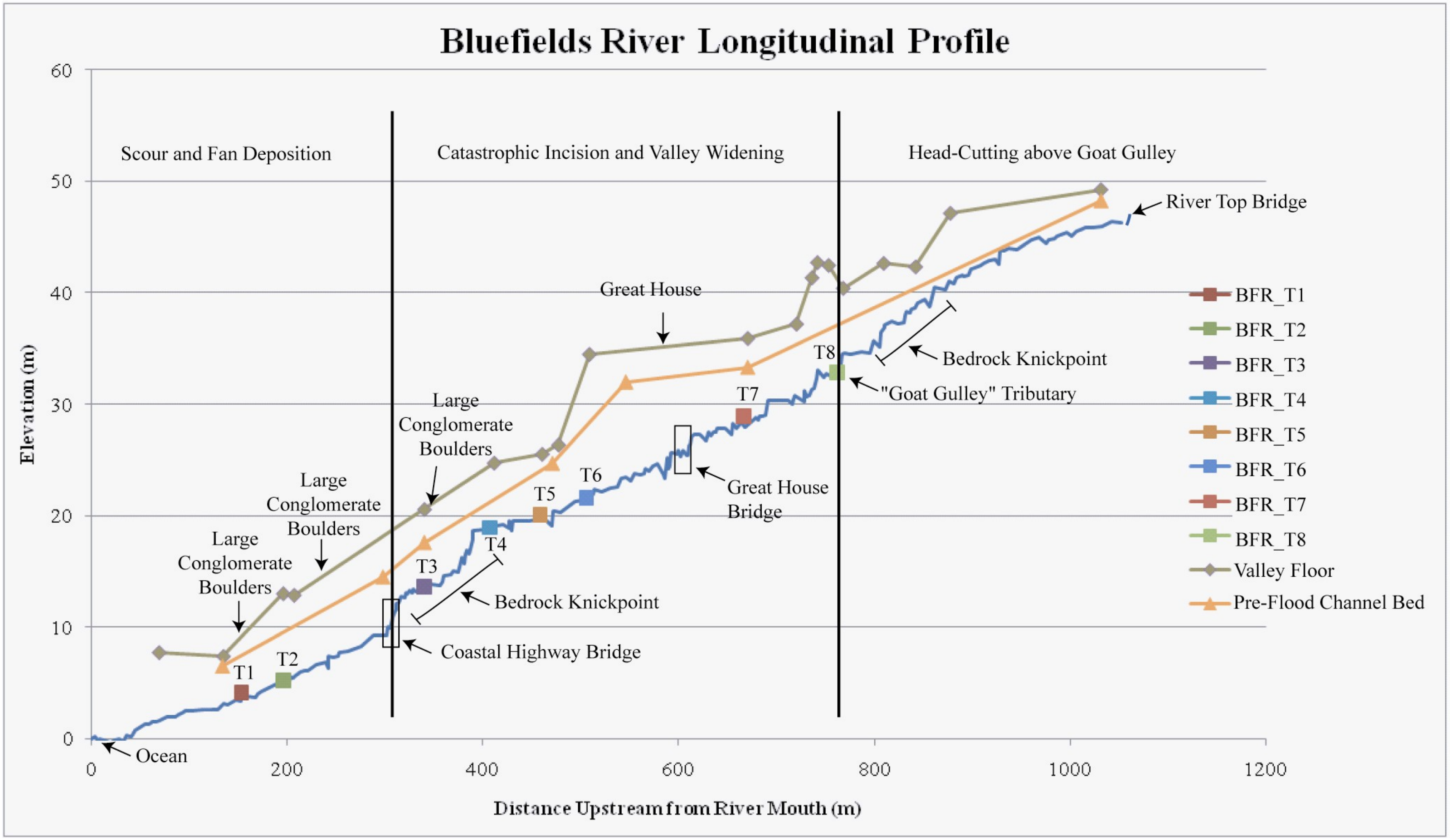


Figure 21. Bluefields River Longitudinal Profile. Elevation of 0 meters was sea level on date and time of the survey (6/2/2009).

Table 2. Channel Bed Slope Trends for the Bluefields River (2009).

Site	Slope	Slope %
T1	0.0270	2.69
T2	0.0311	3.11
T3	0.0549	5.49
T4	0.0199	1.99
T5	0.0191	1.91
T6	0.0418	4.18
T7	0.0290	2.90
T8	0.1051	10.51
River Top Bridge	0.0124	1.24
Average Slope	0.0410	4.10

Cross-Sections. Valley width (about 35 m) and depth (about 10 m) increase dramatically downstream of the Goat Gulley tributary and ratios indicate a deep, entrenched channel between river meter 500 and 700 (Table 3; Figure 22). This suggests that the bedrock was weaker or absent in this segment or that excessive flood waters entered the main Bluefields River from the Goat Gulley tributary coming in from the south (Figure 21). Valley depths range from 5 to 6 meter from river meter 500 to 100 (the fan head) (Figure 22). Valley depths are <2m near River-Top.

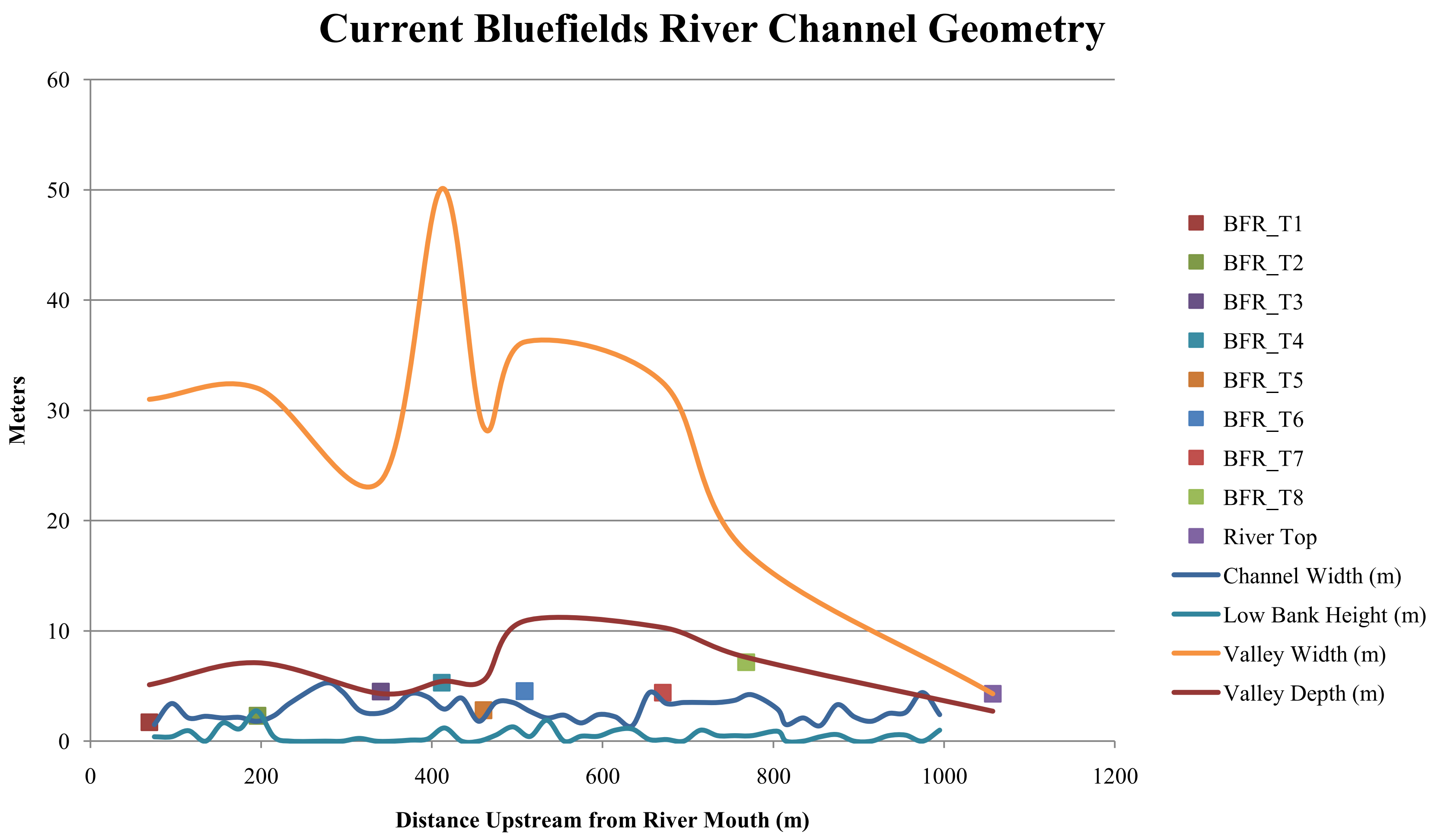


Figure 22. Present-Day Channel Geometry in the Bluefields River.

Table 3. Width/Depth and Confinement Ratios.

Cross-Section	River Meter	Average Transect Valley Wall Height (m)	Valley Width (m)	Valley W:D Ratio[1]	Mean W:D Ratio	Channel Incision Ratio[2]	Mean Channel Incision Ratio
1	69.1	5.08	31.04	6.12	5.4	5.08	5.5
2	195.9	7.15	32.03	4.48		7.15	
3	340.2	4.29	23.64	5.51		4.29	
4	411.6	5.39	50.08	9.30	4.7	5.39	7.9
5	460.6	5.47	28.53	5.22		5.47	
6	508.7	10.87	36.23	3.33		10.87	
7	670.6	10.32	32.5	3.15		10.32	
8	768.2	7.59	17.16	2.26		7.59	
River Top	1077.0	2.65	4.33	1.63	1.6	<1.5	<1.5

[1] Valley entrenchment ratio was calculated by taking the valley width divided by the valley depth.

[2] Channel incision ratio was calculated by taking the average valley wall height divided by the floodplain height

Substrate. The Bluefields River bed is composed of a variety of different substrates including bedrock, gravel and cobble, sand/ fine gravel, and artificial gabion steps to stabilize the channel bed along the low half of the study segment (see Appendix C).

The majority of the channel bed in the Bluefields River is coated with Fluvial Tufa deposits. Tufas are freshwater deposits calcium carbonate that occur at ambient temperatures (Carthew et al, 2003). The rapid deposition of the tufa indicates the source of groundwater to the Bluefields River is highly enriched in dissolved calcium carbonate. The tufa deposits in the Bluefields River coat the entire channel bed in some areas (Figure 23). The location of the tufa bed coatings are mapped in Figure 24. A three point moving average was used to interpolate tufa bed coating between the cross sections (Figure 24). Tufa deposits occurred prior to channel incision in 1979. Evidence pre-1979 tufas include hanging coated bed deposits and large, coated cobbles and boulders within older debris fan deposits (Figure 23).

<u>Conglomerate Blocks</u>. Large boulders that are composed of a conglomerate rock are located near the bedrock knickpoints on the valley floor (Figure 21). The large conglomerate blocks were moved during the debris flow of 1979. The location of the conglomerate boulders are mapped in Figure 21. The locations of the large conglomerate boulders near the bedrock knickpoints indicate a probable local bedrock source. Some of the boulders appear to have been transported for a short distance on top of the debris flow (Figure 21). Alternatively, some of these large boulders may have collapsed or fallen down on top of the previous debris flow deposits after the flood.

<u>Boulder Bar</u>. At the confluence of the Bluefields River and the Goat Gulley tributary, several boulder bar features are present that indicate the influence of an

Figure 23. Tufa Clast in Beach Deposits on the Debris Fan.

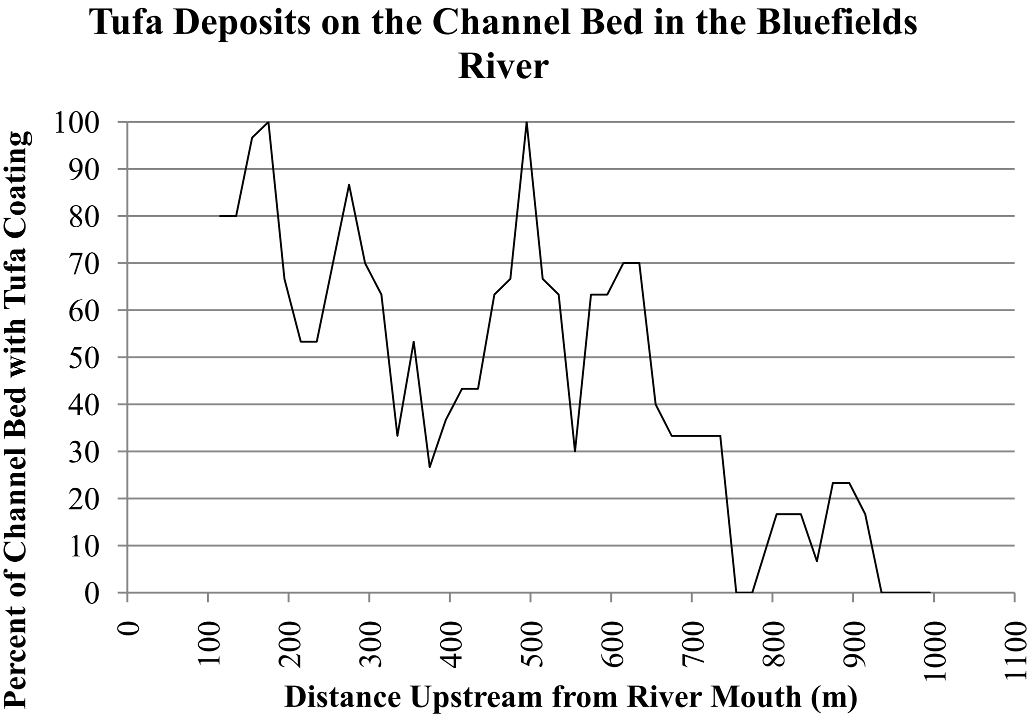


Figure 24. Tufa Bed Coatings in the Bluefields River.

extremely energetic flood that was generated from the Goat Gulley drainage system (Figure 25). Colluvium from the mountain side and boulders/cobbles were transported from the Goat Gulley tributary during the debris flow.

Figure 25. Boulder Bar in the Bluefields River. The boulder bar is located at the confluence of the Bluefields River and the Goat Gulley tributary is evidence of the debris flow on June 12, 1979.

Pre-Flood Channel Bed Elevation

Geomorphic Evidence. The geomorphic evidence of incision can be used to determine pre-flooding channel location and effects of the June, 12th 1979 event. Estimates of the pre-flooding channel geometry and bed location of the Bluefields River were determined in numerous ways using: (i) a reference reach approach, (ii) gravel/cobble lag deposits marking previous bed elevation, (iii) fluvial tufa deposits marking previous bed elevation, (iv) historical road bed materials, (v) historical photographs, and (vi) oral history.

Reference Reach. The reach upstream of the River Top bridge was not affected by the flooding or 1979 of the subsequent head-cutting. There is a stalled 1 m deep head cut at the downstream side of the River Top Bridge, but upstream of the bridge the channel is graded to the bed of the culvert. This reach can be used as a "reference" reach for the approximation of the pre-flooding channel geometry of the Bluefields River. The channel is approximately 4 meters wide, shallow, and has relatively low banks (less than one meter). This reach is believed to resemble the pre-flooding channel geometry because it was largely unaffected by the debris flow and flooding in 1979.

"Hanging" Channel Lag Deposits. Hanging gravel lag deposits can be found in several places in high bank exposures marking the pre-1979 elevation of the Bluefields River bed (Figure 26). The incision into the streambed following the flood and debris flow has exposed the gravel lag or previous channel bed (Figure 26). The gravel lag deposits are typically found one to three meters below the high bank edge or valley floor. Hanging bed deposits are found nearly 9 m above the present thalweg in the middle reaches of the Bluefields River.

Fluvial Tufa Deposits. The elevation of tufa deposits can also indicate previous channel bed elevations (Figure 27). Tufa coatings or concretions tend to be deposited on or near the channel bed where carbon dioxide is released to the atmosphere or removed by photosynthesis from karstic spring- or ground water- fed streams in like the Bluefields River. As the carbon dioxide of the stream water decreases, calcium carbonate or limestone crystallizes on the bed materials, lower banks, vegetation, or any hard surface (even plastic containers). If the channel bed elevation stays stable for a long period, thick coatings of tufa will become concentrated long the location of the channel bed and these

Figure 26. Geomorphic Evidence of Incision in the Bluefields River. The gravel lag is evidence of a former channel bed. Note: Paleo-channel bed is two meters below valley floor and six meters above the current thalweg at river meter 577.

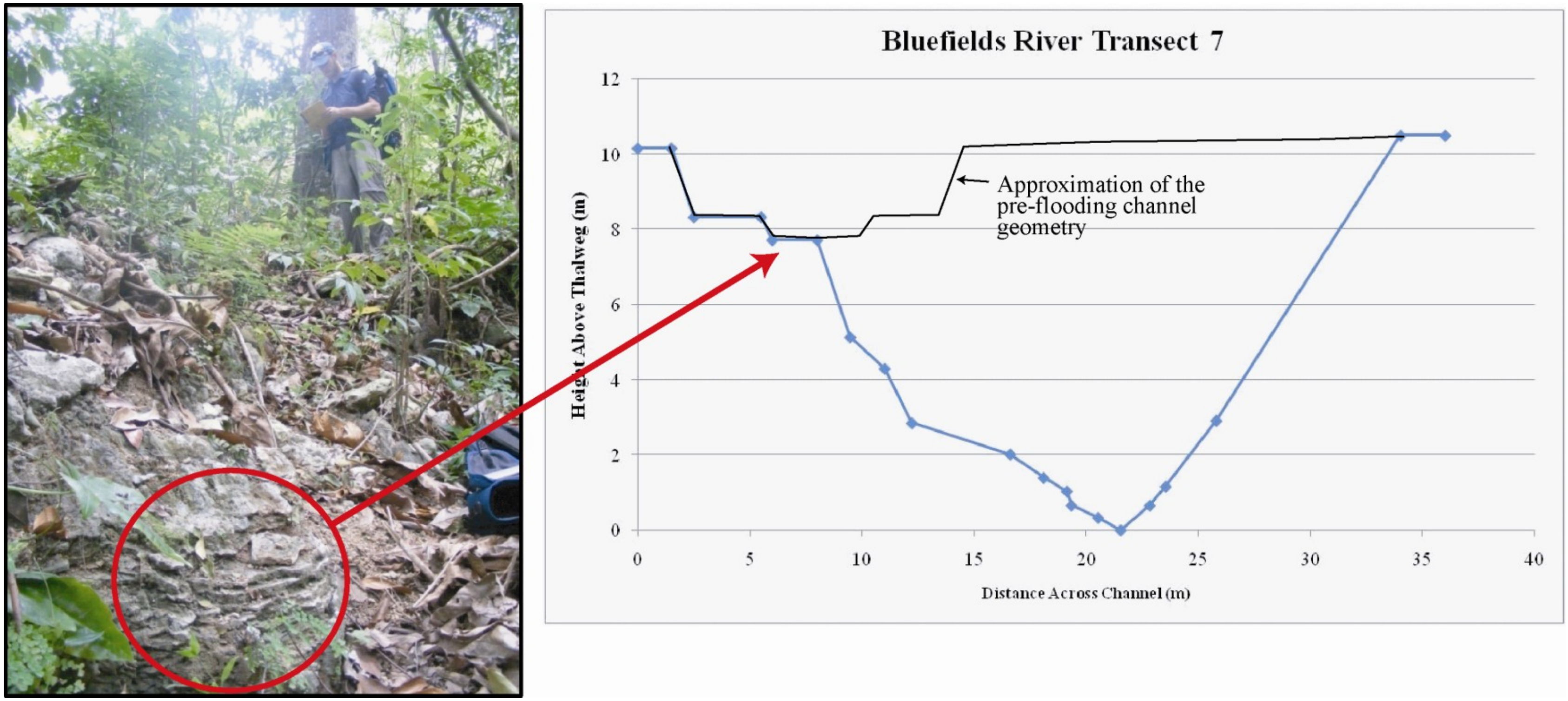


Figure 27. Tufa Deposits. The tufa deposits can be used to estimate the pre-flooding geometry of the Bluefields River. Notes: There is nearly eight meters of incision at river meter 670.6 that can be determined by combining the cross sections with the locations of fluvial tufa deposits.

can be recognized both at the location of the present bed (Figure 24) and as paleo-channel indicators higher up on the valley wall (Figure 27).

It is apparent that tufa deposits were present along the pre-1979 Bluefields River (Figure 27). Larger cobble- and boulder-sized clasts are found in the debris fan of the Bluefields River along the bay (Figure 23). It is probable that the coated clasts were eroded from the previous river bed position and deposited in the fan by the 1979 debris flood. After catastrophic incision following the debris flow in the Bluefields River, some tufa deposits were preserved along the upper banks, high above the present channel bed. The combination of the tufa deposit location and cross-sectional surveys can be used to determine the pre-flooding channel geometry of the Bluefields River (Figure 27). At transect 7, fluvial tufa deposits are about seven meters above the present thalweg (Figure 27).

<u>Historical Bridge Elevations.</u> The road surface, abutment, and culvert elevations of the two bridges that were washed out during the 1979 flood are used here to determine the incision depths along the Bluefields River. The roads that crossed the Bluefields River before 1979 were used by living witnesses living in the area who indicated that bed elevations ranged from 1 m to 2 m below the road surface of the bridges (Table 4). The old Great House bridge was constructed with London red bricks from the ballast of British ships. The base of the bridge abutments for the bridge is now high above the present bed elevation (Figure 28). The depth of the pre-1979 channel bed below the coastal highway is also documented with field, photographic, and witness evidence (Table 4; Figure 10). The present-day River-Top bridge was in-place before the 1979 flood, but did not get washed out. The channel bed on the upstream side of the bridge is about 1.5 m below the road (Figures 17 & 18).

Figure 28. Old Great House Road bridge elevation. Notes: Previous road elevation of the bridge is about four meters above the present channel thalweg. Oral history accounts indicate that the bridge structure was about one meter above the bed at river meter 607.

Table 4. Oral History of the Bluefields River June 12th, 1979 Event

Landform or Feature	Person	Notes
Old Great House Bridge	Mr. Blackwood	When the bridge spanned the pre-flooding Bluefields River he could lean over and drink water out of the channel. There was little difference between the top of the bank elevation and the bridge height. There was water coming down goat gulley for weeks after the river flooded. “River carried large boulders from mountains and washed out bridges.” Cattle could cross river.
Old Coastal Highway Bridge	Son of Construction Worker	My father worked on the coastal highway bridge and could lean over and touch the water from the bridge.
Colonial Pond	Farmer	This area was a pond for the plantations. There were rocks and lots of water coming down goat gulley. There were large boulders falling down the gulley. You would get hit in the head with rock if you walked up the Goat Gulley. I still will not go in the gulley for fear of falling rocks. The pond overtopped and water flowed down Goat Gulley and to Brighton.

Oral History. Elders in the community describe leaning over bridges in the pre-flooding Bluefields River and drinking water from the stream (Table 4). The elders also stated how there was little difference between the top of bank elevation and the bridge height. These witness accounts indicate that the Bluefields River was flowing within 1 m or 2 m of the valley floor surface. Data collected from the Elders was used to approximate the amount of incision that occurred at all bridge crossings. Nearly six meters of incision occurred at the sites of both the old Great House Bridge and the Coastal Highway bridge. Witnesses also state that a large amount of water continued to flow through the Bluefields River for several weeks following the debris flow in 1979.

Aerial Photographic Evidence. There were oblique aerial photographs taken by the WRA immediately following June 12, 1979 (Figure 10). Incision was documented in a photo taken on June 19, 1979. The photograph documents channel incision and bridge destruction at the coastal highway bridge. There was nearly six meters of incision recorded in the photograph (Figure 10).

Volume of Bluefields River Valley Floor Incision

All indicators of the pre-flooding channel bed elevation (gravel lag, road surface elevations, oral history, and a reference reach) were located in each of the surveyed cross sections. The survey cross-sections were then used as a typical channel profile for reaches along the Bluefields River. The cross-sectional area of the surveyed cross section was then multiplied by the distance of the representative reach to obtain a distance-weighted volume estimate. The cross-sectional area and volume of the pre-flooding channel geometry was then subtracted from the volume estimates to yield a total eroded sediment estimate (Figure 18).

The total volume of sediment eroded from valley floor incision was estimated to be 58,276 m^3 (Table 5). The total amount of sediment that was transported to the debris fan is unknown. A photograph taken immediately after the flood and debris flow is further evidence of the massive amount of sediment that was transported (Figure 10). Therefore, the relativity small amount of sediment derived from valley incision in the Bluefields River suggests another source of sediment to the debris flow. The oral history suggests a significant amount of sediment came from the Goat Gulley tributary and ephemeral stream network flowing in to the Bluefields River from the east.

Table 5. Volume of Eroded Sediment by Sub-reach.

Cross Section	Cross Sectional Area (m^2)	Length of Reach (m)	Total Eroded Sediment (m^3)
1	59	66	3,900
2	104	153	15,977
3	72	86	6,152
4	168	59	9,998
5	99	49	4,870
6	210	104	21,800
7	49	128	6,236
8	72	48	3,421
9	12	116	1,377
River Top	8	154	1,169
Total Eroded Sediment from Bluefields River			58,276

CHAPTER 6

RESULTS: DEBRIS FAN FORMATION

Debris Flow Initiation

The debris flow was initiated during June 12, 1979 when torrential rains led to a large flood in the Bluefields River watershed. Flood waters were generated from the entire drainage area of the river. Oral histories (Table 4) and historical photographs (Figures 29 & 30) suggest that the eastern portion of the watershed including Goat Gulley was a major contributor of both flood water and debris. The sediment laden flood waters destroyed bridges and initiated incision along its middle and lower segments of the Bluefields River and formed a relatively large debris fan out into Bluefields Bay (Figure 30). The sources of the sediment to the debris flow were from: (i) mountain slope erosion and failure; (ii) channel incision in upper Goat Gulley; (iii) channel incision in lower Goat Gulley near the confluence with the Bluefields River; and (iv) channel incision in the Bluefields River (discussed previously in Chapter 5) (Figure 30).

Contributions of sediment delivery from mountain areas were not addressed by this study. However, a farmer commented that during the periods after the 1979 flood and other large storms since it was dangerous to go up into the mountain headwater areas of Goat Gulley due to the high frequency of rock falls and unconsolidated slope materials (Table 4).

Witness accounts and aerial photography evidence suggest that additional flood waters possibly flowed into the presently mapped Bluefields River watershed from the Brighton area to the east as karst depressions were progressively filled in and rims over-topped along a fault-line valley. This hydrological "super-connected" condition may

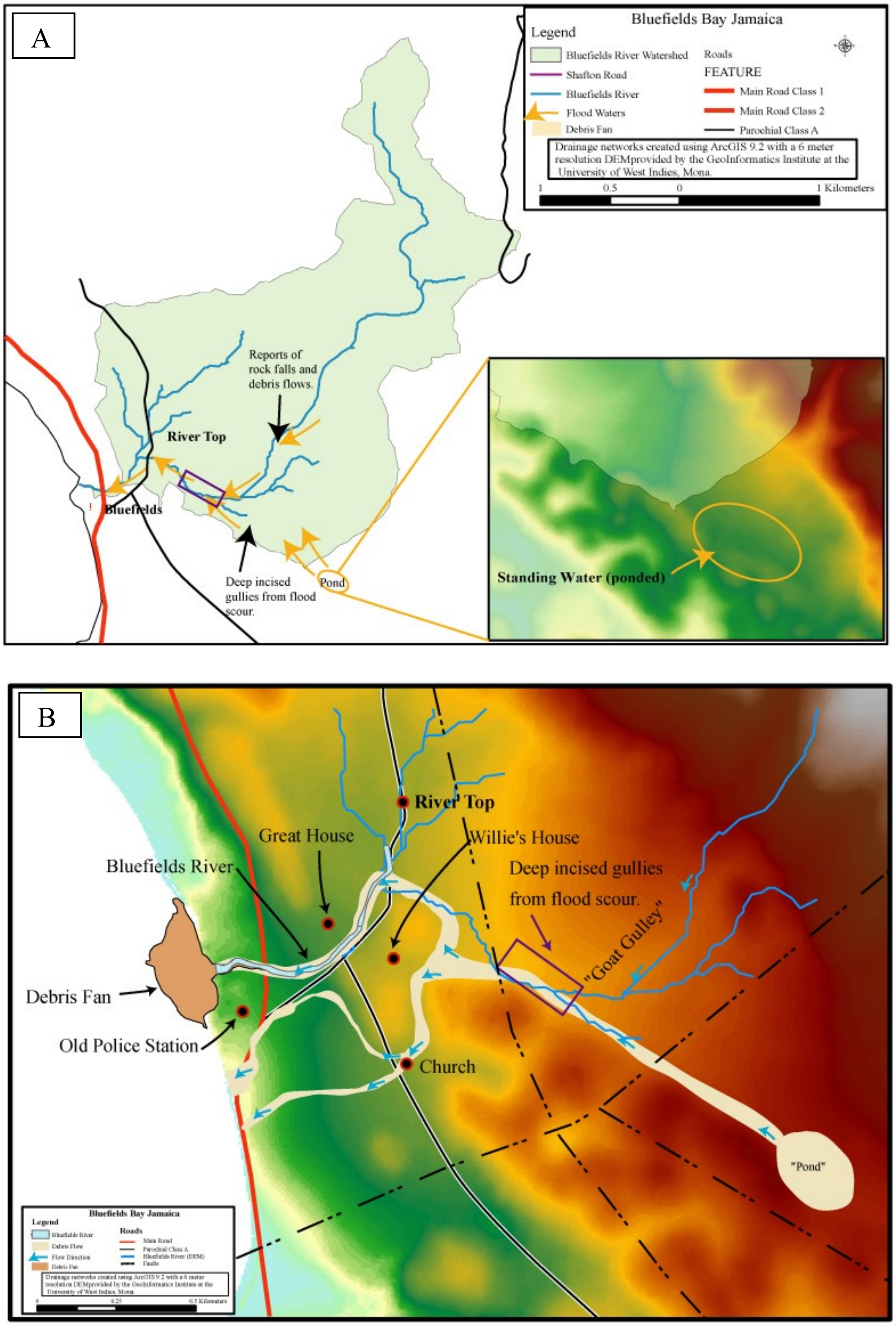


Figure 29. Debris Flow Initiation. On June 12, 1979 water collected in an artificial pond built in colonial times and burst, traveling down the Goat Gulley tributary (A). Note the multiple channel debris flow in the aerial photograph (B).

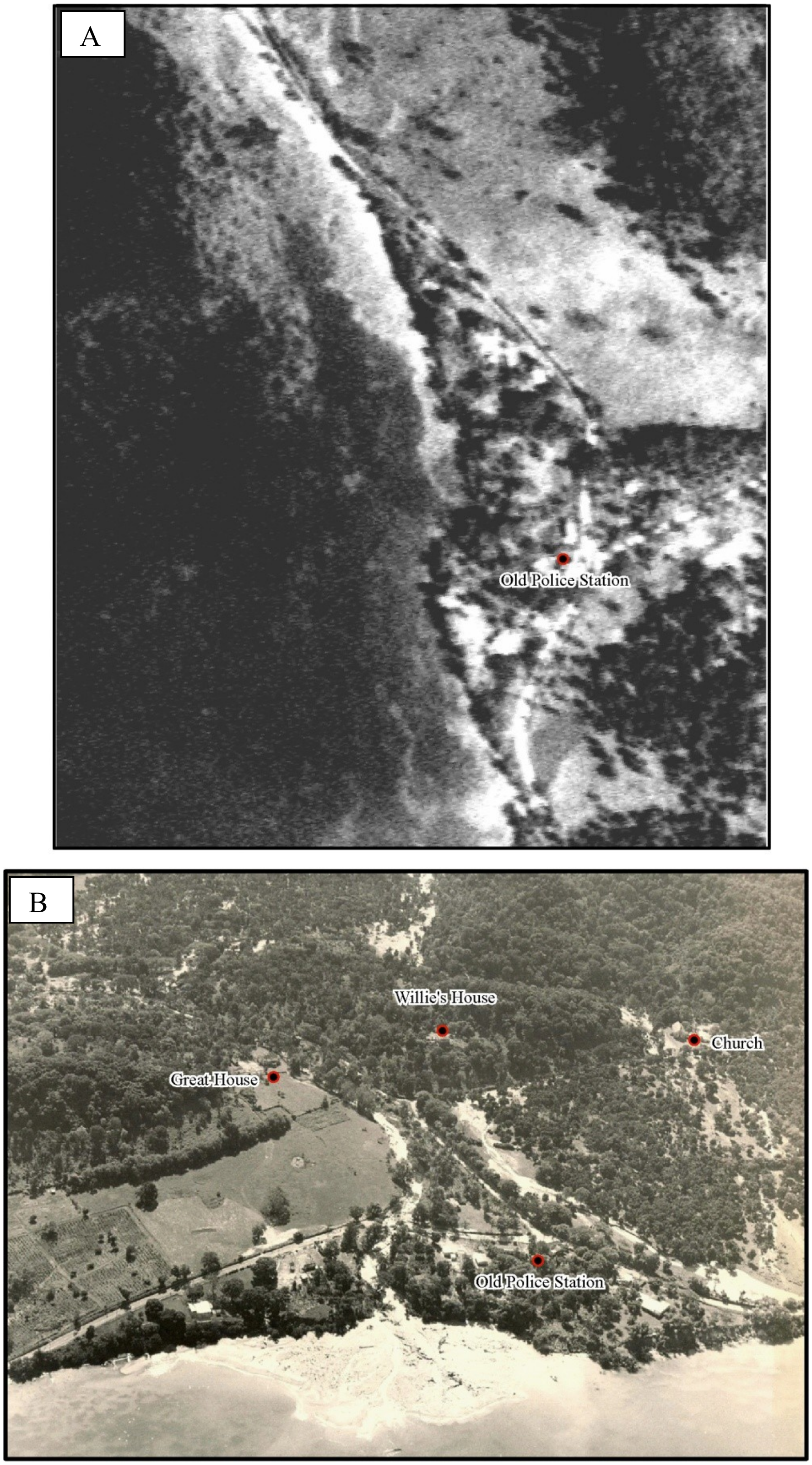


Figure 30. Debris Fan Formation. Aerial photography from 1968 (A) illustrates how the debris fan was much smaller than the debris fan post 1979 (B).

have increased the effective watershed area of the Bluefields River by three times or more. However, additional study is needed to accurately determine the extent of this additional drainage area. It was difficult to determine the exact boundary of the Bluefields River watershed due to geospatial data limitations (i.e., low resolution DEM) and low relief topography present within the faulted, karst limestone valleys.

Besides the overall extreme nature of the 1979 floodplain, there are three lines of geomorphic evidence developed in this study to support super-connected flood hydrology. First, there was a colonial-era pond and dam that failed during the 1979 event (Figure 29). The pond was built in an existing karst depression located along the Goat Gulley valley on the divide between the Bluefields River watershed and the Bluehole River watershed to the south (Table 4; Figure 29). Field observations by the author and his advisor indicated that the size of the pond was roughly about 100 m in diameter as determined by the boundary of an agricultural field located on relatively rich soils believed to be formed in the old pond deposits. The height of the remaining dam works appears to range from 1 to 1.5 meters. Witness accounts describe the pond failure, but it is not known if the pond was holding water before the flood or if it filled during the flood with the older dam works failing as a result. Nevertheless, rough calculations indicate that a catastrophic failure of the pond could have almost doubled the flood peak in the Goat Gulley valley for a short-term period of <30 minutes (Figure 29). While pond failure did not cause the flood, it may have increased the effectiveness of the flood to cause valley incision and generate more debris flow material.

The second example of geomorphic evidence to support a super-connected watershed is the presence of an incised channel and head-cut in the upper Goat Gulley valley that was believed to have formed during the 1979 flood. The channel scar was incised into the upland valley floor of Goat Gulley to a depth of about 5 m below the confluence of the mountain tributary to the north and the karst valley with the old colonial pond to the east (Figure 29). Excessive runoff from the coastal mountains, water crossing the divide from the karst valley to the east, and catastrophic pond failure may have triggered incision that would have supplied large amounts of sediment debris to downstream areas. Sediment derived from the incision of the upper Goat Gulley valley was deposited on the lower Goat Gulley floor to depths of 1 to 2 m and transported downstream to the Bluefields River and over secondary drainage divides to the coast (discussed below).

In addition to incision of the upper Goat Gulley, an incised channel formed along lower Goat Gulley between the Bluefields River confluence and the road where shallow bedrock prevented further head-cut migration. The depth of the incision ranged from about 8 meters near the mouth to 4 meters at the road over a distance of above 100 m.

The third line of evidence supporting the super-connected condition of the Bluefields River watershed involves the over-flow of secondary divides by the flood and the transport of large amounts of debris out onto land areas to the east of the lower Bluefield River and north of the coastal highway (Figure 30). This debris flow split around a ridge to the south and north (Figure 29). The amount of sediment debris crossing the divide was significant and formed fan-like deposits along the foothills of the coastal mountains. Debris had to be cleared from along 1 km of the coastal highway, with dump piles and cuts related to excavation activities still present today. These debris flows indicate that a large amount of water flooded the Goat Gulley valley (divide was over-topped) and that the velocity and competence of the flow was significant (occurrence of extensive debris flows). More field study is needed to determine the paleo-discharge characteristics of the flow in upper Goat Gulley, but it is apparent that an excessive amount of water moved down the valley and suggests that some of this water was contributed from outside the watershed divides delineated by this study.

Historical Changes in River Mouth Shorelines

A colonial map created during the late 1700's and aerial photographs from 1961, 1968, 1991, and 2006 are used to document the changes along the coastline relative to the effect of the fan deposition in 1979 (Figures 14 & 31; Appendix G). The 1961 photograph was used to as the shoreline base reference because it has the smallest RMS error and the earliest photographic evidence of shoreline configuration (Table 6). There are large point to point errors associated with the photo-rectification of the 1968 and 1979 photographs. The aerial photograph taken in 1968 has very poor spatial resolution and contrast (Appendix G). Due to the poor resolution and contrast the 1968 photo has large rectification errors due to the inability to locate solid georeference points (Table 6; Appendix G). The aerial photograph taken in 1979 was an oblique aerial photograph therefore the error associated with the rectification was larger. It is difficult to rectify photographs that are taken at different angles. The oblique nature of the 1979 photograph does not allow for accurate rectification (Appendix G).

Regardless of the influence of errors in rectification, the changes in the extent of shoreline location and debris fan outline are evident (Figure 31). The colonial map specifically shades the land area present at the mouth of the Bluefields River around 1780 (Appendix G). In addition, other maps have labeled this area as a "delta fan." This designation may indicate some aspect of land ownership or possibly the noticeable occurrence different vegetation type(s), mud deposits from inputs by colonial soil

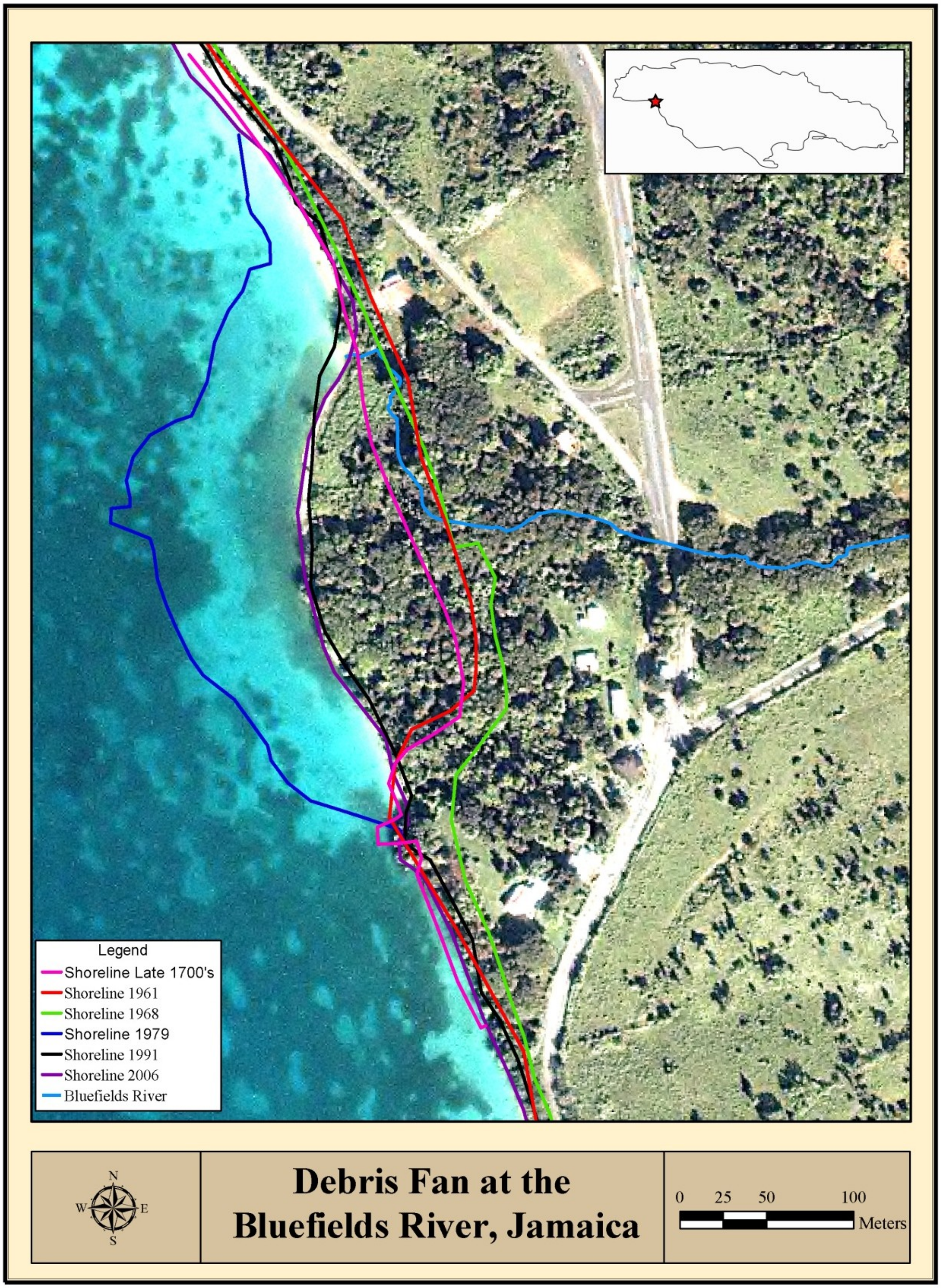


Figure 31. Historical Shoreline Configurations.

Table 6. History of Shoreline Changes.

Year	Extension (m)	Rectification Error[1] (m)	RMS Error
Late 1700's	22	NA	NA
1961	0	6.88	4.24
1968	0	7.55	4.47
1979	179	21.3	NA
1991	75	3.79	4.03
2006	83	NA	NA

[1] Rectification error is the largest measured point to point error in the aerial photographs.

disturbances, and/or coarse-grained deposits similar to the present-day debris fan. However, there is no other information provided than the shoreline configuration. While the shoreline offset in 1780 is about 22 m seaward of the pre-1979 shoreline, the 1780 shoreline shape is very similar to the 1961 configuration suggesting that this offset may be related more to map error than real shoreline changes. If is it assumed that 1780s shoreline location is the same as found in 1961 and 1968, then there has been little change in shoreline extent for at least 200 years prior to the 1979 event.

The 1979 event formed a debris fan at the mouth of the Bluefields River that extended out into the bay approximately 180 m compared to the pre-flood configuration (Table 6). The extent of the fan was reduced by one-half of this distance by coastal by 1991 and has changed little since that time (Table 6; Figure 31). Presently, the debris fan extends out into the bay 80 m compared to its pre-1979 location (Table 6). It is expected that most of the adjustment in debris fan extent would occur immediately after the flood event as fine-grained sediment (sand and silt) would be easily dispersed by wave action.

The present fan area may be protected from erosion by shoreline orientation or obstacles to wave attack, coarse beach deposits that absorb wave energy, and protection by vegetation anchoring.

Field mapping was used to determine the area extent and characteristics of the debris fan deposits. The upstream limit of debris flow deposits presently extends to about 30 m upstream of the current coastal highway bridge. These fan head deposits typically consist of poorly-sorted, sometimes inversely-graded, gravel and cobble clasts within a sandy silt matrix (Figure 32). Post-depositional incision has cut into and exposed these deposits from river-meter 350 to 150 (Figure 21 & 32). There are human artifacts such as bricks, asphalt, and metal hardware within the deposit (Figure 32). Vegetation, lack of exposures, and the water table limited fan deposit observations below meter 150.

Debris Fan Volume

The volume of material deposited in the debris fan in 1979 was estimated to be 116,000 m^3 (Table 7). The present-day volume of the debris fan based on 2006 fan area measurements and the 2009 field survey is 84,000 m^3 (Figure 19). The decrease in volume by almost 30% is assumed to be the result of coastal erosion and the effects of measurement errors which are difficult to assess. However, in general the fan area measurements are probably accurate since the seaward limit of the boulder line on the bay floor used to survey the seaward extent of the fan during field work closely matches up fan area measurements determined using the 1979 aerial photograph of the fan (Figure 20 & Figure 31). The majority of the sediment is fine-grained and has been removed or transported by coastal erosion since the 1979 flood leaving behind coarse gravel and boulders offshore. The total volume of sediment eroded by incision of the Bluefields

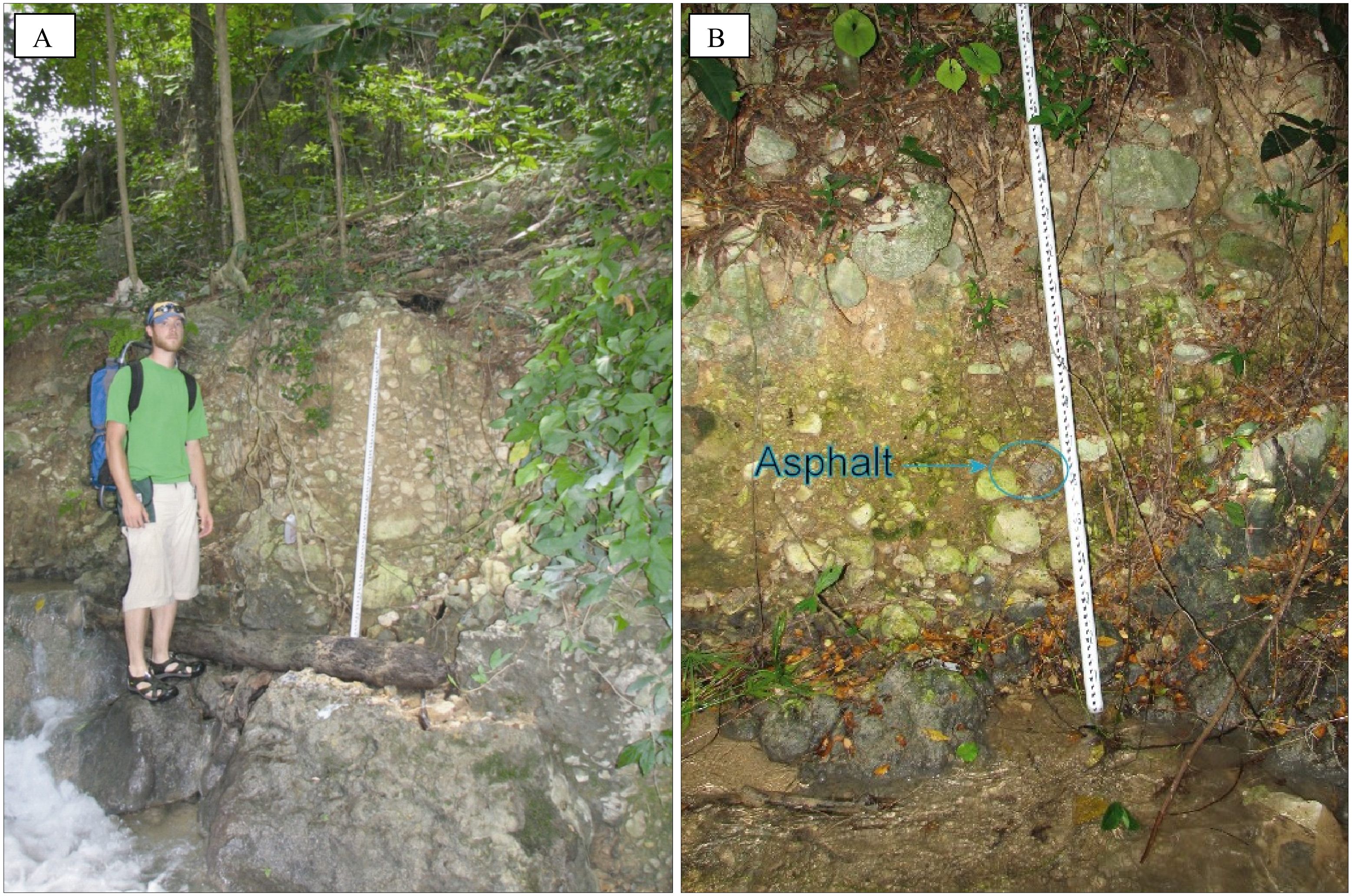


Figure 32. Fan Head Deposits. Present-day incision has exposed debris fan deposits upstream from the Coastal Highway bridge (A). The debris flow deposits are poorly-sorted gravel, cobble, and small boulders that lack imbrication (A and B).

River and the lower Goat Gulley below the road is about 61,000 m^3 (58,000 m^3 from Table 5 with 3,000 m^3 added for Goat Gulley). This volume is about half of that deposited in the debris fan in 1979, suggesting that sediment from upper Goat Gulley or mountain erosion must also be contained in the debris fan (Table 4, Figure 29).

Table 7. Debris Fan Volume

Location	Area (m^2)	Thickness (m)	Volume (m^3)
River Channel from Head to Coastal Highway Bridge	164	Variable	19,887
Head	9,355	2.7	25,258
Mid	22,696	2.3	59,010
Toe	9,106	1.3	11,837
Total Debris Fan Volume (1979)			115,982
Current Debris Fan Estimate (minus toe area, 2006)			84,267

CHAPTER 7

RESULTS: CAUSES OF INCISION AND FAN DEPOSITION

Geology and Climate

In the Bluefields River watershed, the 1979 flood and debris flow was influenced by a combination of geologic, climatic, and human factors. There are primary geologic and climatic factors that reflect the major influence on the generation of the flood and the sediment supply available for the debris flow in the Bluefields River. Secondary factors include human modifications to the landscape and the long term influence of sea level rise on coastal erosion that has shorted channel length along the lower Bluefields River segment.

Geology and Geomorphic Setting. The Bluefields River watershed is a steep mountainous terrain that extends from the ocean to an elevation of 760 meters above sea level. There are several faults that are present in the watershed (Figure 5). The control of previous tectonic activity and subsequent weathering and erosion of the karst landscape affects valley orientation, hill slope processes, and sediment supply to the Bluefields River. Because of the karst topography there are also low drainage divides along the valleys in the area. Weaknesses in the limestone along extinct fault lines also help to create connected valleys that can direct flood waters into the Bluefields River valley. Typically, debris flows very seldom cross drainage divides. However, in 1979 the debris flow and flooding crossed a drainage divide along upper Goat Gulley valley.

Antecedent Conditions. Antecedent rainfall and soil moisture conditions played a major role of the debris flow of 1979. The intense rainfall onto already saturated soils led to increased runoff. In the days before June 12, 1979, western Jamaica had several moderate to heavy rainfall events (Donaldson, 1981). On June 12th, 31.2 cm of rain fell across western Jamaica onto already saturated soils. The total rainfall from June 10th to June 25th was 86 cm (Porter, 1981). Torrential rainfall is not uncommon in western Jamaica. The maximum 24hr rainfall event on record is 44.7 cm in 1951 (Donaldson, 1981). The 24 hr maximum rainfall on June 12, 1979 was 31.9 cm. Although more rain fell in 24 hours in 1959, the torrential rains of did not cause such severe flooding as in 1979.

Antecendent conditions could have also helped karst surface and subterranean conduits to become overwhelmed and thus allow water to flow across drainage divides. Local residents recall seeing increased runoff for several days after the June 12th storm. Mr. Blackwood stated, “The River flowed down the mountainside for some time after the rains” (Table 4). The increased runoff following the storm could be related to a super-connected karst hydrology where the effective drainage area of the Bluefields River could be up to three times larger than currently mapped.

Human Modifications to the Landscape

Grade Control Structures. The bridges that spanned the Bluefields River at the Coastal highway and the Great House prior to flooding in 1979 would have acted as a grade control structures that restricted down-cutting and acted as a sediment trap. Sediment from colonial land use disturbance or natural sources probably accumulated above the bridges that crossed the Bluefields River within the active channel. We have not yet found evidence of the localized deposition of sediment, but if the stream was entrenched similar to the current conditions, the record of sediment accumulation behind the bridges could have been eroded away when the bridges were washed out in 1979.

When the bridges failed during the flood, head-cuts would have probably formed due to the decrease in bed elevation downstream at bridge locations (Figure 21). Field evidence suggests that three head-cuts were initiated along the Bluefields River, one above each bridge and possibly one at the Goat Gulley confluence. One worked its way upstream almost to the current location at the River Top Bridge (Figure 16). A deeply incised channel is evidence of incision in lower Goat Gulley. Large conglomerate boulders along the side of Goat Gulley and Bluefields River are further evidence of the head cutting since the large boulders could have been undermined and broken loose during the flood or left in place while fine-grained sediment was scoured from around the boulders (Figure 21). These large boulders may have acted to limit channel down-cutting prior to flooding, but with the failure of bedrock layers and incision of the bed, these controls were weakened.

Pond Failure. The karst depression that was modified to become a pond during colonial times may have played a critical role in the debris flow in 1979. The dam failure may have doubled the peak flood stage just enough to exceed the threshold of erosion on the valley floor of upper Goat Gulley. This additional supply of sediment debris from the upper portions of the watershed would have contributed to the fan deposit. The deep gulley along the upper Goat Gulley Tributary is evidence that incision that was not limited to the main stem of the Bluefields River. The location of the incised gully was below the site of the pond failure and confluence of the mountain branch of Goat Gulley (Figure 29).

Effects of Land Use Disturbance on Sedimentation. There is a rich cultural history of the settlement of Bluefields Bay in the Parish of Westmoreland, Jamaica. Aboriginal people were the first inhabitants of Bluefields Bay followed by the Spanish and then the British. Each settlement would have altered the land and therefore possibly affected the landscape and sediment delivery to the Bluefields River.

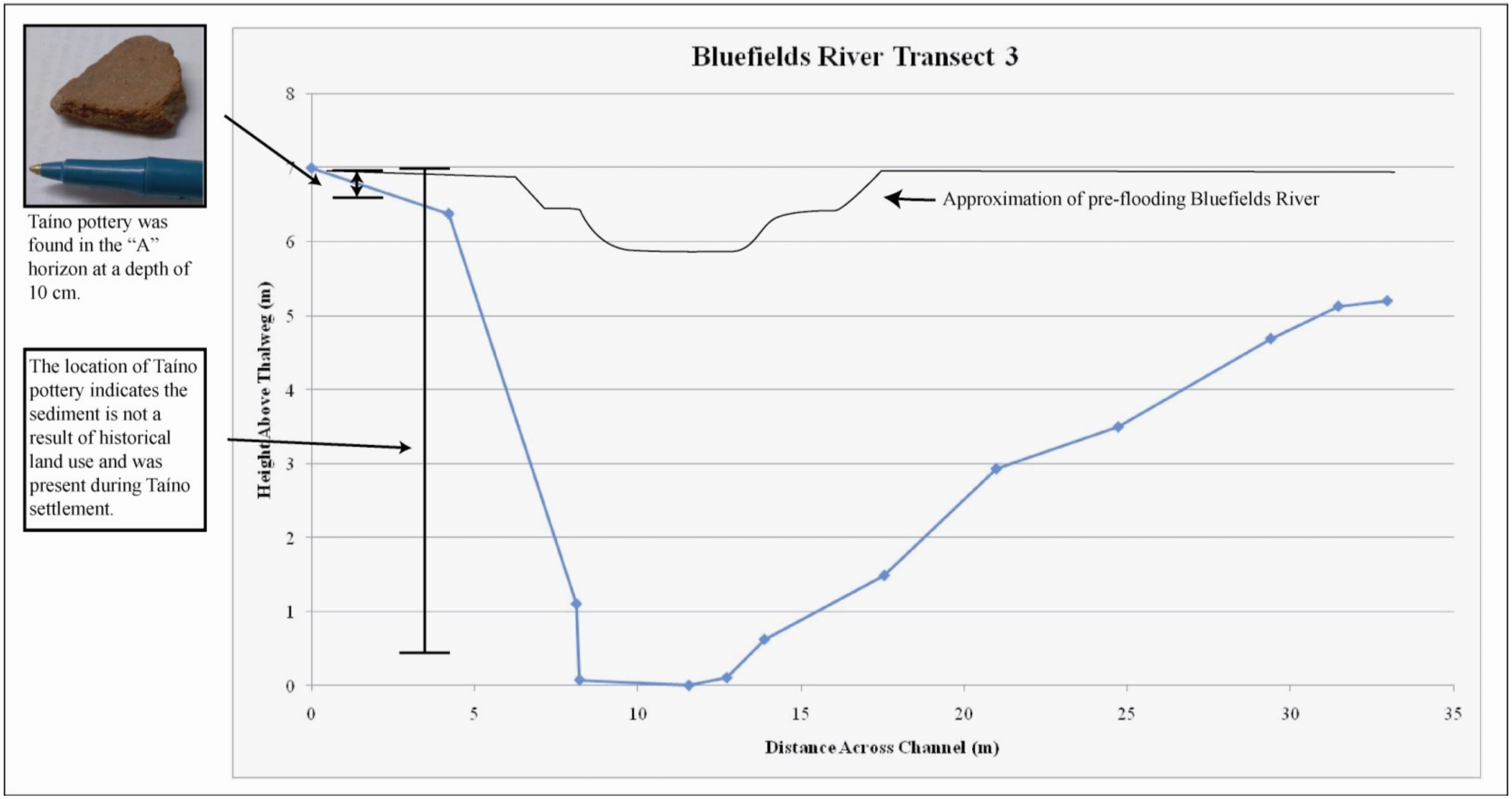
The British would have had the largest impact on the landscape in recent human history. Drastic land use changes would have occurred with the land clearing in Bluefields Bay. The low lying areas were cleared for agriculture and grazing and the steep hillsides were also cleared for farming. The land clearing would have allowed for increased runoff and erosion from the cleared land. Following the collapse of the sugar industry in the late 19th century and the emancipation of Jamaica in 1838, the plantations in the Bluefields area were split up and sold to the former slaves. Some of the cleared land continues to be farmed but much of the land was allowed to return to forest.

With the rich cultural history of Bluefields Bay one would expect that the land use changes during colonial times would have had an impact the Bluefields River. There are several studies that document land use changes in North America (Knox 1972, 1987) but there is little evidence of land use changes and impacts on the Bluefields River. However, a “delta fan” was identified at the mouth of the Bluefields River on colonial maps. The area of the fan was much smaller compared to the 1979 debris fan. Nevertheless, colonial fan deposits at the mouth of the Bluefields River may have been a result of soil erosion from land clearing or channel modifications by the British in the Bluefields River watershed.

Pottery from the Taíno settlements were found on the top surfaces of the banks along the lower reaches of the Bluefields River (Figure 33). This indicates that the banks of the Bluefields River are not composed of overbank sediment of Colonial age. Excessive overbank sedimentation relating to Colonial activities would have buried the pottery. While Taíno pottery was only found at one location on the valley floor surface during this study, many finds were made by and archeological investigation being carried out by the University of Binghamton in New York.

Sea Level Rise

Sea level rise during the Holocene Epoch probably gradually increased slope in the lower reaches of the Bluefields River as transgressing seas shortened channel length by shoreline erosion (Figure 7). Shoreline erosion inland over thousands of years would shift the shoreline inland and steepen coastal bluffs. Thus process would have made the lower reach more susceptible to incision since increased slope would add more erosive power to the stream for the same amount of runoff. This effect could have worked in an additive manner with the failure of the coastal highway bridge to increase the rate or depth of channel incision.



Taíno pottery was found in the "A" horizon at a depth of 10 cm.

The location of Taíno pottery indicates the sediment is not a result of historical land use and was present during Taíno settlement.

Figure 33. Land Use Changes and Impacts on Sedimentation. Pottery from the Taíno settlement was found on the tops of the banks indicating historical land use changes had little effect on sedimentation at this location.

CHAPTER 8

CONCLUSIONS

It is important to be able to recognize the influence of infrequent, large floods on channel form within the constraints of longer-term watershed disturbances. There are three main variables that control the erosion and supply sediments in a watershed: precipitation and runoff (climate), soil erodibility and basin relief (geology), and vegetation and land use (surface resistance) (Knighton, 1998). Large magnitude floods can drastically alter channel morphology and sediment transport. Little is known about the geomorphic response of Jamaican rivers to climate, geology, and historical human disturbance. The Bluefields River in Bluefields Bay, Jamaica provides a great opportunity to study channel change and stream response to a large magnitude flood. This study investigates the effects of extreme rainfall and flooding on the geomorphology of the present-day Bluefields River near Belmont, Westmoreland, Jamaica.

Heavy rain combined with low infiltration rates of the karst topography leads to periodic flooding in Jamaica and has been documented on several occasions by the Jamaican government (Donaldson and Walters, 1979). However, on June 12, 1979 a severe tropical depression caused major flooding in southwestern Jamaica. This flood resulted in destruction of property, 41 deaths, and substantial changes to the form of the Bluefields River. Geomorphic effects of the 1979 flood include extensive incision into underlying residuum and colluvial soils, bedrock block transport, and formation of a large debris fan at the mouth of the Bluefields River.

The cause of the debris flows was a combination of a number of factors including excessive rainfall, karst geology, removal of grade structures (bridges), pond failure, mountain runoff, and antecedent soil conditions. When the flood and debris flow destroyed the Coastal Highway and Great House bridges, the result was over steepened slopes and channel incision. The bridges acted as temporary grade control structures that trapped sediments upstream and locally steeped the channel downstream. After the debris flow destroyed the bridges the increased runoff led to head cutting and catastrophic incision upstream of the bridges along the Bluefields River and lower Goat Gulley.

The pond failure combined with the water and sediment being transported down the ephemeral upper stream network of Goat Gulley to cause incision of the upper Goat Gulley. Sediment released from the upper Goat Gulley as well as channel incision by the Bluefields River contributed sediment to the debris fan. Evidence of mass of sediment transported in visible in photographs taken in June 1979 (Figure 10). The debris fan created in 1979 was estimated contain of volume of sediment of 116,000 m^3 (Table 7). The volume of the debris fan that is still present at the mouth of the Bluefields River is estimated to be 84,000 m^3. Coastal erosion has reworked and removed sediment that was present in the debris fan. The amount of sediment produced by incision of the Bluefields River and lower Goat Gulley channels is about half (62,000 m^3) of the total amount of sediment transported in 1979. This imbalance suggest that an additional sediment supply from incision of the upper Goat Gulley or mountain slope failure must have contributed to debris fan accumulation.

The Bluefields River provides an excellent opportunity to study channel morphology changes as a result from a catastrophic event. The history of Bluefields Bay Jamaica is rich with three settlement periods and changes in land use and land cover. Despite the changes in land use we do not find a distinct impact of human accelerated sedimentation on the Bluefields River. The changes in land use seem to have little effect on the channel morphology of the Bluefields River, not including the human modifications due to bridges and aqueducts. Nevertheless, the imprint of human activities on sediment supply and sedimentation may be present higher up in the watershed in upland valleys, hill slope deposits, and field edges. Further, sediment delivery and transport may have been very efficient in this steep, mountain watershed and most excess sediment may have made it to the bay and affected bay sediments, fish habitats, and coral reef health.

On July 28, 2009 the ministry of Agriculture and Fishers declared Bluefields Bay as a fish sanctuary. This designation means the bay will be protected from fishing and managed as breeding and feeding areas to support the fishery and local economy. The Bluefields River supplies sediment to Bluefields Bay which may supply nutrients and substrate for the growth of sea grass (Williams, 1990). Sea grass is important habitat for juvenile fish within the bay. The sediment supply to Bluefields Bay over historical and present-day time-scales may influence the health of the sea grass in Bluefields Bay. Thus, further studies into understanding sediment inputs to Bluefields Bay can be important for both land and fishery managers in Jamaica.

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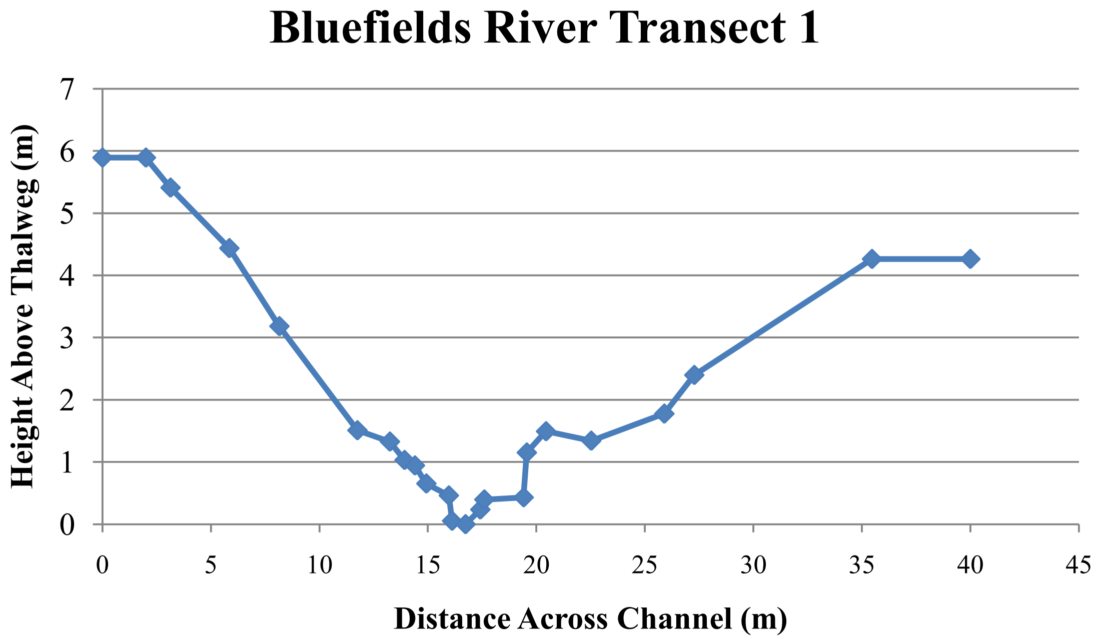
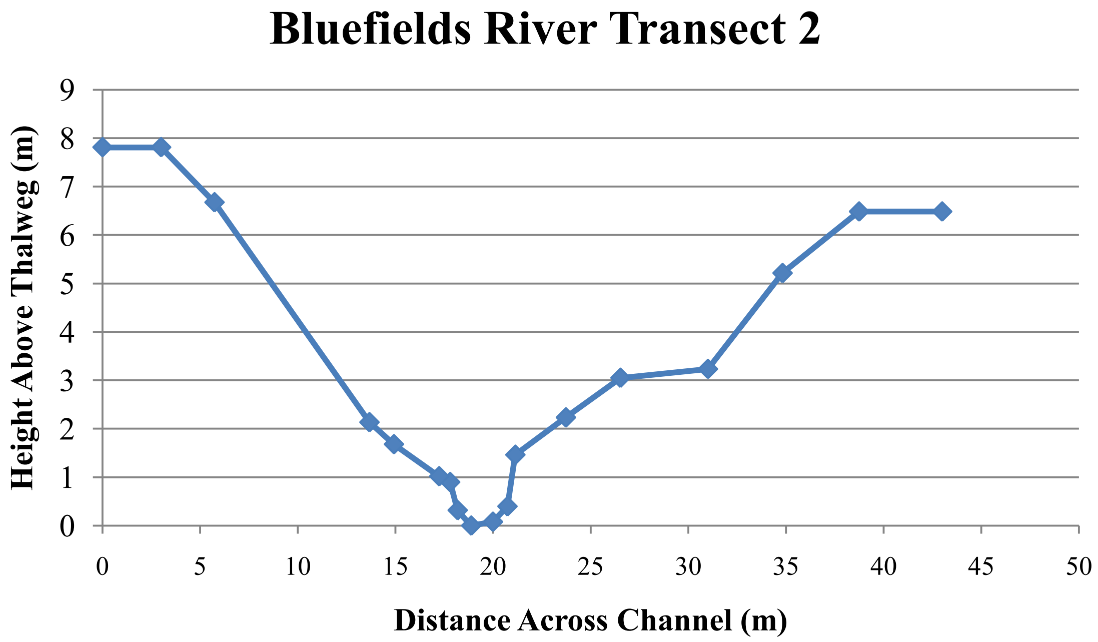
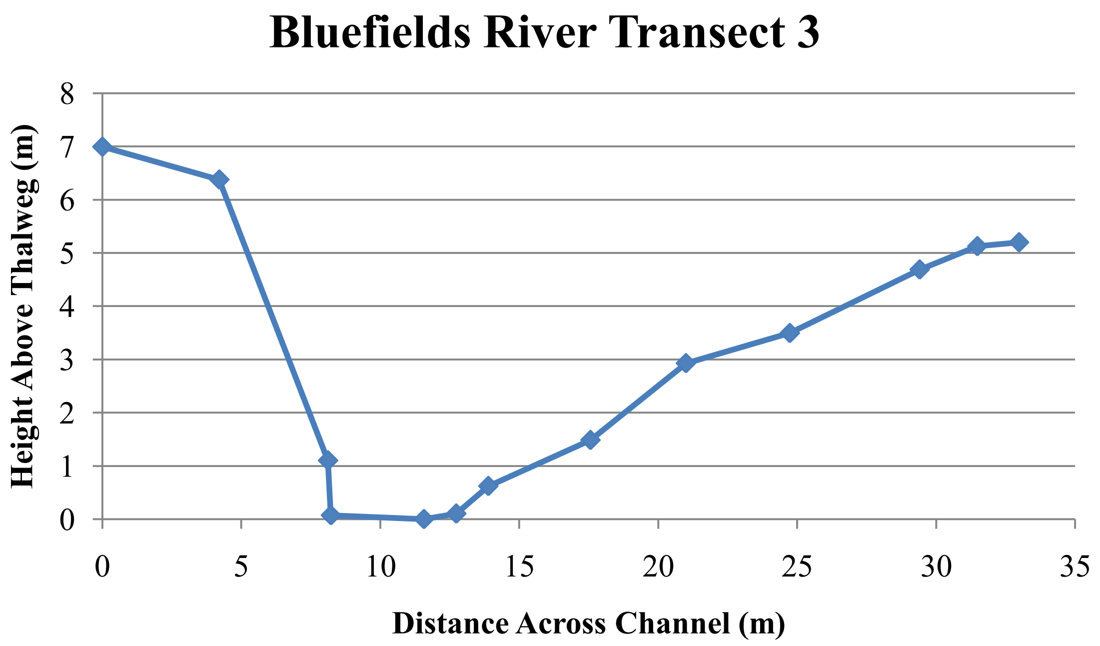
APPENDICES

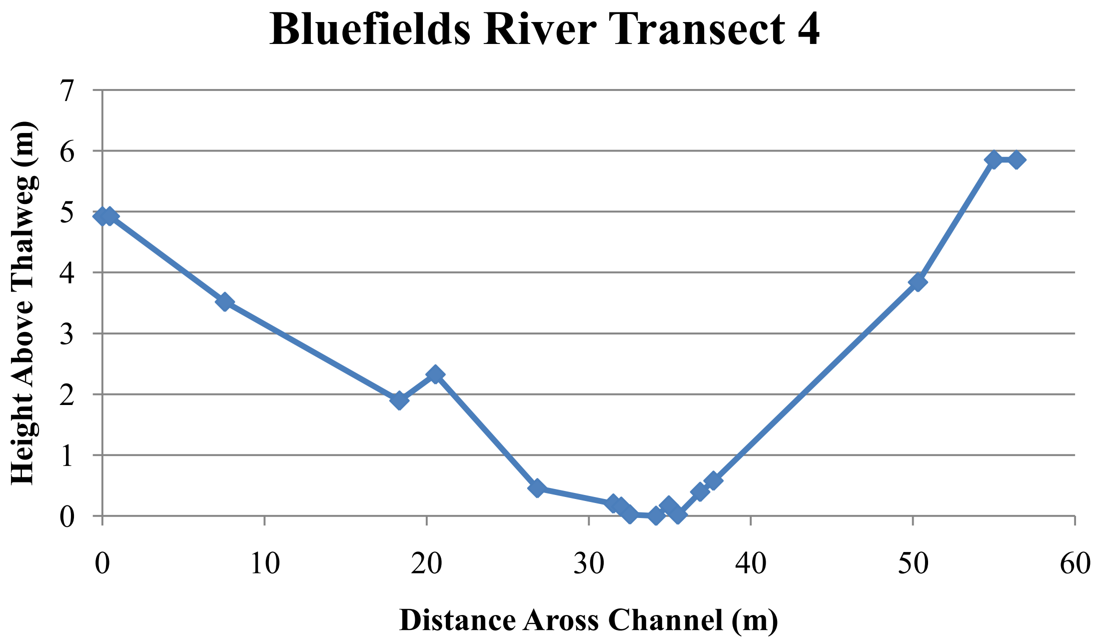
Appendix A. Cross Sections



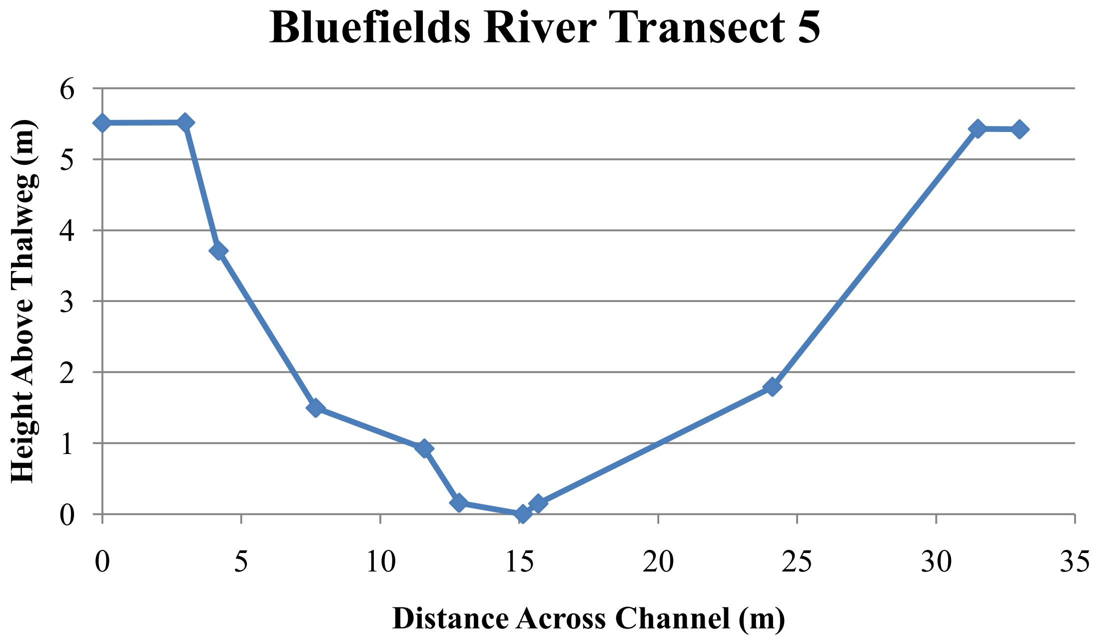


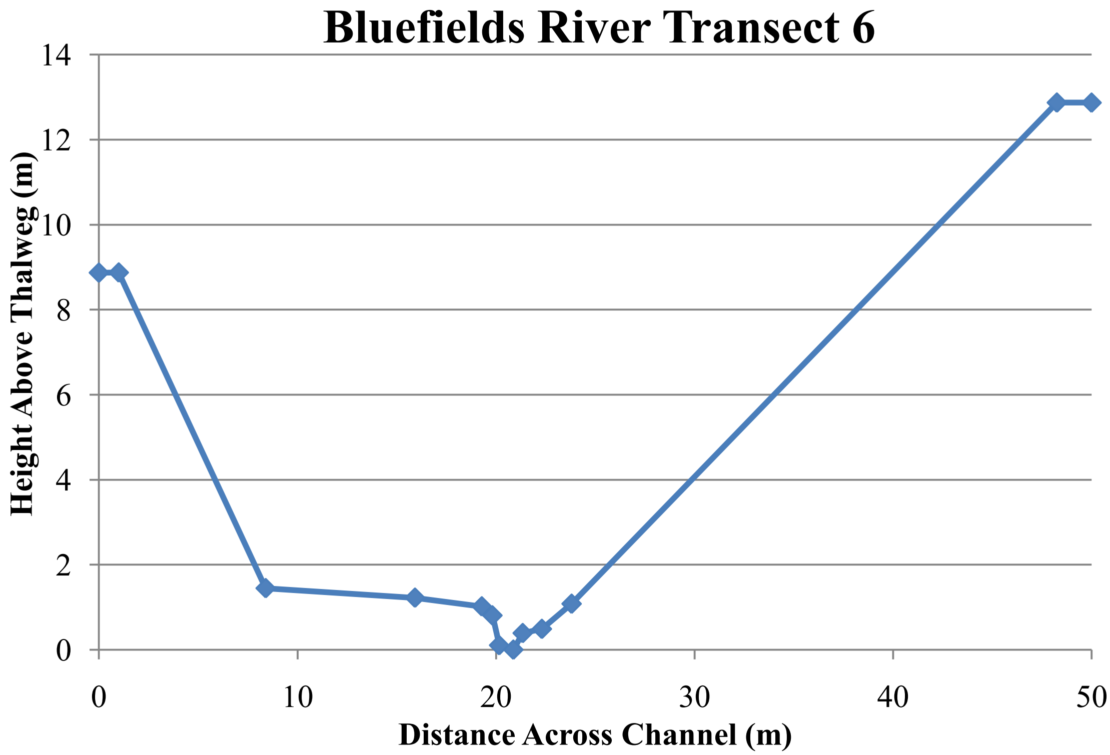
Appendix A Continued. Cross Sections



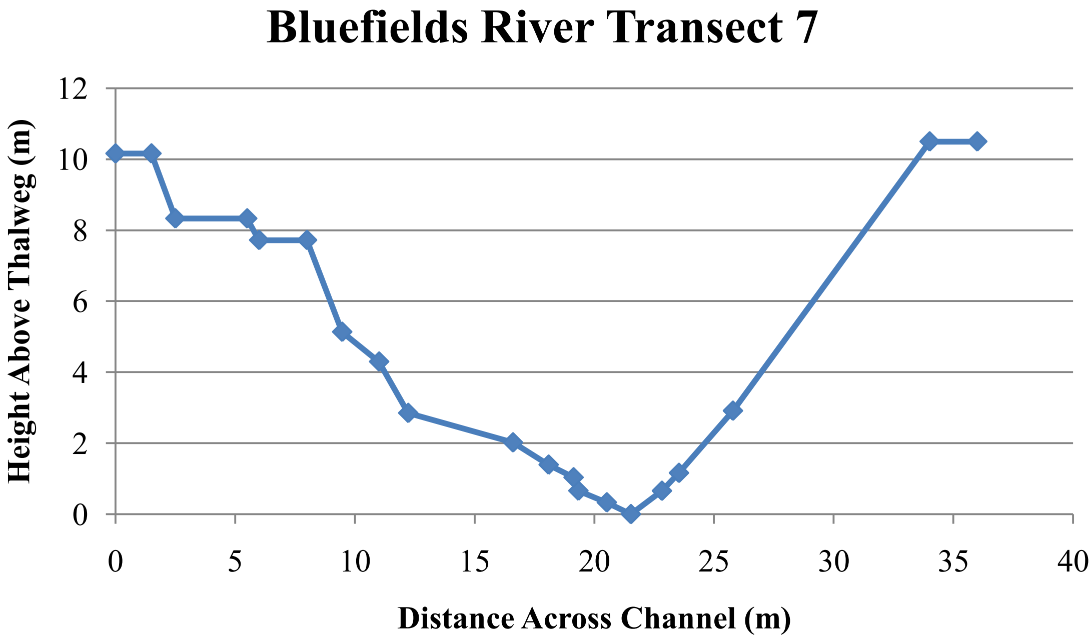


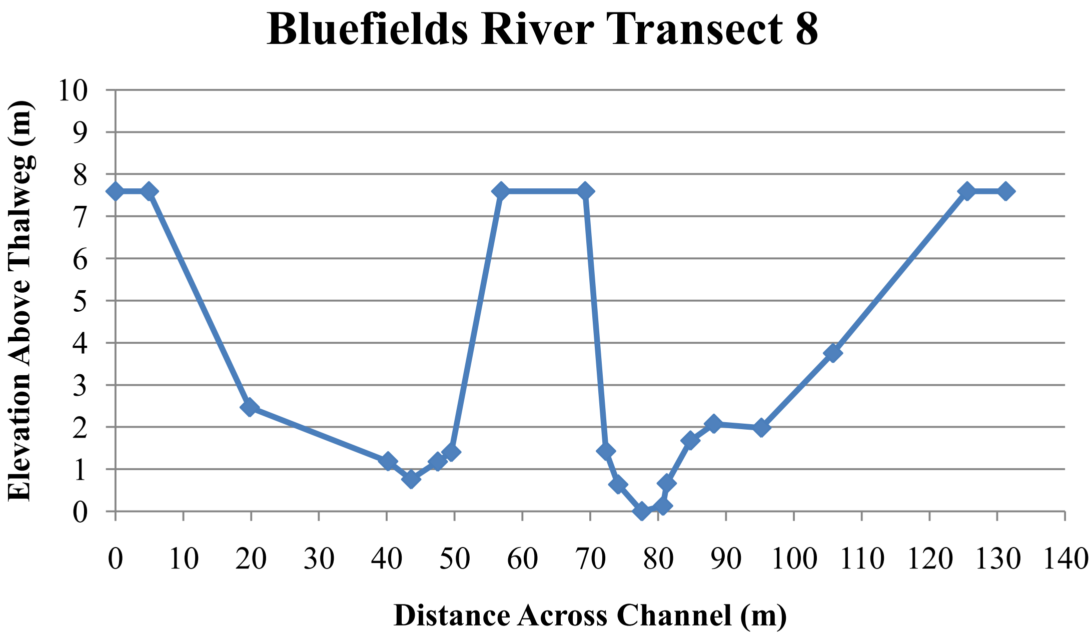
Appendix A Continued. Cross Sections





Appendix A Continued. Cross Sections





Appendix B. Cross Sectional Data

Cross Section 1 Data

Distance Across Channel (m)	Height Above Thalweg (m)	Notes
0.00	5.89	
2.00	5.89	Height Terrace
3.14	5.41	Edge of Terrace
5.85	4.44	Mid
8.15	3.18	Mid
11.75	1.51	High Terrace
13.25	1.33	TOB
13.92	1.03	
14.40	0.94	
14.93	0.65	
15.96	0.46	
16.11	0.05	Toe
16.73	0.00	Tw 905
17.41	0.24	Toe
17.60	0.40	Bar
19.41	0.43	Toe
19.56	1.15	
20.44	1.49	TOB
22.53	1.34	
25.90	1.78	
27.28	2.40	
35.47	4.26	High Surface off line
40.00	4.26	

Appendix B Continued. Cross Sectional Data

Cross Section 2 Data

Distance Across Channel (m)	Height Above Thalweg (m)	Notes
0.00	6.48	High surface
3.92	5.21	
7.74	3.23	
12.22	3.05	
15.01	2.23	
17.60	1.46	TOB
18.01	0.40	TOB
18.75	0.08	Tw 848
19.86	0.00	
20.56	0.32	Toe
20.94	0.90	TOB
21.50	1.02	
23.82	1.68	
25.08	2.13	
33.01	6.67	High surface
38.74	7.81	High surface
43.00	7.81	

Appendix B Continued. Cross Sectional Data

Cross Section 3 Data

Distance Across Channel (m)	Height Above Thalweg (m)	Notes
0.00	5.20	
1.50	5.13	High Surface
3.58	4.69	
8.25	3.50	
11.99	2.93	
15.42	1.49	
19.10	0.62	TOB
20.25	0.10	TOB
21.41	0.00	TOB
24.76	0.07	Gauge
24.87	1.10	Top of Gauge .3
28.78	6.38	High Surface
32.99	6.99	High Surface

Appendix B Continued. Cross Sectional Data

Cross Section 4 Data

Distance Across Channel (m)	Height Above Thalweg (m)	Notes
0.00	4.92	
0.46	4.92	High Surface
7.56	3.52	Top Gravel Lens
18.32	1.89	Old FP
20.55	2.32	
26.83	0.45	
31.52	0.20	TOB
32.01	0.15	Edge
32.54	0.02	Toe
34.15	0.00	TW
34.94	0.17	Edge
35.50	0.02	Toe
36.87	0.39	TOB
37.70	0.58	Bench
50.31	3.84	Gravel Lens
55.00	5.85	High Surface
56.39	5.85	

Appendix B Continued. Cross Sectional Data

Cross Section 5 Data

Distance Across Channel (m)	Height Above Thalweg (m)	Notes
0.00	5.42	
1.50	5.43	High Surface
8.89	1.79	TOB
17.32	0.15	Toe-edge
17.87	0.00	Tw 575
20.17	0.16	Edge
21.42	0.92	TOB
25.33	1.50	
28.82	3.71	
30.03	5.52	High Surface
33.00	5.51	

Cross Section 6 Data

Distance Across Channel (m)	Height Above Thalweg (m)	Notes
0.00	8.87	
1.00	8.87	High Surface
8.40	1.45	
15.92	1.22	
19.29	1.02	TOB
19.82	0.81	TOB
20.16	0.11	Edge
20.88	0.00	Tw
21.35	0.39	
22.31	0.49	Edge
23.81	1.08	
48.25	12.87	High Surface
50.00	12.87	

Appendix B Continued. Cross Sectional Data

Cross Section 7 Data

Distance Across Channel (m)	Height Above Thalweg (m)	Notes
0.00	10.50	
1.99	10.50	TOB
10.21	2.91	
12.46	1.16	
13.17	0.66	edge
14.47	0.00	Tw
15.48	0.33	Bar
16.66	0.66	Edge
16.86	1.04	
17.91	1.39	
19.39	2.02	
23.77	2.85	
24.99	4.30	
26.53	5.13	
28.00	7.72	
30.00	7.72	Old floodplain ?
30.50	8.33	
33.50	8.33	
34.50	10.16	TOB
36.00	10.16	

Appendix B Continued. Cross Sectional Data

Cross Section 8 Data

Distance Across Channel (m)	Height Above Thalweg (m)	Notes
0.00	7.59	TOB
1.50	7.59	TOB
6.03	2.47	Edge
12.25	1.19	Tw
13.29	0.76	Edge
14.48	1.18	TOB
15.09	1.40	Toe
17.33	7.59	TOB
21.10	7.59	Edge
22.04	1.43	Tw
22.59	0.63	Tw
23.65	0.00	Edge
24.60	0.13	
24.77	0.66	
25.83	1.68	
26.89	2.08	
29.02	1.98	
32.24	3.75	
38.27	7.59	
40.00	7.59	

Appendix C. Photo Log

River Top Bridge- Upstream (River meter 1077)

River Meter 937- Upstream

Appendix C Continued. Photo Log

River Meter 917- Downstream

River Meter 876- Upstream

Appendix C Continued. Photo Log

River Meter 837-Downstream

River Meter 817- Downstream

Appendix C Continued. Photo Log

River Meter 768.2- Upstream

River Meter 768.2- Goat Gulley Downstream

Appendix C Continued. Photo Log

River Meter 757- Upstream

River Meter 737- Upstream

Appendix C Continued. Photo Log

River Meter 697-Upstream

River Meter 657-Upstream

Appendix C Continued. Photo Log


River Meter 617- Upstream


River Meter 577- Downstream

Appendix C Continued. Photo Log

River Meter 577- Upstream

River Meter 537- Downstream

Appendix C Continued. Photo Log

River Meter 517- Upstream

River Meter 477- Upstream

Appendix C Continued. Photo Log

River Meter 437- Downstream

Appendix C Continued. Photo Log

River Meter 415- Upstream

Appendix C Continued. Photo Log

River Meter 397- Upstream

River Meter 340.2- Downstream

Appendix C Continued. Photo Log

River Meter 330 Downstream

River Meter 330 - Upstream

Appendix C Continued. Photo Log

River Meter 230- Upstream

River Meter 195.9- Downstream

Appendix C Continued. Photo Log

River Meter 69.1 Upstream

River Meter 69.1- Upstream

Appendix C Continued. Photo Log

River Meter 69.1- Downstream

Appendix C Continued. Photo Log

River Meter 55- Downstream

Appendix C Continued. Photo Log

River Meter 0

Appendix D. GPS Points

Comment (Location)	Latitude	Longitude
Colonial Pond	18.161247158	-78.011361152
Colonial Pond	18.161253131	-78.011361178
Gulley cut 1 4 m deep	18.163076793	-78.012842986
Goat Gulley trib rd crossing	18.165413785	-78.017082992
Old Great House bridge east	18.168049666	-78.024066775
Old Great House Rd end east	18.167922469	-78.024217897
OLD GH end road west red brick	18.168055024	-78.024497202
Old hwy bridge 1	18.167335212	-78.026974040
New bridge coastal hwy	18.167139400	-78.026752317
Old hwy east	18.167005451	-78.026837383
Old hwy east	18.166313962	-78.026836863
Old hwy east end	18.166167181	-78.026819444
Tr3	18.167171311	-78.026225620
T4	18.167280389	-78.025664289
T5	18.167266533	-78.025031647
T5 second gps	18.167366089	-78.024997225
T6	18.167505416	-78.024796592
T7	18.168569114	-78.023903209
T8	18.169112045	-78.023944823
Old great house bridge	18.167959179	-78.024000713
RiverTop br west	18.178216620	-78.026643597

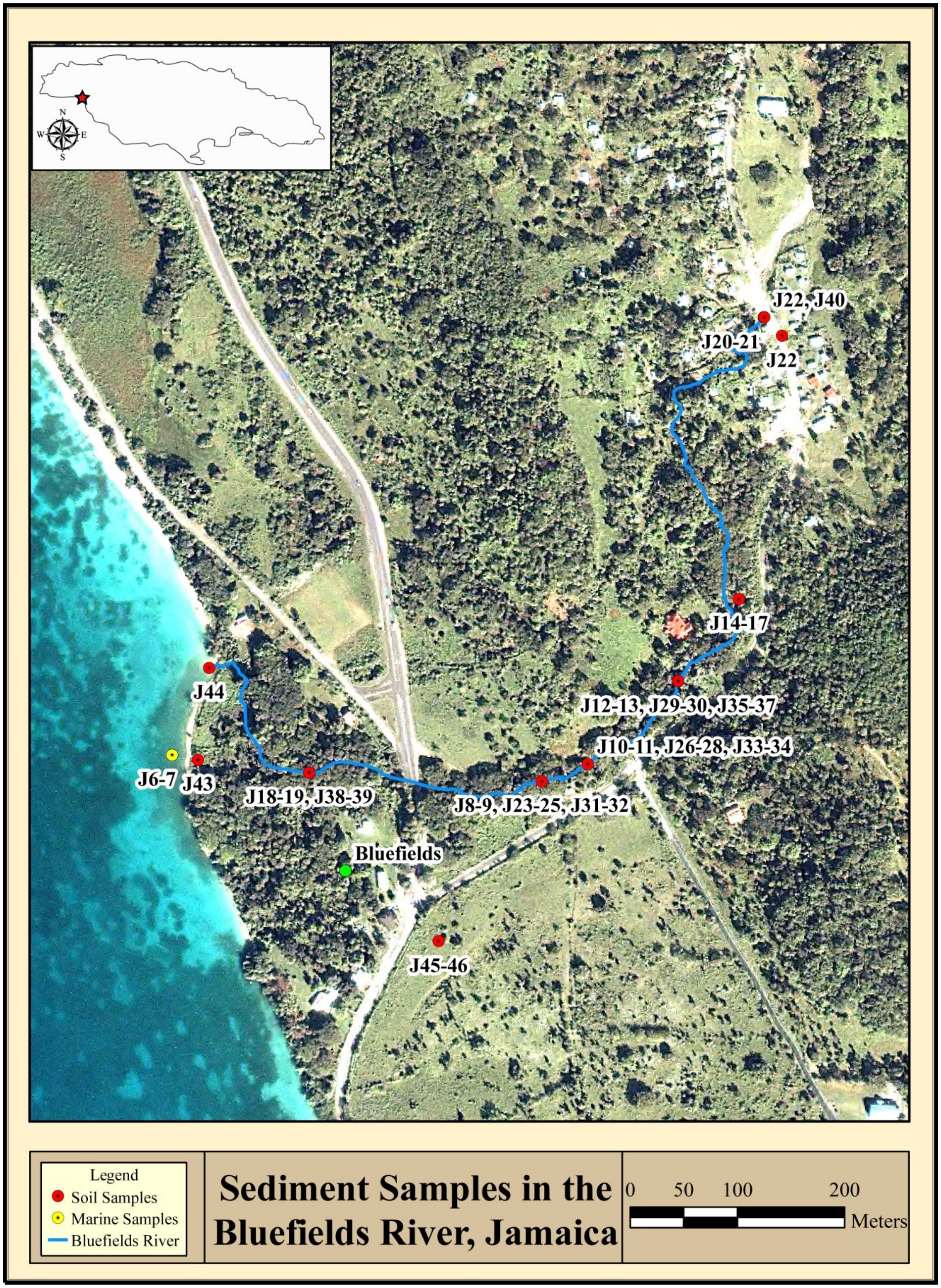
Appendix D Continued. GPS Points

Comment (Location)	Latitude	Longitude
Survey 1- River Top	18.170839388	-78.023852011
Survey 1- River Top GPS 2	18.170613441	-78.023685742
Survey 2- GPS 1	18.170413673	-78.024451312
Survey 2- GPS 2	18.169926367	-78.024408072
Survey 3- GPS 1	18.169711712	-78.024266968
Survey 3- GPS 2	18.169446573	-78.024048315
Survey 4- GPS 1	18.169105236	-78.023930226
Survey 5-GPS 1	18.168644885	-78.023757690
Survey 5-GPS 2	18.168493389	-78.023958517
Survey 6-	18.168236576	-78.023993420
Survey 7	18.168100919	-78.024280640
Survey 8-	18.167394195	-78.024940943
Survey 9-	18.167121562	-78.025413521
Survey 10-	18.167168708	-78.025401517
Survey 11-	18.167010204	-78.026200061
Survey 12-	18.167218649	-78.026946880
Survey 13	18.167206305	-78.027344923
Survey 14	18.167624748	-78.028156505
Fan Survey	18.167947586	-78.028104286
BFR mouth	18.168135672	-78.028487651
End fan	18.168491491	-78.028505405
BFR mouth2	18.168194109	-78.028487954

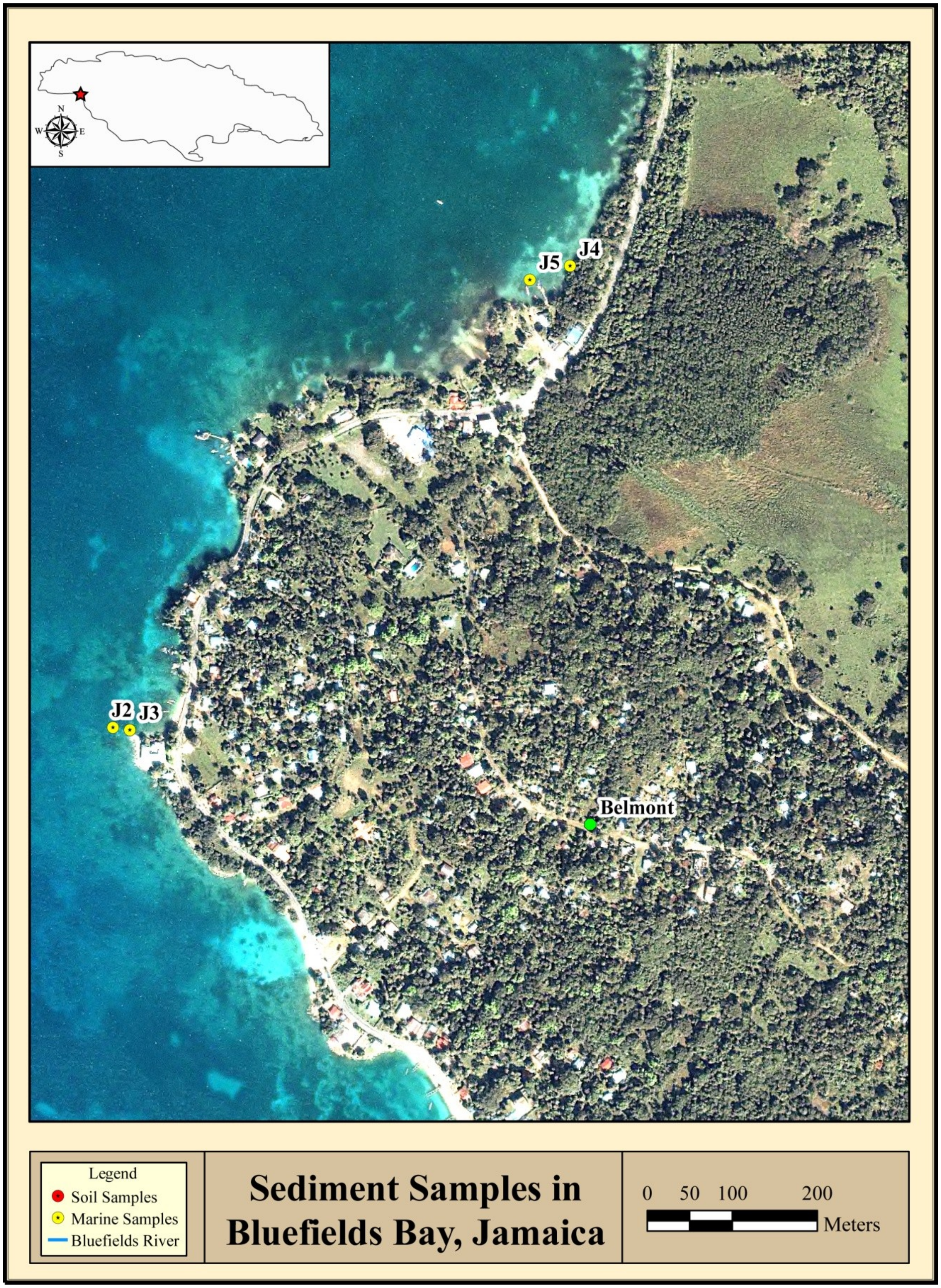
Appendix D Continued. GPS Points

Comment (Location)	Latitude	Longitude
Fan1	18.168023887	-78.028495883
BFR mouth3	18.167976288	-78.028485843
Fan2	18.167900122	-78.028512537
BFR mouth 3	18.167794125	-78.028529872
Fan 3	18.167689831	-78.028555925
Conglomerate 1ft,2ft	18.167620499	-78.028577417
Fan 4	18.167567439	-78.028602816
Fan 5	18.167426605	-78.028605082
Fan 6	18.167328444	-78.028617833
Fan 7	18.167146437	-78.028612965
Fan 8	18.167080070	-78.028642371
End fan east	18.166901449	-78.028635445
GPS 2	18.168120217	-78.028456867
T1	18.167272188	-78.027869311

Appendix E. Sediment Sampling Maps



Appendix E Continued. Sediment Sampling Maps



Appendix F. Sample Attributes and Geochemistry

Type	Sample Number	Site	Site	Sample #	Form	River M	Munsell Color	Notes
J	1					0.0		Crushed Bed Coating
J	2	15m offshore from sunset	M	1	Marine	0.0	2.5 YR 8/2	Sunset Cottages
J	3	Near gazebo	M	2	Marine	0.0	2.5 YR 8/3	Sunset Cottages
J	4	Above water level under mangrove	M	3	Marine	0.0	2.5 YR 8/2	BPCA
J	5	15 m offshore of fishing beach	M	4	Marine	0.0	2.5 YR 7/1	Fishing Beach
J	6	Debris Fan	M	5	Marine	0.0	2.5 YR 8/2	Debris Fan
J	7	Debris Fan	M	6	Marine	0.0	2.5 YR 7/2	Debris Fan
J	8	Gauge on BFR	1	1	Channel	340.0	10 YR 6/4	
J	9	Gauge on BFR	1	2	Channel	340.0	10 YR 7/2	
J	10	Omars Field	2	3	Channel	407.2	10 YR 6/2	
J	11	Omars Field	2	4	Channel	407.2	11 YR 6/2	
J	12	Old great house bridge	3	5	Channel	741.1	12 YR 6/2	
J	13	Old great house bridge	3	6	Channel	741.1	13 YR 6/2	
J	14	Confluence of Goat Gulley and BFR	4	7	Channel	761.9	10 YR 5/2	
J	15	Confluence of Goat Gulley and BFR	4	8	Channel	761.9	10 YR 6/2	
J	16	Confluence of Goat Gulley and BFR	4	9	Channel	761.9	10 YR 6/2	
J	17	Confluence of Goat Gulley and BFR	4	10	Channel	761.9	10 YR 7/4	
J	18	30 m US of debris fan	5	11	Channel	153.4	10 YR 7/4	

Appendix F Continued. Sample Attributes and Geochemistry

Type	Sample Number	Site	Site	Sample #	Form	River M	Munsell Color	Notes
J	19	30 m US of debris fan	5	12	Channel	153.4	10 YR 8/2	
J	20	Rivertop Bridge	6	13	Channel	1052.5	2.5 YR 8/1	
J	21	Rivertop Bridge	6	14	Channel	1052.5	10 YR 5/1	
J	22	Rivertop Bridge	6	15	Channel	1052.5	10 YR 5/2	
J	23	Gauge on BFR	1	1	Bank	340.0	10 YR 4/3	A Horiz, Pottery
J	24	Gauge on BFR	1	2	Bank	340.0	10 YR 8/2	B/E
J	25	Gauge on BFR	1	3	Bank	340.0	2.5 YR 8/3	C Horiz, Shells
J	26	Omars Field	2	4	Bank	407.2	10 YR 5/3	A Horiz, Shells
J	27	Omars Field	2	5	Bank	407.2	10 YR 8/3	
J	28	Omars Field	2	6	Bank	407.2	10 YR 8/3	
J	29	Old great house bridge	3	7	Bank	741.1	10 YR 8/3	
J	30	Old great house bridge	3	8	Bank	741.1	10 YR 7/8	Concretions
J	31	Gauge on BFR	1	1	FP	340.0	10 YR 6/2	
J	32	Gauge on BFR	1	2	FP	340.0	10 YR 6/2	
J	33	Omars Field	2	3	FP	407.2	10 YR 6/2	
J	34	Omars Field	2	4	FP	407.2	2.5 YR 8/3	Charcoal
J	35	Old great house bridge	3	5	FP	741.1	10 YR 8/3	
J	36	Old great house bridge	3	6	FP	741.1	10 YR 5/4	
J	37	Old great house bridge	3	7	FP	741.1	10 YR 6/3	
J	38	30 m US of debris fan	5	8	FP	153.4	10 YR 5/4	
J	39	30 m US of debris fan	5	9	FP	153.4	10 YR 5/4	
J	40	Rivertop Bridge	6	10	FP	1052.5	10 YR 7/2	

Appendix F Continued. Sample Attributes and Geochemistry

Type	Sample Number	Site	Site	Sample #	Form	River M	Munsell Color	Notes
J	41	BPCA- MG Topsoil	MG	0	Mangrove	0.0	10 YR 7/1	
J	42	Fishing Beach	MG	2	Mangrove	0.0	10 YR 8/2	
J	43	Debris Fan	7	Fan 1	Fan	90.0	10 YR 6/2	BPCA- MG Topsoil
J	44	Debris Fan	7	Fan 2	Fan	90.0	10 YR 6/2	Fishing Beach
J	45	Arc Site	ARC 1	1	Arc	0.0	10 YR 5/4	Fan
J	46	Arc Site	ARC 1	2	Arc	0.0	10 YR 7/4	Fan
J	47	Coral (Crushed)				0.0		A Horiz, Arc Site
J	48	Brain Coral (Crushed)				0.0		B/E Horiz, Arc Site
J	49	Staghorn Coral (Crushed)				0.0		
J	50	White Limestone (Crushed)				0.0		
J	51	Asphalt (Crushed)				0.0		
J	52	Pottery (Crushed)				0.0		
J	53	Brick (Crushed)				0.0		

Appendix F Continued. Sample Attributes and Geochemistry

Sample ID	Element Concentration (ppm)										
	Zn	Cu	Cd	Fe	Cr	Mn	Ni	Sr	Ca	Zr	Mo
J 1 Crushed	ND	ND	62	565	138	ND	ND	943	475430	13	17
J 2 <250um	ND	ND	59	2677	233	ND	ND	5789	427244	96	16
J 3 <250um	ND	ND	57	1810	216	ND	ND	6375	429012	96	20
J 4 <250um	ND	ND	55	1418	297	ND	ND	6770	455124	106	15
J 5 <250um	16	ND	48	4361	158	ND	ND	5254	385328	108	18
J 6 <250um	10	ND	50	3741	177	ND	ND	3247	418844	56	22
J 7<250um	8	ND	40	3399	214	ND	ND	4389	387662	78	23
J 8<250um	32	ND	69	2982	224	ND	ND	592	425414	18	15
J 9<250um	32	ND	56	3168	127	ND	ND	541	409383	25	22
J 10<250um	50	ND	53	3768	157	ND	ND	578	421457	28	19
J 11<250um	35	ND	55	3403	173	ND	ND	538	403940	22	23
J 12<250um	39	ND	42	4641	229	ND	ND	557	411862	40	22
J 13<250um	49	ND	49	4469	142	ND	ND	512	397679	25	21
J 14<250um	113	ND	53	12962	82	320	24	862	334115	65	15
J 15<250um	100	ND	59	10818	143	42	21	458	260904	59	24
J 16<250um	49	15	69	4359	163	ND	ND	542	395069	37	19
J 17<250um	73	ND	49	4158	206	ND	ND	545	397737	39	20
J 18<250um	32	ND	47	3729	194	ND	ND	600	413481	20	16
J 19<250um	25	ND	61	4882	193	ND	ND	884	409700	33	16
J 20<250um	27	ND	48	4897	169	ND	ND	608	479940	18	18
J 21 <250um	112	149	51	6877	154	74	ND	571	355479	32	18
J 22 <250um	78	21	64	7365	95	ND	ND	571	352026	79	16

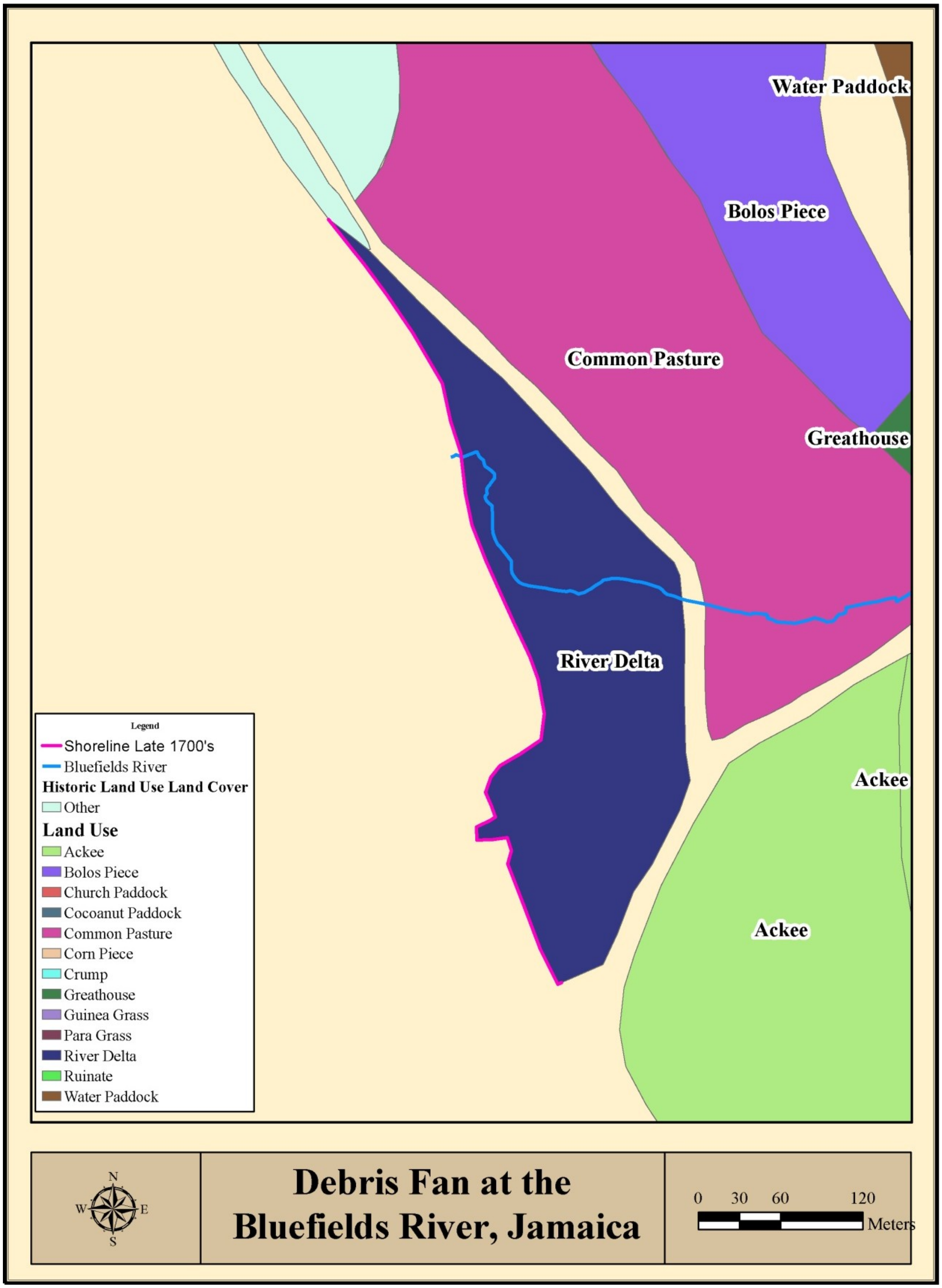
Appendix F Continued. Sample Attributes and Geochemistry

Sample ID	Element Concentration (ppm)									
	Zn	Cu	Cd	Fe	Cr	Mn	Ni	Sr	Ca	Zr	Mo
J 23 <250um	120	20	36	11496	112	330	24	506	300331	78	24
J 24 <250um	20	ND	43	3650	122	ND	ND	498	426064	31	21
J 25 <250um	43	ND	72	6843	170	49	ND	483	429951	37	18
J 26 <250um	114	16	47	13958	168	497	41	441	299700	69	19
J 27 <250um	18	ND	47	3356	130	ND	ND	501	432109	31	21
J 28 <250um	20	ND	68	3189	114	ND	ND	481	433399	24	23
J 29 <250um	38	ND	49	2143	94	ND	ND	679	416572	31	25
J 30 <250um	100	39	53	41996	72	2570	103	579	422603	34	16
J 31 <250um	140	30	45	29418	197	1197	68	348	170418	109	24
J 32 <250um	156	28	61	31257	132	1171	66	384	197295	111	21
J 33 <250um	42	ND	33	4055	167	ND	ND	521	405349	32	19
J 34 <250um	32	ND	ND	3201	218	ND	ND	498	390485	20	22
J 35 <250um	41	ND	47	5896	158	ND	22	655	405840	48	22
J 36 <250um	18	ND	49	2581	135	ND	16	774	451623	27	18
J 37 <250um	78	ND	54	11212	66	64	34	654	300794	70	16
J 38 <250um	59	ND	53	12827	178	721	26	532	341773	62	18
J 39 <250um	60	ND	51	15526	260	934	32	466	342317	51	20
J 40 <250um	22	ND	42	1923	143	ND	ND	578	445457	30	18
J 41 <250um	15	ND	36	5580	146	48	ND	5368	409663	105	13
J 42 <250um	10	ND	47	2078	257	ND	ND	6217	454500	106	13
J 43 <250um	55	ND	63	5013	104	58	ND	502	364218	33	18
J 44 <250um	43	ND	71	5069	166	63	ND	534	379774	39	19

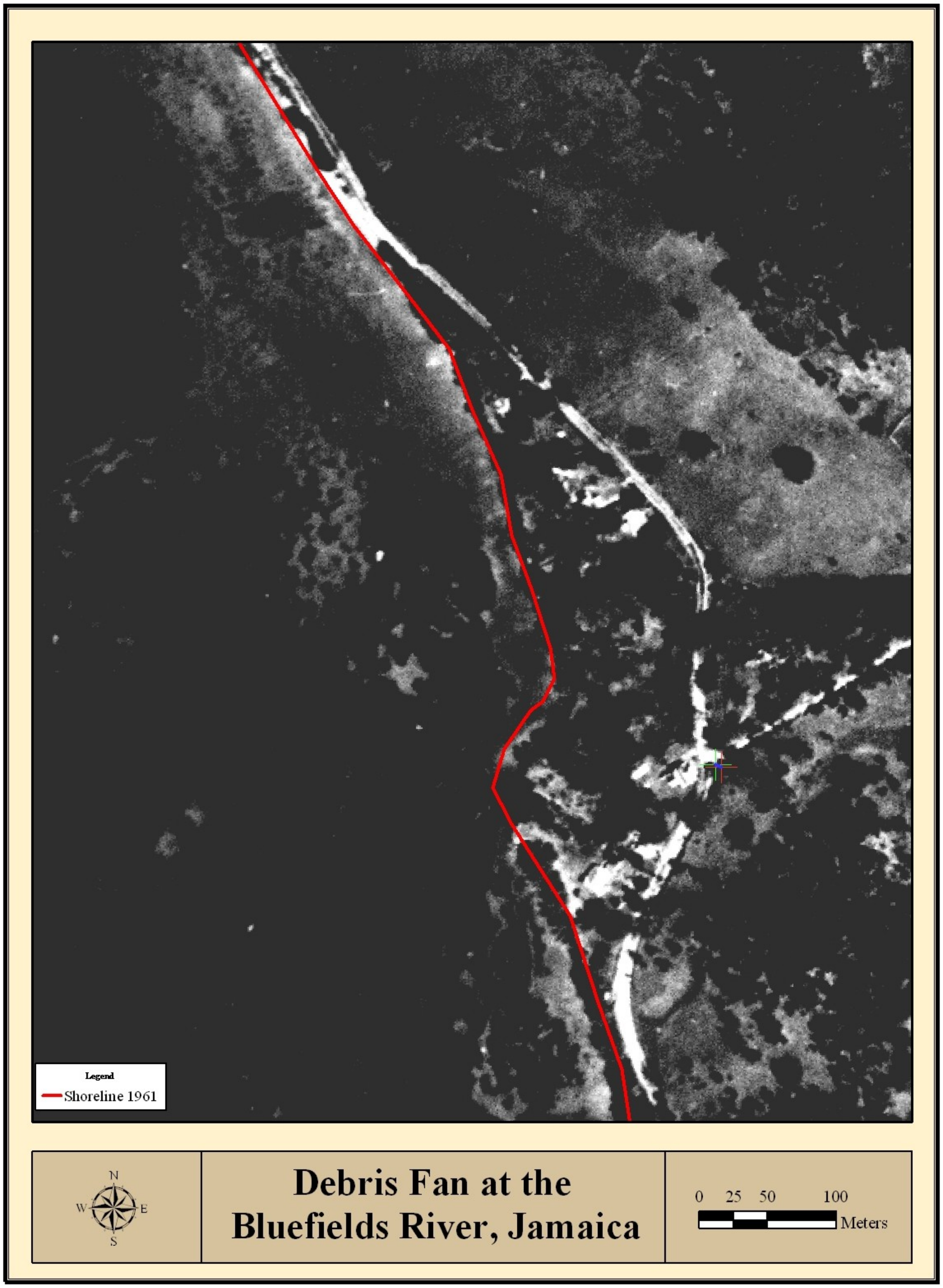
Appendix F Continued. Sample Attributes and Geochemistry

Sample ID	Element Concentration (ppm)										
	Zn	Cu	Cd	Fe	Cr	Mn	Ni	Sr	Ca	Zr	Mo
J 45 <250um	131	19	42	12401	99	646	30	515	306650	64	18
J 46 <250um	48	ND	55	8158	110	132	18	566	383508	40	24
J 47 Crushed	989	1320	ND	ND	ND	111	ND	ND	ND	157702	30
J 48 Crushed	1978	859	ND	ND	ND	111	48	ND	ND	158315	37
J 49 Crushed	2913	3310	ND	995	ND	148	ND	ND	ND	117351	57
J 50 Crushed	1243	1395	ND	590	ND	86	50	ND	ND	53068	55
J 51 Crushed	1022	1041	ND	ND	ND	163	48	ND	ND	133593	37
J 52 Crushed	679	1115	ND	ND	ND	46	ND	ND	ND	92174	34
J 53 Crushed	572	1146	ND	586	ND	69	ND	ND	ND	56360	92

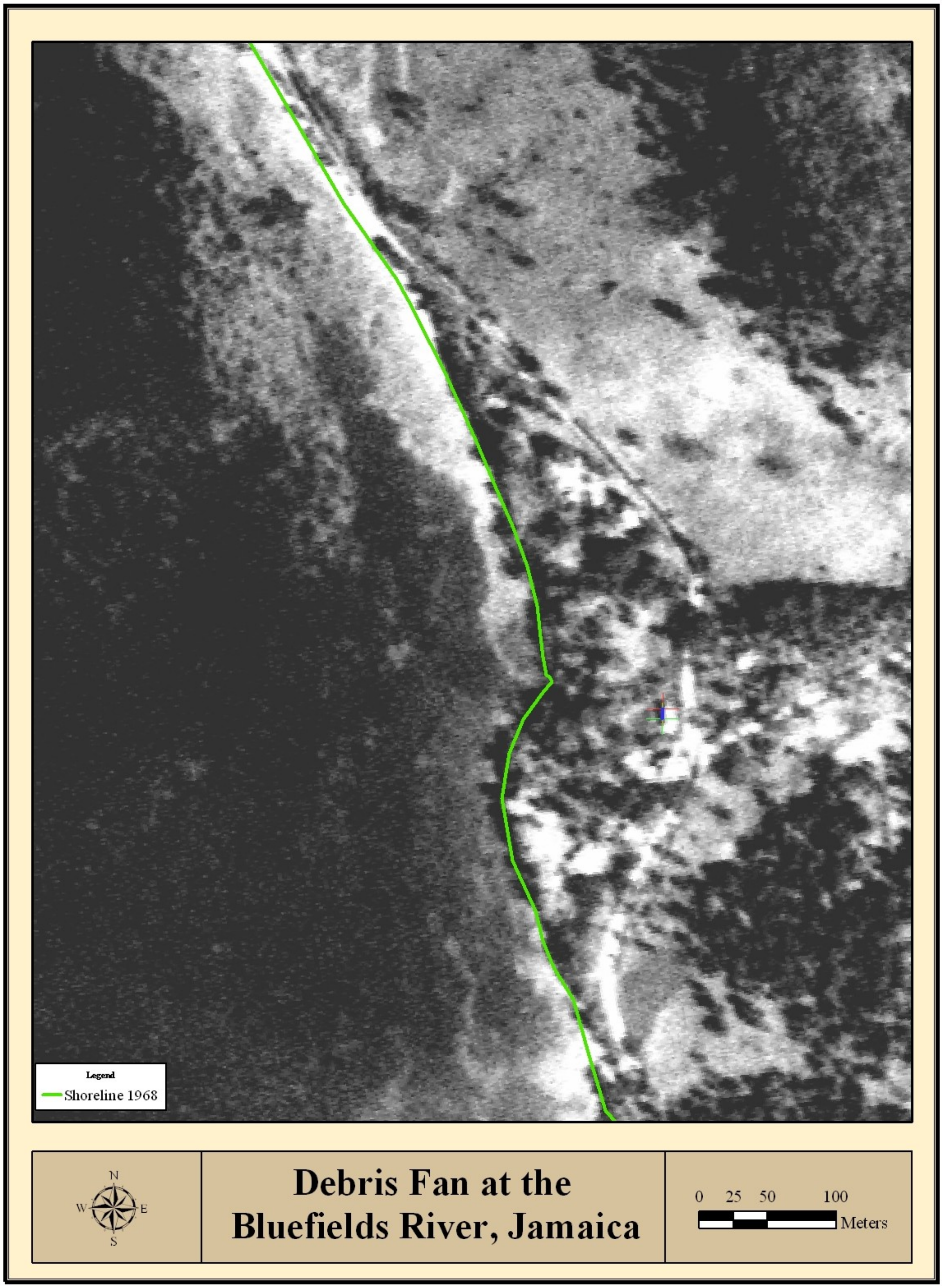
Appendix G. Aerial Photographs and Maps



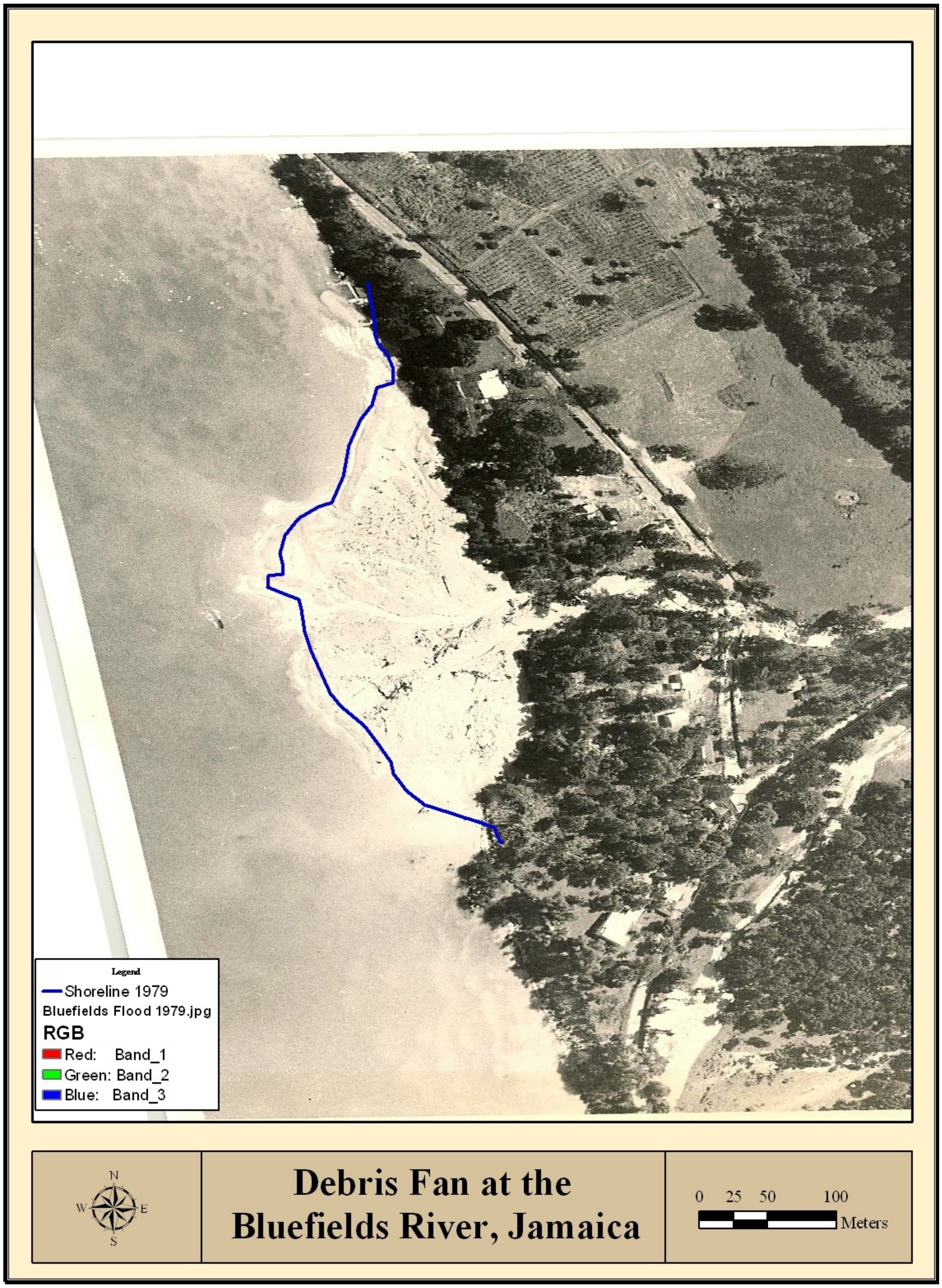
Appendix G Continued. Aerial Photographs and Maps



Appendix G Continued. Aerial Photographs and Maps



Appendix G Continued. Aerial Photographs and Maps



Debris Fan at the Bluefields River, Jamaica

Appendix G Continued. Aerial Photographs and Maps

Appendix G Continued. Aerial Photographs and Maps