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Geomorphic Response to Catastrophic Flooding in a Karst Mountain Stream System, Brighton-Blue Hole Watershed, Southwest Jamaica

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GEOMORPHIC RESPONSE TO CATASTROPHIC FLOODING IN A KARST MOUNTAIN STREAM SYSTEM, BRIGHTON-BLUE HOLE WATERSHED, SOUTHWEST JAMAICA

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Master of Science, Geospatial Sciences in Environmental Geology

By

Sarah Madeline LeTarte

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ABSTRACT

The geomorphic effects of flooding are poorly understood in the karst, mountain watersheds along the southwest coast of Jamaica. This study describes the flow path and geomorphic response of an extreme flood event in the Brighton-Blue Hole watershed (BBHW) (6.8 km2) near Belmont, Westmoreland, Jamaica. A tropical depression classified as a >100-year rainfall event produced 32 inches of rain in a 24 hour period in Westmoreland on June 12, 1979. For this study, geomorphic indicators of flood disturbance in BBHW were assessed in 2017-18, finding that channel system responded to the flood with channel incision, debris flows, and flooding in communities. Flood effects were controlled by: (i) a structurally controlled fault block valley which decreased the elevation of the watershed divide allowing piracy of floodwater from BBHW, across the divide, and into the Bluefields River increasing flood stage there; (ii) karst depressions at progressively descending elevations which caused floodwaters to become impounded and thus attenuated stream power downstream; (iii) a morass/wetland and mangrove forest system separated from the sea by a beach barrier thus created a low area which slowed and retained flood waters before they flowed to sea via a culvert under a coastal highway; and (iv) overtopping and failure of the rim of a karst depression which produced the most destructive flood and channel response, including 9 deaths. A flood risk map was created for communities in BBHW using the areas of inundation by floodwaters and locations of geomorphic effects for reference. BBHW is relatively resilient to flooding when compared to neighboring watersheds. However, climate change and future development in the watershed threaten to increase the potential for flood damage and create higher risk to the community.

KEYWORDS: fluvial geomorphology, resilience, extreme flooding, karst, Jamaica

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INTRODUCTION

Caribbean countries are often affected by extreme flooding which leads to extensive loss of life and property (Nkemdirim and Jones, 1978; Carby and Ahmad, 1995; Gupta, 2000). To address disaster in the region, the fifteen countries of the Caribbean Community (CARICOM) created the Caribbean Disaster Emergency Management Agency (CDEMA), which was organized in 2005 after floods from Hurricane Hugo devastated the region. Island nations in the Caribbean region are affected by a wide variety of natural hazards due to their tectonic setting, geology, climate and topography. The severity of natural hazards are often exacerbated by poor land use and environmental management practices (Carby, 2011). About 77% of the disasters in the Caribbean are attributed to natural hazards, the majority of which involve flooding and windstorms (Collymore, 2007). Between 1980 and 2012, 200 floods were reported in the region and 125 involved deaths (Andrewin et al., 2015). To better understand the relationship between floods and stream morphology in the Caribbean, it is important to understand the ways climate, geological setting, and land use factors affect floods there.

Climate Factors

According to the updated Koppen climate classification system, the Caribbean has a tropical climate with regular warm temperatures, averaging 68 degrees Fahrenheit, which provide a constant source of humidity from evaporation (Peel et al., 2007). This warm, moist air provides a source of heavy precipitation to the islands due to prolonged cyclonic rain events caused by tropical cyclones, fronts, troughs, and intense hurricanes due to their proximity to the Atlantic Hurricane Belt (Watts, 1990; Gupta, 2000; Rasmussen, 2004; Peel et al., 2007; Taylor et al., 2011; Burgess et al., 2015a; Nandi et al., 2016). Gupta (1999) reported that in general, a 24 hour rainfall event which produces hundreds of millimeters of rain is relatively common, with a recurrence interval on the order of decades. Also common are high intensity rainfall events which last for several days. Precipitation in the Caribbean is characterized by its seasonal regime. Most islands experience two wet periods, from May to June and September to November (Nkemdirim, 1979; Taylor et al., 2011; Burgess et al., 2015a; Nandi et al., 2016). Rains during the wet season that are not associated with large, cyclonic tropical storms do cause floods which are relatively high intensity when compared to more temperate regions, but typically carry half the discharge of the larger cyclonic tropical storm floods. These floods are calculated to have a recurrence interval of 2 years and are able to erode and deposit sediment, typically less than cobble-size, as debris flows within channels, but larger sized sediments are not mobilized in any but the large, cyclonic tropical storm-driven floods (Gupta, 1975; Gupta, 1995; Gupta and Ahmad, 1999).

In Jamaica, Burgess et al. (2015b) calculated rain intensity duration curves outlining the relationship between storm duration, intensity, and recurrence interval for the island using precipitation data recorded from 1895-2015 at Sanger International Airport in Montego Bay on the northern coast of the island and Norman Manley International Airport in Kingston on the southeastern coast of the island. For a 5-year event, the lowest recurrence interval modeled rainfall intensity for a 24-hour period ranged from 5.7-7.3 mm/hr (5.4-6.9 in/day) which is equivalent to the 100-year events reported for Kansas by the Kansas Department of Transportation, an example of a temperate area of the United States (McEnroe, 1997; Burgess et al., 2015b). For a 100-year event in Jamaica, the rainfall intensity for a 24-hour period ranged from 17.5-17.8 mm/hr (16.5-16.8 in/day) across the island (Burgess, et al., 2015b).

Geologic Factors

Geology can also affect the generation and intensity of floods. Geology in the Caribbean is largely homogeneous, with most islands composed of igneous bedrock overlain by karstic sedimentary rock (Gupta, 2000; Mitchell, 2004; Day, 2010). Most of the islands are situated in a tectonically active area between the North American and Caribbean plates and the Gonâve microplate (Benford et al., 2014; James-Williamson et al., 2014). Therefore, Caribbean islands are typically dominated by high relief, mountainous terrain. Uplift can create steep basins as channels incise and that incision can lead to bank failure, which can widen channels and increase sediment load (Knighton, 1998; Yanites et al., 2010; Mathew et al., 2016). Streams in areas with high relief are generally supplied with sediment from episodic slope failures (Clark and Wilcock, 2000; Gupta, 2000; Osterkamp, 2002; Larsen and Wieczorek, 2006; Pike et al., 2010). Karst drainage networks also dominate the islands; karst systems contain several diagnostic features including sinkholes, caves, sinking streams, and springs (Parise, 2003). Bedrock knickpoints can also indicate areas where water is pirated from surface channels into the subsurface (Woodside et al., 2015). Karstic surface collapses and depressions are generally linear and regular patterned and are thought to be a result of dissolution along fault generated fissures, rather than dramatic cavern collapses (Sweeting, 1958; Day, 1976; Day, 2007). In general, surface collapse represents a relatively minor hazard in Jamaica, and catastrophic subsidence is not often recorded (Day, 2007). However, floods are hazardous and flood damage in karst terrain is particularly severe due to rapid increases in surface flow along ephemeral channels and springs.

In the humid tropical climate of the Caribbean, islands are affected by intense biochemical weathering and experience a lack of extensive physical weathering. This highly weathered bedrock leads to extensive slope failures and mass wasting events (Gupta, 2000;

Osterkamp, 2002). Mass wasting occurs when the ratio of shear strength, which is a resisting force, and shear stress, which is a driving force, becomes unbalanced, lowering slope stability (Costa, 1984; Ritter et al., 1995). Rainfall can also increase the likelihood of mass wasting events as the addition of water removes support, increases mass, and increases pressure. At a smaller scale, rainfall can increase the buoyancy and capillary tension of particles, pushing them apart (Ritter et al., 1995). Mass wasting events that occur as a result of the addition of water are referred to as debris flows, which can be thought of as an intermediate between waterfloods and dry land sliding (Costa, 1984; Manning et al., 1992; Gupta, 2000).

Manning et al. (1992) mapped 478 slope failures along 108 km of roads in central Jamaica, the majority of these consisted of shallow slope failures of soil and friable bedrock mobilized by intense rainfall. Additional slope failure mapping was conducted by Maharaj (1993) who identified 866 slope failures near Kingston, in southern Jamaica, following a rainfall event. The minimum amount of rainfall to facilitate shallow slides on reasonably graded slopes of 25 degrees was found to be approximately 300 mm over a 24 hour period (Ahmad et al., 1993a). The relatively frequent slope failures provide a large amount of sediment to Caribbean streams in a short amount of time during extreme floods (Gupta, 2000; Osterkamp, 2002; Larsen and Wieczorek, 2006). These failures can also be exacerbated by the streams themselves as active removal of slope toes by high-stage stream flows can remove downslope support of bank sediments (Ahmad et al., 1993b; Ritter et al., 1995).

In Jamaica, extreme flooding and debris flows represent a significant environmental hazard with a semi-regular recurrence interval, mainly due to heavy rains, low infiltration rates, and karst topography (Donaldson and Walters, 1981). The Office of Disaster Preparedness and Emergency Management reported an average of 14 significant events per decade on the island.

Events between 2002 and 2007 have resulted in US $1.1 billion in damages (Mandal and Maharaj, 2013).

Land Use Factors

The influence land use change has on flooding in the Caribbean is complex, but is primarily caused by an increase in sediment and discharge into the system (Gupta, 2002; Ramirez et al., 2009). Land use change in the Caribbean began with the arrival of humans to the islands beginning in 5,000 BP, when indigenous people cleared land for agriculture by burning (Rouse, 1993; Clark and Wilcock, 2000). Although these early land use changes did affect some geomorphic processes, the Caribbean islands underwent intense land use change beginning in the colonial period in the early 16th century (Watts, 1990; Rouse, 1993). The Spanish and English built vast plantations on the islands and grew economically valuable crops such as sugar cane, tobacco, and cotton. European settlers cleared large plots of land leaving bare, unvegetated slopes, straightened streams, and built settlements and roads (Watts, 1990). Increased sedimentation and runoff associated with past colonial land clearing for agriculture in Puerto Rico led to narrow, deeper channels and increased the frequency of landslides (Clark and Wilcock, 2000). The amount and size of sediment delivered to streams increased and led to large-scale slope failure and gullying (Clark and Wilcock, 2000).

Urbanization in the Caribbean has recently exacerbated flooding by increasing runoff due to increased impervious area (Clark and Wilcock, 2000). Additionally, roads, earthworks, and walls can all impede debris flows leading to temporary dams or where they block flood waters, function as temporary dams themselves. These temporary dams cause an increased slope downstream until slope failure or dam breaks cause catastrophic flash floods (Carby and Ahmad, 1995). Karst watersheds can also be heavily influenced by urban land use change. Surface connections can be blocked by anthropogenic debris and development which can cause pooling at the surface or sudden flash floods as water breaks through these blockages (Day, 1976; Molina and McDonald, 1988; Day, 2010).

Jamaican Stream Characteristics

Streams in Jamaica exhibit six main characteristics: (i) low drainage density, (ii) narrow, deep valleys with confined channels and steep sideslopes, (iii) high stream gradient, (iv) coarse valley alluvium, (v) braided streams with multiple channels and bars on coastal plains, (vi) depositional forms which indicate high-magnitude floods and landslides (Gupta, 1975; Gupta, 1983; Ahmad et al., 1993b). During a large magnitude flood, material can be quickly eroded, leaving sediment-deprived channels which begin to accrete inset features during more frequent, less intense floods (Gupta and Ahmad, 1999). The final form of streams is then a function of floods with differing intensities, frequencies, and erosional/depositional effects (Gupta, 1975; Day, 1976; Gupta, 1983; Ahmad et al., 1993b; Gupta, 1995; Gupta and Ahmad, 1999).

Typically, Jamaican streams display a channel-within-channel morphology characterized by large channels with steep banks, gullies, or bedrock channels created via infrequent, high-magnitude floods. Within these larger channels are smaller, inner channels which carry water and sediment during the wet seasons (Gupta, 1975; Gupta, 1988; Ahmad et al., 1993b; Gupta, 1995; Fielding, 1999; Gupta and Ahmad, 1999). Upland streams are often straight and exhibit cascade or step-pool morphologies, which occur where structurally controlled, confined valleys cause intense incision, this incision will continue upstream until reaching limestone bedrock knickpoints, which act as steps (Gupta, 1975; Jones, 1981; Ahmad et al., 1993b; Gupta, 1995;

Gupta and Ahmad, 1999). On the coastal plain, braided reaches with gentle pool-riffle morphologies are common. Coastal stream morphology is generally thought to be the result of discharge during wet seasons, as more bank erosion and sediment transport occurs. During the dry season when discharges are low to non-existent the sediment load carried by the stream cannot be transported and instead forms extensive bars and braiding (Gupta, 1975). Hurricanes or other cyclonic storms determine the size and sediment load of most channels. Bedload transported during large flood events is typically coarse, boulders of up to 2 meters can be frequently moved (Gupta, 1975; Gupta, 2000). During a large magnitude flood, material can be transported to coastal fans, leaving sediment-deprived channels which begin to accrete inset features during other seasonal and non-cyclonic storms, which are relatively smaller and more frequent (Gupta, 2000).

Geomorphic Effects of Floods

The geomorphic effects left behind after floods in Jamaica can be used to conceptualize and determine flood routes and severity (Table 1) (Gupta, 1975; Jones, 1981; Gupta, 2000). In Jamaican streams, extreme flooding can leave behind dramatic debris fans and flows where slope breaks and hillslopes denuded with floodwaters fail (Jones, 1981; Manning et al., 1992; Ahmad et al., 1993a; Ahmad et al., 1993b; Maharaj, 1993; Gupta and Ahmad, 1999). Where these slope failures occur along streams, banks can collapse delivering sediment to the stream and leaving behind identifiable collapsed banks and scars (Jones, 1981; Manning et al., 1992; Ahmad et al., 1993b; Maharaj, 1993). Where stream slope is high, upland streams exhibit intense incision as a result of flooding and gullies and bedrock channels are created or enlarged. These features often persist until a flood of large intensity readjusts stream form, which can sometimes take hundreds of years. Perched boulders, boulders in the channel which are much larger than surrounding sediments, and boulder bars can be found where slope is high and flood stream power is increased temporarily (Gupta, 1975; Ahmad et al., 1993a; Gupta, 1995; Gupta and Ahmad, 1999). These large sediments can also be an indicator of debris fans or collapsed banks which deliver large, colluvial sediments to the stream and may obstruct future flows (Ahmad et al., 1993a).

Jamaican streams also exhibit geomorphic effects due to the unique karstic topography there. During floods, low-lying areas and closed sinkholes with poor infiltration can cause ponding of floodwater at the ground surface and in some cases actively supply surface depressions with groundwater (Day, 1976). Swallow holes, areas where a surface stream channel flows directly into an underground conduit, can also supply floodwaters to the surface as the structures overfill, they are then defined as estavelles (Day, 1976). Some of these flooded depressions can be quite dramatic and are more accurately referred to as temporary lakes (Eyre, 1981; Jones, 1981). These temporary lakes can last for several months, as in the case of Newmarket in southwestern Jamaica, and can be easily identified using near-infrared aerial imagery (Eyre, 1981). Even where flooded depressions are not as intense, a lack of vegetation and saturated soil can indicate regular denouement (Day, 2010).

Flood Disasters in Jamaica

Some evidence of the geomorphic effects of floods have been reported for north and southwest Jamaica. Between May 24th and June 4th, 1986, the island of Jamaica experienced intense flooding as a result of a stationary front which produced a maximum rainfall intensity of 1,270 mm over a 12-day period in the southern parishes (UNDRO, 1986). Severe flooding and landslides destroyed or buried countless buildings, 15 bridges, and 300 roads. Restoration of infrastructure cost nearly US $4.3 million and 49 people were killed (Collymore, 1992; Collymore 2007). Peak discharge on the Yallahs River in southern Jamaica reached 453 m^3/s for 12 hours, this long duration indicates that a sediment supply from tributaries and slope failures upstream is necessary to maintain high sediment concentration (Gupta and Ahmad, 1999). At peak discharge, the Yallahs River was found to have the stream power necessary to transport boulders up to 0.5 m for 12 hours (Gupta and Ahmad, 1999). For the entire duration of the flooding, the Yallahs was capable of moving bed material and eroding the coarse material stored in bars, banks, floodplains and low terraces (Gupta and Ahmad, 1999). In orthern Jamaica, the Cave River sinkhole system is calculated to have the capacity to transport 70 m^3/s of discharge (Molina and McDonald, 1988). During the 1986 floods, the system was quickly over-burdened by 286 cubic meters per second leading to widespread flooding in the small village of Aenon Town (Molina and McDonald, 1988).

Hurricane Gilbert made landfall on the island of Jamaica on September 12, 1988, as a Category 3 storm. This storm is considered to be the most expensive natural disaster in Jamaica's history; damages were estimated at US $800 million and 45 people were killed. Although most rainfall fell into the Caribbean Sea, 250 mm of rain did fall on the island in a 24-hour period (Eyre, 1987; Barker and Miller, 1990). This rainfall was preceded by winds, averaging 133 kph (83 mph), with gusts up to 222 kph (138 mph) recorded in Montego Bay. This intense wind stripped trees of leaves and destroyed vegetation, this lack of canopy cover exacerbated runoff conditions and weakened slopes, leading to widespread landslide damage (Barker and Miller, 1990; Manning et al., 1992; Ahmad et al., 1993a; Carby and Ahmad, 1995).

Manning et al. (1992) mapped 478 landslides along roadways north of Kingston in southeastern Jamaica following Hurricane Gilbert. Increased silt and turbidity was recorded in the Morant, Plaintain Garden, and Rio Bueno rivers (UNEP, 1989). In the Hope River in eastern Jamaica, Gupta found that 32,410 metric tons of suspended sediment were transported by the floodwaters during Hurricane Gilbert, compared to the 18.1 metric tons of material carried daily by the stream in the dry season (2000). Many rivers and gullies flowed at high peak discharges and estimated peak velocities ranged from 1.2-7.0 m/s (Barker and Miller, 1990; Ahmad et al., 1993a; Gupta, 2000). Peak discharge on the Yallahs River in southern Jamaica reached 523.5 m^3/s, the recurrence interval of a discharge of this magnitude was calculated to be on the order of a 25-year event (Ahmad et al., 1993a; Gupta, 2000). Peak velocity was recorded at 3.9 m/s and was sufficient to move boulder-sized material, which was deposited 3 km downstream with overbank flood deposited material nearly 200 m from banks (Ahmad et al., 1993a).

Hurricane Ivan was a category 4 storm when it passed near to the island of Jamaica on September 11, 2004, while the island was still recovering from Hurricane Charley, a category 1 storm, which passed south of the island on August 10, 2004. As a result of Hurricane Ivan, 17 people were killed and damages were estimated to be US $360 million. Maximum 24-hour rainfall of 518 mm and a cumulative rainfall of 709.4 mm were recorded in Kingston, exceeding the 100-year rainfall event total of 529 mm (PIOJ, 2004). Flood waters remained high for several weeks after the storm due to saturated soils and high stream discharge (IFRC, 2004). The Barnett River in Montego Bay on the north coast of the island overtopped its banks and caused flooding up to 1.2 meters (Associated Press, 2004). Along the Hope River in eastern Jamaica, a maximum 24-hour rainfall of 365 mm was recorded, which is on the order of a rainfall event with a 10-25 year recurrence interval (Mandal et al., 2016). The peak flood discharge there was calculated at over 226 m^3/s, which also corresponds to a 25-year event. At Gordon Town, in southeastern

Jamaica, the banks of the Hope River were heavily eroded, overburdening the stream with boulder sized sediment and debris as large as automobiles (Mandal et al., 2016).

Although extreme flooding has been studied in eastern Jamaica and the typical hydrologic and geomorphic effects of such events have been described and analyzed, only a small number of studies have focused on western Jamaica (Blake and Pyne, 1981; Donaldson and Walters, 1981; Eyre, 1981; Jones, 1981; Porter, 1981; Dryer, 2010). Data describing flood response to the June 12, 1979, flood in Bluefields River watershed was collected and described by Dryer (2010). This watershed drains 4.9 km^2 of karst uplands starting at maximum elevation of 760 meters at a distance of 3.5 km from the sea. The large majority of the stream flows perennially, although an ephemeral tributary, Goat Gulley, is only activated during large scale flood events. The average slope of the channel is 1-5%, which increases to 10% where the channel is influenced by bedrock knickpoints. Eight cross sections were used to calculate the volume of eroded sediment. Dryer (2010) described the mechanism of the flood in Bluefields River and drew four main conclusions:

1. Runoff from the east in what is now understood to be Brighton-Blue Hole River crossed the divide between the two watersheds into the Bluefields River, increasing flood stage there.
2. Incision of the upland valleys and a large debris flow caused by a dam break at Shafston Blue Hole, an upland spring, provided large amounts of sediment to the system very quickly.
3. The middle and lower reaches of the Bluefields River channel were incised nearly 9 meters.
4. Eroded sediment from the channel and transported from uplands (116,000 m^3) increased the size of the fan at Bluefields Bay to 180 meters long.

Purpose and Objectives

This study will assess the effects of an extreme flood on the BBHW in western Jamaica on June 12-13th, 1979. The Brighton-Blue Hole River is located approximately 1.3 kilometers to the southwest of the Bluefields River. Catastrophic flooding destroyed buildings and caused nine deaths. However, geomorphic response initially appeared to be less intense than in nearby watersheds. Extensive flooding and debris flows were documented in the community of Bluefields, but little such evidence was reported for the BBHW. A study of geomorphic effects in BBHW and how they are similar and differ when compared to neighboring watersheds, such as the Bluefields River, can be used to better understand the causes, processes, and geography of the hydrologic and geomorphic response of watersheds to extreme floods along the southwest coast of Jamaica.

The purpose of this research is to document the hydrological factors and geomorphic response of BBHW to the 1979 flood and to compare and contrast the response with the nearby Bluefields watershed to develop a better understanding of flood risk in Jamaica. Past studies have been done on the geomorphic effects of flooding in the Caribbean (Ahmad et al., 1993a; 1993b; Gupta and Ahmad, 2000; Gupta, 2002; Collymore, 2007; Ahmad, 2008; Pike et al., 2010). Hydrological data, including the climate and rainfall, of Jamaica has also been the subject of limited study (Nkemdirim and Jones, 1978; Nkemdirim, 1979; O'Hara, 1991; Rassmussen, 2004; Burgess et al., 2015a; Burgess et al., 2015b). However, previous study of geomorphic effects of flooding in Jamaica has focused mainly on the populated northern and southeastern coasts (Gupta, 1975; Day, 1976; Molina and McDonald, 1988; Mandal and Maharaj, 2013).

This research will expand on the scope of previous study by Dryer (2010) to better understand flood effects on stream systems in southwestern Jamaica. Objectives are to:

1. Delineate stream networks and drainage areas to identify hydrologic connections, karst drainage, and potential sediment transport pathways in BBHW;

2. Assess the occurrence and spatial distribution of karst features and geomorphic indicators to determine downstream patterns of geomorphic response; and
3. After comparing the results of this study to those from Dryer (2010), develop a regional conceptual model for geomorphic response in coastal watersheds in southwestern Jamaica.

The information gathered from this research can benefit scientific research and the people of southwestern Jamaica. Flooding does pose a significant risk in southwestern Jamaica (PIOJ, 2012). Extreme floods can lead to loss of life and property and a lack of data makes management difficult. As of 2018, the city of Savanna-la-Mar in Westmoreland began development of a $600,000 USD flood control master plan. The project aims to improve early warning systems as well as community resilience to flood damage (CARTS, 2018). An updated and accurate regional conceptual model of floods can be used in similar community projects. The ecological health of Bluefields Bay Fishing Sanctuary is also at risk from large influxes of flood-related debris flows. Coastal areas with healthy, extensive mangrove forests, like the Brighton-Blue Hole area, can experience a buffering effect on increased sedimentation as mangroves filter sediment from water entering the bay (Weaver and Schwagerl, 2009; Bell and Lovelock, 2013). Bluefields Bay, as well bays in Jamaica in general, are an important source of income for many coastal residents, either via fishing or tourism and bay health is imperative for their livelihoods.

Table 1. Geomorphic effects associated with flooding and karst topography in Jamaica

Geomorphic effects	Location in stream	Reference
Debris flows	Where streams exit uplands; below denuded hillslopes	Jones, 1981; Manning et al., 1992; Ahmad et al., 1993; Maharaj, 1993; Gupta and Ahmad, 1999
Channel incision	Confined valleys; where streams exit uplands through erodible soils and slope is high	Jones, 1981; Maharaj, 1993; Gupta and Ahmad, 1999
Water-filled depressions	Low-lying areas, karstic depressions or fault block valleys (poljes) over-burdened with flood discharge and sediment	Day, 1976; Jones, 1981; Eyre, 1981; Molina and McDonald, 1988; Day, 2001; Day, 2007; Day, 2010
Bedrock channels	High gradient slopes, confined valleys; where limestone bedrock in present on land surface	Eyre, 1981; Jones, 1981; Manning et al., 1992; Gupta and Ahmad, 1999
Collapsed banks	Where incision or water saturation weakens banks	Jones, 1981; Manning et al., 1992; Ahmad et al., 1993; Maharaj, 1993
Perched boulders	Where slope is high; where banks have collapsed; associated with debris fans	Gupta, 1975; Ahmad et al., 1993; Gupta, 1995; Gupta and Ahmad, 1999; Gupta, 2000

STUDY AREA

The BBHW (6.8 km^2) drains to Bluefields Bay in Westmoreland Parish in southwestern Jamaica. It is surrounded by the Bluefields River watershed (6.2 km^2) to the west and Robin's River watershed (20.2 km^2) to the east (Fig. 1). Its main channel heads at 595 meters above sea level (masl) the coastal mountains and flows 6.3 km to the Caribbean Sea. Most channels are ephemeral, but during rain events convey discharge through a karst landscape of losing and gaining reaches, springs, and karst depressions. In the lower portion of the watershed, flow is released from Blue Hole Spring into a 330 m long perennial reach which flows through a large morass wetland and mangrove forest before entering Bluefields Bay, a no-take fish sanctuary (MOA, 1979; MOA, 2012).

Geology

Jamaica is the third-largest island country in the Caribbean Sea region. The island sits on the eastern edge of the Nicaragua rise between the Gonâve microplate and the Caribbean plate (Fig. 2) (Benford et al., 2014; James-Williamson et al., 2014). The island underwent four periods of geological change. From the Cretaceous (145-66 mya) to the early Eocene (~56 mya) volcanism and rifting formed and uplifted the island arc. A period of extension during the early Paleogene (~60 mya) created two noteable north-northwest (NNW) trending troughs, the Wagwater, in eastern Jamaica, and Montepelier-Newmarket, in western Jamaica. A long period of tectonic stability from the middle Paleogene (~50 mya) to the Middle Eocene (~40 mya) allowed for extensive carbonate deposition. These carbonates can be separated into two groups, the earlier Yellow Limestone Group which dates to the Middle Eocene and the thickly bedded

(300 m thick) White Limestone Group, which dates from the middle Eocene to the middle Miocene (Robinson and Mitchell, 1999; Mitchell, 2004). Faulting and deformation during the Middle Miocene through the Holocene has reactivated many faults and led to further uplift, exposing the fringe Coastal Group (Mann and Burke, 1984; Robinson and Mitchell, 1999; Benford et al., 2014).

Extensive dissolution of the Yellow and White Limestone groups in northwest and north-central Jamaica has created an area of classic karst topography known as the Cockpit Country. This area is dominated by enclosed depressions surrounded by round, conical hills referred to as cockpits. The margins of this landscape are dominated by a combination of cockpit, doline, and tower features. Dolines in the area are slightly oval to circular depressions. Tower karst features in Jamaica typically form where the limestone has been block faulted (Mitchell et al., 2003; Mitchell et al., 2008). Walls are steep and long and structurally controlled valleys, also referred to as poljes, are formed by down faulting (Sweeting, 1958; Day, 1976; Day, 1979; Mitchell et al., 2003; Day, 2007; Mitchell et al., 2008). The boundaries of true Cockpit Country are controversial but associated rock units were identified by Wadge and Dixon using SEASAT-SAR Imagery as far southwest as 6.6 km from the village of Belmont (Fig. 3) (1984).

The BBHW is dominated by the Bonny Gate member, a heavily dissected subgroup of the larger Montpelier formation of the White Limestone Group, which was deposited during the period of stability between the Middle Eocene to Middle Miocene (Robinson and Mitchell, 1999). The area is also active tectonically. NNW trending faults, first generated during the Paleogene extensional period, have become reactivated as reverse faults, the largest of these is the Brompton Fault north of the watershed. These faults are known to have created isolated mountain ranges in southwestern Jamaica and likely have formed the valleys and peaks associated with the Bluefields Mountains, which form the headwaters of BBHW are located (Benford et al., 2014). A large, reactivated Paleogene (Pg) NNW striking strike-slip fault forms a restraining bend at the BBHW, with the compressional uplift occurring underneath the central region of the watershed and the extensional valley forming south of the watershed. Eastern striking faults associated with older Cretaceous (K) uplift are also present in the BBHW and have been reactivated as strike-slip faults (Fig. 4). Generally, in areas where well-developed karst systems are bisected by faults, surface features such as sinkholes, depressions, and springs are fault controlled and faults indicate the direction of underground conduits (Day, 1976; Day, 2007).

The heavily dissected Bonny Gate member has led to the formation of a well-developed karst system in the BBHW (Fig. 5). The term "well-developed" is used here to describe a landscape where surface depressions and springs are common. Surface depressions in the BBHW are varied in shape and hydrology. Depressions which are round and enclosed are referred to as sinkholes (Sweeting, 1958; Day, 2010). After a rainfall event, runoff collects in these depressions as it slowly percolates through fractures in the limestone bedrock into underground conduits and the low points of these depressions are commonly devoid of vegetation and some even support small, semi-permanent ponds (Day, 1976). These depressions can become easily denuded during floods due to low infiltration rates (Day, 1976; Day, 2007; Day, 2010). Elongated valleys in BBHW, which have formed parallel to NNW structural trends and represent down-faulted blocks can in some cases be interpreted as polje (Mitchell et al., 2003). These flat-bottomed valleys drain via swallow holes, also called ponors, which are open surface connections to underground conduits by which water can flow directly underground (Mitchell et al., 2003; Lyew-Ayee et al., 2007). These polje are usually long or irregular in shape and during high flood stage as the swallow hole becomes inundated with water will form temporary lakes. In such cases, the swallow holes can also be defined estavelles which act as swallow holes during dry seasons, but deliver water to the surface during wet seasons (EPA, 1999). Some hills in the watershed are more conical in shape and surround round sinkholes, this relationship is more indicative of a cockpit karst landscape (Sweeting, 1958; Mitchell et al., 2003; Lyew-Ayee et al., 2007; Day, 2010). As the BBHW is located on the southwestern margins of the Cockpit Country of northern Jamaica, the landforms here may represent the transition from true cockpit karst to more doline/tower type found on the margins of Cockpit Country (Sweeting, 1958; Mitchell et al., 2003; Mitchell et al., 2008). Caves are also common place and can be used to assess karst conduit pathways from the surface (Fincham, 1998).

Climate

Jamaica has a semi-tropical climate and prevailing winds are northeastern trade winds. Average daily temperatures range from 80° F on the coast to 55° F in uplands (Allsworth-Jones, 2008). The 30-year mean rainfall for the island, calculated by the Meteorological Society of Jamaica using rainfall data from 1971-2000, is 1,773 mm per year with a mean number of 123 rainy days. In Westmoreland, the 30-year mean rainfall was calculated at 2,081 mm per year. The area is also of relatively high relief and orographically enhanced precipitation is particularly significant. As the warm, moist trade winds reach the southwestern coast of Jamaica, they are uplifted by the coastal frontal range, which cools the air and causes intense precipitation (Gamble et al., 2010). This orographic uplift accounts in some cases for the large amount of rainfall and it can be assumed that the coastal areas of Westmoreland receive less rain, probably nearer to the country's average (Naughton, 1982).

Jamaica is considered to be at high risk due to anthropogenic climate change because of its geographic location, population centers which are located in coastal and floodplain areas, heavy economic reliance on agriculture and tourism, dependence on rainfall for water, small gross domestic product (GDP), and limited hazard forecasting ability (Taylor et al., 2018). The area has already experienced an increase in mean air and water temperature of 0.5°C from 1961 to 2010 (Stephenson et al., 2014). Over the same period annual total precipitation, daily rainfall intensity, and heavy rainfall events have also increased (Stephenson et al., 2014).

The Intergovernmental Panel on Climate Change Report for 2018 describes the risk of Small Island Developing States (SIDS) to a 1.5°C to 2°C increase in the global temperature. This change in temperature is associated with a 0.20 meter sea level rise globally by 2050. The projected sea level changes regionally are considered to be higher than the global average for areas of the Caribbean region, including Jamaica, and related threats include an increase in flooding and erosion, as well as permanent inundation (Hoegh-Guldberg, 2018). The cities of Belmont and Bluefields are located along the coast, while the small community of Brighton is located along the stream in the BBHW. These communities are all at risk to an increase in flooding associated with global anthropogenic climate change.

Soils

Modern soil descriptions and mapping in Jamaica were first published in the "Green Books," by the Soil Science Department of the University of the West Indies in 1958. These initial surveys recorded soil description, landform type, and parent material at the parish level (MOA, 1964). Later more detailed surveys containing chemical characterization and USDA taxonomic classes were developed by the Jamaican Ministry of Agriculture with assistance from the Government of the Netherlands (MOA, 1989). Copies of the survey for the parish of Westmoreland are not available. However, a preliminary soil series for the BBHW in Westmoreland, Jamaica was created using a combination of soil surveys available online from the ISRIC – World Soil Information Collection and from the CRIES (Comprehensive Resource Inventory and Evaluation System) Jamaican Resource Assessment report, which is a detailed report which classifies soil series based on texture and internal drainage (Fig. 6) (MOA, 1964; Barker, 1970; CRIES, 1982; Batjes et al., 1986; MOA, 1989).

All soil series in the BBHW were developed from the white limestone bedrock of the Bonny Gate member with the exception of Frontier clay which is an entisol formed by recent alluvium transported to the coastal plain (Table 2). The Deepdene, Boghole, and Carron Hall clays are well-developed and made up of fine clay-sized sediment associated with depositional environments on the coast, in valley bottoms, depressions, and the swampy coastal morass area. The Frontier, Deepdene, Boghole, and Carron Hall clays also have low infiltration rates which can intensify flooding. The most common soil series in the BBHW is the Bonnygate stony loam which covers nearly 70% of the watershed. The Bonnygate stony loam is a well-drained, aluminum-rich soil which formed mainly in colluvial, steep slopes ranging from 20 to 35%. The Bonnygate stony loam is an entisol with poorly formed horizons and a high erosion hazard. Locations of known channel incision and debris flows during the 1979 flood were located on Bonnygate stony loam. These debris flows created debris fans and valley splays composed of gravel-, cobble-, and boulder-sized sediment in the upland areas upstream of the Robins River Road. The Union Hill stony clay is a relatively under-developed soil found in the eastern most extreme of the BBHW. It contains cobble to boulder-sized clasts of limestone in a clay matrix and has a high erosion hazard. Due to its unsorted composition and position on the flanks of hills it likely formed by debris flows and may also provide cobble- to boulder-sized sediment to the stream during floods.

Land Use

Three groups have historically inhabited the island, the Taino, the Spanish, and the British. The island was first inhabited by the Taino people, who came from the South American mainland (Rouse, 1993). The Taino built ball courts and large plazas, culivated domestic crops on a large scale, and raised domestic animals (Newsom and Wing, 2004). In Jamaica, there is evidence of agricultural land clearing using a slash-and-burn technique. This was used to create fields for corn, which was a relatively unpopular crop. Their staple food crop, yuca, was instead grown in soil mounds called *conucos* which decreased soil erosion (Rouse, 1993).
Evidence found in middens near the village of Bluefields shows that a large majority of the Taino diet consisted of fish, Azevedo (2015) described a widescale fishing culture in Bluefields large enough to effect fish populations in Bluefields Bay. This heavy reliance on fish likely decreased the amount of widescale agricultural land use change that occurred in the area during the pre-colonial period.

Jamaica was established as a Spanish colony from 1509 to 1655. A Spanish settlement, Oristan, was located near the Bluefields River (Rouse, 1993). Many Taino were enslaved initially to mine and pan for gold and silver (Allsworth-Jones, 2008). After gold and silver were not found in the area, focus switched to growing cash crops in the area. The population of the Taino was by this time was depleted from 5,000 to only 300 people and the Spanish instead began to rely on African slave labor (Ogilby, 1673). There are records of at least one significantly sized farm located near Oristan where corn, tobacco, pimento, cocoa, and sugarcane was cultivated (Gardner, 1873; Curtin, 2010). There is no record, however, of what land use change, if any, occurred in the BBHW during this period. The Spanish abandoned Oristan, due to a perceived "unhealthy situation" and the majority of the population moved to St. Jago de la Vega, now called Spanish Town, in 1534 (Ogilby, 1673)

Intense land use change on the island began after it was established as a British colony in 1655, it remained a colony until 1962 (Watts, 1990). During the early colonial period, from the late 1600s to the mid-1800s sugar became the staple export and an agricultural boom began. During this period, agricultural land clearing led to heavy deforestation throughout Jamaica (Watts, 1990). However, in BBHW, the main land use was for livestock (Fig. 7). The majority of the land was used as common pasture or to grow hay or subsistence crops. However, the swampy lower watershed appears to have been channelized and drainages from the springs to the morass, referred to in colonial maps as "para grass," were dug. Additionally, some of the springs, Blue Hole Spring, Big Dismel, and Shafston Blue Hole were either fully or partially walled (Dryer, 2010). The Robins River Road and village of Brighton were built atop rims of poljes where road fill was unnecessary.

After the emancipation of Jamaican slaves in 1838, plantations near the village of Belmont, particularly Belmont and Beeston Springs, were subdivided and sold to former slaves who continued to work the land. Shafston Estate, located in the upper watershed was not subdivided or cultivated and so returned to its undisturbed forested state (Gosse and Hill, 1851; Scolaro, 2013). However, many of the British changes to the landscape are still visible today, particularly in the forested lands associated with the Shafston Estate. Springs remained walled, were regularly cleared of vegetation, and their drains were maintained up to at least 1979 (Dryer, 2010). In more modern times, agriculture is much more common and forest has been cleared for farming. Deforestation remains a problem in Jamaica and the island has experienced losses in forest cover since the 1980s (Eyre, 1987; Evelyn and Camirand, 2003). Between 2001 and 2010, the island experienced the most losses in forest cover of any other Caribbean country (Aide et al., 2013). Deforestation is also caused by urban development around the village of Belmont. Some mangrove forest has been cleared for buildings and a major highway (A-2) also bisects the mangrove forest. Another road, the Robins River Road, bisects the watershed near the village of Brighton (Fig. 8).

June 12, 1979 Flood

Focusing study on one specific flood offers an opportunity to study the geomorphic response to a large flood in southwestern Jamaica. Tropical Depression One moved slowly off the coast of western Jamaica from June 12-13, 1979. Over 1,000 homes were destroyed, damages cost upwards of US $24 million USD, and 40 people died (Government of Jamaica, 1979). The area had also experienced seven weeks of above average intensity rainfall before June 12 (Blake and Pyne, 1981; Donaldson and Walters, 1981). Additionally, much of the area was still recovering from another record-breaking rainfall event on April 25, 1979, in which 300 mm of rain fell over a 24 hour period (Blake and Pyne, 1981).

Locals reported that nearly all rain fell in a 10 hour period, from the night of June 12 to the early morning of the June 13. The maximum rainfall intensity recorded from this storm was 812 mm (32 in) over a 24-hour period in the town of Friendship, Westmoreland (Blake and Pyne, 1981). Several rain gages, including one in the town of Bluefields, were destroyed by the intense rainfall (Blake and Pyne, 1981). This was well above the previous rainfall maximum of 466 mm (18 in) in a 24-hour period recorded during Hurricane King on October 16, 1950 and the published 24-hour rainfall intensity for a 100 year event of 225 mm (9 in) (Eyre, 1981). When compared to the rainfall intensities calculated by Burgess et al. (2015b) the rainfall intensity on June 12, 1979 is over two times greater than those calculated for a 100-year rainfall event.

In Westmoreland, runoff rates were high due to the steep karst landscape and low infiltration rates (Jones, 1981). The storm devastated the area and the flooding left large depressions filled with standing water, widened and deepened gullies and channels, and deposited debris fans and slope failures (Jones, 1981). Karst valley flooding was so severe that the towns of Brighton, Enfield, Exeter, Leamington, and New Market were submerged. The depth of standing water in Newmarket was recorded at 24 meters and was so damaging that the town was later moved to higher ground (Government of Jamaica, 1979; Eyre, 1981; Jones, 1981). There is also evidence of channel incisions in the BBHW, where a gully was entrenched 15 meters, and along the Bluefields River, where channels incised up to 9 m (Jones, 1981; Dryer, 2010). Debris flows were extensive along the Bluefields River and produced a debris fan which extended 150 meters into Bluefields Bay (Dryer, 2010).

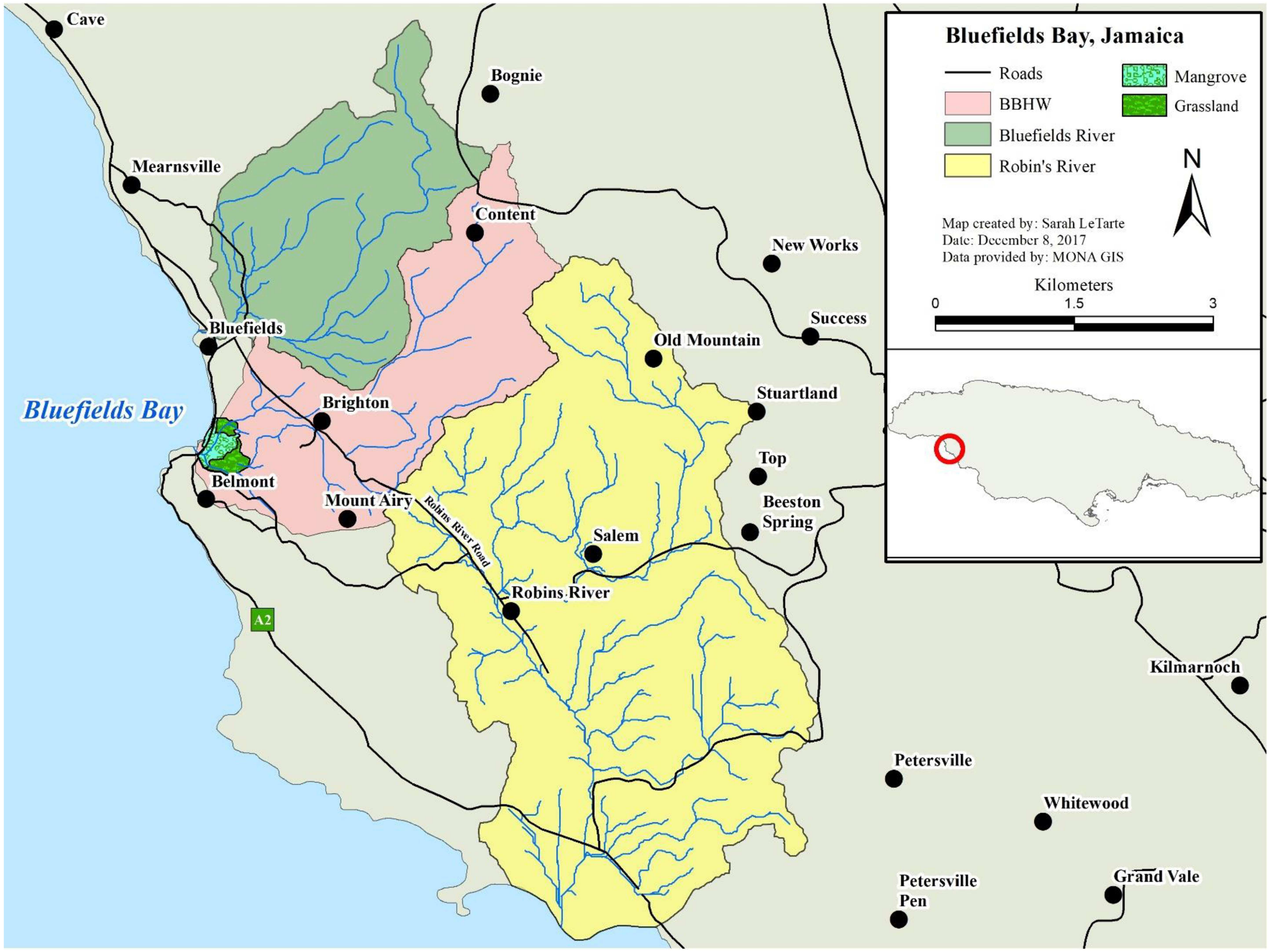


Figure 1. A location map of the BBHW with nearby watersheds noted

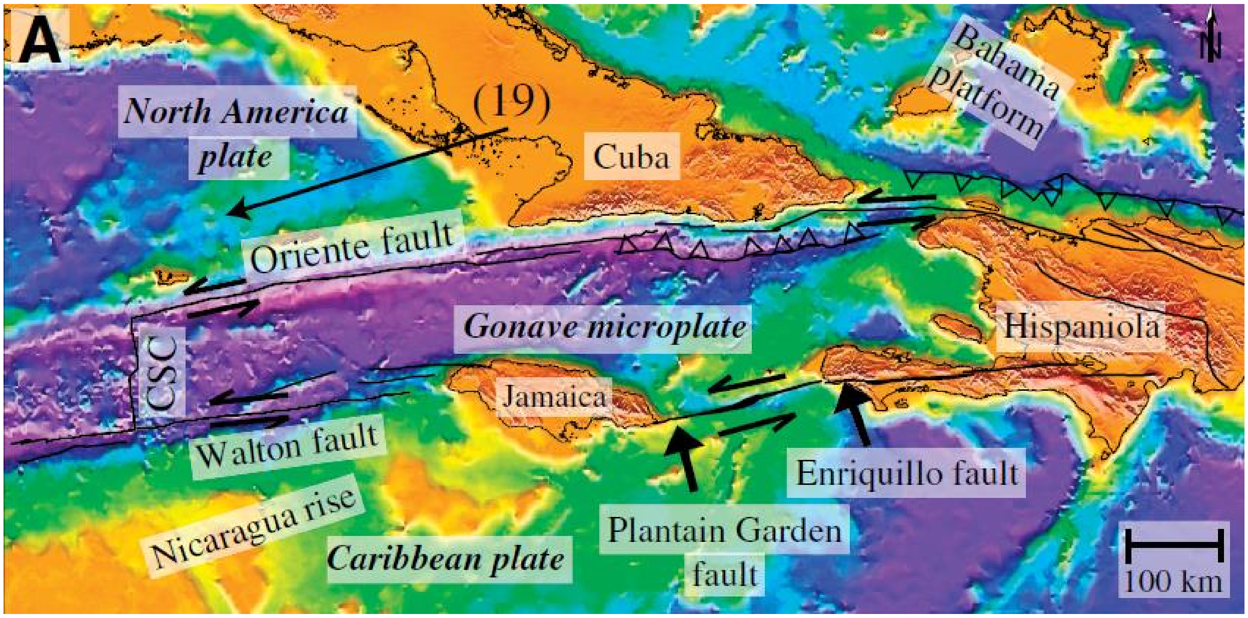


Figure 2. The tectonic setting of Jamaica. Source: Benford et al., 2014

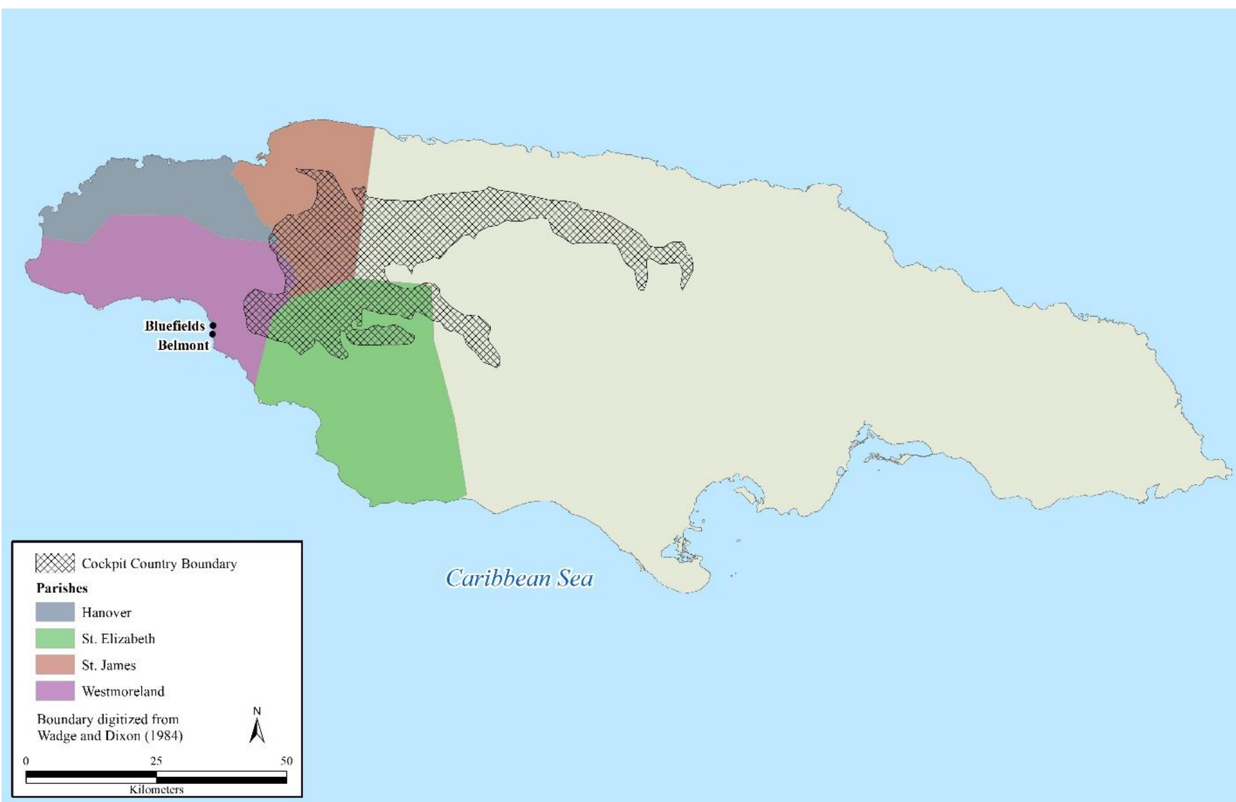


Figure 3. A comparison of the location of the associated rock units of Cockpit Country

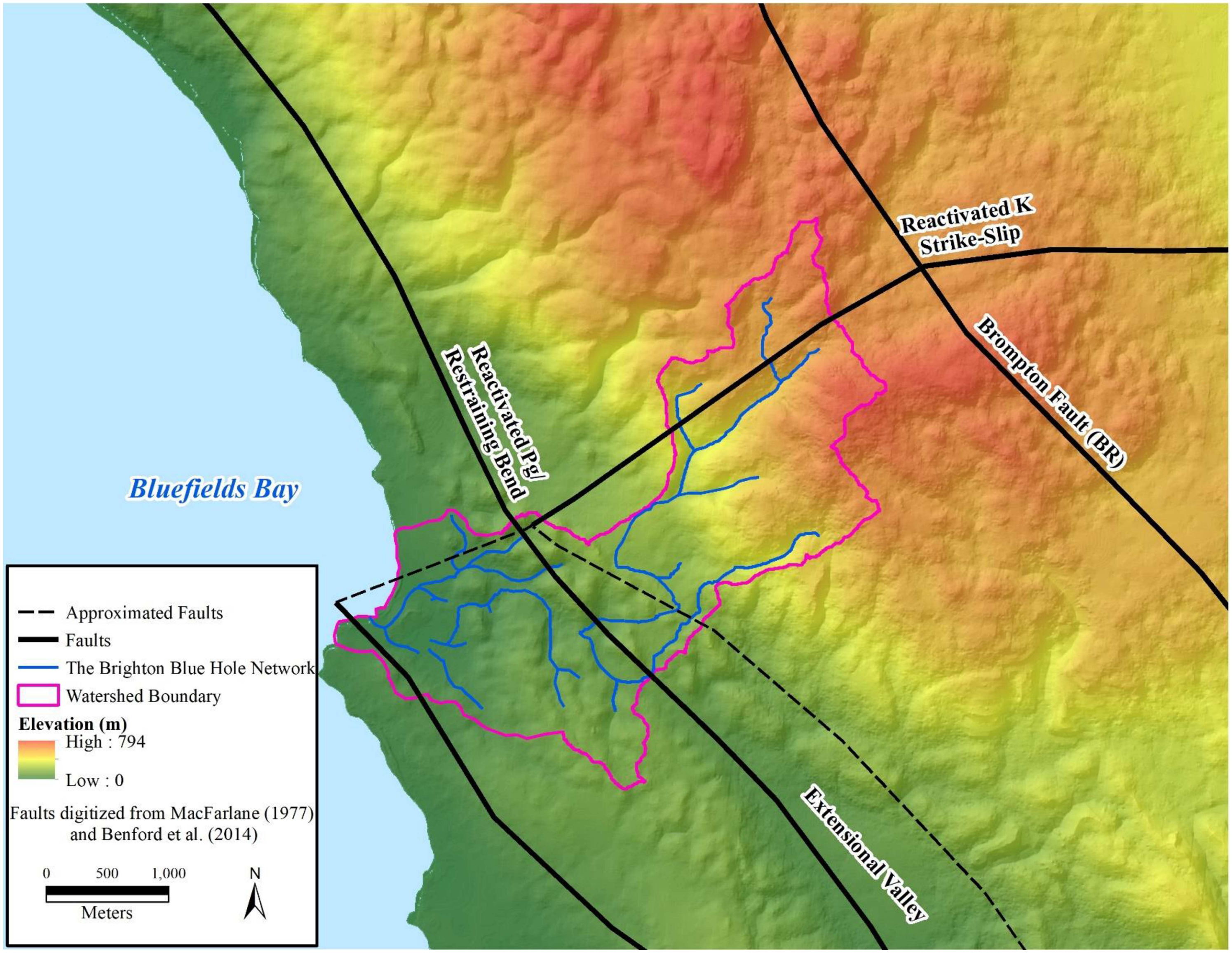


Figure 4. Faults and structural landforms in the BBHW

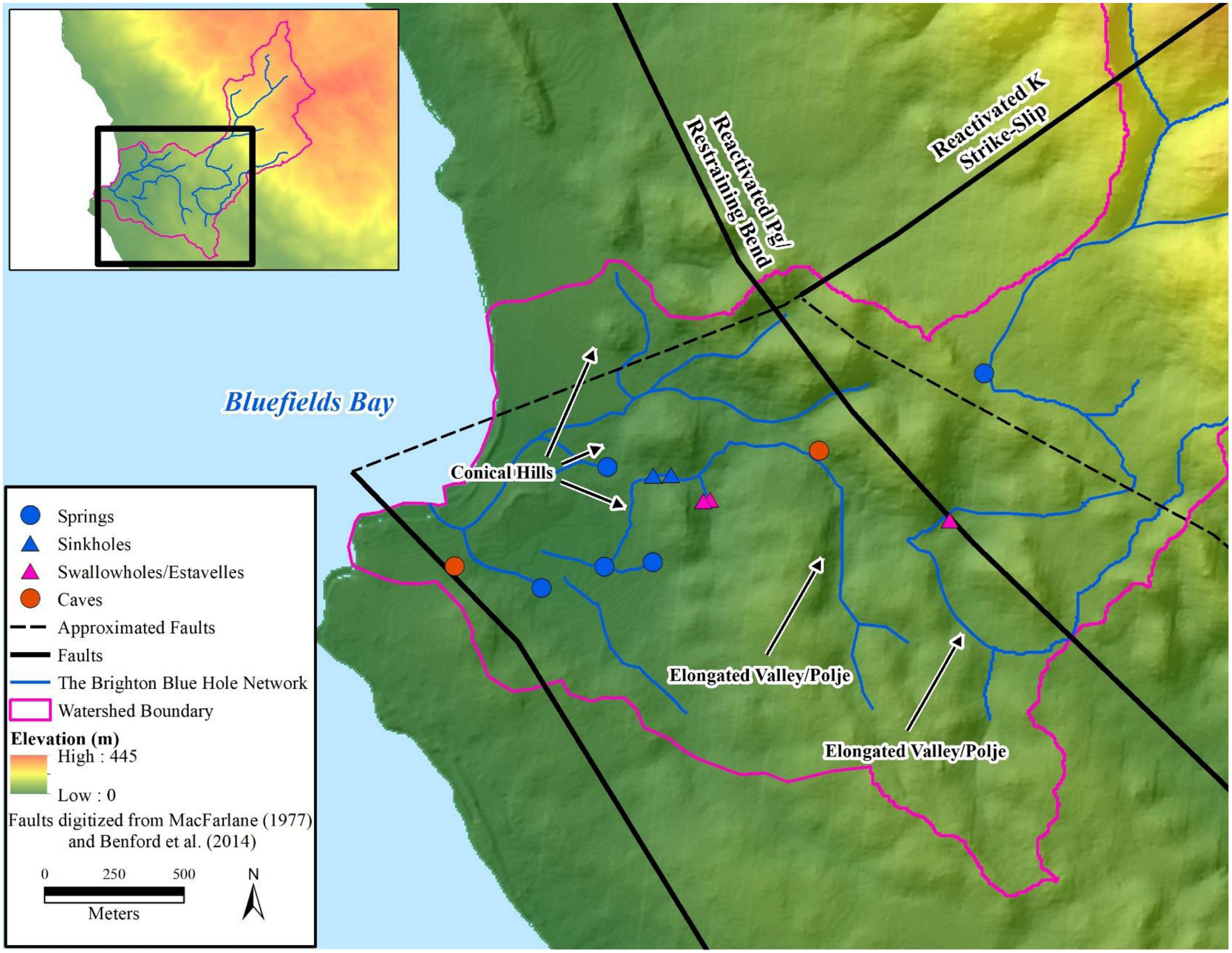


Figure 5. Karst landforms and related tectonics in the BBHW

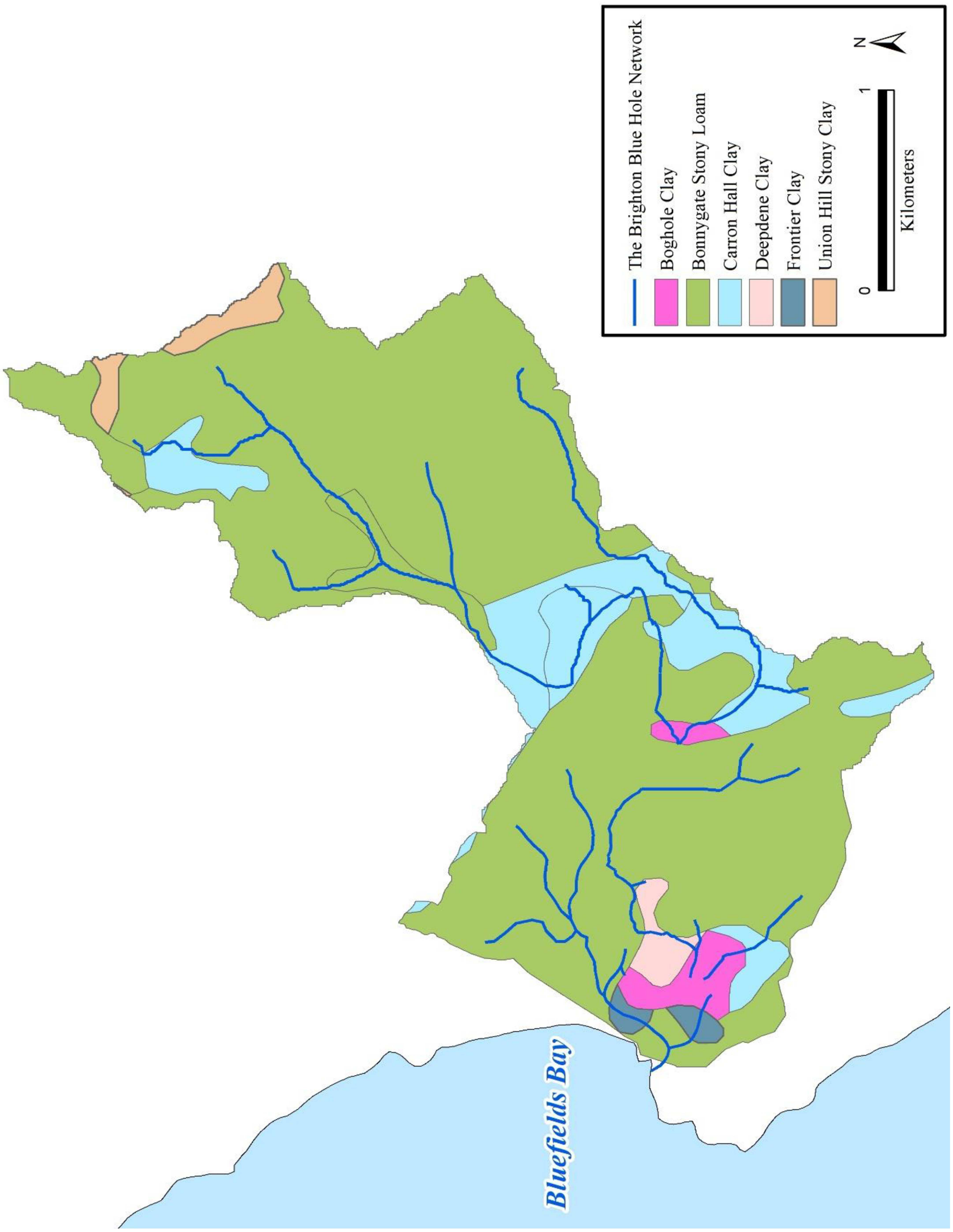


Figure 6. Soil series of the BBHW

Table 2. Soil series in the BBHW

Series	Slope	Taxonomic Class	Order	Landform	Internal Drainage	Moisture Supplying Capacity	Erosion Hazard	Mineralogy	Parent Material
Boghole clay	0-5	Umbric paleaquults	Ultisol	Hollows	Very slow	High	Slight	Kaolinitic	Limestone
Bonnygate stony loam	20-35	Lithic troporthents or lithic ustorthents	Entisol	Steep (20-35%)	Very rapid	Very low	High	Gibbsitic	Limestone
Carron Hall clay	5-30	Typic chromuderts	Vertisol	Hills	Slow to moderate	High	Moderate	Montmorillonitic	Limestone
Deepdene clay	2-10	Aquic tropudults	Ultisol	Hollows on gentle slopes (2-10%)	Very slow	High	Moderate	Mixed	Limestone
Frontier clay	0-2	Tropic fluvaquent	Entisol	Coastal plains	Very slow	Very high	Slight	Montmorillonitic	Recent alluvium
Union Hill stony clay	10-30	Lithic eutropepts	Inceptisol	Flanks of hills	Moderate	High	Moderate to high	Mixed	Limestone

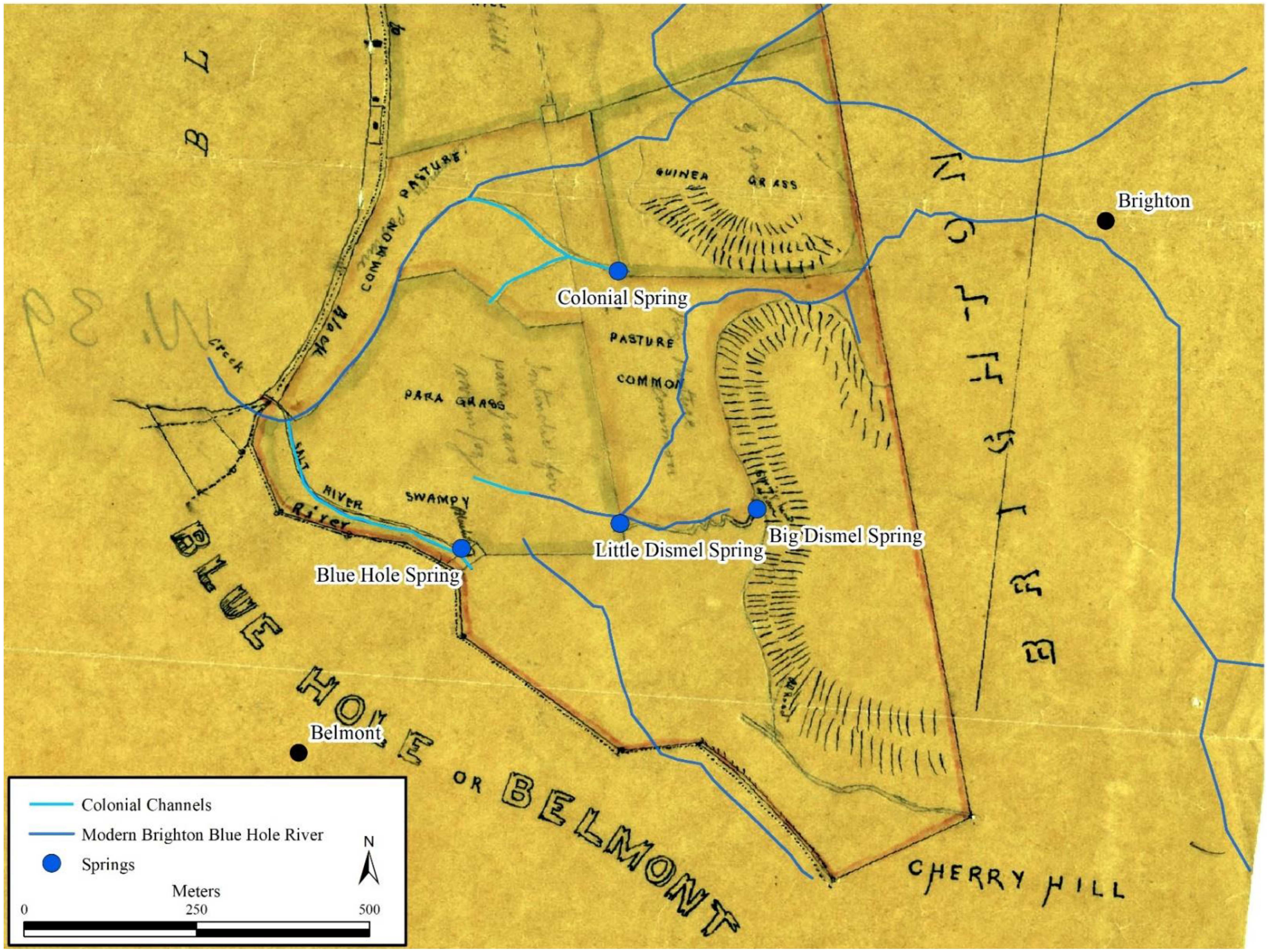


Figure 7. Land use outside of Belmont, Jamaica in the late 1700s, date and author unknown. Source: The National Library of Jamaica (accessed, June, 2017)

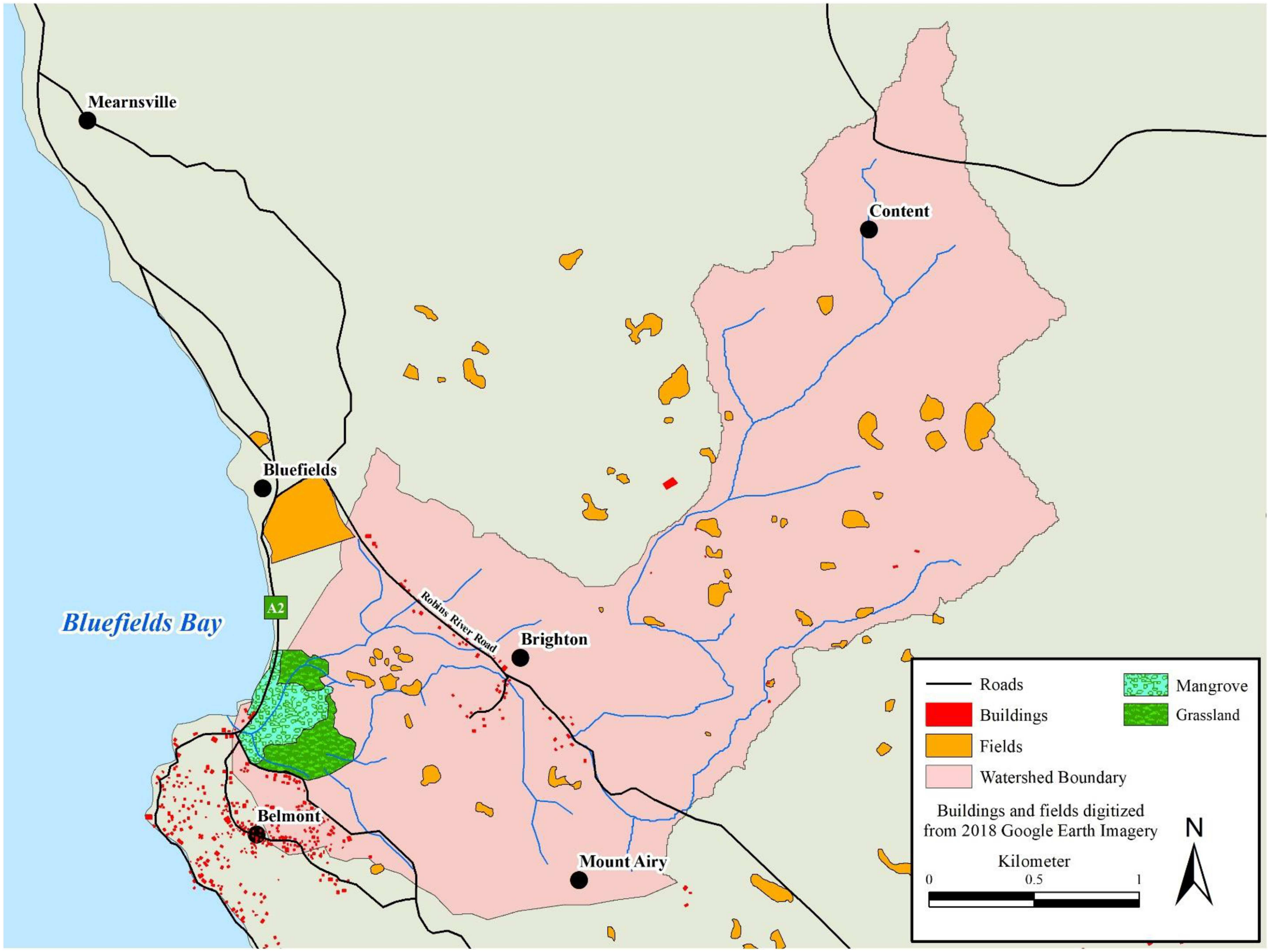


Figure 8. Current land use in the BBHW

METHODS

This research focuses on the effects of intense flooding on surface channel morphology in the BBHW. This was accomplished using a combination of field and computer-based methods. An incised, bedrock channel, referred to as The Brighton-Blue Hole Gorge, was surveyed via longitudinal profile and channel cross sections using an auto-level. A detailed survey of surface points of interest was performed throughout the watershed using a Trimble Global Positioning System (GPS) to locate evidence for flood mechanisms, karst development, and the surface channel network of the BBHW. A 6-m resolution digital elevation model (DEM) and a combination of field features, historical maps, aerial images, and previous studies were used to identify the drainage network of the watershed. Longitudinal profiles were used to determine channel slope and evaluate landform locations.

Field Methods

Gorge Survey May 2017. Channel surveys were used to measure water surface and channel bed slopes. Step and pool spacing, pool depth, and riffle slope were also calculated using the longitudinal profile (Harrelson et al., 1994; Dryer, 2010). A longitudinal profile was also used to describe reach morphology, as well as identify other surface features, such as knickpoints (Harrelson et al., 1994; Dryer, 2010). Elevations were determined from stadia rod readings at a minimum of five points per pool and at changes in slope in the Brighton-Blue Hole Gorge (Harrelson et al., 1994). Extreme changes in channel slope from pool to pool, as well as heavy vegetation necessitated the use of differential leveling. In total, the longitudinal survey was 254 meters long, totaling 83 points, and included 7 instrument positions.

Cross sectional surveys can delineate channel form and should be taken perpendicular to flow and include elevations of important surface features located outside of the channel including floodplains, geological benches, and any bankfull indicators (Harrelson et al., 1994; Dryer, 2010). Variations in cross-section morphology and bank conditions can indicate geomorphic change (Harrelson et al., 1994; Dryer, 2010). Twenty-one cross-sections were surveyed along the Brighton-Blue Hole Gorge by running a measuring tape from one bank toe to the other with elevation points collected using an auto-level at approximately one meter intervals (Appendix A). Cross-sections were evenly spaced across each pool longitudinally. Because of the different lengths of each pool, the number of transects varied from 3 to 6 per pool. Elevations of several bedrock benches or strath terraces and possible “original stream bed” indicators were also recorded along the surveyed channel.

Flood Indicator Mapping. Visual stream tracking and flood indicator mapping were used to assess flood routing and geomorphic effects of the 1979 flood. This flood was assumed to be the most destructive flood in the area based on stream gage data from 1979-2018 for the Bluefields River collected by the Water Resources Authority of Jamaica. Indicators can indicate channel instability, significant changes in bed elevation, flood depth, cross-sectional area, and channel pattern (Osterkamp, 2002; Lord et al., 2009). Geomorphic indicators were proposed for use as an environmental tool by the Commission on Geological Sciences for Environmental Planning of the International Union of Geological Sciences since they relate to surface processes which occur over periods of up to 100 years (Berger, 1997).

In the Caribbean, where weathering rates, sediment transport, and vegetation differ from the temperate areas for which the concept of geoindicators were first proposed, a new tropical geoindicator reference was required (Osterkamp, 2002). In this study, a Trimble Geo 7x GPS unit and GPS camera were used to record geoindicators such as, surface features, channels, possible flood debris deposition, and other geomorphic effects indicative of extreme flooding in Jamaica (Appendix B). A data dictionary was created which classified each point as a spring, sinkhole (later distinguished as swallowhole if appropriate), cave, incised channel, headcut, channel flow path, or local deposition (cobble pile or boulder pile) (Table 3). These surface features can be used to estimate soil erosion, rainfall-runoff relations, sediment storage, and short term land surface and hydrological changes (Osterkamp, 2002). These effects can also be used to assess flood mechanisms and routes. Karst surface features were also mapped as geoindicators to assess underground and surface karstic channel connections affecting flood routing. Overall, channel locations were mapped by visual stream tracking to assess stream morphology and to improve the drainage network.

Computer Methods

A variety of GIS methods were utilized to create an accurate drainage network of the BBHW and then to use the network for quantitative analysis of flooding where possible. Longitudinal profiles for three reaches were determined, depressions were analyzed spatially, and stream power calculation was attempted.

Step One, Drainage Network from DEM Processing. A surface drainage area for the BBHW was created using ArcMap 10.5.1 and a 6-m resolution DEM raster purchased from MonaGIS at the University of the West Indies Mona Campus in Kingston, Jamaica. This was performed by first converting the filled DEM into a stream network using tools in the Agricultural Conservation Planning Framework toolbox (Fig. 9) (USDA, 2017). This filled DEM network was later compared to the original unfilled DEM to better represent flow through depressions in the well-develop karst landscape. The D8 Terrain processing tool of this toolbox runs Fill, Flow Direction, Flow Accumulation, and Hillshade on an unfilled DEM as a single operation. The Flow Direction and Flow Accumulation output rasters were used with the Flow Network Definition Area Threshold tool which applies a user-defined area threshold, or area of upstream drainage in acres. The tool was run using a decreasing area threshold, from 100 – 5 acres. The flow line created with an area threshold of 30 acres was found to represent the appropriate amount of detail, but when compared to the other sources of stream data this network was found to be associated with some error due to the complexity of the landscape in BBHW. The DEM-derived flow network underrepresented small coastal streams, directed flow into road depressions, represented complex underground karstic connections as surface flow, and to reroute flow around artificial topographic highs formed by high vegetation. This toolbox also contains the tool Manual Cutter, which allows flow under roads and through culverts to be accurately represented (USDA, 2017). This tool was not selected for use in this study because of the complex hydrology of the watershed. The hydrological conditions at roads is not well understood at each road crossing within the watershed. Many valleys located near roads likely overfill during floods and water either pools behind the road or crosses underneath it via culverts or karst conduits.

Step Two, Drainage Network Improvement. The resulting drainage network was compared to aerial imagery from 1991, IKONOS satellite imagery from 2004, two scanned and georectified topographic maps (Survey Department of Jamaica, 1969; Survey Department of Jamaica, 1987), a map by Eyre (1981), a historical map from the 1700s, and visually tracked channel GPS points to determine the most accurate flow line of channels in the BBHW. This method of stream channel verification located 8,964 m of previously unrepresented streams, which is 94.8% of the total length of channels in the BBHW.

Step Three, Longitudinal Profiles. The improved drainage network was used to create a longitudinal profile of three subwatersheds, the main channel, a northern tributary which crosses the morass, and a southern tributary which drains the uplands, as well as calculate drainage density. The profile was created following the method outlined by Gartner (2016) using the basic Spatial Analyst toolbox in Arcmap. The Construct Points tool was used to create a point shapefile with points every 10 m along the new flow network, the Extract Multi Values to Points tool was then used with elevation data from the DEM to generate a table with distance and elevation. These values were used to generate a longitudinal profile chart in Excel. The drainage density was calculated as the total length of the improved stream network divided by the basin area. These products were both dependent on the created flow network and so may have errors associated with the user-defined area threshold and the combination of a flow network generated using several sources. Although the DEM caused some errors in the initial flow network, the channel morphology in the BBHW is complex and affected by the karst landscape. The elevation data associated with the DEM is relatively high resolution (6 m) and can be assumed to be suitable for further GIS processing. To that end, the Identify Impeded Flow tool of the ACPF toolbox was used to identify depressions in the DEM by subtracting the elevations from newly created filled DEM raster from the elevations of the original unfilled DEM raster. The output Depth Grid raster which was produced was compared to aerial imagery to investigate locations of possible karst depressions or locations of large temporary lakes during high flood stage.

Stream power can be used to indicate erosive potential of the stream. Stream power calculation was attempted after Gartner (2016) using information generated from the DEM including longitudinal profiles, flow accumulation data and cross sections. This was unsuccessful due to most channels not being in equilibrium and also because of a complex karst network. These channels are morphologically complex and banks and flood capacity can be difficult to determine. Although bankfull stage could have been calculated using stream gage data, but there are no gages in the BBHW. Where water is routed through underground conduits, stream power on the surface may be underrepresented as most powerful flows are not located at the surface (Woodside et al., 2015).

Interviews with Residents

Interviews were conducted with residents during visits to the area and via Skype by Dryer (2010) and this author (Table 4). Residents were able to describe flood conditions and routes at the time of the 1979 flood. This information was used with GIS and geoindicator data to create a theoretical flooding scenario for the BBHW during the 1979 flood.

Table 3. Surface features recorded by Trimble GPS

Features Recorded	Relationship to flooding	Reference
Spring	Can rapidly overflow with floodwaters.	Eyre, 1981; Day, 2010
Sinkholes	Associated depressions can overfill due to poor infiltration.	Jones, 1981; Manning et al., 1992; Ahmad et al., 1993; Maharaj, 1993; Gupta and Ahmad, 1999
Swallow holes	Can both supply and take water from the surface during flooding. Associated with poljes.	Jones, 1983; Maharaj, 1993; Gupta and Ahmad, 1999
Caves	Where they are still connected to the active conduit system may overfill with floodwater.	Fincham, 1998; Day, 2010
Incised channels	Where a large influx of floodwater creates sediment-derived "hungry waters" channel incision can occur. Also indicates an increase in stream power.	Eyre, 1981; Jones, 1981; Maharaj, 1993; Gupta and Ahmad, 1999
Headcut	Indicates incision, most headcuts are bedrock knickpoints which are either tectonically or karst related.	Jones, 1981; Maharaj, 1993; Gupta and Ahmad, 1999
Channel flow path	Can be used to determine surface connections during high flood stage.	Gupta, 1975; Jones, 1981; Manning et al., 1992
Local depositions (cobble pile; boulder pile)	Indicates where breaks in channel slope are closely related spatially; local decreases in stream power.	Jones, 1981; Manning et al., 1992; Ahmad et al., 1993; Maharaj, 1993; Gupta and Ahmad, 1999

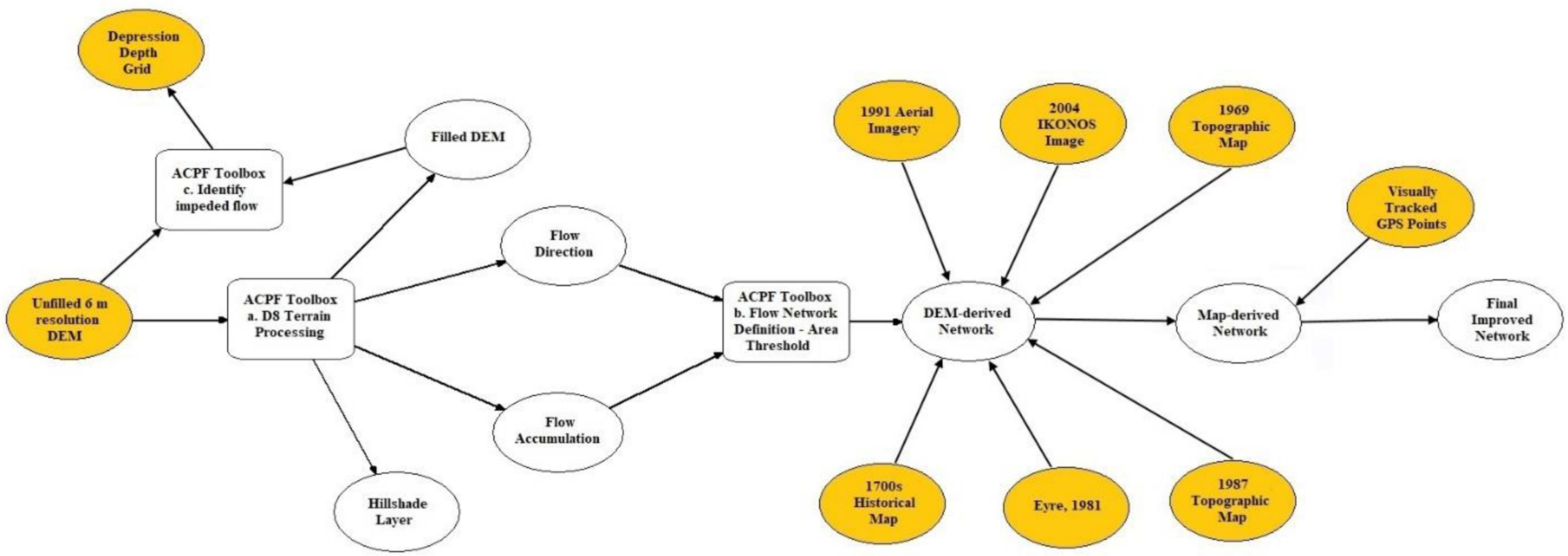


Figure 9. GIS workflow for drainage network generation and improvement

Table 4. Interviews conducted with residents during trips to the area in 2010 and 2018

Resident	Feature	Notes
Wolde Kristos	Flooding in Belmont	Water ponded in the morass and didn't cross the A-2 highway. Some water did cross the Blue Hole Road in Belmont, flooding some homes (Wolde Kristos, pers.comm., 2019).
Merna	Blue Hole Spring Maintenance	My father cleared the area surrounding the Blue Hole Spring of vegetation and mud. After public water supply, people stopped using the spring and he stopped (Merna, pers. comm., 2018).
Selvin	Brighton Center Saddlecut	The water filled behind the [Brighton] road as it rained all night. Late at night the flood water crossed the road. The flood washed a store away with nine people inside. We found the debris from the store and recovered bodies from the mangrove forest (Selvin, pers. comm., 2018).
Arnett Campbell	Blue Hole Spring	Blue Hole Spring changed after the 1979 flood. Top soil and debris was washed into it after the [Brighton] road broke (Dryer, 2010).
Farmer	Shafston Blue Hole Dam Break	This area was a pond for the plantations...The pond overtopped and water got trapped behind a stone wall. This wall broke and water flowed down Goat Gulley [Bluefields River] and to Brighton (Dryer, 2010).

RESULTS AND DISCUSSION

A combination of topographic stream data from a 6-m resolution DEM, scanned and georectified maps, and GPS locations of flood indicators were combined to create a channel network for the BBHW. An initial drainage network was first created using the ACPF toolbox in Arcmap with an area threshold of 30 acres as this threshold provided the best-fit initial drainage network (Fig. 10). This network was associated with some errors. First, coastal plain channels were particularly difficult to map using the ACPF toolbox method due to their small size and multi-channeled morphology. Second, near where channels cross roadways, the associated road depressions pirated drainage and represented these roads as channels. Third, many underground conduits or areas associated with sinkholes were represented by channels at the surface, sometimes even crossing ridges or topographic highs. Finally, where high canopy vegetation was located near topographically low unvegetated areas, such as in the morass, the elevations of vegetation were not affectively subtracted out of the purchased DEM and an artificial high was created which affected the routing of flow.

The DEM-derived network was improved using a combination of aerial imagery, maps, and illustrations (Table 5). The DEM-derived network was first compared to a 1:50,000 topographic map (Survey Department of Jamaica, 1987), which confirmed the large headwater tributary and several coastal channels, and work by Eyre (1981) which described the large tributary and channels between Shafston Blue Hole and depressions upstream of Robins River Road. Aerial imagery from December 1991 and the historical map from the British colonial period showed two channels flowing from Blue Hole Spring and Little Dismel Spring towards the morass. This imagery was also used to visualize the channel at "Creek", the channel parallel to the coastal road, and where a large tributary crosses Robins River Road in the southeastern part of the watershed (Fig. 11). IKONOS satellite imagery from 2004 was provided by The Nature Conservancy, the channels flowing from Blue Hole Spring and Little Dismel Spring were still visible, as well as the channel flowing parallel to the coastal road. Although channels were not symbolized on the 1:12,500 map (Survey Department of Jamaica, 1969), its detailed contours were used to infer channels which crossed Robins River Road north of the community of Brighton and also to confirm the southeastern most tributary upstream of Robins River Road (Fig. 10).

The preliminary drainage network was finalized using visual "ground-truthing" with GPS point locations collected by Dryer (2010), Ebert (2010), students on the May 2016 study away trip to the area, and this author in 2017 and 2018 (Fig. 12). Many channel points were collected on the coastal plain as most development is centered on this area and these channels can pose a particular risk in terms of management (Table 7). Visual "ground-truthing" was successful in mapping approximately 1,949 m of previously unrepresented sub-one meter streams on the coastal plain that were not detected by the ACPF toolbox flow method. Ground-truthing confirmed an underground conduit that directs flow from the large polje upstream of the Robins River Road to the polje upstream of Brighton. Where the main channel flows traversely through the polje valley before funneling flow into the underground conduit which flows underneath Robins River Road and the nearby ridge via a swallowhole was located. The four crossings along Robins River Road were also confirmed using ground-truthing.

Available topographic maps and the DEM were not of an appropriate resolution to detect the complete BBHW drainage network as it missed particularly small surface features such as coastal streams and small headcuts. This imagery was also unable to accurately represent complex karstic connections between surface and groundwater. Ultimately, field investigation and GPS mapping were needed to describe the entire drainage network (Fig. 13).

Channel and Valley Features

Longitudinal profiles were created for three subwatersheds of the BBHW. These profiles were combined with surface features mapped with Trimble GPS units in May 2017, January 2018, and May 2018 and indicate a significant geomorphic response to the 1979 flood (Table 6) (Appendix B). Landforms and surface features also indicate a well-developed karst drainage system (Table 7) (Appendix B). The Main Channel subwatershed contains the longest central channel of the BBHW from the headwaters in the uplands to the sea. This main channel was subdivided into three reaches moving downstream, a detailed field survey was also performed on an incised subreach within this subwatershed. The Northern Tributary subwatershed drains the morass area in the northern portion of the watershed. The Southern Tributary subwatershed heads in the uplands and drains the southern portion of the front range. These subwatersheds were selected for their spatial distribution across the BBHW and their differences in topography, soils, and karst landforms. These profiles can be used to assess the spatial relationships between channel and valley features in the BBHW.

Main Channel Subwatershed. The Main Channel subwatershed (5.0 km^2) contains the main channel which flows 6.3 km from the steep uplands at an elevation of 595 masl to the sea. In the uplands, channels are ephemeral and slopes are steep. As the channel flows from the uplands towards the coastal plain, it is bisected by the fault block valley formed by the reactivated Pg restraining bend. Channels in this valley are incised and flow through bedrock or step-pool channels at breaks in slope. Downstream of this valley, there is also evidence of channel control by fissures orientated perpendicularly to the restraining bend where a channel has been incised leaving confined, steep, bedrock walls, referred to as the Brighton-Blue Hole Gorge. Near the coast, channels become difficult to distinguish. There are shallow headcuts and several karst landforms. The GIS longitudinal profile of the main channel was separated into three subreaches to allow for more detailed study. An additional field survey was performed on the Brighton-Blue Hole Gorge along the coastal reach.

Upland Reach. The upland reach of the main channel of the BBHW begins at 595 masl in the steep uplands and flows 2.6 km to just past the Shafston Blue Hole Spring located at river station 2,520 m. The reach ends at river station 2,700 (Fig. 14). Surface features were not collected using a GPS unit in the steep uplands due to difficulty of access, but depressions can be identified at rivers stations 200 m, 340 m, 420 m. A large step-down with a slope of 38% begins where the upland channel enters a deep, confined valley at 480 m and a more gradual step-down begins where the main channel enters the extensional valley at 1,700 m. Soils along the reach are mainly Bonnygate stony loam. This soil is associated with high infiltration rates and high erosion potential. Union Hall clay is found at the head of the upland reach; this clay is associated with moderate infiltration rates and moderate erosion potential. Both of these soils contain large fragments of limestone and have moderate-high erosion potential. This indicates that these soil are capable of supplying cobble to boulder-sized sediment from bank failure or debris fans along this reach (Fig. 15).

Mid-Valley Reach. The second longitudinal profile taken along the main channel was measured along the 2.4 km long reach with a slope of 6% which flows across the fault block valley (Fig. 16). This reach is directed transversely across the valley by the rim of a polje depression. A channel that has the potential at high flood stages to cross this rim flows perpendicularly to the mid-valley reach from river station 2,600 m to 3,800 m. This reach displays a series of step-pool sequences, with alternating areas of incision and deposition. The step-pool reach from river station 3,066 m to 3,144 m forms a significant bedrock channel which is incised 2.5 m. The areas of incision and deposition are closely associated and are never more than 70 m apart. The sediment deposited in the debris fans is large, cobble-or boulder-sized, but the fans are small with an average area of 166 m^2. The soil along this reach is the Bonnygate stony loam, which likely supplies the large sediment and the debris fan is likely produced by the incised channels that are nearby. The spatial relationship of the incised channels and debris fans indicates a dissipation of flow energy during floods and most debris fans are deposited within the fault block valley. A karst depression, which functions hydrologically as an estavelle during floods, is located south of this channel near river station 3,850 m. There appears to also be a dramatic change in elevation on this profile, with a slope of 35%, this dramatic change was not noted in field surveys and is located where the drainage network turns sharply so could be an error caused by inaccurate GIS data or possibly error caused by high tree canopies. It is, however, located at the boundary of a large depression noted by Eyre (1981) and the 1:12,500 topographic map (1969) and near where the reactivated Pg restraining bend bisects the watershed, and so is likely associated with the rim of a polje. Further field surveys would be required to verify the slope of this reach (Fig. 17).

Coastal Reach. The coastal reach was measured along a 1.6 km long reach where channel slope is 4%. The profile begins at river station 4,500 m, just downstream of Brighton Road. Brighton Road is built along a ridge formed by the shared wall of two polje depressions and so water is not found at the surface except during high flood stages. Downstream of Brighton Road in the village of Brighton from river stations 4,470 m to 4,640 m, a heavily incised, bedrock channel, the Brighton-Blue Hole Gorge, was formed by floodwaters crossing this ridge (Fig. 18). The walls of the Brighton-Blue Hole Gorge consist of white limestone bedrock, overlain by paleo-colluvium and heavily dissected White Limestone. In most cases, where gorge walls are capped by soil the layer is under 2 meters. There is evidence of structural joints and fractures, indicating that the geomorphology of the gorge is geologically controlled and its location may be associated with dissolution of limestone bedrock along fault fissures.

The Brighton-Blue Hole Gorge was selected as a subreach of the coastal reach and a detailed field survey was performed. The subreach consists of seven pools each separated by limestone knickpoints. Average pool length is 25 m and average pool depth is 5 m. Channel slope within the gorge is 15% . The surveyed slope is similar to one calculated using the DEM and suggests that the DEM is suitable for reach-scale evaluations. There is evidence of possible 3 m incision during the 1979 flood (Fig. 19). Although Jones (1981) reported incision of up to 15 meters during the 1979 flood, no obvious scars or evidence of this is clear today. At the gorge, the stream can be classified as bedrock channel under the Montgomery and Buffington classification system for channel-reach morphology in mountain streams (2002). In bedrock streams, longitudinal profiles have a steeper slope and streams exhibit high sediment transport capacity, although this has not been studied extensively in ephemeral mountain streams. A large debris fan (19,745 m^2) is located directly north of this subreach and has large, cobble to boulder-sized sediment and as the soil along this subreach is the Bonnygate, this fan was likely formed by incision along this subreach.

After the main channel leaves the Brighton-Blue Hole Gorge it flows onto the coastal plain (Fig. 20). There are headcuts much shallower than those found upstream, that are likely associated with migrating headcuts in fine sediment deposits left after the 1979 flood. Shallow headcuts facing downstream of two estavelles south of the main channel at river stations 4,900 m and 4,946 m indicate their ability to direct flow underground and to the surface during high flows. Continuing downstream, a shallow headcut steps down to a sinkhole along the channel at river station 5,035 m, the output of this sinkhole is not known. A surface channel connects this sinkhole to an estavelle downstream at river station 5,100 m which directs flow into a 250 m long incised reach at high flows. This incised reach flows through the Deepdene clay, a soil formed in fine sediment in hollows on gentle slopes. A small surface channel connects this incised reach to the Little Dismel Spring at river station 5,500 m and the spring is closely associated with an unvegetated depression filled with fine sediment at river station 5536 m. This indicates sediment from the incised reach likely was deposited in the Little Dismel Spring and also filled in the wetland. A small headcut along the channel between the Little Dismel Spring and the upstream Big Dismel Spring 165 m east of river station 5,500 m indicates additional floodwater and sediment into the Little Dismel Spring and the morass. West of Little Dismel Spring at river station 5,700 m is the Blue Hole Spring, a small drainage channel from the British colonial period still drains this spring into the morass and mangrove forest. The stream finally flows from river station 6,050 m as a 330 m perennial reach known locally as "Creek" through a large morass made up of a mangrove forest and a surrounding swampy grassland before entering Bluefields Bay (Fig. 21).

Morass Tributary Subwatershed. The Morass Tributary subwatershed (1.2 km^2) contains a main channel which flows 1.5 km through the morass before emptying into Creek (Fig. 22). The watershed covers the northern section of the morass and a small section of moderate elevation, maximum elevation is 122 masl associated with the front range. The soils of the watershed are all fine clays associated with low infiltration rates with the exception of the soils on the area at higher elevation, which are Bonnygate stony loam. The main channel of the watershed heads above the Robins River Road and crosses it at river station 300 m. A small tributary directly north of the main channel flows across the Robins River Road through a cement culvert and joins the main channel at river station 770 m, there is a small headcut in fine sediment located at this confluence. Another small headcut was observed in a gravel deposit at river station 1,000 m upstream of the morass and upstream of the confluence with a small channel draining the Colonial Spring, which is indicated on a British colonial map, but is now heavily vegetated and hard to distinguish on the surface. The channel enters the morass at river station 1,060 m and continues until the confluence with Creek at 1,500 m (Fig. 23).

Southern Tributary Subwatershed. The Southern Tributary subwatershed (0.6 km^2) contains a large southern tributary which heads in the uplands at 460 m before flowing 2.9 km into its confluence with the main channel (Fig. 24). Like the upland channels of the Main Channel subwatershed, this upland tributary drains the Bonnygate stony loam, and supplied some cobble to boulder-sized sediment during the 1979 flood. At approximately river station 1,200 m it crosses into a fault block valley with Carron Hall clay as fill. The slope of the main channel is 13% and there seems to be evidence of steps and possible headcuts, these points were not verified in the field via GPS due to difficulty of access. The two channel crossings at Robins River Road are visible on the longitudinal profile at river stations 2,060 m and 2,770 m (Fig. 25).

Flooding in the Brighton-Blue Hole Watershed

A flood scenario for the BBHW during the June 12, 1979 flood was created using a combination of longitudinal profiles, cross sectional profiles, oral accounts and GPS indicators. This flood scenario was used with a combination of Depth Grid data, historical and current land use, and spatial karst feature information to assess flood risk for communities in BBHW.

June 12, 1979 Flood History. An underground karst connection which was proposed by Dryer (2010) could have potentially supplied water to both the Bluefields and the Brighton-Blue Hole watersheds at very high flows, but this research instead found evidence of supply from a saddle cut at the upland Shafston Blue Hole Spring (Fig. 26). This mechanism is supported by work by Eyre (1981), Jones (1981), and first-hand accounts (Table 4).

Floodwater was generated in the large upland tributary due to rainfall associated with Tropical Depression One. While rainfall was so intense it destroyed the gage at Bluefields, a rainfall amount of 32 inches was recorded in Friendship, Westmoreland (Blake and Pyne, 1981). The area experienced seven weeks of heavy rain before the arrival of Tropical Depression One and so karst conduits and soil were likely heavily saturated. Although the soils which dominate the uplands, the Bonnygate stony loam and Union Hill stony clay, have high infiltration rates, they were fully saturated and so a large amount of rainfall was routed along surface channels at high stream power to the Shafston Blue Hole Spring (187 masl). Additionally, the large amounts of floodwater in karst conduits increased their internal pressure and caused the rapid supply of groundwater to the surface through the Shafston Blue Hole Spring. The Shafston Blue Hole Spring is located at the bottom of a depression within a fault block valley where the divide between the Bluefields River watershed and the BBHW is lowered. The combination of rapid surface flow and groundwater exfiltration rapidly over-filled this depression until it formed a temporary lake. When a threshold was reached, floodwaters crossed the lowered divide and flowed into both the Bluefields River watershed and the BBHW. Floodwaters flowing into the Bluefields River were rich in sediment and created a large debris fan downstream of this saddle cut. Additionally, these floodwaters moved at a high velocity and stream power and were able to heavily incise channels, delivering even more sediment to the system there.

Floodwaters spilling from the Shafston Blue Hole Spring depression flowed in two directions, to the south through the mid-valley reach and east over the rim into the Robin River Road polje (88 masl) via a temporary flood channel. The floodwaters moving though the mid-valley reach had a high stream power capable of moving large sediment associated with the Bonnygate stony loam, but stream power attenuated as it moved through the valley. This is illustrated by the large, number of incised reaches with closely associated coarse debris fans. The Robins River Road polje is normally drained by an estavelle which quickly became overburdened with floodwater moving through underground conduits. This polje filled both via exfiltration from the estavelle and from the two surface channels and also formed a temporary lake. However, because the velocity and stream power of floodwaters were attenuated through the mid-valley reach before entering the polje, the geomorphic response was less catastrophic than in the Shafston Blue Hole depression. The Robins River Road runs along the rim of the polje and was covered in standing water from the temporary lake, but high velocity, destructive flows did not cross it. Water levels of the temporary lake were high enough to cover the Robins River Road for over a month and the road was rebuilt in its current location (Eyre, 1981).

Water from the temporary lake at the Robins River Road polje were transported via underground conduits underneath the road to the Brighton Center polje (66 masl). Pressurized, saturated karst conduits slowly filled the polje over the course of several hours on the night of June 12, 1979 (Eyre, 1981; Porter, 1981). In the early morning according to first-hand accounts, floodwaters from the Brighton Center polje burst across the Brighton Road at Brighton Center with a large booming sound, washing away a building and killing 9 people. A large debris fan of coarse material north of Brighton Road produced from material eroded from Brighton Center was observed by Eyre (1981) using satellite imagery taken on July 19, 1979. Downstream of Brighton, floodwaters were routed through the Brighton-Blue Hole Gorge, entrenching it at least 3 meters, although work by Jones (1981) reports incision up to 15 meters. The gorge displays a dramatic step-pool morphology and the small, coarse debris fans located downstream of it indicate an attenuation of stream power as floodwaters moved through the gorge into the coastal foothills area.

In the coastal foothills area, two estavelles overfilled with flow which was routed towards the main channel where it flows through a confined valley. This temporarily increased stream power and allowed for some incision of the fine-grained Deepdene clay, but not of the more coarse-grained Bonnygate stony loam. Downstream of the incised channel, floodwaters flowed onto the flat, coastal plain and stream power was again attenuated. Fine material eroded by the weaker floodwaters from the incised reach in the coastal foothills was deposited downstream in the Little Dismel Spring and the associated depression. The floodwaters were then routed towards the morass area.

The morass area received floodwater from both the main channel and the morass tributary. Floodwaters were slowed completely by the morass due to an increase in roughness associated with vegetation and the low slope. This floodwater sat in the bowl-shaped morass area and was prevented from entering the bay by the beach barrier. Wolde Kristos described flooding in the morass near the village of Belmont during the 1979 flood; water pooled in the morass but was blocked by this beach barrier and funneled through Creek and the culvert under the A-2 highway and into the bay. Some water did cross the Blue Hole Road in Belmont and inundated some buildings, but these homes were located near a cave which may have supplied groundwater to the surface (Kristos, pers. comm., 2019).

Flood Risk. Flood risk maps have been created for larger communities in western Jamaica using geomorphic analysis with data from one specific flood (Mandal and Maharaj, 2013; Mandal et al., 2016). Maps have not been created for the small, rural communities of western Jamaica, although the risk for flooding there is particularly high (Nkemdirim and Jones, 1978; Nkemdirim, 1979; Naughton, 1982; O'Hara, 1991; Collymore, 2007; Gamble et al., 2010). Buildings digitized from 2018 Google Earth imagery were compared to Depth Grid depressions, surface features which indicate flooding, and historical accounts to create flood risk maps for the communities of Brighton and Belmont. These maps illustrate community risk in the event of a flood with the intensity of the June 12, 1979 flood and can be used in planning and flood mitigation.

There are isolated buildings in the upland area upstream of the Robins River Road, but none appear to be closely related to surface flood indicators spatially. The village of Brighton located at the intersection between Robins River Road and a small street referred to as Brighton Road. The village and associated roads were built where the rim of a polje forms a high ridge and a saddle cut occurred in 1979. As of 2018, 9 buildings are located in this area, all are family homes. Additionally, 5 buildings in the village of Brighton are located within the temporary lake boundaries observed by Eyre (1981). There is also a large cave located in the village of Brighton. Although there is no evidence of it affecting flooding during the 1979 flood, it is a groundwater conduit which may play a major role in floods (Fig. 27). Although there are several fields along incised channels and estavelles where the front range meets the coastal plain downstream of the Robins River Road, buildings near these fields are not visible and so more assessment is needed to determine flooding risk. Although they are close spatially, most fields are located on topographic highs where infiltration is better and so are unlikely to be flooded. Some isolated fields are located on areas of deposition and were noted on surface feature surveys, these fields could represent areas of economic loss in the event of a large flood.

The largest concentration of buildings in the BBHW is in the village of Belmont along the coast of Bluefields Bay. Mainly buildings are located around the morass area and along Creek. A cave which has the potential to supply groundwater to the surface during high flows is located near a small cluster of buildings. The A-2 highway in Belmont and the buildings on the coast, particularly the community center which is now the location of the Bluefields Bay Fisherman Friendly Society are built on a beach barrier landform at a higher elevation (2 m higher). Many buildings and the A-2 highway were spared from significant flood damage due to the relationship between the beach barrier landform and the morass (Fig. 28).

The karst topography of the BBHW effects flooding and both increases and decreases risk to communities. The polje depressions slow floodwater and keep debris flows isolated in the uplands. These poljes can put communities at risk where buildings are located along rims, such as in Brighton. These rims have the ability to fail during intense flows, rapidly releasing floodwater and sediment into populated areas. As floodwaters fill underground conduits to the pressure inside the karst system increases, reactivating inactive conduits and springs (Day, 1979; 2010). These previously inactive features can cause water to pool and flow at the surface in unexpected places and can put Belmont and coastal buildings at risk.

The risk of these communities to flooding will likely increase as a result of anthropogenically-caused climate change (Hoegh-Guldberg et al., 2018; Taylor et al., 2018). As sea level rises, Belmont may be temporarily protected from inundation with seawater by the beach barrier. However, when this beach barrier is over-topped or when rising seas inundate Creek, the morass will be flooded. The loss of the morass due to seawater inundation will affect flooding in Belmont from floodwaters coming from the uplands. These floodwaters will not be slowed or contained and will have the ability to reach the town. Tropical storm severity and frequency is also likely to increase (Hoegh-Guldberg et al., 2018; Taylor et al., 2018). This increase in rainfall will increase the frequency of catastrophic floods similar in severity to the 1979 flood. Brighton will be at risk as the amount of rainfall necessary to over-top the nearby polje falls more frequently.

Comparison to the Bluefields River

Field observations reveal that although there appeared to be a difference in geomorphic response between the BBHW and Bluefields watersheds during the 1979 flood, the BBHW did respond to flood waters with incision and debris flows. These high energy flood indicators are located largely in forested areas and in some cases can be difficult to distinguish on the landscape due to vegetation cover and isolation. Differences in response between the two watersheds was found to be caused by differences in topography, karst development, and coastal landforms.

The Bluefields River drains higher elevations from a steep mountain front and stream gradient along the front is high, 26% and so the channel has the capacity to develop fast moving water and debris flows. Conversely, the front range channels of the BBHW have a slope of 14% and likely stream power during the initial flood stage is not as intense. A large, structurally controlled fault block valley lowers the watershed divide at the Shafston Blue Hole. During high flood stage this lower divide allowed piracy of floodwater from the BBHW by the Bluefields River increasing flood stage there resulting in valley incision and large debris flows that deposited material for 475 m. The topography of the watersheds are also significantly different.

The main stem of the Bluefields River drops 700 meters over 4 kilometers directly into the sea, the coastal plain of the watershed is relatively narrow. Conversely, the BBHW descends 595 m in nearly 5 kilometers. Channels flow from the steep upland headwater channels in a series of steps, slowing velocity well before the stream enters the bay. Channels also transverse nearly 1.2 km of flat, coastal plain before entering the bowl-shaped morass area. This combination of topographic features slows floodwaters before they flow into the bay through Creek.

Differences in response are also due to an extensive karstic connection in the BBHW. The Bluefields River is perennial and although underground karst channels likely exist, the presence of a complex network of springs and sinkholes on the coastal plain in the BBHW indicates that such a network maybe more developed there. Although the intensity of flooding in karstic landscapes can be increased by the presence of such features, they can also provide a conduit for flood waters without affecting surface anthropogenic development or leaving geomorphic evidence of flooding. Their presence can also change stream velocity and lead to a series of closely spatial related areas of incision and deposition. In the case of the 1979 flood, flood waters from the large eastern-most headwater tributary were stopped by the large depression at the Shafston Blue Hole spring, rather than being funneled down the main channel of the BBHW. This depression filled until a threshold was reached and flood water flowed in both the Bluefields River and the BBHW. Where the Bluefields River had a well-developed channel which funneled this extra water and debris toward the main channel and bay, flood waters instead flowed into a series of two depressions in the BBHW where surface channels are less developed. These depressions at descending elevations functioned hydrologically as poljes and allowed for floodwater to more slowly descend from uplands attenuating stream power. Unlike Bluefields River, debris flows generated in the steeper areas of the BBHW were gradually slowed and deposited upstream only a short distance from the source, never more than 70 m, rather than directed into the bay.

The coastal landforms of the two watersheds also differ, the Bluefields River is connected by steep slopes to the sea so eroded coarse sediment and floodwaters were able to reach the sea at high stream power and velocity. The Bluefields River also flowed directly from the coastal plain into the bay as sediment rich flows because of the lack of a beach barrier or morass. Unlike the Bluefields River watershed, slopes, and thus stream power, decrease in the BBHW before reaching the bay and so most erosion on the coastal plain occured in fine clay soils and so intense debris flows of coarse material like those found in the Bluefields River watershed were not produced. There is also evidence that the morass acted as a sediment sink in the BBHW, slowing floodwaters and allowing for deposition of fine sediment into the morass area. The beach barrier funneled these sediment poor floodwaters into Creek and spared much of Belmont from serious damage. Mangrove forests have been known to buffer sedimentation and by filtering water can protect bodies of water from intense sediment influx (Weaver and Schwagerl, 2009; Bell and Lovelock, 2013).This appears to be the case in the BBHW and the lack of intensive mangrove growth along the mouth of the Bluefields River may contribute to the generation of a sediment fan there.

Table 5. GIS raster layers used to improve DEM-derived network

Type	Description	Reach Identified	Source
Aerial Imagery	JAM91-001 - 1:1500 imagery of the lower watershed (1991)	Drain channels from Blue Hole Spring; northern morass channel; where channel exits gorge	The Nature Conservancy
IKONOS Imagery	High-resolution (1 m) true color imagery of southwest Jamaica (2004)	Drain channels from Blue Hole Spring; northern morass channel	The Nature Conservancy
Topographic map	1:50,000 full color topographic map (1987)	Headwater reach; channel at "Creek"; northern morass channel; gorge channel at Brighton Road; southern crossing at Robins River Road	Survey Department of Jamaica
Topographic map	1:12,500 black and white topographic map (1969)	Channels crossing Robins River Road; southern tributary	Survey Department of Jamaica
Hand drawn illustration	Drawn from 1979 aerial imagery of the upper watershed (1979)	Main channel upstream of Robins River Road; channel at gorge	Eyre, 1981

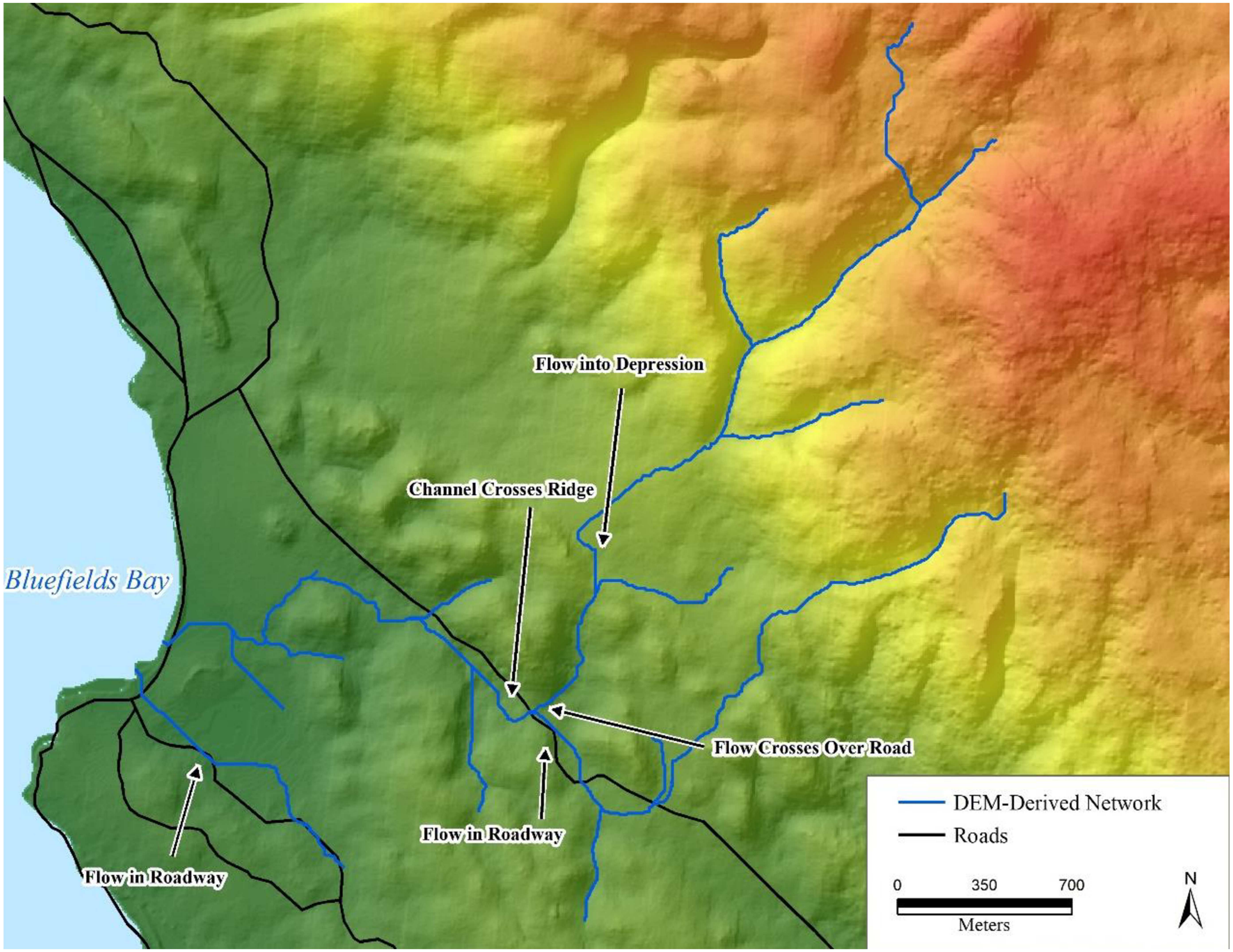


Figure 10. Flow network generated using the ACPF toolbox with selected errors noted

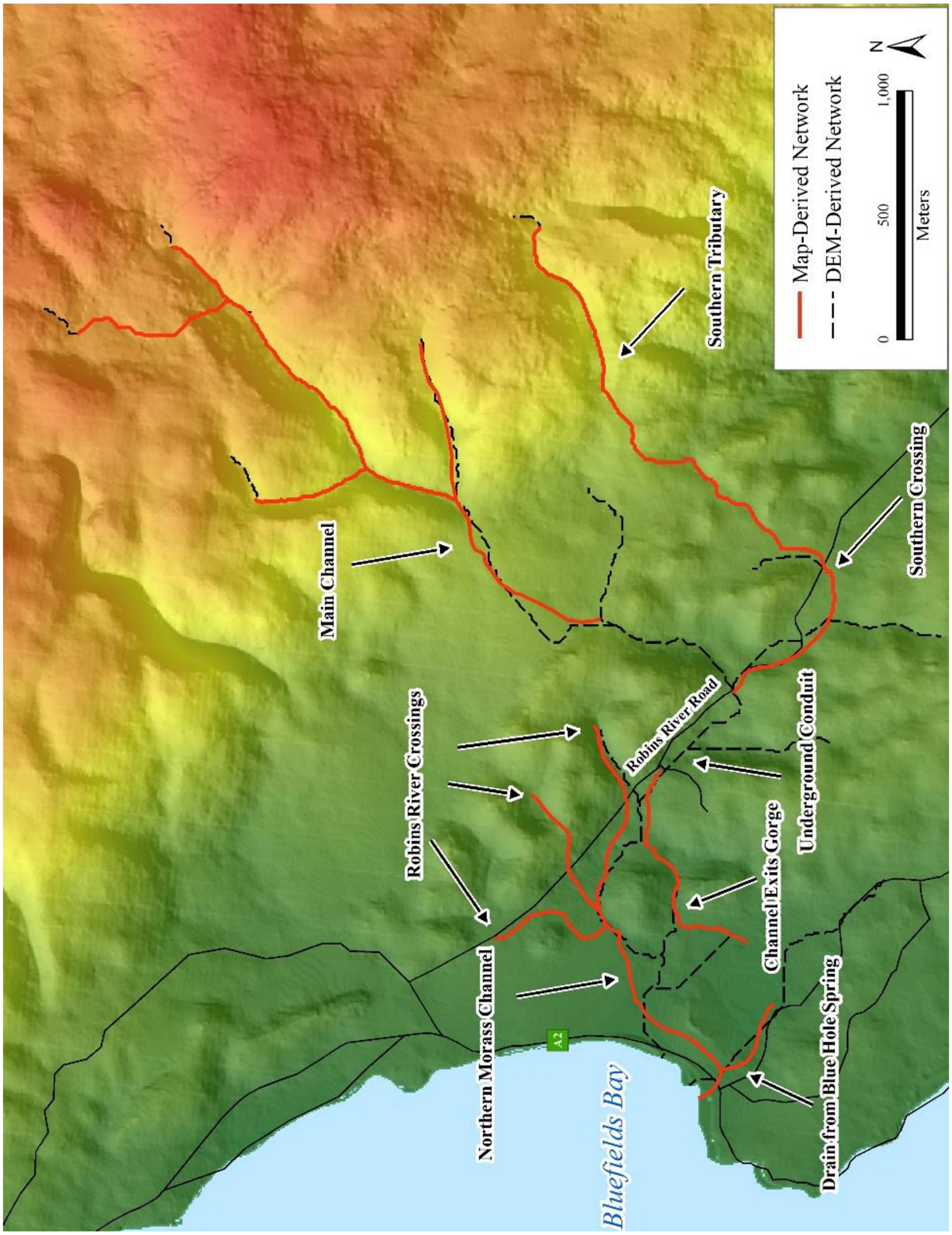


Figure 11. Flow network improvements made using comparisons to GIS raster layers

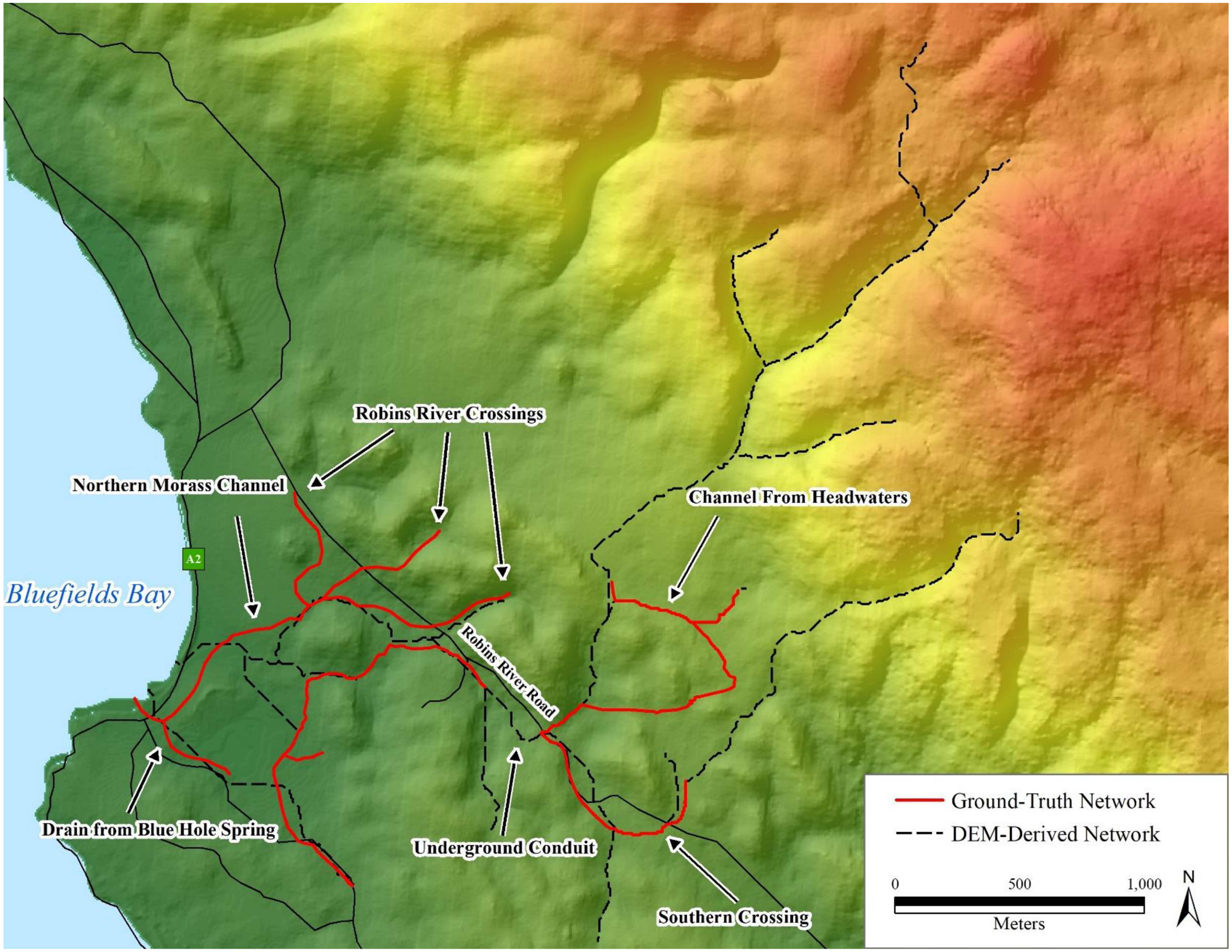


Figure 12. Flow network improvements made using GPS points from field surveys

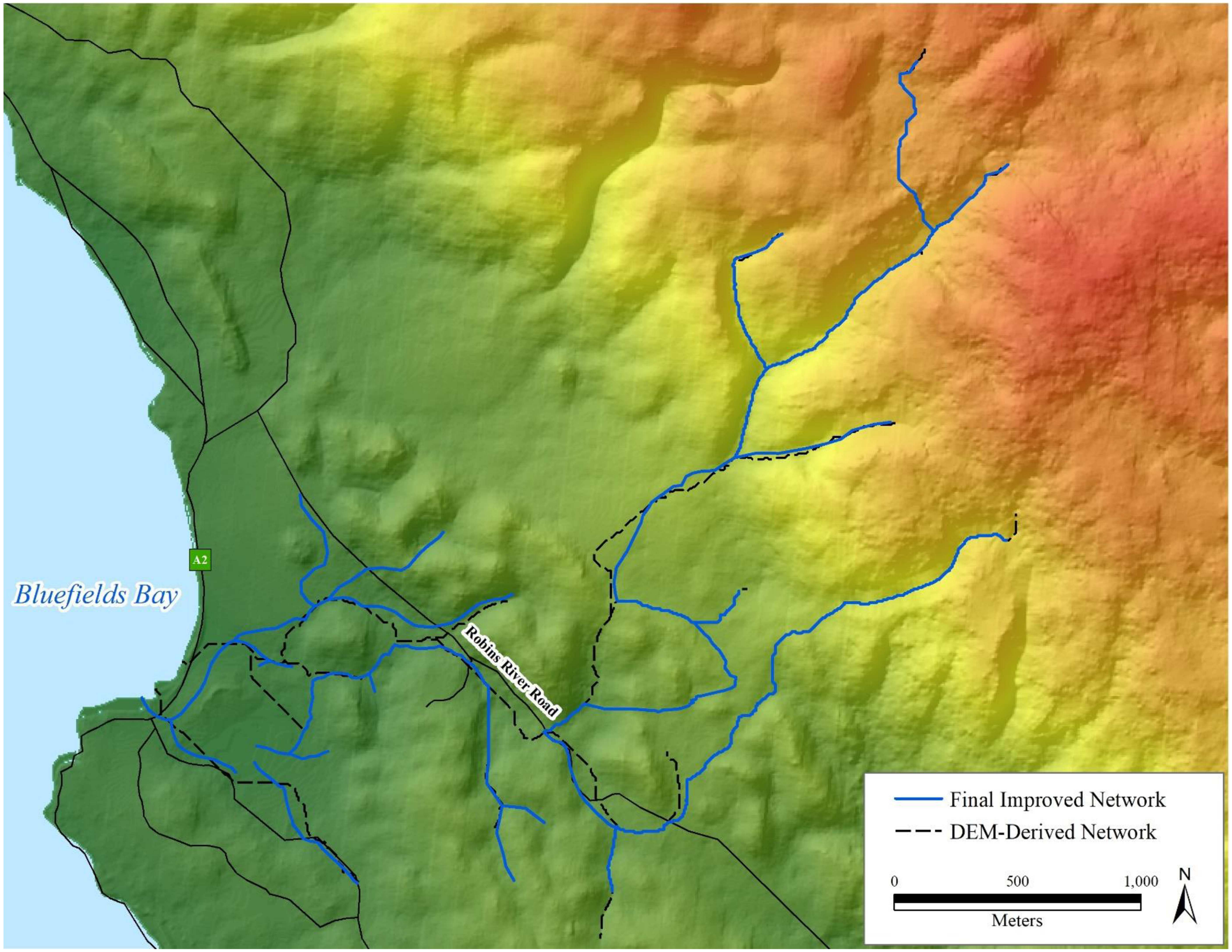


Figure 13. Final, improved flow network

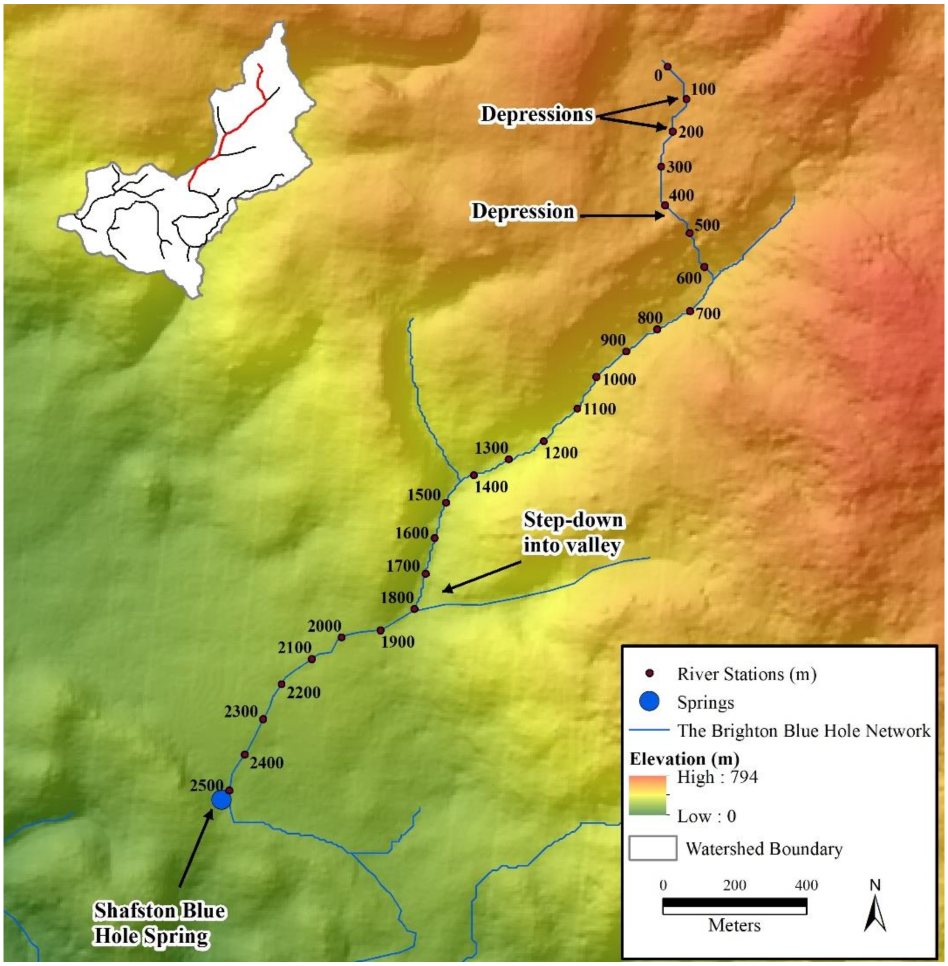


Figure 14. Location map of the upland reach of the main channel

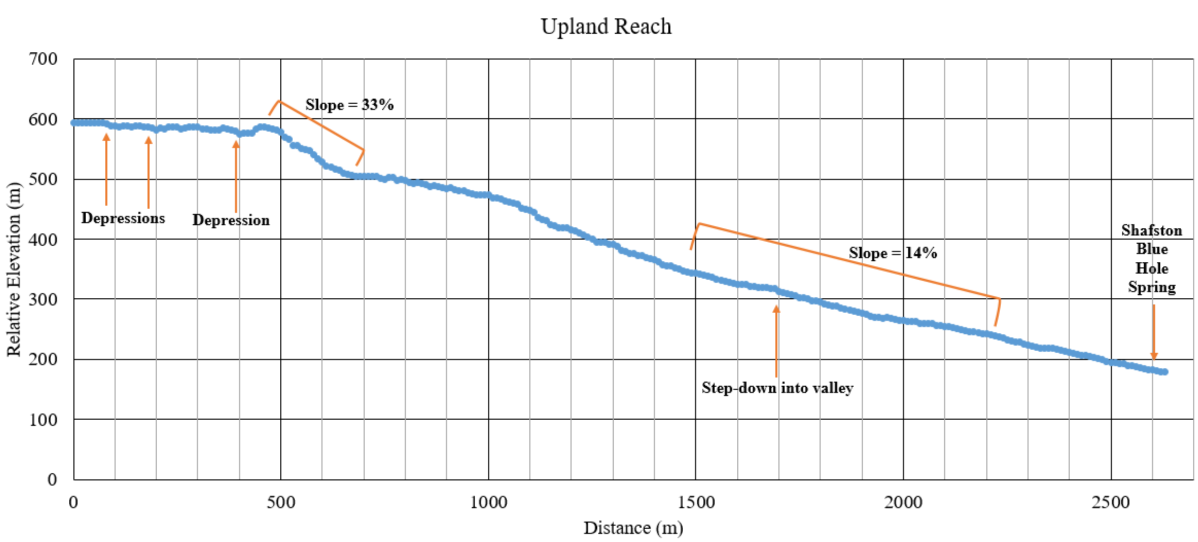


Figure 15. Longitudinal profile of the upland reach of the main channel

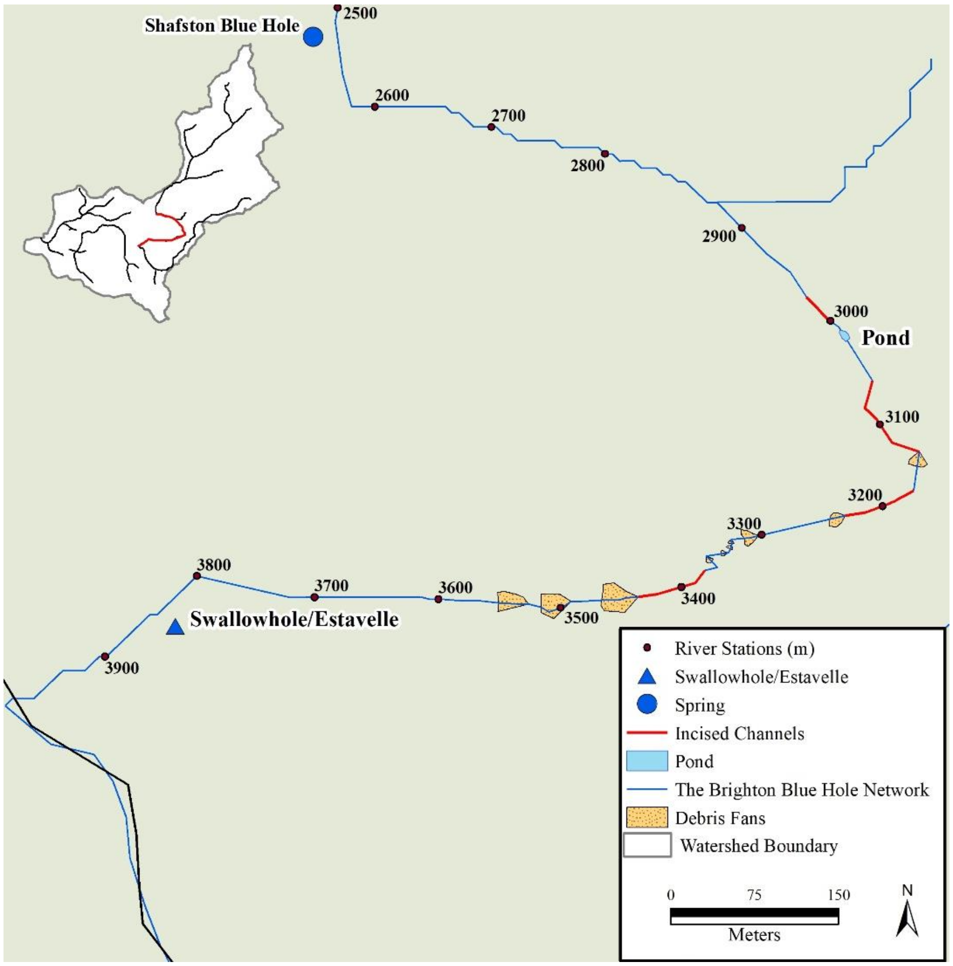


Figure 16. Location map of the mid-valley reach of the main channel

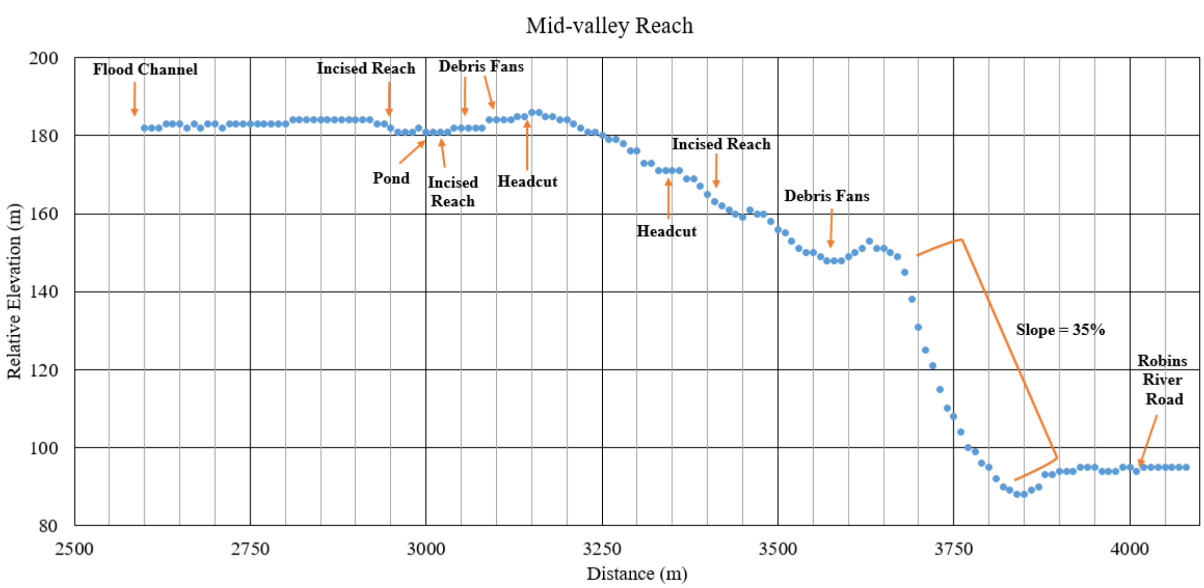


Figure 17. Longitudinal profile of the mid-valley reach of the main channel

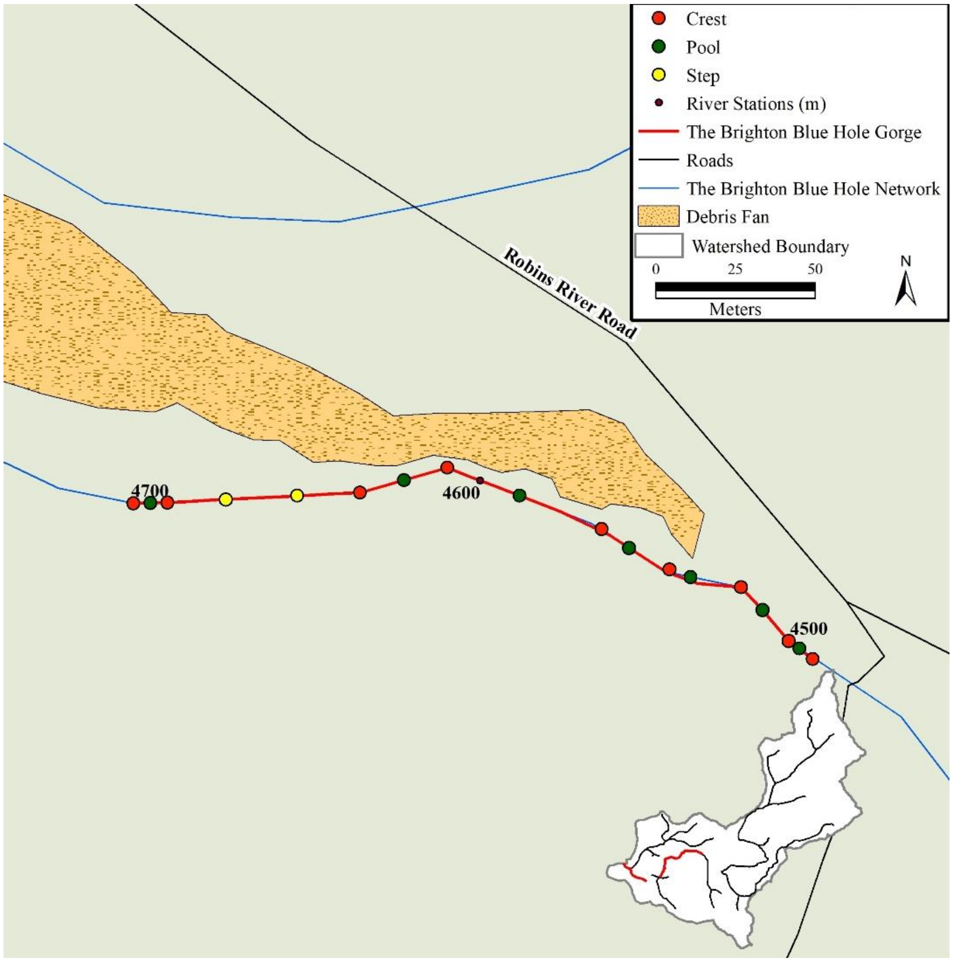


Figure 18. Location map of Brighton-Blue Hole Gorge

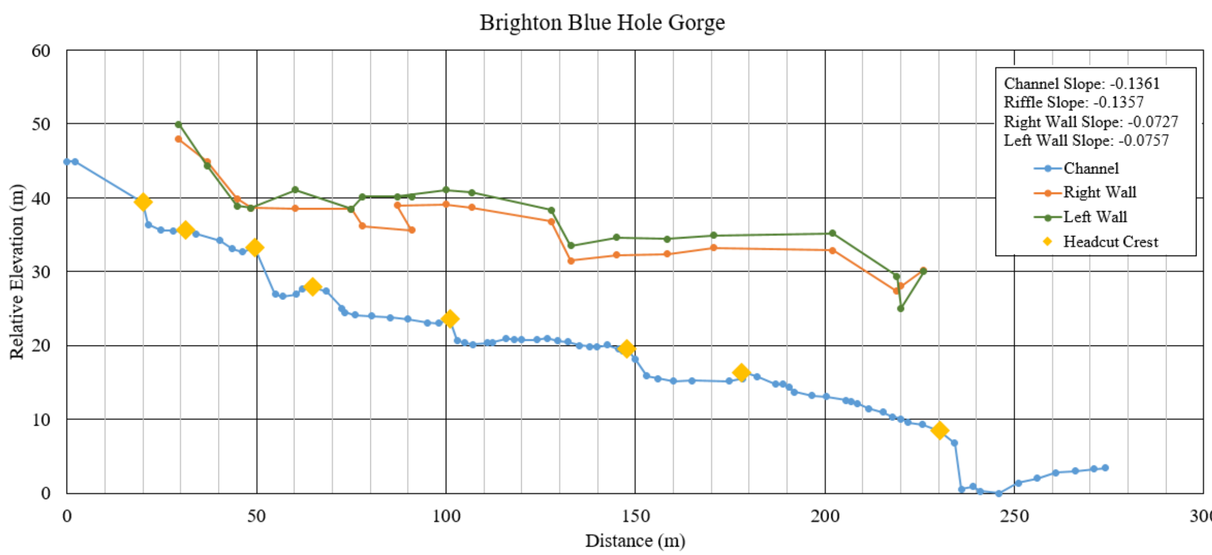


Figure 19. Longitudinal profile of Brighton-Blue Hole Gorge

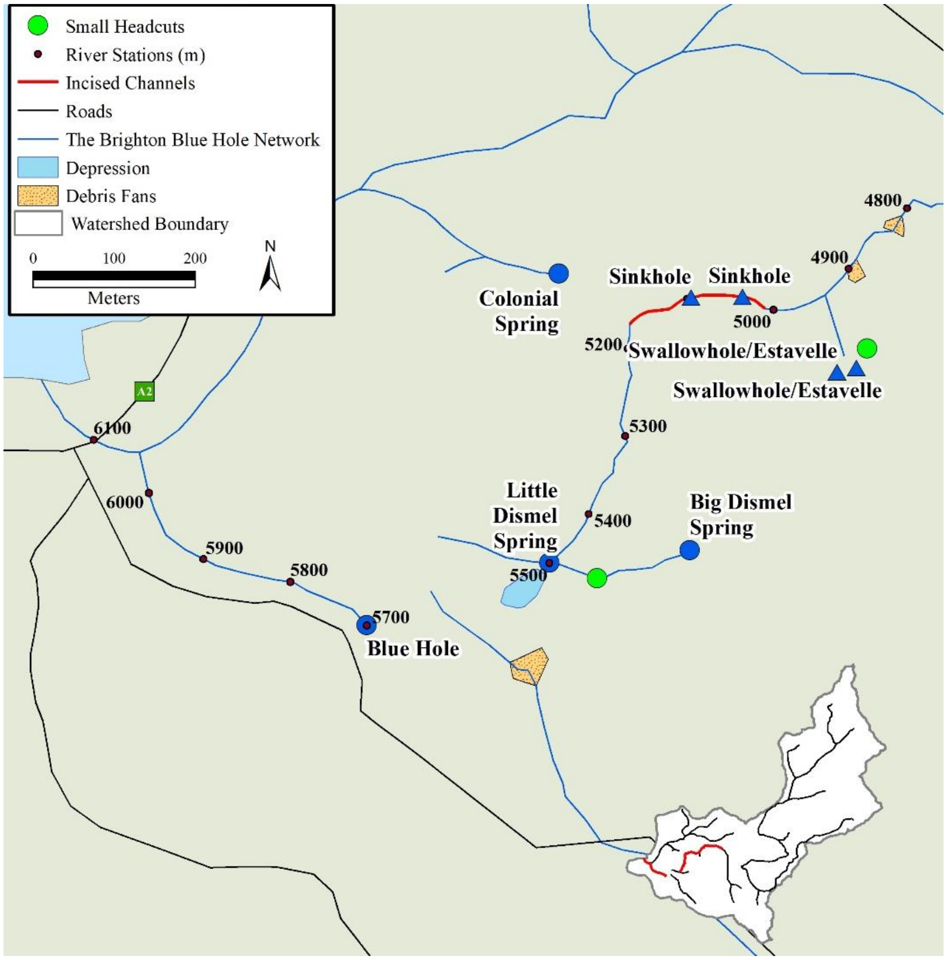


Figure 20. Location map of the coastal reach of the main channel

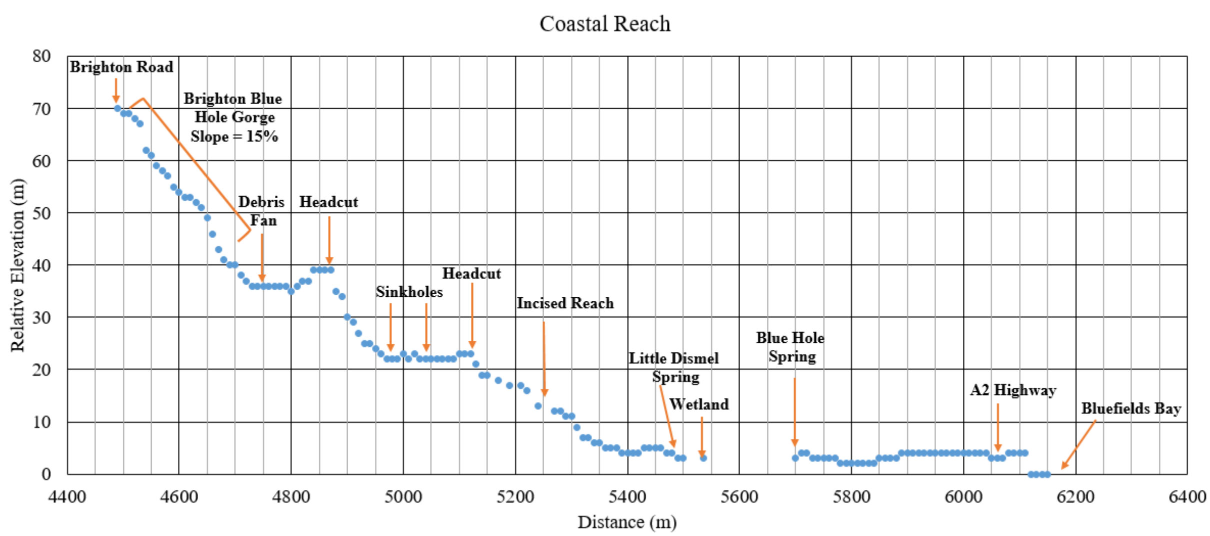


Figure 21. Longitudinal profile of the coastal reach of the main channel

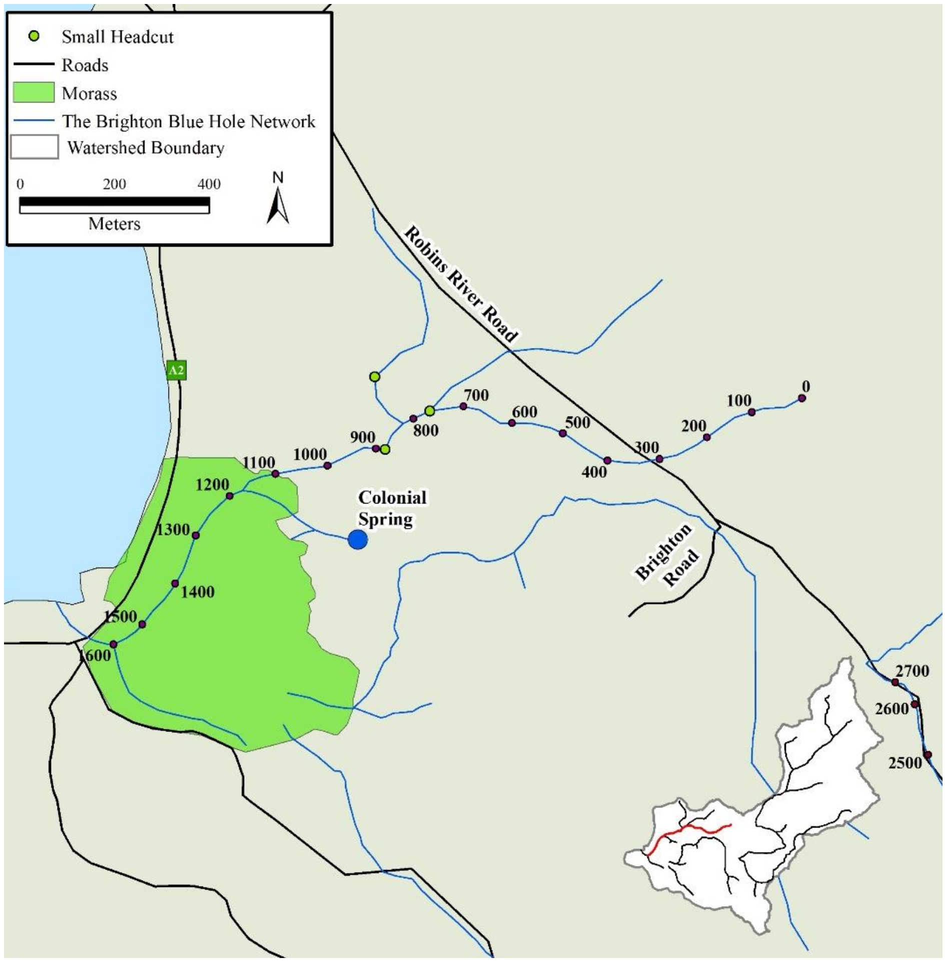


Figure 22. Location map of Morass Tributary subwatershed

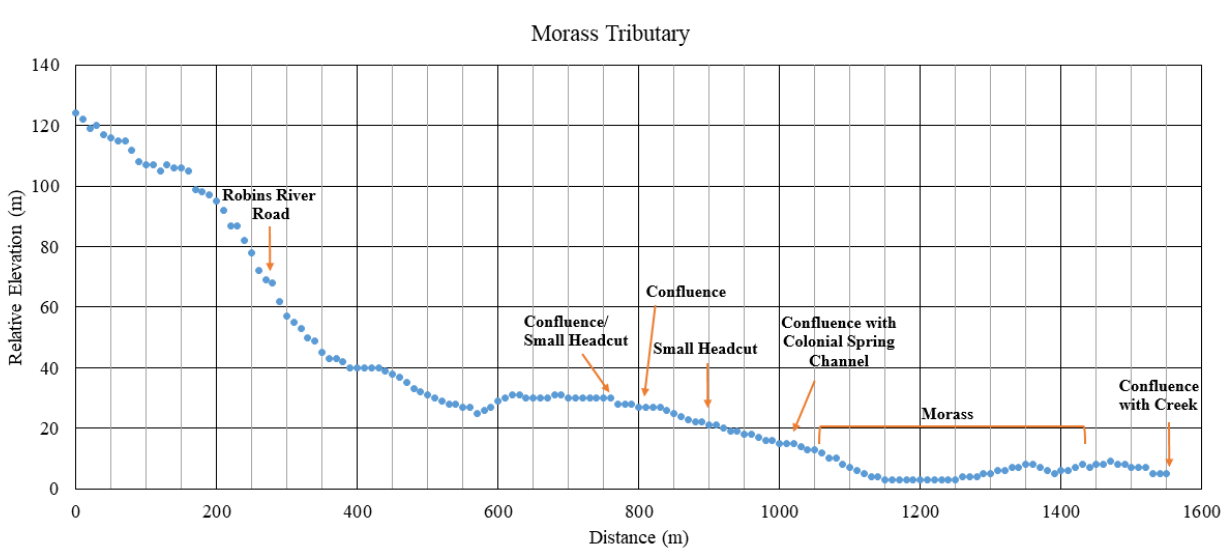


Figure 23. Longitudinal profile of Morass Tributary subwatershed

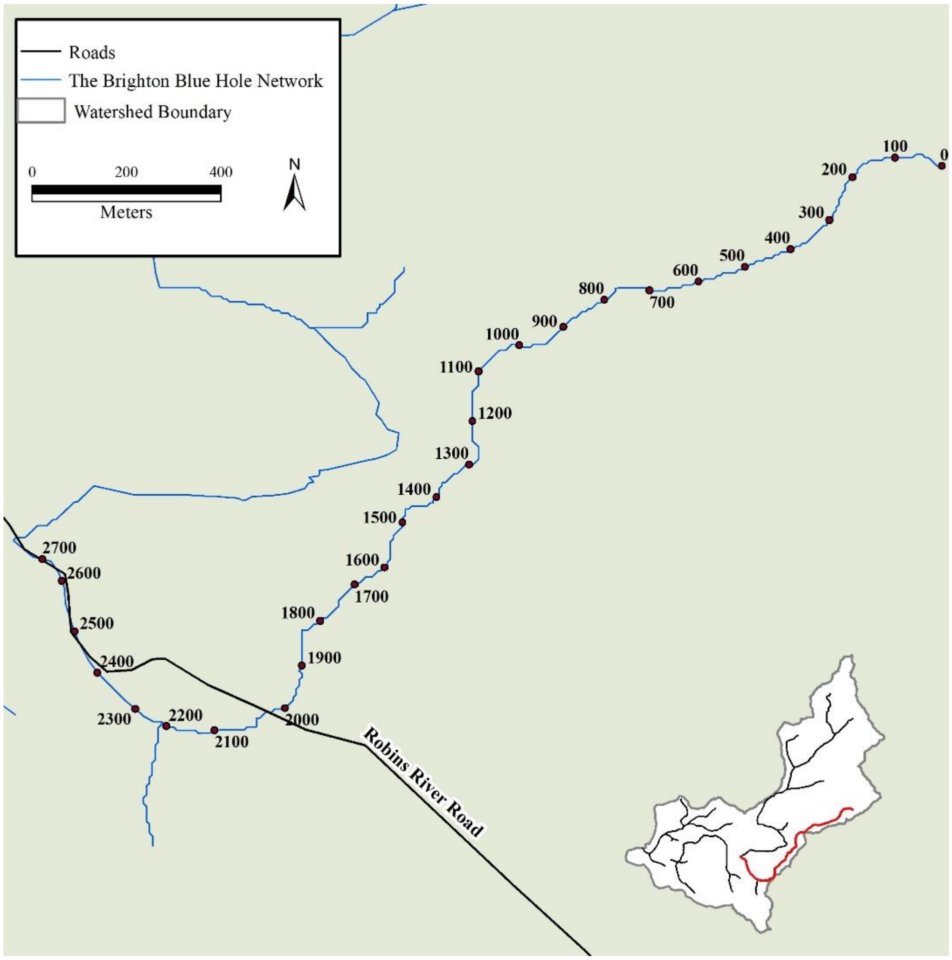


Figure 24. Location map of Southern Tributary subwatershed

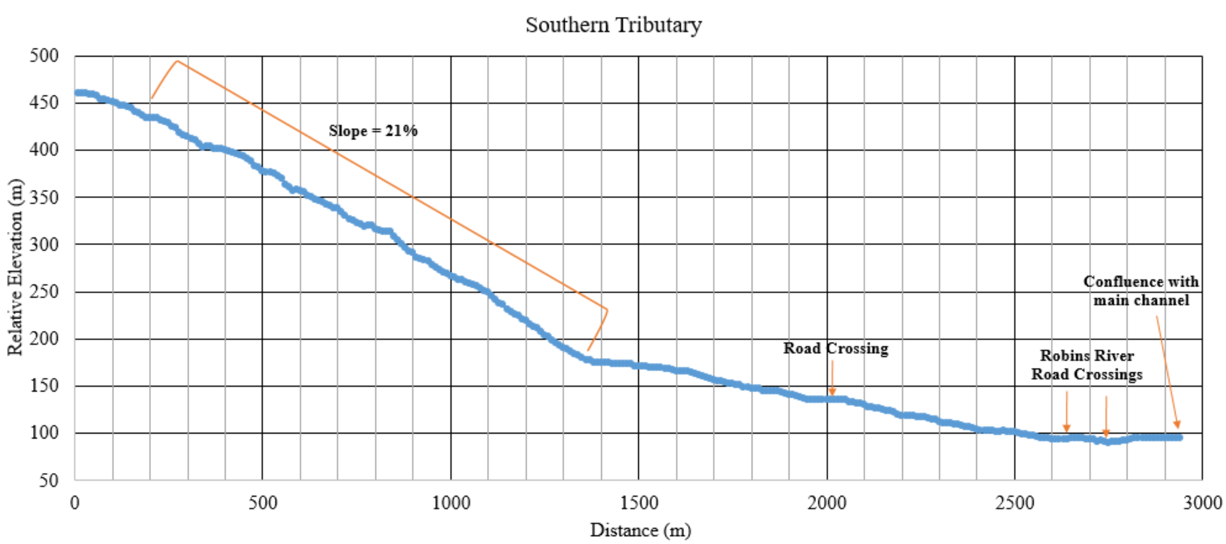


Figure 25. Longitudinal profile of Southern Tributary subwatershed

Table 6. Karst features in the BBHW

Subwatershed	Reach	Feature	River Station (m)	Elevation (masl)
Main Channel	Upland	Depression	100	587
		Depression	200	582
		Depression	420	577
		Step-down into valley	1,800	273
		Extensional valley	1,900-2,500	220-187
		Shafston Blue Hole Spring	2,520	187
	Mid-valley	Karst Depression/Pond	3,023	181
		Swallowhole/Estavelle	20 m south of 3,848	88
	Coastal	Rim of polje	4,988	127
		Swallowhole/Estavelle	120 m south of 4,900	39
		Swallowhole/Estavelle	100 m south of 4,946	39
		Sinkhole	5,035	22
		Sinkhole	5,100	22
		Colonial Spring	150 m west of 5,100	15
		Big Dismel Spring	165 m east of 5,500	5
		Little Dismel Spring	5,500	3
		Wetland	5,548	3
		Blue Hole Spring	5,700	3
Morass	Morass Tributary	Colonial Spring	186 m south of 955 m	15
South	Southern Tributary	Step-down into valley	1,200	215

Table 7. Fluvial features in the BBHW

Reach	Feature	River Station (m)	Elevation	Length (m)	Area (m2)
Upland	-	-	-	-	-
Mid-valley	Confluence	2,600	182	-	-
	Incised channel	2,976	182	24	-
	Incised channel	3,066	181	90	-
	Debris fan	3,144	182	5	25
	Incised channel	3,179	181	5	-
	Debris Fan	3,217	184	38	22
	Debris Fan	3,300	176	4	24
	Debris Fan	3,320	173	0.5	4
	Debris Fan	3,321	173	1	8
	Debris Fan	3,324	173	1	6
	Debris Fan	3,350	171	2	7
	Incised channel	3,360	169	80	-
	Debris fan	3,440	161	30	18
	Debris fan	3,490	159	19	16
	Debris fan	3,529	155	12	15
	Confluence	3,800	94	-	-
Coastal	Brighton-Blue Hole Gorge	4,470	69-40	250	-
	Debris fan	10 m north of 4,500	40-30	400	19,745
	Debris fan	4,820	36	4	8
	Debris fan	4,900	30	4	6
	Small headcut	115 m south of 4,900	36		-
	Small headcut	88 m south of 4,946	34		-
	Incised channel	5,000	23-13	250	-
	Debris fan	132 m south of 5,500	5	40	10
Morass Tributary	Confluence	770	27		-
	Small headcut	770	27		-
	Small headcut	150 m north of 830	24		-
	Confluence	830	21		-
	Small headcut	892	21		-
	Confluence	1,600	15		-
Southern Tributary	-	-	-	-	-

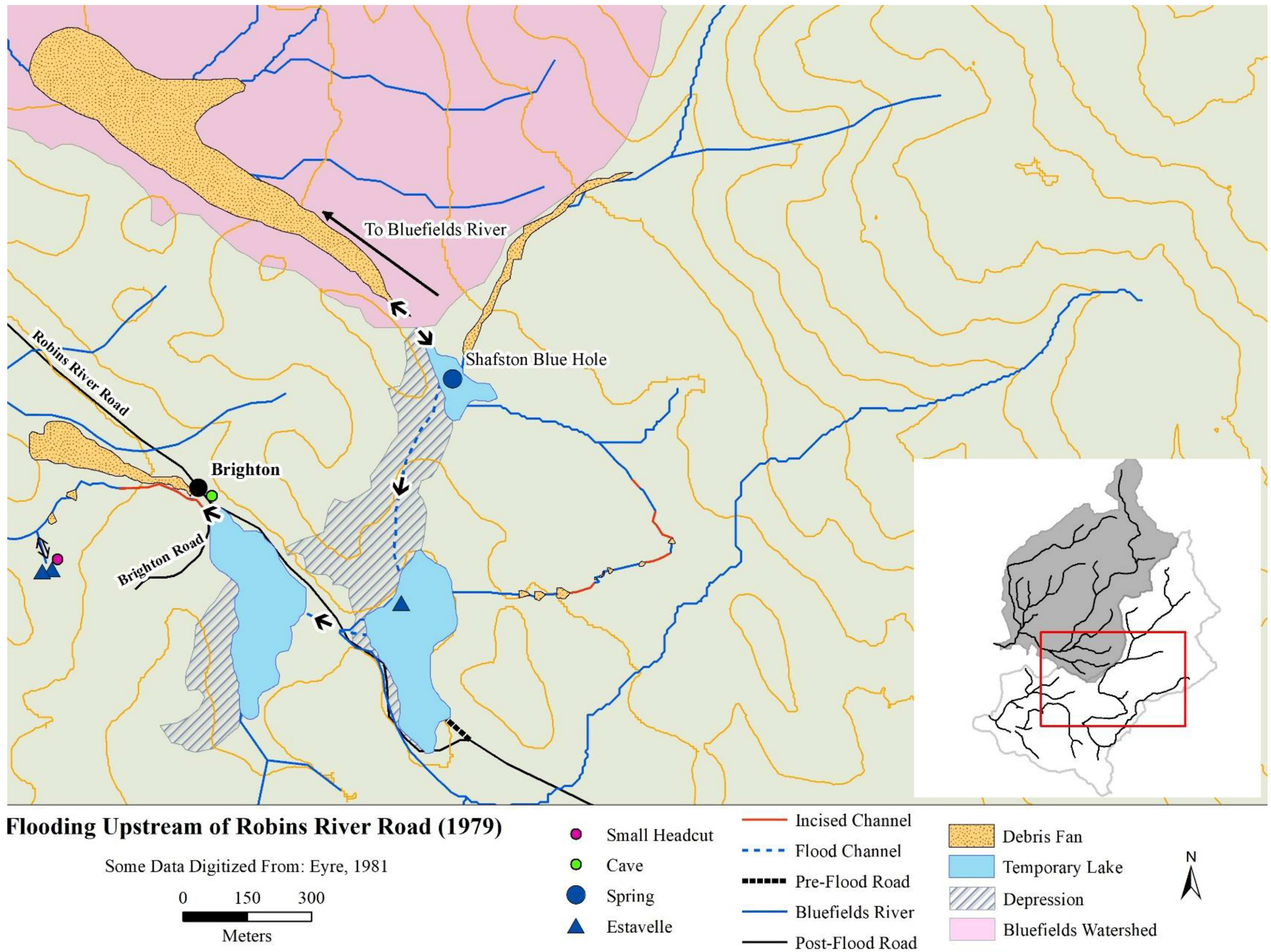


Figure 26. Flooding during the June 12, 1979 flood upstream of the Robins River Road

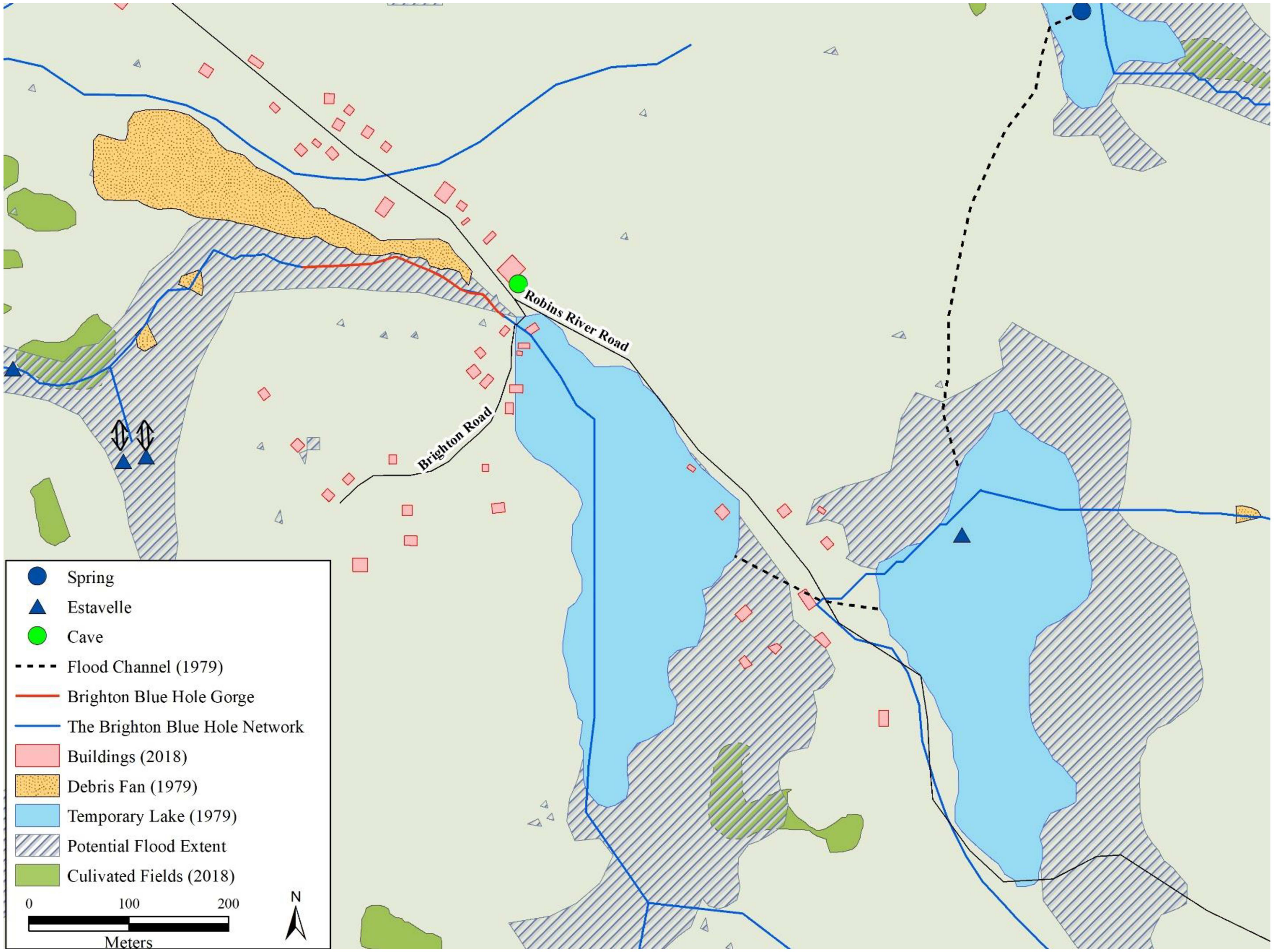


Figure 27. Flood risk map for the village of Brighton

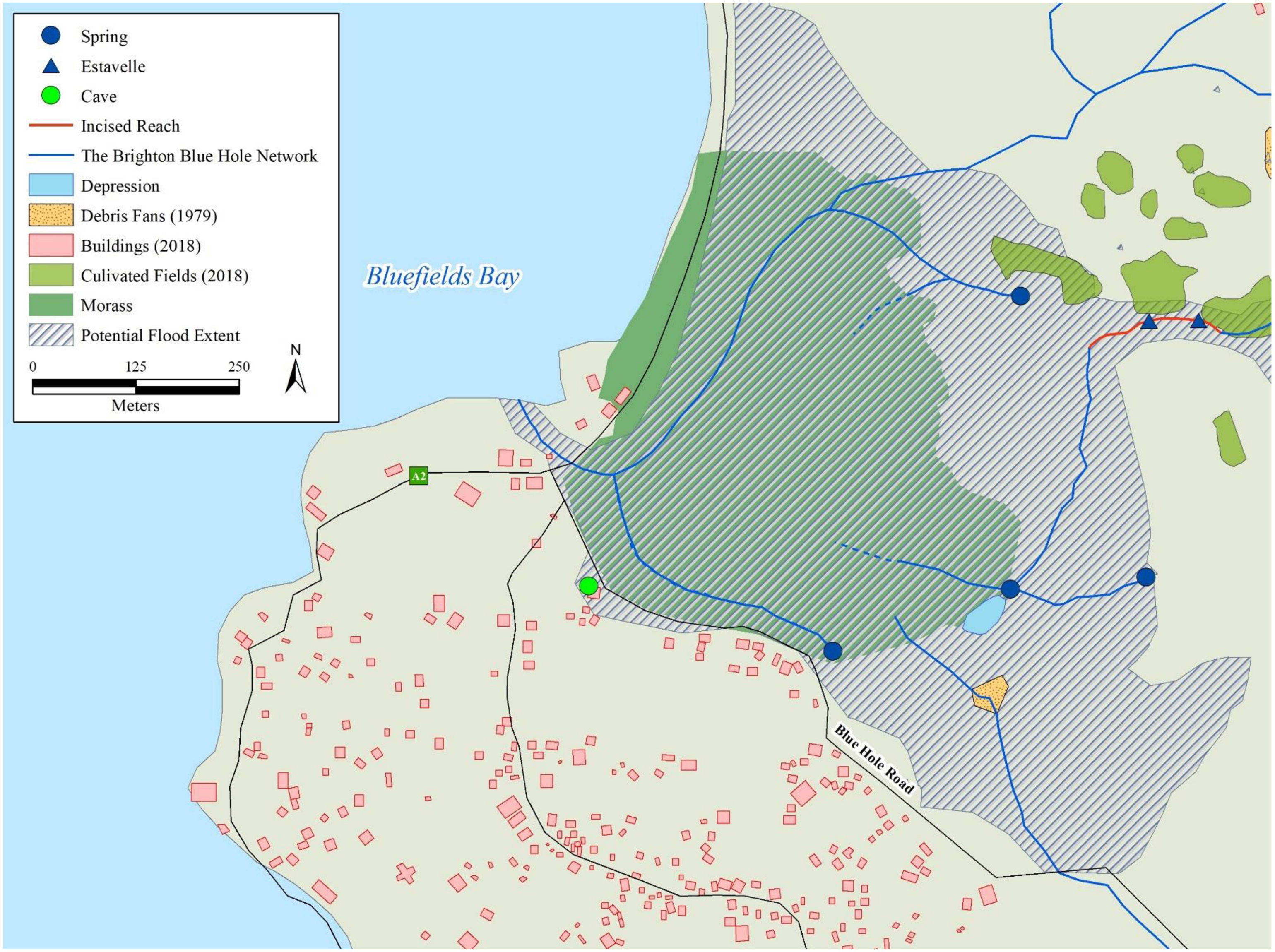


Figure 28. Flood risk map for the village of Belmont

CONCLUSIONS

Geomorphic assessment is a useful basic method for flood assessment in ungaged streams. The purpose of this research was to document the geomorphic response and remaining surface effects in the BBHW from the 1979 flood and to compare and contrast the response with the nearby Bluefields watershed to develop a better understanding of flood risk in Jamaica. This research found that the BBHW did have a significant response to extreme flooding including, deep standing water in mountain valleys, channel incision and debris fans, and in some places locally increased stream power from karst directed flow. On June 12, 1979, because of a large storm event preceded by a long period of record-breaking rain, regularly ephemeral channels were activated, groundwater pooled at the surface, channels incised and released sediment. The assessment of the geomorphic effects of this flood leads to the following main conclusions:

1. **A 6-m resolution DEM was not appropriate for drainage network creation everywhere in the BBHW.** The DEM was not detailed enough to detect sub-one meter channels and had artificial high associated with unsubstracted tree canopies. A combination of the DEM, satellite and aerial imagery, previous studies, and field surveys were successful in creating an accurate drainage network of the BBHW. Longitudinal profiles created with the final drainage network confirmed more pronounced areas of incision, depressions, and other surface features which were measured in the field.
2. **The geomorphic effects of the June 12, 1979 were in many cases still visible on the landscape.** Headcuts, incised channels, areas of deposition, and saddle cut chutes could still be identified on the surface nearly 40 years later. This both illustrates the severity of this flood, but also the veracity of physical inventory of surface features as a method for describing floods, especially in understudied or ungaged areas even in heavily vegetated, isolated watersheds.
3. **A well-developed karstic landscape of poljes, sinkholes, and estavelles effected flood routing and severity in the BBHW.** BBHW was found to display many of the karst features associated with the margins of Cockpit Country. While karst features allow water to rapidly move downgradient underground and add to flood severity, they also created areas of disconnection and energy dissipation in fault block valleys.

4. **Land use changes beginning in the colonial period have affected the severity of flood damage in the BBHW.** In the village of Brighton, roads and buildings were built along a ridge between two pjoles. This area was the site of a major saddle cut and wash out during the June 12, 1979 flood and topography indicates risk to this community in the event of another large scale flood. A wall built during the British colonial period near Shafston Blue Hole spring may have held back water until finally failing. In the village of Belmont, buildings and roads were built on a topographic high associated with a beach barrier landform and the morass acted as a sink for floodwaters, this may increase resilience to flooding there.
5. **Comparisons between the Bluefields River watershed and the BBHW show a difference in response between the two watersheds.** These differences are due to an increased resilience in the BBHW due to differences in karst development, topography, and mangrove presence.
    a. During flooding, sediment and flood waters were prevented from reaching the Bluefields Bay via the BBHW by an extensive karst network and a gradual step-down in topography. A series of karst depressions at gradually decreasing elevations slowed flow and caused deposition by degrees as flow moved downstream.
    b. Geomorphic evidence indicates that the Bluefields Bay was at least partially protected by the coastal mangrove forest located at the mouth of the Brighton-Blue Hole River. Presently, human development is disturbing and, in some cases, removing this forest. This may present a hazard to the bay in future flood events.
6. **Current land use and climate change can affect future flood severity in BBHW.** Land development in the village of Brighton is currently disturbing the morass sink area and can affect the buffering effect it has on floodwaters and debris flows. A global climate change is expected to increase temperature by at least 1.5° C in the next 50 years. This change is predicted to increase sea level, as well as increase the frequency and intensity of tropical storms in the Caribbean. Coastal communities such as Belmont could experience an increase in flooding due inundating from sea level into the morass which will affect its ability to act as a sink. Communities in flood prone areas, such as Brighton will be at great risk due to an increase in severity of tropical storms which can overload poljes with intense rainfall.

In the future, the results of this study can be used to begin more detailed geomorphic studies of this area. Studies of channel morphology and flood behavior are limited in southwestern Jamaica. The soil information, land use data, improved drainage network, and imagery purchased and developed for this study can be used in future research. Similar work can be done on the Robin's River watershed to assess its hydrological connection. Dye-tracing or geophysical methods can be used to assess karst connections in greater detail and better understand karst conduit influence on watershed hydrology. A detailed deposition volume calculation can be performed to assess how much material was deposited in the morass area or in the polje valleys.

This information found in this study is necessary for planning and mitigating future flood damage. Flood hazard maps which were created for this study can be used as preliminary surveys of flood risk for the communities of Belmont and Brighton, with improved soil and land use polygons these maps could be used in planning and mitigation for these communities. This work found some flood risk in Brighton, but found that the undisturbed coastal landscape may attenuate floods in Belmont. If present land use disturbs this coastal landscape and infilling of the morass or loss of vegetation occurs in the mangrove forest, the resilience in Belmont may be effected.

REFERENCES

Ahmad, R., 2008, A new examination of floods in the region debris floods and debris flows in the Caribbean: enduring geohazards in the Caribbean. University of the West Indies Press, Kingston, p. 141-156.

Ahmad, R., Earle, A. H., Hugues, P., Maharaj, R., and Robinson, E., 1993a, Landslide damage to the board river water supply pipeline, Bromley Hill, Jamaica: Case study of a landslide caused by hurricane Gilbert (1988): Bulletin of the International Association of Engineering Geology-Bulletin de l'Association Internationale de Géologie de l'Ingénieur, v. 47, no. 1, p. 59-70.

Ahmad, R., Scatena, F., and Gupta, A., 1993b, Morphology and sedimentation in Caribbean montane streams: examples from Jamaica and Puerto Rico: Sedimentary Geology, v. 85, no. 1-4, p. 157-169.

Aide, T. M., Clark, M. L., Grau, H. R., López-Carr, D., Levy, M. A., Redo, D., Bonilla-Moheno, M., Riner, G., Andrade-Núñez, M. J., and Muñiz, M., 2013, Deforestation and reforestation of Latin America and the Caribbean (2001–2010): Biotropica, v. 45, no. 2, p. 262-271.

Allsworth-Jones, P., 2008, Pre-Columbian Jamaica: Tuscaloosa, University of Alabama Press, 337 p.

Andrewin, A. N., Rodriguez-Llanes, J. M., and Guha-Sapir, D., 2015, Determinants of the lethality of climate-related disasters in the Caribbean Community (CARICOM): a cross-country analysis: Scientific reports, v. 5, p. 1-10.

Associated Press, 2004, Hurricane Ivan lashes Jamaica: The Sydney Morning Herald, September 12, 2004: (accessed March 9, 2019).

Azevedo, D. M., 2015, Late Taino Occupation of Jamaica: A zooarchaeological analysis of faunal materials from the Bluefields Bay Site [Master’s thesis]: Utah State University, 210 p.

Barker, D., and Miller, D., 1990, Hurricane Gilbert: anthropomorphising a natural disaster: Area, p. 107-116.

Barker, G., 1970, Soil and land-use surveys No. 25 for Jamaica, Parish of Trelawny: The Regional Research Centre, Kingston, Jamaica, 29 p.

Batjes, N., Bouwman, A., and Sinclair, K., 1986, Jamaica Physical Land Evaluation System (JAMPLES): Ministry of Agriculture, Kingston, Jamaica, 17 p.

Benford, B., Tikoff, B., and DeMets, C., 2014, Interaction of reactivated faults within a restraining bend: neotectonic deformation of southwest Jamaica: Lithosphere, v. 7, no. 1, p. 21-39.

Bell, J., and Lovelock, C. E., 2013, Insuring mangrove forests for their role in mitigating coastal erosion and storm-surge: an Australian case study: Wetlands, v. 33, no. 2, p. 279-289.

Berger, A., 1997, Assessing rapid environmental change using geoindicators: Environmental Geology, v. 32, no. 1, p. 36-44.

Blake, J., and Pyne, I., 1981, The meteorology of the June 12 disaster: Journal of the Geological Society of Jamaica, v. 20, p. 3-13.

Burgess, C. P., Taylor, M. A., Stephenson, T., Mandal, A., and Powell, L., 2015a, A macro-scale flood risk model for Jamaica with impact of climate variability: Natural Hazards, v. 78, no. 1, p. 231-256.

Burgess, C. P., Taylor, M. A., Stephenson, T., and Mandal, A., 2015b, Frequency analysis, infilling and trends for extreme precipitation for Jamaica (1895–2100): Journal of Hydrology: Regional Studies, v. 3, p. 424-443.

Carby, B.E., 2011, Caribbean implementation of the Hyogo Framework for action HFA mid-term review: Disaster Risk Reduction Centre, University of the West Indies, Castries, Saint Lucia. 86 p.

Carby, B. E., and Ahmad, R., 1995, Vulnerability of roads and water systems to hydro-geological hazards in Jamaica: Built Environment (1978-), v. 21, no. 2/3, p. 145-153.

Climate Change Adaptation and Risk Reduction Technology and Strategies to Improve Community Resilience (CARTS), 2018, Consultancy services for the preparation of a Floodwater Control Master Plan for Savanna La Mar, Westmoreland, Jamaica: Westmoreland Municipal Corporation (WMC), Savanna-La-Mar, Jamaica, 7 p.

Clark, J. J., and Wilcock, P. R., 2000, Effects of land-use change on channel morphology in northeastern Puerto Rico: Geological Society of America Bulletin, v. 112, no. 12, p. 1763-1777.

Collymore, J., 1992, Planning to reduce the socio-economic impacts of natural hazards on Caribbean society, Journal of the Geological Society of Jamaica, Geological Society of Jamaica, p. 89-96.

Collymore, J., 2007, Disaster impacts on the Caribbean, *in* Stoltman, J., ed., International Perspectives on Natural Disasters: Occurrence, Mitigation, and Consequences: New York City, Springer, p. 303-322.

Costa, J. E., 1984, Physical geomorphology of debris flows *in* Costa, J.E., Fleisher, P.J., eds., Developments and Applications of Geomorphology, New York, Springer-Verlag, p. 268-317.

Comprehensive Resource Inventory and Evaluation System (CRIES), 1982, Jamaican Resource Assessment: Comprehensive Resource Inventory and Evaluation System Project, Kingston, Jamaica, 89 p.

Curtin, M.R., 2010, The story of Westmoreland: A Jamaican Parish: Jamaica National Foundation, Kingston, Jamaica, 327 p.

Day, M., 1976, The morphology and hydrology of some Jamaican karst depressions: Earth Surface Processes and Landforms, v. 1, no. 2, p. 111-129.

Day, M., 1979, The hydrology of polygonal karst depressions in northern Jamaica: Zeitschrift für Geomorphologie, v. 32, p. 25-34.

Day, M., 2007, Natural and anthropogenic hazards in the karst of Jamaica: Geological Society, London, Special Publications, v. 279, no. 1, p. 173-184.

Day, M., 2010, Human interaction with Caribbean karst landscapes: past, present and future: Acta Carsologica, v. 39, no. 1, p. 137-146.

Donaldson, L. and Walters, W.O., 1981, Hydrologic aspects of June 12, flood rains on Newmarket Sub-Basin: Journal of the Geological Society of Jamaica, v. 20, p. 61-77.

Dryer, W. P., 2010, Catastrophic valley entrenchment and debris fan formation in the Bluefields River, Westmoreland Jamaica [Master's thesis]: Springfield, Missouri State University, 138 p.

Ebert, J. E., 2010, Integrated watershed management in Bluefields Bay, Jamaica [Master's thesis]: Springfield, Missouri State University, 195 p.

Environmental Protection Agency (EPA), 1999, A lexicon of cave and karst terminology with special reference to environmental karst hydrology: Environmental Protection Agency Office of Research and Development, Washington DC, 200 p.

Evelyn, O. B., and Camirand, R., 2003, Forest cover and deforestation in Jamaica: an analysis of forest cover estimates over time: International Forestry Review, v. 5, no. 4, p. 354-363.

Eyre, L.A., 1981, The flood disaster of June 12; a satellite overview: Journal of the Geological Society of Jamaica, v. 20, p. 14-32.

Eyre, L. A., 1987, Jamaica: test case for tropical deforestation?: Ambio, p. 338-343.

Fielding, C., 1999, Varieties of fluvial form: the relevance to geologists of an expanded reality, *in* Miller, A. J. and Gupta, A., eds., Varities of Fluvial Form: Chichester, UK, John Wiley & Sons, p. 497-505.

Fincham, A. G., 1998, Jamaica underground: The caves, sinkholes, and underground rivers of the island: Kingston, Jamaica, University of West Indies Press, 447 p.

Gamble, D. W., Campbell, D., Allen, T. L., Barker, D., Curtis, S., McGregor, D., and Popke, J., 2010, Climate change, drought, and Jamaican agriculture: local knowledge and the climate record: Annals of the Association of American Geographers, v. 100, no. 4, p. 880-893.

Gardner, W.J., 1873, A history of Jamaica: from its discovery by Christopher Columbus to the year 1872: London, Elliot Stock Publishing, 529 p.

Gartner, J., 2016, Stream power: Origins, geomorphic applications, and GIS procedures: Water Publications, v. 1, 35 p.

Gosse, P.H. and Hill, R., 1851, A naturalist's sojourn in Jamaica, London: Longman, Brown, Green, and Longmans Publishing, 499 p.

Government of Jamaica, 1979, Reconstruction programme for flood damage in western Jamaica consequent on June 12 flood rains: Ministry papers no. 56, 17 p.

Gupta, A., 1975, Stream characteristics in eastern Jamaica, an environment of seasonal flow and large floods: American Journal of Science, v. 275, no. 7, p. 825-847.

Gupta, A., 1983, High-magnitude floods and stream channel response, *in* Collinson, J.D. and Lewin, J., eds., Modern and Ancient Fluvial Systems: Chichester, UK, John Wiley & Sons, p. 219-227.

Gupta, A., 1995, Magnitude, frequency, and special factors affecting channel form and processes in the seasonal tropics: Washington DC American Geophysical Union Geophysical Monograph Series, v. 89, p. 125-136.

Gupta, A., 2000, Hurricane floods as extreme geomorphic events: IAHS Publication, p. 215-228.

Gupta, A., 2002, Geoindicators for tropical urbanization: Environmental Geology, v. 42, no. 7, p. 736-742.

Gupta, A., and Ahmad, R., 1999, Urban steeplands in the tropics: an environment of accelerated erosion: GeoJournal, v. 49, no. 2, p. 143-150.

Harrelson, C.C., Rawlins, C.L., Potyondy, J.P., 1994, Stream channel reference sites: an illustrated guide to field technique: United States Department of Agriculture (USDA), Washington DC, 61 p.

Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., et al., 2018, Impacts of 1.5ºC Global Warming on Natural and Human Systems, *in* Masson-Delmotte, V., Zhaj, P., Pörtner., H.O., Roberts, D., Skea, J., et al., eds., Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty: The Intergovernmental Panel on Climate Change, Geneva, Switzerland, 138 p.

James-Williamson, S. A., Mitchell, S. F., and Ramsook, R., 2014, Tectono-stratigraphic development of the Coastal Group of south-eastern Jamaica: Journal of South American Earth Sciences, v. 50, p. 40-47.

Jones, E. B., 1981, Geomorphological implications of the June 12 floods; a preliminary view: Journal of the Geological Society of Jamaica, v. 20, p. 42-60.

Knighton, D., 1998, Fluvial forms and processes: a new perspective: London, Routledge Publishing, 400 p.

Larsen, M. C., and Wieczorek, G. F., 2006, Geomorphic effects of large debris flows and flash floods, northern Venezuela, 1999: Zeitschrift für Geomorphologie Neue Folge, Supplementband, v. 145, p. 147-175.

Lyew-Ayee, P., Viles, H.A., and Tucker, G.E., 2007, The use of GIS-based digital morphometric techniques in the study of cockpit karst: Earth Surface Processes and Landforms, v. 32, p. 165-179.

Lord, M. L., Germanoski, D., and Allmendinger, N. E., 2009, Fluvial geomorphology: monitoring stream systems in response to a changing environment, *in* Young, R. and Norby, L., eds., Geological Monitoring: Boulder, CO, Geological Society of America, p. 69-103.

Maharaj, R. J., 1993, Landslide processes and landslide susceptibility analysis from an upland watershed: a case study from St. Andrew, Jamaica, West Indies: Engineering Geology, v. 34, no. 1-2, p. 53-79.

Mandal, A., and Maharaj, A., 2013, Flooding in Jamaica with assessment of riverine inundation of Port Maria, St Mary: Bulletin de la Société Géologique de France, v. 184, no. 1-2, p. 165-170.

Mandal, A., Stephenson, T. S., Brown, A. A., Campbell, J. D., Taylor, M. A., and Lumsden, T. L., 2016, Rainfall-runoff simulations using the CARIWIG simple model for advection of storms and hurricanes and HEC-HMS: implications of Hurricane Ivan over the Jamaican Hope River watershed: Natural Hazards, v. 83, no. 3, p. 1635-1659.

Mann, P. and Burke, K., 1984, Neotectonics of the Caribbean: Reviews of Geophysics and Space Physics, v. 22, no. 4, p. 309-362.

Manning, P. A., McCain, T., and Ahmad, R., 1992, Landslides triggered by 1988 Hurricane Gilbert along roads in the Above Rocks area, Jamaica: The Journal of the Geological Society of Jamaica, no. 12, p. 34-52.

Mathew, M. J., Menier, D., Siddiqui, N., Kumar, S. G., and Authemayou, C., 2016, Active tectonic deformation along rejuvenated faults in tropical Borneo: inferences obtained from tectono-geomorphic evaluation: Geomorphology, v. 267, p. 1-15.

McEnroe, B. M., 1997, Rainfall intensity tables for Kansas counties: Kansas Department of Transportation, Topeka, KS, 317 p.

Ministry of Agriculture and Fisheries (MOA), 1964, Major soil types of Jamaica: Ministry of Agriculture and Fisheries, Kingston, Jamaica, 16 p.

Ministry of Agriculture and Fisheries (MOA), 1979, The Fishing Industry Act: Ministry of Agriculture and Fisheries, Kingston, Jamaica, 20 p.

Ministry of Agriculture and Fisheries (MOA), 1989, Guidelines for soil survey and land evaluation in Jamaica (semi-detailed surveys): Ministry of Agriculture and Fisheries, Kingston, Jamaica, 72 p.

Ministry of Agriculture and Fisheries (MOA), 2012, The Fishing Industry (Special Fishery Conservation Area) regulations, 2012: Ministry of Agriculture and Fisheries, Kingston, Jamaica, 18 p.

Mitchell, S. F., 2004, Lithostratigraphy and palaeogeography of the White Limestone Group: Cainozoic Research, v. 3, no. 1/2, p. 5-29.

Mitchell, S.F., Miller, D.J., and Maharaj, R., 2003, Field guide to the geology and geomorphology of the Tertiary limestones of the Central Inlier and Cockpit Country: Caribbean Journal of Earth Science, v. 37, p. 39-48.

Mitchell, S.F., Miller, D.J., Ganapathy, S., Spence, B., 2008, Defining the boundaries of the Cockpit Country: Ministry of Agriculture and Fisheries and Ministry of Lands and Mines, Geology Division, Kingston, Jamaica, 76 p.

Molina, M., and McDonald, F., 1988, Sinkhole management and flooding in Jamaica: Environmental Geology and Water Sciences, v. 12, no. 2, p. 113-116.

Nandi, A., Mandal, A., Wilson, M., and Smith, D., 2016, Flood hazard mapping in Jamaica using principal component analysis and logistic regression: Environmental Earth Sciences, v. 75, no. 6, p. 465.

Naughton, P. W., 1982, Some aspects of rainfall for Jamaica, West Indies: Revista Geográfica, no. 96, p. 60.

Nkemdirim, L.C., and Jones, E. B., 1978, Flood regions in Jamaica/Les zones d'inondation en Jamaïque: Hydrological Sciences Journal, v. 23, no. 1, p. 63-83.

Nkemdirim, L. C., 1979, Spatial and seasonal distribution of rainfall and runoff in Jamaica: Geographical Review, p. 288-301.

Ogilby, J., 1673, America: being the latest, and most accurate description of the New World: London, 674 p.

Osterkamp, W., 2002, Geoindicators for river and river-valley monitoring in the humid tropics: Environmental Geology, v. 42, no. 7, p. 725-735.

Parise, M., 2003, Flood history in the karst environment of Castellana-Grotte (Apulia, southern Italy): Natural Hazards and Earth System Science, v. 3, no. 6, p. 593-604.

Peel, M. C., Finlayson, B. L., and McMahon, T. A., 2007, Updated world map of the Köppen-Geiger climate classification: Hydrology and Earth System Sciences Discussions, v. 4, no. 2, p. 439-473.

Pike, A. S., Scatena, F. N., and Wohl, E. E., 2010, Lithological and fluvial controls on the geomorphology of tropical montane stream channels in Puerto Rico: Earth Surface Processes and Landforms, v. 35, no. 12, p. 1402-1417.

Planning Institute of Jamaica (PIOJ), 2004, Jamaica: Macro-socio-economic and environmental assessment of the damage done by Hurricane Ivan Sept 10-12, 2004: Planning Institute of Jamaica, Kingston, Jamaica, 76 p.

Planning Institute of Jamaica (PIOJ), 2012, Annual report 2012: Planning Institute of Jamaica, Kingston, Jamaica, 93 p.

Porter, A.R.D., 1981, And the rains came in western Jamaica: June 1979 – some effects: Journal of the Geological Society of Jamaica, v. 20, p. 42-60.

Ramírez, A., De Jesús-Crespo, R., Martinó-Cardona, D. M., Martínez-Rivera, N., and Burgos-Caraballo, S., 2009, Urban streams in Puerto Rico: what can we learn from the tropics?: Journal of the North American Benthological Society, v. 28, no. 4, p. 1070-1079.

Rasmussen, M. T. N., 2004, Macroeconomic implications of natural disasters in the Caribbean: International Monetary Fund, Washington DC, 25 p.

Ritter, D. F., Kochel, R. C., and Miller, J. R., 1995, Process geomorphology: Boston, McGraw-Hill, 652 p.

Robinson, E, and Mitchell, S.F., 1999, Upper Cretaceous to Oligocene stratigraphy in Jamaica: *in* S.F. Mitchell ed., Contributions to Geology: University of the West Indies, Mona, no. 4, p. 1-47.

Rouse, I., 1993, The Tainos: rise and decline of the people who greeted Columbus, New Haven, CT, Yale University Press. 224 p.

Scolaro, N.S., 2013, The rise and fall of markets along Bluefields Bay, Jamaica: [Master's thesis]: Springfield, Missouri State University, 288 p.

Stephenson, T.S., Vincent, L.A., Allen, T., Meerbeeck, C.J., McLean, N., et al., 2014, Changes in extreme temperature and precipitation in the Caribbean region, 1961-2010: International Journal of Climatology, v. 34. p. 2957-2971.

Survey Department of Jamaica, 1969, Topographical Preliminary Edition – Jamaica: Government of Jamaica, Map 34C, scale 1:12,500, 1 sheet.

Survey Department of Jamaica, 1987, Black River: Government of Jamaica, Jamaica (Metric Edition) Series 1 Map 10, scale 1:50,000, 1 sheet.

Sweeting, M. M., 1958, The karstlands of Jamaica: The Geographical Journal, v. 124, no. 2, p. 184-199.

Taylor, M. A., Stephenson, T. S., Owino, A., Chen, A. A., and Campbell, J. D., 2011, Tropical gradient influences on Caribbean rainfall: Journal of Geophysical Research: Atmospheres, v. 116, no. D21.

Taylor, M.A., Clarke, L.A., Centella, A., Bezanilla, A., Stephenson, T.S., et al., 2018, Future Caribbean climates in a world of rising temperatures: the 1.5 vs 2.0 dilemma: Journal of Climate, v. 31, p. 2907-2926.

United Nations Disaster Relief Organization (UNDRO), 1986, Jamaica floods June 1986 UNDRO situation report: United Nations Department of Humanitarian Affairs, Geneva, Switzerland: (accessed March 2019).

United Nations Environment Programme (UNEP), 1989, Assessment of the economic impacts of Hurricane Gilbert on coastal and marine resources in Jamaica: United Nations Environment Programme, Geneva, Switzerland: (accessed March 2019).

Wadge, G., and Dixon, T.H., 1984, A geological interpretation of Seasat-Sar imagery of Jamaica: The Journal of Geology, v. 92, no. 5, p. 561-581.

Watts, D., 1990, The West Indies: patterns of development, culture and environmental change since 1492, Cambridge University Press, 644 p.

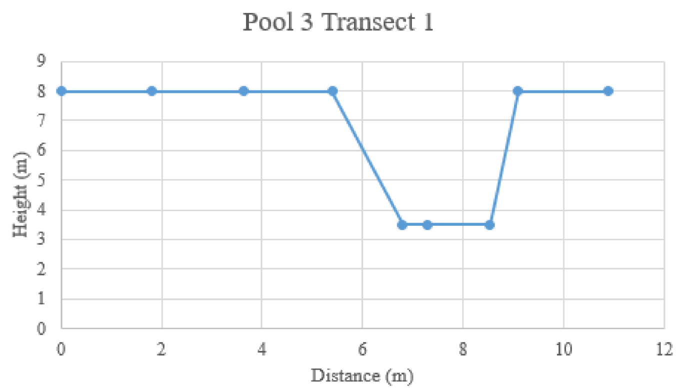
Weaver, P.L. and Schwagerl, J.J., 2009, U.S. Fish and Wildlife Service refuges and other nearby reserves in southwestern Puerto Rico: United State Forest Service International Institute of Tropical Forestry, San Juan, Puerto Rico, 122 p.

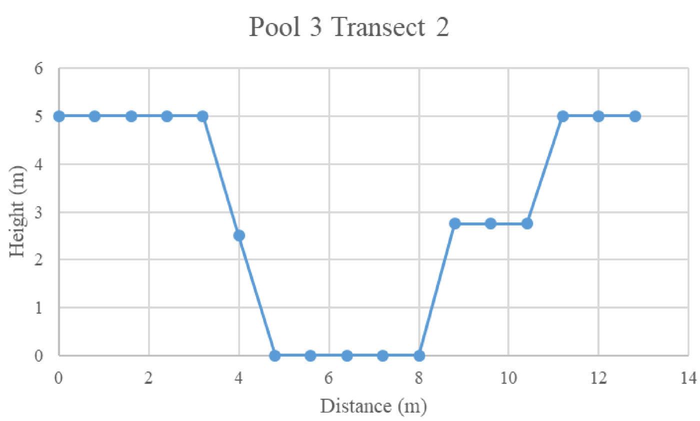
Woodside, J., Peterson, E.W., Dogwiler, T., 2015, Longitudinal profile and sediment mobility as geomorphic tools to interpret the history of a fluviokarst stream system: International Journal of Speleology, v. 44, no. 2, p. 197-206.

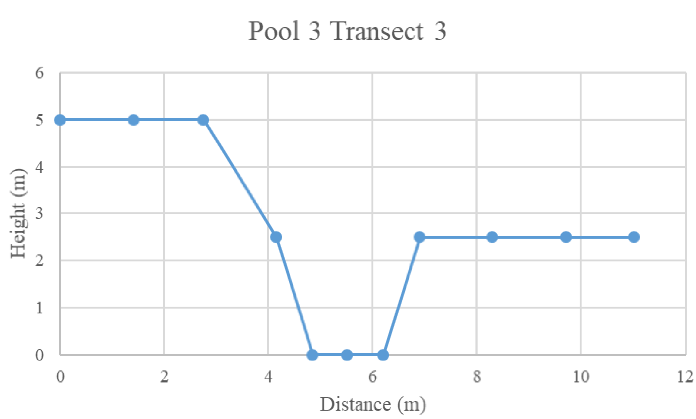
Yanites, B. J., Tucker, G. E., Mueller, K. J., Chen, Y.-G., Wilcox, T., Huang, S.-Y., and Shi, K.-W., 2010, Incision and channel morphology across active structures along the Peikang River, central Taiwan: Implications for the importance of channel width: Bulletin, v. 122, no. 7-8, p. 1192-1208.

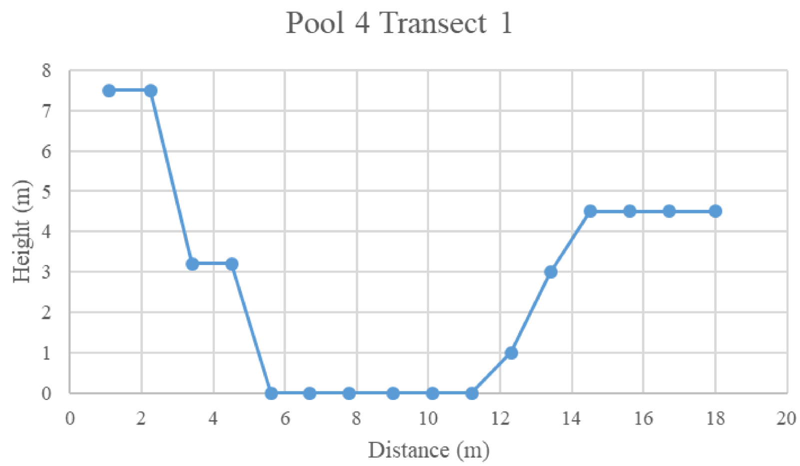
APPENDICES

Appendix A – Cross-Sections of the Brighton-Blue Hole Gorge









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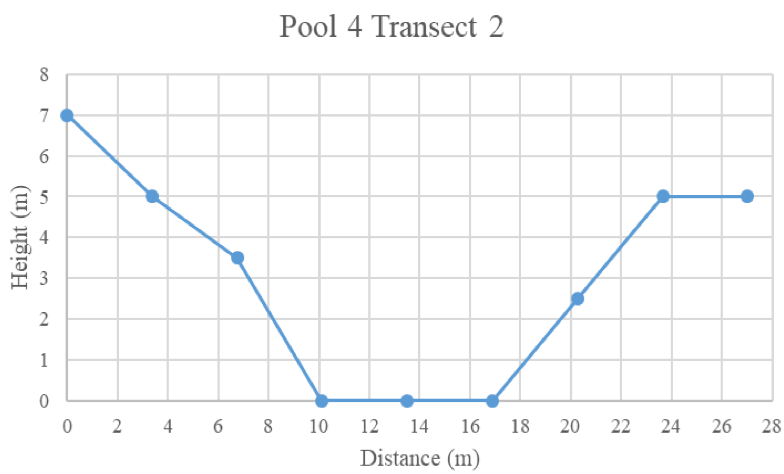

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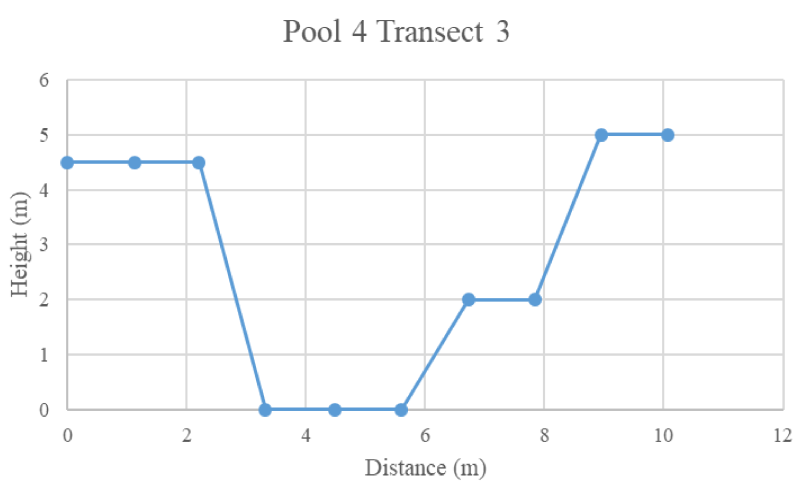

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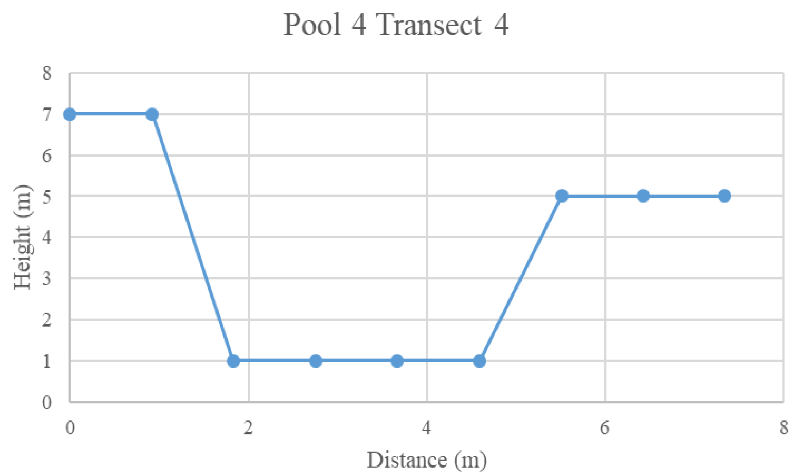
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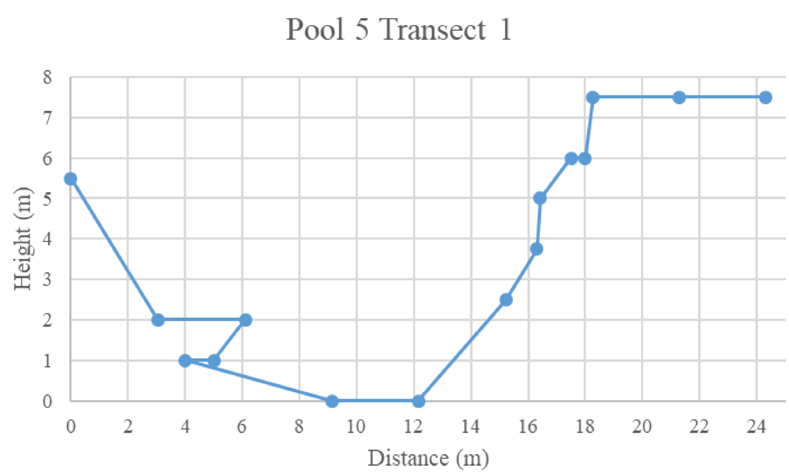
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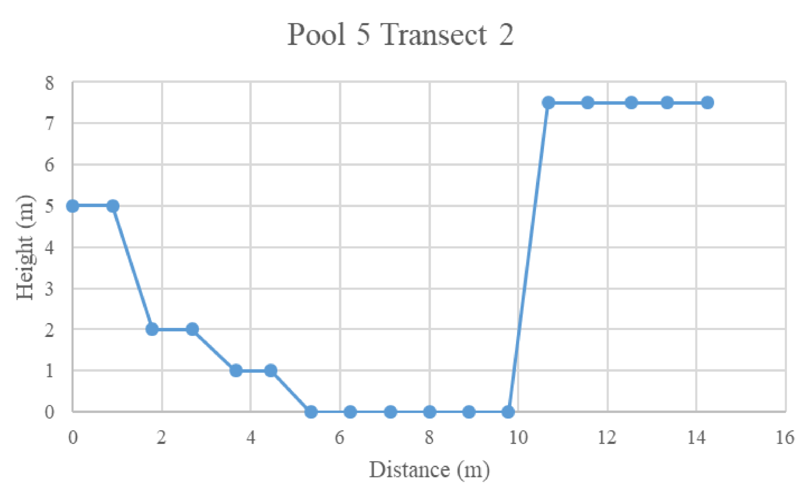
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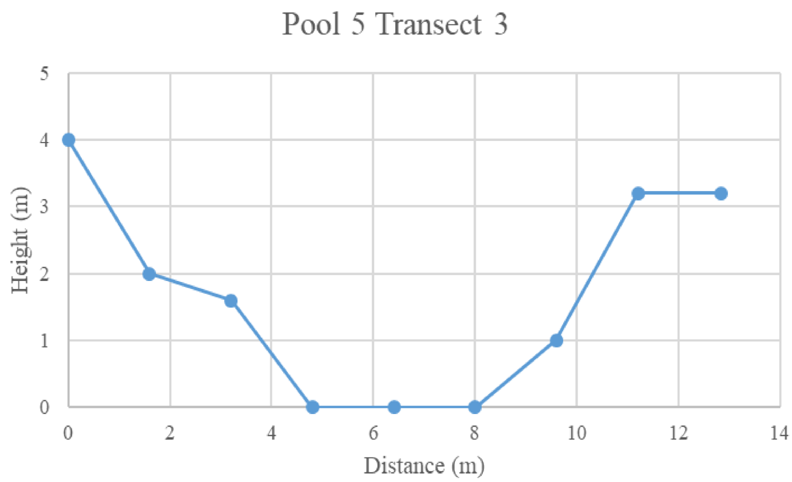
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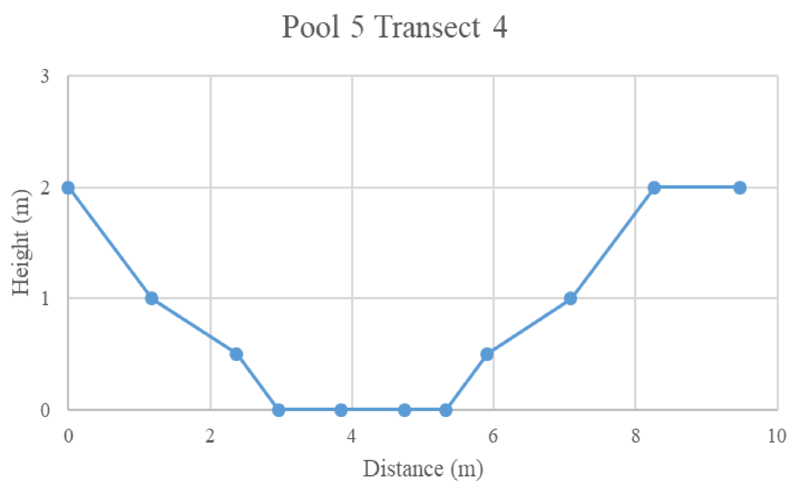
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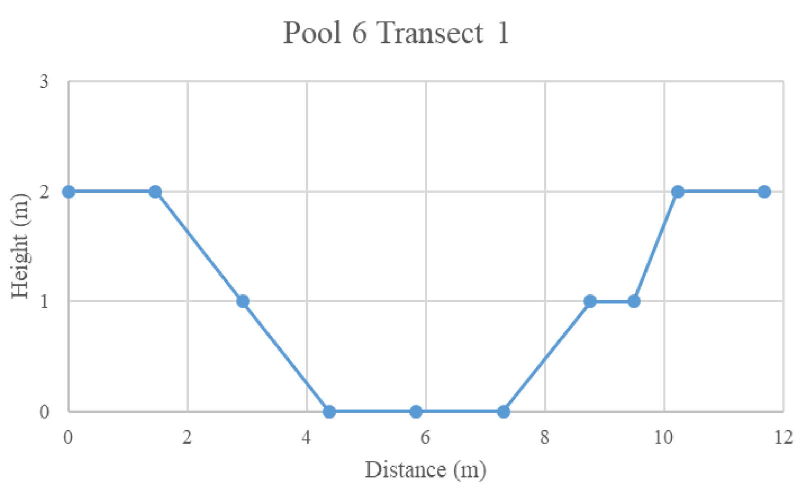
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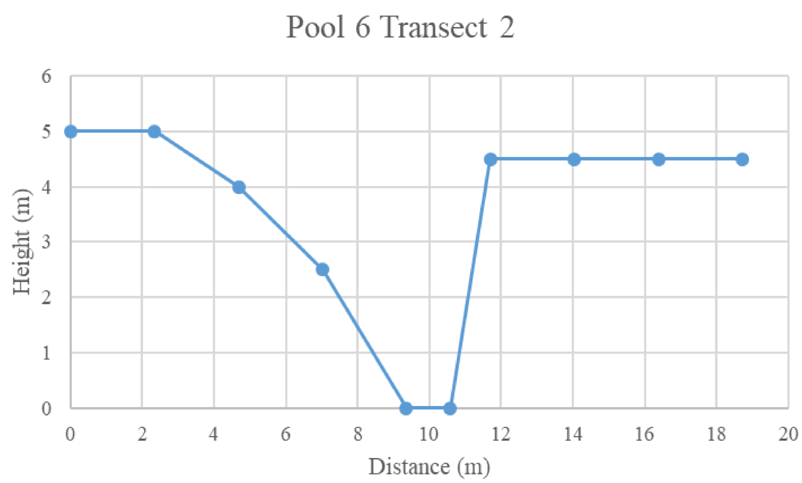
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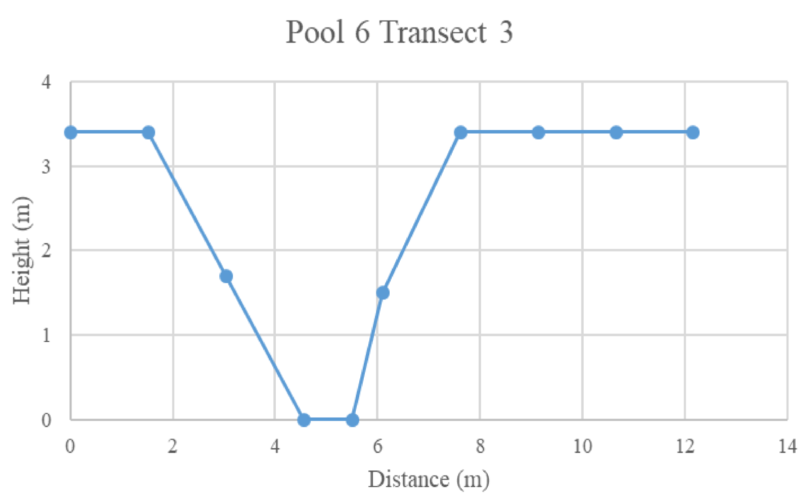
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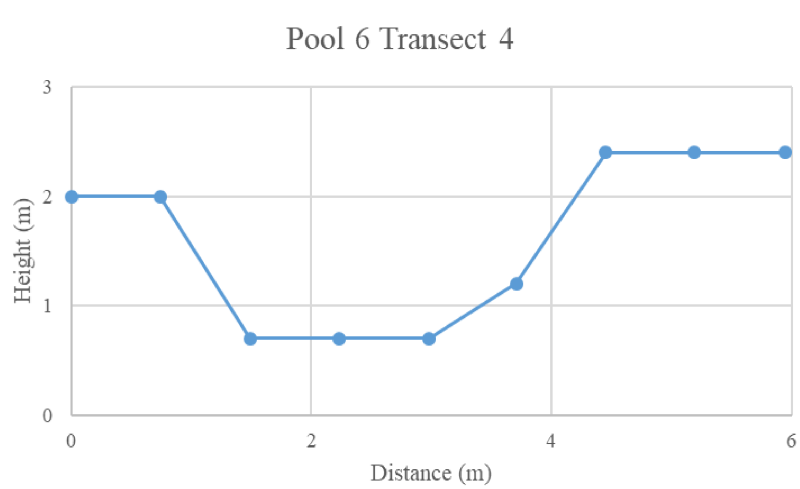
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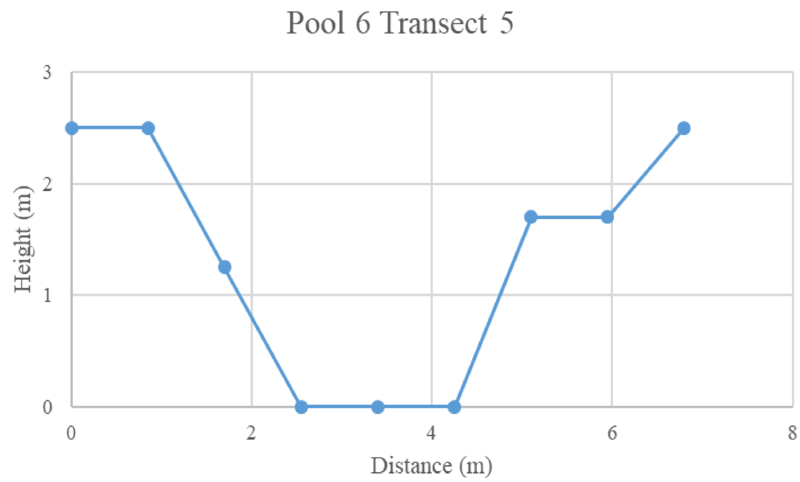

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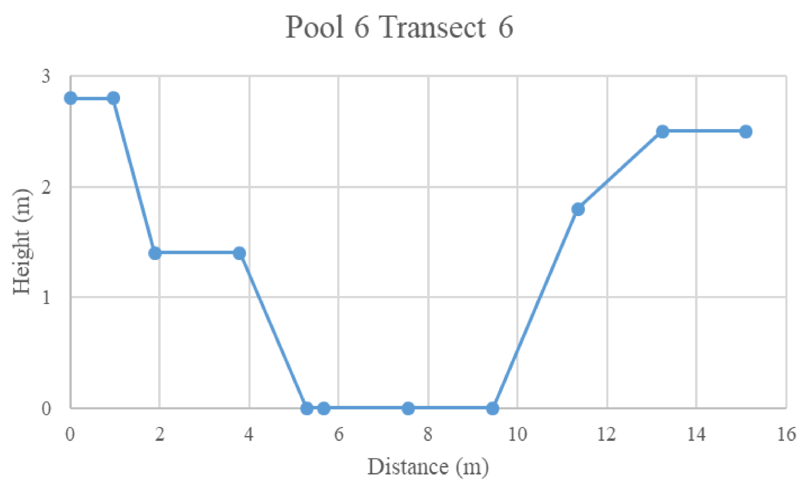

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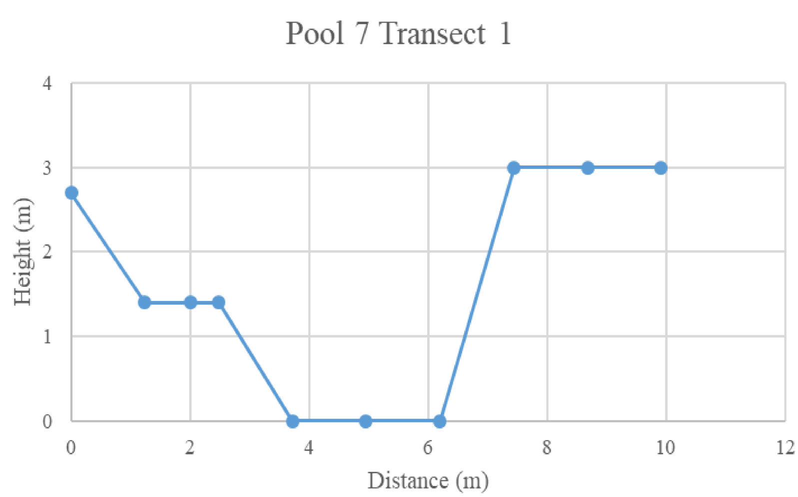

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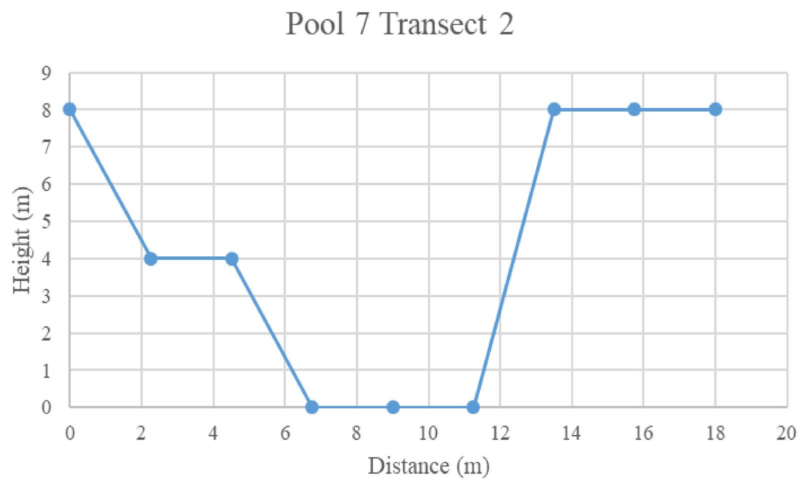
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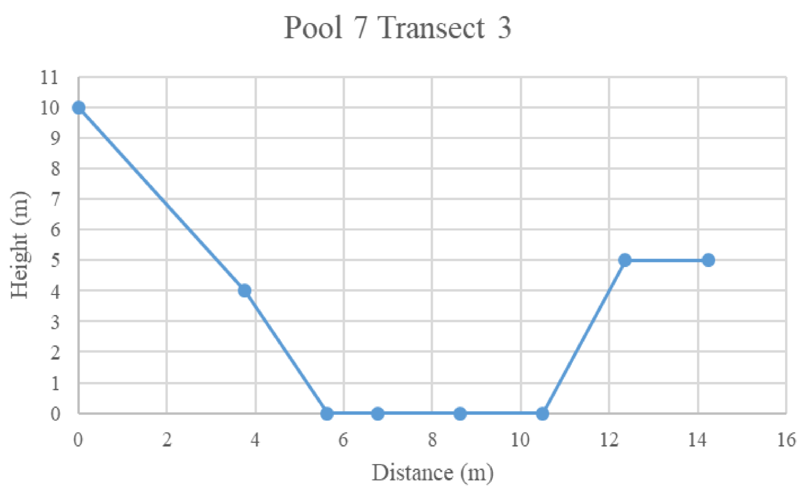
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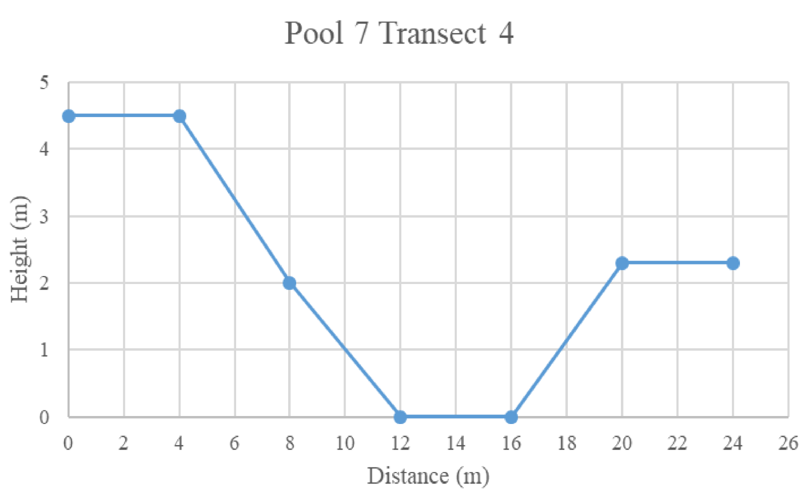
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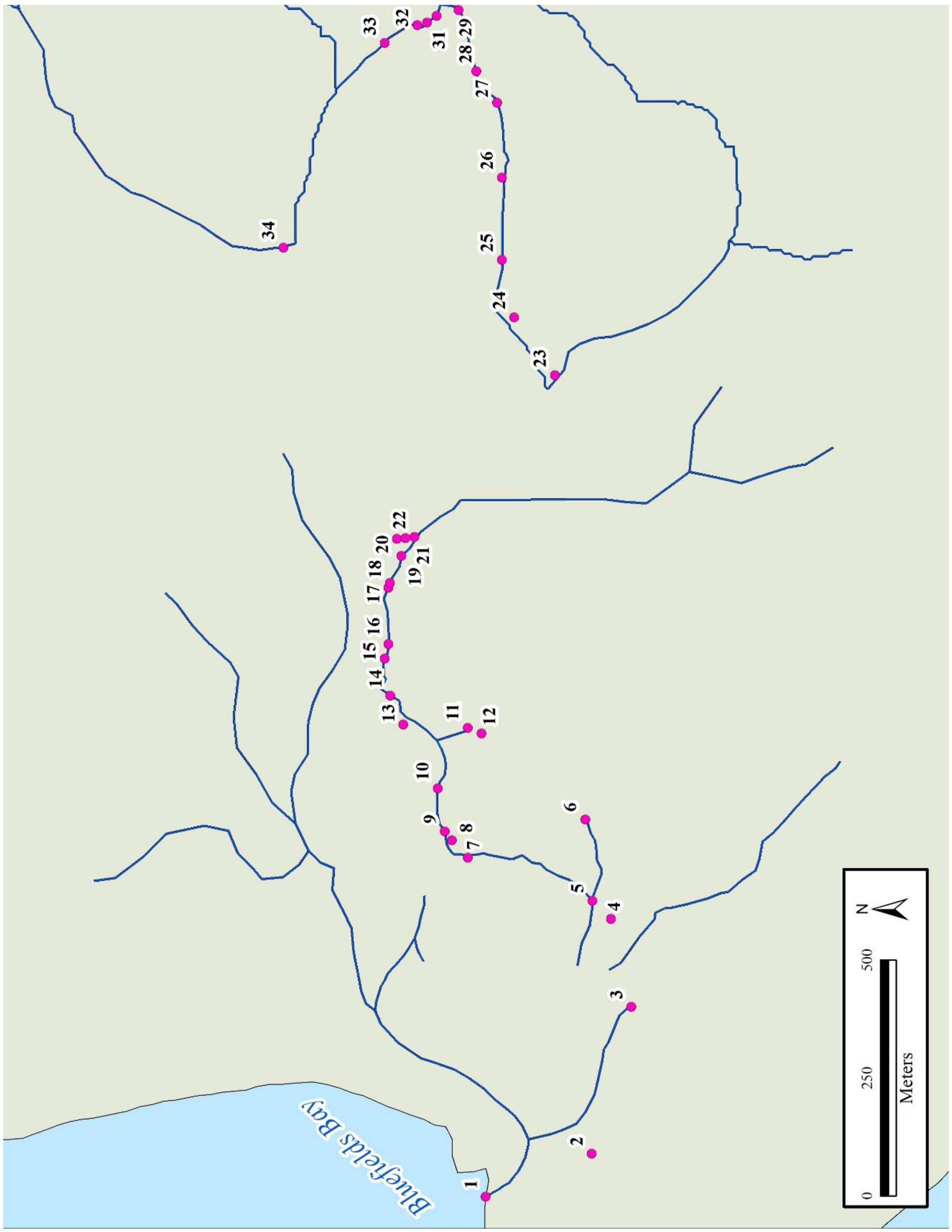
Appendix B – Photo Log of Physical Geoindicators in BBHW



Appendix B-1. Map of Photograph GPS Locations

Appendix B-2. Coordinates of Physical Geoindicators

ID	Description	Longitude	Latitude
1	Creek Mouth	-78.02846	18.15692
2	Cave	-78.028278	18.1547
3	Blue Hole Spring and Morass	-78.025474	18.15393
4	Depression	-78.023798	18.15432
5	Little Dismel Spring	-78.023453	18.15468
6	Big Dismel Spring	-78.021898	18.15482
7	Channel	-78.022632	18.15706
8	Incised Channel	-78.0223	18.15736
9	Incised Channel Wall	-78.022125	18.1575
10	Sinkhole	-78.021307	18.15763
11	Estavelle	-78.020157	18.15706
12	Estavelle	-78.020259	18.1568
13	Confined Valley	-78.020091	18.15829
14	Boulder Bar	-78.01954	18.15854
15	Wall of Brighton-Blue Hole Gorge	-78.01883	18.15864
16	Headcut/Bedrock Knickpoint	-78.018551	18.15857
17	Scour Cave	-78.017475	18.15857
18	Wall of Brighton-Blue Hole Gorge	-78.017384	18.15854
19	Gorge Headcut	-78.016868	18.15833
20	Brighton Cave	-78.016542	18.15841
21	Gorge right bank/road fill	-78.016528	18.15825

Appendix B-2 (con't). Coordinates of Physical Geoindicators

ID	Description	Longitude	Latitude
22	Crossing at Brighton Road	-78.016508	18.15808
23	Polje valley	-78.013423	18.1554
24	Estavelle	-78.012322	18.15618
25	Channel/ boulder bar	-78.011222	18.15641
26	Boulder wall	-78.009653	18.15641
27	Small, incised channel	-78.008221	18.1565
28	Debris fan	-78.007622	18.15689
29	Incised channel	-78.006455	18.15724
30	Scour cave	-78.006567	18.15765
31	Headcut	-78.006692	18.15784
32	Bedrock gorge	-78.006742	18.15802
33	Pond	-78.007083	18.15864
34	Depression/Shafston Blue Hole Spring	-78.010986	18.16058

Appendix B-3. Point 1 - Blue Hole Creek Mouth Which Crosses the Beach Barrier Landform Along the Coast of the Bluefields Bay

Appendix B-4. Point 2 – Cave in Belmont, May Be a Remnant Spring and Could Overfill During High Flood Stage

Appendix B-5. Point 3 – Blue Hole Spring, This Spring Is No Longer Used a Supply of Water and so Currently Is Over-Vegetated

Appendix B-6. Point 3 – Morass, Tall Grass Indicates Where Swampy Area Begins. This Area Acts as a Sink for Floodwater and Debris Flows During Floods

Appendix B-7. Point 4 – Depression, This Area Is Filled with Fine, Clay Sediment That Was Likely Deposited Here During the 1979 Flood

Appendix B-8. Point 5 – Little Dismel Spring, This Spring Is Difficult to See on the Surface Because of Overfilling with Fine Sediment. Disturbed Vegetation Is Anthropogenic

Appendix B-9. Point 6 – Big Dismel Spring, This Spring Is Cleared Regularly and Used to Water Livestock

Appendix B-10. Point 7 – A Confined Channel with High Valley Walls Runs Parallel to Path. at High Flood Stages Channel Fills in Path Completely

Appendix B-11. Point 8 – Incised Channel Downstream of Lower Sinkhole. This Reach Incised 3 M and Delivered Fine Sediment to the Little Dismel Spring and Wetland

Appendix B-12. Point 9 – Bedrock Wall on Left Bank of Incised Channel, Fine Sediment Within the Channel Was Eroded in 1979

Appendix B-13. Point 10 – Sinkhole Because It Is Heavily Vegetated, Could Be a Deep Plunge Pool Migrating from the Head of the Incised Channel

Appendix B-14. Point 11 – Estavelle, Can Deliver Groundwater to the Surface at High Flood Stages

Appendix B-15. Point 12 – Estavelle, at Low Flood Stages Functions as an Open Conduit Leading Underground

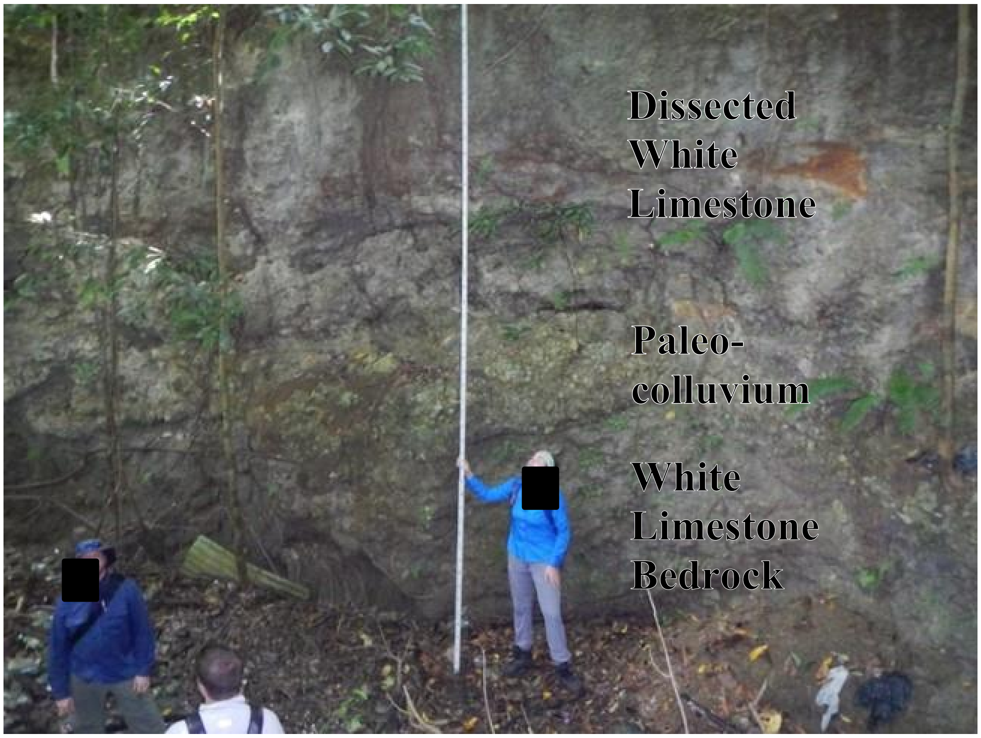
Appendix B-16. Point 13 – The Confined Valley Which Caused Channel Incision Downstream of the Brighton-Blue Hole Gorge

Appendix B-17. Point 14 – Boulder Bar, This Debris Flow Is Made up of Large Boulders Which Were Likely Moved from the Brighton-Blue Hole Gorge 50 m Upstream.

Appendix B-18. Point 15 – The Gorge Wall of the Brighton-Blue Hole Gorge, Noted Fractures Indicate Structural Control of This Landform

Appendix B-19. Point 16 – Headcut/bedrock Knickpoint Within the Brighton-Blue Hole Gorge Facing Upstream from the Bottom of Pool 7, a Difference of 9 m

Appendix B-20. Point 17 – A “Scour Cave” on the Wall of the Brighton-Blue Hole Gorge Is an Erosional Feature Which Indicates the Removal of Wall Material Along Fractures



Appendix B-21. Point 18 – Brighton-Blue Hole Gorge Wall, Walls Are Made up of Limestone Bedrock Which Is Difficult to Erode Layered with More Friable Material


Appendix B-22. Point 19 – Brighton-Blue Hole Gorge Headcut Facing Downstream from the Bottom of Pool 3, a Difference of 5 m

Appendix B-23. Point 20 – Brighton Cave, a Cave in Brighton Which Has the Potential to Deliver Water to the Surface at High Flood Stages

Appendix B-24. Point 21 – Gorge Right Bank/Road Fill

Appendix B-25. Point 22 – Downstream of Brighton Road Where the Saddle Cut in the Village of Brighton Occurred, the Head of the Brighton-Blue Hole Gorge Noted

Appendix B-26. Point 22 – Upstream of Brighton Road Where the Saddle Cut in the Village of Brighton Occurred, the Depression Overfilled and Spilled over the Road

Appendix B-27. Point 23 – Polje Valley Taken Facing East

Appendix B-28. Point 23 – Polje Valley Taken Facing Southeast

Appendix B-29. Point 24 – Estavelle Directly Upstream of Robins River Road Which Contributed to Overfilling in the Polje Valley It Drains

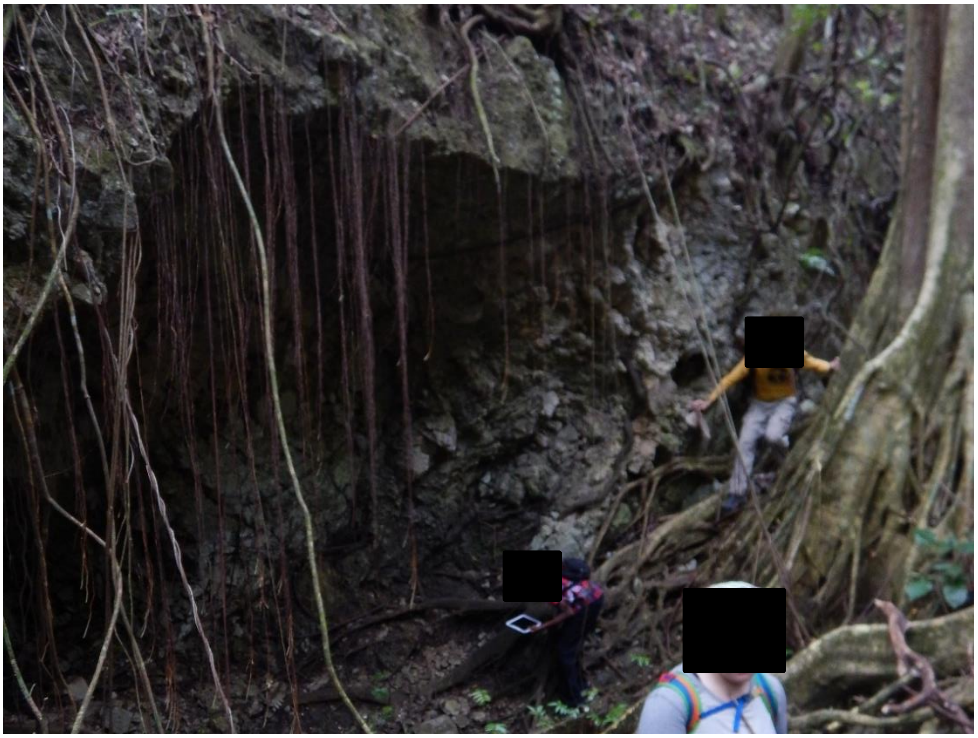
Appendix B-30. Point 25 – Channel/Boulder Bar, the Coarse Material Deposited Here Was Generated by Incised Channels Flowing Through Bonnygate and Union Hall Soils

Appendix B-31. Point 26 – Boulder Wall, Although There Is No Evidence of Influence on Flow, It Indicates the Deposition of a Large Amount of Large Sediment Here

Appendix B-32. Point 27 – Small Incised Channel in the Coarse Bonnygate and Union Hall Soils of the Uplands

Appendix B-33. Point 28 – A Debris Fan Composed of Unsorted Fine and Coarse Sediment. These Fans Are Used as Isolated Farm Fields Today

Appendix B-34. Point 29 – Incised Channel in Coarse Material Delivered Large Clasts to Boulder Bars Downstream



Appendix B-35. Point 30 – A “Scour Cave” on the Wall of a Bedrock Channel Along the Mid-Valley Reach Where Material Was Eroded from the Wall

Appendix B-36. Point 31 – A Headcut in the Coarse Material Along the Mid-Valley Reach Bedrock Channel

Appendix B-37. Point 32 – Facing Downstream Towards the Bedrock Gorge in the Mid-Valley Reach. Noted the Depositional Features of Coarse Material

Appendix B-38. Point 33 – A Surface Water Feature Which Is Likely Karst Controlled Along the Mid-Valley Reach, Note the Coarse Material

Appendix B-39. Point 34 – The Depression of the Shafston Blue Hole Spring. the Spring Is No Longer Visible at the Surface and May Have Been Filled with Sediment in 1979

Appendix B-40. Point 34 – The Depression of the Shafston Blue Hole Spring. the Low Divide Between Watersheds and Steep Uplands Noted