Effects of flood dynamics on island geomorphology in a large mixed bedrock-alluvial anabranching river: a case study of the Vaal River near Parys.

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Declaration

I declare that “Effects of flood dynamics on island geomorphology in a large mixed bedrock-alluvial anabranching river: a case study of the Vaal River near Parys” is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

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Abstract

Rare-infrequent magnitude floods of shorter duration events are significant natural hazards and play a key role in shaping river channel and island geomorphology. For a given river or channel, there is a relationship between the magnitude of a flood, frequency of a flood and duration of a flood, once a flood exceeds a reach-averaged erosional threshold geomorphic change can begin to occur.

Expansion of conceptual models for the response of mixed bedrock alluvial influenced dryland rivers to such floods is of increasing scientific importance. The Vaal River near Parys in the Free State Province is characterised by a variable degree of mixed bedrock-alluvial anabranching channels which divide and re-join around the islands. In this study the historical aerial images and flow data from 1938 to 2016 were used to determine the effects of flood dynamics on island geomorphology in a large mixed bedrock-alluvial anabranching river: Vaal River near Parys.

The historical aerial images and flow data reveals some minor island geomorphological changes during flood of rare magnitude, infrequent and shorter duration. The highest flood in the record was the one which was found having a recurrence interval of 20-50 years. The changes observed in the mixed bedrock-alluvial anabranching river in the Vaal River near Parys, indicate some minor decrease in the island bar area during flood of rare magnitudes, infrequent and shorter duration with recurrence interval of 20-50 years.

The findings in this study area also reveals that the island bars in the area of study shows some degree of stability, however for the past 78 years the islands bar have not change the position. The impact of flood dynamics on island geomorphology in a large, mixed bedrock-alluvial anabranching river is not yet researched in the area of study (Vaal River), these findings will contribute to enhanced analysis of the Vaal River, relatively the impacts of extreme floods in island and channel geomorphology.

Key words: Flood regime; island changes; channel planform dynamics; multiple-thread river

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LIST OF ABBREVIATIONS

DWS: Department of Water and Sanitation

DWAF: Department of Water Affairs and Forestry

GEV: General Extreme Value

GEVpwm: General Extreme Value using probable weighted moments

GIS: Geographical Information System

Km: kilometre

Km^2: kilometre square

LN: Log Normal

LP3: Log Pearson type III

M^3/s: cubic metre/second

NGI: National Geo-Spatial Information

CHAPTER 1: INTRODUCTION

1.1 Background and rationale

Floods are of great importance in shaping river channels and in carrying out large amounts of geomorphological work, especially in dryland rivers with variable flow (Heritage et al., 2000). Floods are essential to our understanding of fluvial geomorphology since they are the events during which significant geomorphological changes occur naturally, and geomorphological work is achieved by movement of sediment (Hooke, 2015). The physical effects of floods include channel deepening, channel widening, modification in channel position, erosion and movement of large amounts of sediment of various sizes, change in channel shape and characteristics, and deposition of sediment within channels, on floodplains and in sediment sinks (Hooke, 2015). Floods are also important in shaping the biophysical characteristics and functioning of rivers in semi-arid environments (Robert, 2007). Among the world's most significant natural hazards high-magnitude floods play a key role in the shaping of riparian environments across a wide range of physiographic and hydroclimatic zones (Woodward et al., 2010). For example, the Sabie River in South Africa experienced a large flood in February 2000 (with a return interval of approximately 100 years), which removed most riparian trees and shrubs (Heritage et al., 2001). High magnitude flood events can significantly modify many components of the river system, and can have an impact on ecological functioning and associated socioeconomic activities (Van Niekerk et al., 1995; Williams and Balling, 1996).

For the Sabie River, at some sub-reaches the channel type (e.g., degree of bedrock and alluvial exposure) and changing hydraulic conditions (shear stresses widely >1000 N m–2 across the river around peakflow), largely controlled the spatial patterns of erosion, deposition, and vegetation changes (Milan et al., 2018). And in some subreaches of Sabie River the impact of flood sequencing and relative flood magnitude resulted in remnant islands and vegetation that survived the 2000 floods to be removed during the smaller 2012 floods owing to their wider exposure to flow (Milan et al., 2018).

Many dryland river systems display a condition of extreme flow variability, dominated by periods of low flow and progressive sediment accumulation (McMahon et al., 1992), which are punctuated by extreme floods that produce a variety of changes in river morphology (Heritage, 2004). In the Gila River in Arizona, observed channel morphology was associated with a prior large magnitude flood event that resulted in channel enlargement (Stevens et al., 1975).

Extreme discharge has been shown to contribute significantly to channel shape in two eastern Jamaican streams (Gupta, 1975). Extreme flows have shaped the fluvial forms of the bedrock-influenced Burdekin River, Australia (Wohl, 1992). In the Limpopo river basin there is a clear positive correlation between floods and fluvial changes (Spaliviero, 2014).

Flood events also have major impacts, many of them beneficial, on ecology and maintenance of biodiversity, geodiversity, and the delivery of ecosystem services. This is well demonstrated in semiarid South Africa where normal rainy periods are characterized by strong plant production in uplands and in riparian zones, organic litter of good quality, relatively light herbivory by vertebrates with abundant feces returning selective nutrients to the soils (Robert et al., 2001). In some lowland rivers flow variability is important in geomorphology, as it maintains the complexity of the instream environment (Thoms and Sheldon, 2000). In the Barwon-Darling River in Australia the historical flow and channel survey data were used and indicated that cross-section morphology of the unregulated river was complex and characterized by a series of benches or flat surface; while the benches offered aquatic habitats during high flow events (Thoms and Sheldon, 2000). Understanding flood impacts is therefore essential in conservation and ecosystems management (Charlton, 2008).

Periodic stripping floods have been highlighted as an important mechanism behind fluvial change in Australian, Indian, North American, and South Africa river systems (Womack and Schumm, 1977; Baker, 1977; Nanson, 1986; Kale et al., 1996; Bourke and Pickup, 1999). Changes in channel style along the Sabie River following floods have been highly variable, with certain channel types seeming to be more vulnerable to major modification than others (Heritage et al; 2004). Extreme flows also trigger the development of streamlined islands or ridges along the channel, with the vertical accretion of ridges being promoted by frequent overbank flows during the wet season (Nanson and Huang, 1998).

A highly variable flow regime is also a significant factor in promoting anabranching development, particularly in many alluvial anabranching rivers where this occurs in conjunction with mechanisms to block or constrict channels (e.g. channel sedimentation, vegetative or ice jams, flow ponding; Tooth, 2004). Many large rivers are characterised by anabranching patterns, rivers with multiple channels supported by stable islands, such as the Amazon in Brazil, Congo in Zaire, Parana in Argentina (Latrubesse, 2008), Orange River in the Northern Cape Province of South Africa (Tooth, 2004), and the Vaal River near Parys in the Free State Province of South Africa. Channels in anabranching rivers divide and re-join around semi-permanent ridges, bars or islands (Tooth, 2004). Anabranching channels are characterised by the large stable, typically vegetated islands that do not periodically adjust with annual flow variability (Latrubesse, 2008).

Anabranching channels can also in rare cases develop where water is abstracted from rivers for irrigation, industry or for cooling, as islands remain exposed for longer periods and become stabilised by vegetation (Kleinhans et al., 2012). The hydrology of a river can be significantly altered by water resource development, through extraction of water for irrigation purposes or for coal fired power stations, and through the construction of dams, weirs and levees (e.g. Maheshwari et al., 1995). Even though demands on the water resources of rivers in dryland areas are usually high as in the study area considered in this thesis, there are inadequate data explaining their hydrological and geomorphological response to development. Excessive abstractions of water from rivers affect the flow of water in the channel and sediment transport. There are three coal fired power stations located within the Upper Vaal River Water Management Area which support electricity generation in the Gauteng area. The Department of Water and Sanitation (DWS) has indicated that there are 12 200 ha of land under irrigation in the Upper Vaal Water Management Area, which demands approximately 9% of the entire Water Management Area water supply (DWAF 2003). Data on the impacts of flow variability on island geomorphology in large mixed bedrock-alluvial anabranching rivers are essential in order to enhance understanding of flood dynamics and the variability of geomorphic responses in such rivers, and for management purposes, including the determination of environmental flow requirements (Rountree, 2013)

Local erosion and sediment supply may increase if vegetation from banks or hillslopes is removed by a flood (Tooth, 2000). This effect is demonstrated in a study from Bavaria on bedload transport, where sediment fluxes in moderate events after an extreme event were much higher than in comparable events before the large flood (Gintz et al., 1996). Flood event responses can be affected by any change in vegetation over time. Changes may include gradual growth of vegetation after a resetting event (fire or other natural event) at the site itself or upstream (Hooke, 2015). These changes have an effect on the sediment supply and amount of deposition. For example, growth of vegetation can reduce erodibility of the banks and floodplain and increase roughness, thus resulting in increasing resistance and decreasing velocity of flow (Hooke, 2015).

The Vaal River near Parys in the Free State Province is characterised by a variable degree of mixed bedrock-alluvial anabranching channels which divide and re-join around semi-permanent islands. Some of these islands are extensively cultivated, used as residential land, or used for industrial purposes, and this indicates a degree of permanence. Many of the large rivers in Southern Africa are characterised by a mixed bedrock-alluvial anabranching pattern (e.g. Orange River in the Northern Cape Province, Sabie River in Mpumalanga Province). In the study area the impact of flood variability on island geomorphology has not been studied. Comparable studies have been conducted in the Sabie River in Mpumalanga Province (Heritage et al., 2000, Milan et al., 2018, Rountree et al., 2000) and in the Orange River in Northern Cape Province (Tooth, 2004). This study will investigate the effect of floods peaks on island geomorphology. The research will aim to improve understanding of the correlation between flood dynamics and island geomorphological changes in the river.

1.2 Aim and objectives of the research

1.2.1 Aim

The aim of the project is to investigate the effect of flood dynamics on island geomorphology in the Vaal River near Parys.

1.2.2 Specific objectives

- To review and determine metrics of flood magnitude, duration and frequency that could play a role in fluvial island geomorphological change.
- To review and determine metrics of island geomorphological change that can be detected and measured using image analysis.
- To investigate relationships between metrics of flood magnitude, duration and frequency and metrics of island geomorphological change over the past ~78 years.

1.3 Research problem

In comparison with temperate rivers, dryland rivers respond differently, both physically and biologically, to hydrological change (Thoms and Walker, 1993; Davies et al., 1994), and this response may differ across a range of spatial and temporal scales (Walker et al., 1995). During large flood events, when the erosive power of the flow is greatly increased, channel shape can be modified and this depends on how much resistance is provided by the bed and banks of the channel (Charlton, 2008). River banks comprising mostly of silt and clay are generally regarded as having strong cohesion and high resistance to bank erosion (Schumm, 1963), while channels formed in unconsolidated sand or gravel alluvium offer much less resistance to erosion than those cut in bedrock.

Floods of high magnitude are among the most common and significant natural hazards in the world. They play a crucial role in shaping river channel-floodplain morphology and riparian ecology (Milan et al., 2018). Highly variable flow regimes are key to morphological development for many dryland rivers (Tooth and Nanson, 2011; Tooth, 2013). Rare, high-magnitude floods in some bedrock- influenced dryland rivers have been shown to control the morphological responses and also to be responsible for doing the most geomorphic work (Baker, 1977). Due to more erodible soils, less vegetation covers and flashy character of floods in dryland environments floods have the potential to cause greater landform change (Molar et al., 2002).

The study along a 50-km-long reach of the bedrock-influenced Sabie River Kruger National Park Mpumalanga South Africa has shown some evident in the impact of flood sequencing and relative flood magnitude in the bedrock-influenced Sabie River, some subreaches, remnant islands and vegetation that survived floods in 2000 were removed during the smaller 2012 floods due to their broader exposures to flow (Milan et al., 2018).

extreme events such as Hurricane Camille in Virginia has been dramatically modify the fluvial landscape (Williams and Guy, 1973) while in Pennsylvania Hurricane Agnes induced only minor changes (Moss and Kochel, 1978). Periodic stripping has been indicated as an important mechanism behind mophological changes in Australian, Indian and North American river systems (e.g., Womack and Schumm, 1977; Baker, 1977; Nanson, 1986; Kale et al., 1996; Bourke and Pickup, 1999). In the Gila River in Arizona, observed channel morphology was associated with a prior large magnitude flood event that resulted in channel enlargement (Stevens et al., 1975).

In dryland areas, bank stability is influenced by high bank strength due to fine-grained sediment cohesion, and low vegetation densities, which in some cases are not sufficient to effectively strengthen banks (North et al., 2007). For example, trees that are hundreds of years old in the anabranching river systems of arid central Australia illustrate that there is channel stability over very long periods (Makaske, 2001). Most flows are able to modify channels formed in sandy alluvium because relatively less energy is used to set the individual sand grains in motion (Charlton, 2008). Since the area under study is characterized by a variable degree of mixed bedrock-alluvial anabranching channels which divide and re-join around (semi-permanent) islands, this research will determine if the area under study is resistant to erosion during high flow.

High flow and moderate flow has been observed in other rivers modifying the channels, this research will investigate if the floods of rare magnitude, duration and frequency events have an influence on islands, bars and general channel modification in the study area. It is also important to understand and foresee the possible physical impacts of flood dynamics on the channel form and island geomorphology. The study will determine if there is a significant correlation between flood duration, magnitude, frequency and island geomorphological changes in the mixed bedrock-alluvial anabranching rivers in the area of study.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The objective of this chapter is to present a review of previous work on effect of flood dynamics on island geomorphology in large mixed bedrock-alluvial anabranching rivers in dryland environments. In order to achieve this, the chapter starts with the definition of flood, and that will guide this study. Within this outline, the impacts of flood dynamics in dryland anabranching rivers is provided. This literature review will follow the specific objectives of the study to provide a systematic review on various approach that are used to determine the impact of flood dynamics on island and channel geomorphology.

2.2 Definition of a flood

Floods are essential to our understanding of fluvial geomorphology since they are the events during which significant geomorphological changes occur, and through which geomorphological work is achieved by the movement of sediment (Hooke, 2015). In general rivers literature, a flood is commonly defined in terms of high water levels or flow that exceeds the bankfull capacity of the river channel, but in drylands a "flood" happens every time there is water in the normally dry channel, regardless of the amount (Graf, 1988; Cooke et al., 1993). Four types of flood in dryland rivers have been identified: flash floods, single-peak events, multiple-peak events and seasonal floods (Graf, 1988). Most dryland rivers are characterised by flash flood hydrographs, which are typically produced by convectional precipitation (Graf, 1988). Flash floods are associated with high runoff coefficients that results from the dominance of Hortonian overland flow in runoff generation, (Walters, 1989; Rhoads, 1990; Hassan, 1990; Reid et al., 1994; Dick et al., 1997).

2.3 Causes of flood

The flow in natural channels is unsteady as it regularly fluctuates through a perennial rivers sequence of normal flows, floods and low or no-flow periods, in response to input of precipitation to the catchment (Charlton, 2008). Precipitation is a primary driving factor in flow and flood or sequence. In dryland regions, hydrological variability is often associated with highly variable precipitation and low rainfall–runoff ratios especially during winter seasons (Thoms and Sheldon, 1999). For example, many semi-arid river systems exhibit extreme flow variability, dominated by periods of low flow or no flow and progressive sediment accumulation (McMahon et al., 1992). Precipitation is highly variable in time and space and most of the rivers in dryland environment are characterised by long periods without flow

(Tooth, 2000). In semi-arid areas, rainfall frequently occurs at high intensities over ground with uneven vegetation cover resulting in high erosional effectiveness of rain-drops (Thornes, 1994).

Dryland rivers are characterised by hydrological variability. In the variety of rivers in areas of high flow variability extreme floods have been shown to have a major morphological role (Heritage, 2004). Regular flows are confined within a channel and episodic high flows overflow on the banks and floodplain of the river. Such periodic stripping influence the removal of sediment, through erosion and downstream transport, is observed as essential to the functioning of such systems (Dollar, 2002).

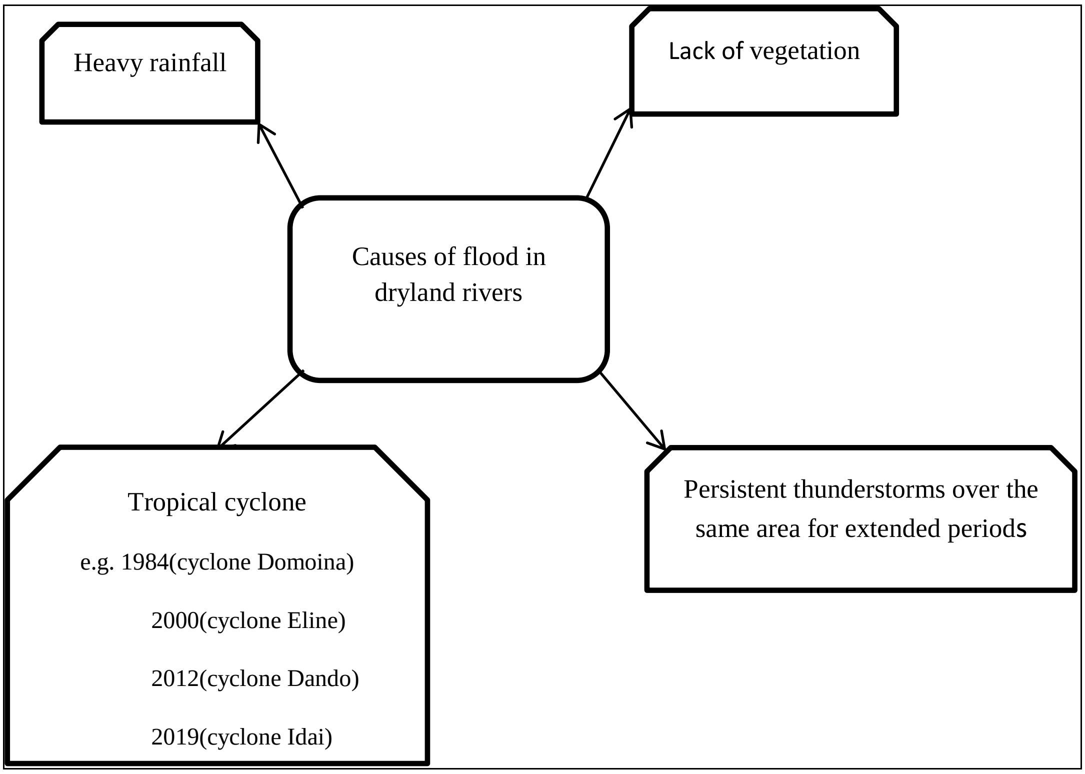

Figure 2. 1: causes of flood in dryland rivers

2.4 Comparison of flood hydrology in semiarid rivers

Dryland rivers are usually considered to transport large quantities of sediment both as suspended load and as bedload during flood events, relatively there are few quantitative data about this assumption (Sharma and Murthy, 1994; Reid and Laronne, 1995; Reid and Frostick, 1997). Dryland channels are frequently considered to be more sensitive to the effects of catastrophic floods (Tooth, 2000). Due to the limited resistance of dominantly sandy bank materials and the relative paucity of restraining vegetation many semiarid channels are susceptible to the erosive effects of large floods (Slatyer and Mabbutt, 1964; Mabbutt, 1977; Wolman and Gerson, 1978). Even though some channels are heavily vegetated with trees, grasses and shrubs sometimes are subjected to flood-related changes. In many semiarid rivers the destruction of in-channel vegetation and channel morphology during large flood flows has been indicated (Baker, 1977; Osterkamp and Costa, 1987; Lisle, 1989), though the process thresholds giving rise to vegetation removal are little known (Thornes, 1994b).

Bertoldi, et al (2014) studies in the Megra River in Italy (2009) resulted in two scenarios; first case, during large floods the vegetation was totally removed and the final topography was corresponding to those without vegetation, the second scenario, vegetation survives flood erosion after each flood occurrence and the total biomass also increased, and thus build vegetated bars. In this second case some vegetation shows resistance towards rare flood and they slowly build up and the bed morphology is strongly altered by the occurrence of vegetation, which stops the migration of bed forms and induces higher deposits.

Extreme floods often have long-lasting effects on dryland channel morphology. In some semiarid areas, the impact of large floods often persists for long periods with channel forms sometimes representing the effects of the last major event (Tooth, 2000). Dryland rivers are characterised by steep flood frequency curves as the slopes are established by a few, very large events, and frequently skewed, reflecting the high ratio of large to small floods (Tooth, 2000).

Although in many characteristics of flood hydrology semi-arid rivers as whole exhibit similarities, the conditions across semi-arid rivers are not similar and considerable inter-regional differences exist (Tooth, 2000). For example, worldwide hydrological data sets assessments show that rivers in the Australian and southern African arid zones are characterised by highly variable flow regimes, yearly flows and peak discharges than rivers in other arid parts of the world. While flow regimes in North American arid zone rivers are less variable than elsewhere (McMahon, 1979; Finlayson and McMahon, 1988; McMahon et al., 1992). In terms of specific mean annual peak flows inter-regional differences also exist, for example, the rivers in the arid eastern Mediterranean tend to produce higher specific peak flow than rivers in other arid areas (McMahon 1979). The reasons for these differences are not completely understood, but previous researchers suggested that the variability in flows characteristic of Australian and southern African rivers are associated with great rainfall variability, and possibly also from higher rates of evapotranspiration typical of these continents (Finlayson and McMahon 1988. and McMahon et al. 1992). In the Mediterranean arid rivers flows occur mainly in the cooler winter months when evapotranspiration is reduced, whereas in arid Australia, southern Africa and North America, flows are typically less seasonal and summer events are often subjected to high evapotranspiration losses (Williams and Balling, 1996).

2.5 Equilibrium and non-equilibrium conditions in semiarid rivers

In the semi-arid Henry Mountains of Utah, the self-adjusting and roughly balanced conditions between rates of sediment erosion, transport, and deposition in streams were observed by Gilbert's in 1877, and is where the concept of equilibrium in geomorphology originates (Tooth and Nanson, 2000). After some period of time the concept of equilibrium started to receive little attention, equilibrium in a river was defined as one in which gradient is carefully adjusted to provide just those conditions required for transport of the sediment load from upstream over a period of years (Markin, 1948). Erosion or deposition will occur, and local gradient will adjust, when a stream's gradient becomes locally too shallow or too steep (Markin, 1948). In the application of equilibrium concepts to ephemeral rivers many researchers have experienced challenges, usually by representing extensive and sometimes rapid variations in channel form to the extent that it is impossible to identify a medium- or long-term average condition (e.g., Stevens et al., 1975, 1977; Rendell and Alexander, 1979; Thornes, 1980; Graf, 1983a; Clark and Davies, 1988).

Four criteria that may be used to measure the existence of equilibrium in rivers where suggested: “(1) an significant steady relationship between pattern and process such that, despite on-going processes (e.g., deposition and erosion), average channel form remains stable over time; (2) temporal and spatial sediment transport continuity, such that sediment input to a reach equals sediment output; (3) strong correlations between system variables; and (4) an adjustment to maximum efficiency, although this may involve a compromise between conflicting tendencies, such as the different requirements for efficiency of flow conveyance as compared to efficiency of sediment transport” (Richards, 1982).

Temporal variability in semiarid river channels is described by the unsteady nature of flow and sediment transport, and by the common significance of large floods as a dominant control on channel morphology (Tooth, 2000). The patterns and processes of many semiarid fluvial systems are notably discontinuous due to this extreme variability, and rivers are sometimes typified by a lack of equilibrium between process and form. These characteristics of dryland rivers differ strongly with many perennial rivers in more humid regions, where process and form are strongly interlinked, and constant mutual adjustments may occur (Richards, 1982;

Knighton, 1998). Finlayson and McMahon (1988) used a global database to determine that semiarid rivers are more variable in terms of monthly discharge than those of humid regions (Puckridge et al. 1998). Nonlinear temporal response of runoff to rainfall and basin size, and highly variable seasonal flow characteristics are the main hydrological features of dryland rivers (McMahon, 1979).

The study was conducted in the Channel Country and in Northern plain of Australia dryland rivers in order to determine if those rivers resemble the characteritics of non-equilibrium condition, and it seem as they resemble the characteristics of equilibrium condition. Cohesive muds, and riparian vegetation low gradients, confining terraces, long duration floods generating only low to moderate unit stream powers, all these support in producing stable channels that are able to adjust in an integrated manner to prevailing flow and sediment discharge (Tooth and Nanson, 2000).

The most important factors accounting for the discontinous operation of dryland river is the role played by large flood events, and flood frequency curves are frequently steep, as the slopes are set by a less, very huge flows, and often skewed, reflecting the large ratio of high- to low magnitude flows (Tooth and Nanson, 2000). This symbolise that geomorphically active floods are probable to be of large relative magnitude (Richards, 1982; Graf, 1988). The long-term histories of many dryland rivers have been dominated by recurrent large floods this was demonstrated by slackwater deposits preserved in bedrock canyons (Patton et al., 1979; Kochel et al., 1982; Baker, Kochel, et al., 1983; Baker, Pickup, and Polach, 1983; Ely and Baker, 1985; Partridge and Baker, 1987; Pickup et al., 1988; Smith, 1992; Ely et al., 1993; O'Connor et al., 1994; Wohl et al., 1994), and downstream alluvial reaches had dramatically impacted by these high-magnitude floods (Pickup, 1991; Patton et al., 1993).

Wolman and Gerson, 1978 proposed that following extreme flood, dryland rivers experience recovery times that are significantly longer than those of perennial channels in more humid environments, due to the moderately small number of low-magnitude flows which are able to repair damage between large floods intervals. The effect of major flood frequently continues for long periods of time (Tooth and Nanson, 2000). Many researchers have published the importance of vegetation in channel recovery following large flood event (e.g., Schumm and Lichty, 1963; Burkham, 1972; Osterkamp and Costa, 1987), destructive floods should produce nearly irreparable changes in channel morphology, in some dryland regions where sediment-trapping vegetation is minimal (Wolman and Gerson, 1978). Channels has considerable implications for concepts of river behaviour due to the dominant influence of extreme floods on dryland channels, for example equilibrium between channel form and a representative channel-forming event is impossible if channel recovery times exceed the recurrence intervals of major channel-changing floods (Richards, 1982). Due to the underlying assumptions of continuous system operation with well-defined feedback mechanisms, there are difficulties in applying concepts of equilibrium river behaviour because those assumptions are not always met in semiarid environment (Graf, 1988a).

Many studies in semiarid areas suggested that rivers that are typically non equilibrium systems has largely been restricted to relatively small, steep, often sparsely vegetated, headwater reaches dominated by short-lived, high-magnitude floods (Tooth and Nanson, 2013). The role of vegetation in channel recovery following extreme floods have been documented (Schumm and Lichty, 1963; Burkham,1972; Osterkamp and Costa, 1987), for instance Wolman and Gerson in (1978) recommended that in some dryland area destructive floods should produce nearly irreparable changes in channel morphology where sediment-trapping vegetation is minimal. Many studies of major historical channel changes due one or more large floods in drylands rivers are available (Baker, 1977 and Osterkamp and Costa, 1987), one of the best documented examples is the quick enlargement of the Santa Cruz River during the Tucson flood of October 1983 (Baker, 1984). Overall, small, steep, headwater channels in semiarid areas have sand and gravel bedloads and are characterised by short-lived flash floods that produce high to moderate unit stream powers (Tooth and Nanson, 2013).

Erosion thresholds tend to be low, where formed in unconsolidated alluvium and where vegetation is sparse or absent (Tooth and Nanson, 2013). In the lower unconfined reaches of Northern plain central of Australia, in the last few decades' large floods have resulted in a range of changes, including channel widening and migration, extension of channel termini into floodouts, avulsion, and splay formation (Tooth and Nanson, 2013). For example, most of the change since 1950 has involved the initiation and growth of splays in the lower reaches of the Woodforde River and most changes have been occurred between 1971 and 1978, probably largely in response to the major 1974 flood as recognized from the aerial photographs and since then little further change has occurred, despite subsequent large floods (Tooth and Nanson, 2013).

Channels are susceptible to dramatic change during large floods, as unit stream powers generated during floods typically exceed these erosion thresholds, (Schick, 1974; Hereford, 1986; Clark and Davies, 1988; Bourke and Pickup, 1999). In some cases, peak unit stream powers may even be great enough to cause bedrock erosion. The relatively high frequency of major channel-modifying floods possibly means that rivers rarely reach conditions for equilibrium (Richards, 1982). Where unit stream powers generated during floods is high and exceeding alluvial thresholds, channels also can be highly susceptible to change (e.g., Schumm and Lichty, 1963; Burkham, 1972; Hereford, 1984).

Previous researchers have emphasized the importance of pre-existing morphology influencing impact, the morphology of the river can gradually or rapidly adjust back to pre-flood morphology once it has been modified or altered by a flood event (Richards, 1999). This is mainly controlled by the flows and the supply of sediment (Wolman and Gerson, 1978). In some cases, the new channel morphology is maintained or even improved by positive response and the channel form continues on a differing direction from previous (Tooth, 2000). As noted in some case studies, due to the fact that the channel is already adjusted to higher discharge and the recovery time is extremely long a change in morphology caused by a previous flood is a reason given in some cases of little impact of a later flood (Wolman and Gerson, 1978 and Brunsden and Thornes, 1979).

Many alluvial channels in humid rivers adjust their geometry in order to reach equilibrium with the prevailing flow and sediment discharge regime. However, in the application of equilibrium concepts in dryland rivers, many researchers have encountered problems due to sometimes sudden variations in channel form to the extent that it is not possible to identify a medium- or long-term average condition (e.g., Stevens et al., 1975, 1977; Rendell and Alexander, 1979; Thornes, 1980; Graf, 1983; Clark and Davies, 1988). In many cases, there are difficulties in transferring concepts of equilibrium channel behaviour in dryland areas, since humid areas lies in the underlying assumptions of continuous system operation with well-defined feedback mechanisms, and that assumptions are not always met in drylands (Graf, 1988). The one most considerable important factor accounting for the discontinuity operation of dryland rivers is the role played by large flood event. As the slopes are set by a few, very large flows, Flood frequency curves for dryland rivers are often steep, and frequently skewed, reflecting the large ratio of high- to low magnitude flows. This means that geomorphically, effective floods are probable to be of great relative magnitude (Richards, 1982; Graf, 1988).

2.6 Relationship between flood magnitude and frequency

The flow regime is characterised by temporal hot seasonal variations in flow duration, magnitude and frequency of floods (Poff and Lytle, 2004). However, the characteristics of the flow are of significance in determining channel form; since the flow of water in a channel provides the energy required shaping the channel and the channel form is a product of the flow experienced by the channel (Pickup and Reiger, 1979). For a given river or channel, there is a relationship between the magnitude of a flood and the frequency of a flood (Heritage, et al, 1999). Costa and O'Connor (1995) suggested the relationship between flood magnitude and flood duration as a control on channel. This suggestion was argued, once a flood exceeds a reach-averaged erosional threshold geomorphic can begin to occur (Dean and Schmidt, 2013). The effectiveness of an event such as flood of a given frequency in terms of its performance of work is determinate by its magnitude and by the frequency with which it returns. Therefore, a great, short duration flood pulse may cause rapid rates of geomorphic change, but a longer duration flood of smaller magnitude may result in greater total channel reset due to the fact that the length of time above the erosion threshold is greater than that of the other flood. During higher magnitude flood much more sediment is expected to be transported, although, this also depends on availability (Hooke, 2015). The occurrence of floods and their physical impacts on the fluvial geomorphology are often determined by the evidence of morphological change and from deposits and these sequences of evidence are used to conclude frequency, especially in the longer-term; The assumption from this evidence is that the impact at any specific location are comparative to the magnitude of the flood as measured by the peak flow (Hooke, 2015).

Previous researchers considered that for the given frequency of occurrence the most effective or dominant discharge affecting channel capacity and morphological form was that which transported most bed sediment through the channel (Wolman and Miller 1960). The effective or dominant discharge was found to be similar to the peak of a plot of the product of sediment transport and discharge frequency, and to the bankfull discharge (Heritage, 2001). In temperate zones the most geomorphic work in terms of sediment transport was found to be carried out by floods of moderate magnitude and frequency rather than rare large magnitudes events (Wolman and Miller, 1960). However, the flow frequency data derived from the morphological units of the Sabie River in the semi-arid zones reveal that the system bears no similarity to the condition described for temperate alluvial system (Heritage, 2001). In the semi-arid zones evidence indicated a tripartite division of the morphological features based on the flow regime of Sabie River (Heritage, 2001). The research indicate that this tripartite segregation may be related to morphological features which are frequently inundated which are associated with the perennial distributaries, seasonal flowing channels and very rarely inundated large-scale macro channel units. The greatest cause of dissimilarity is the lack of any well-defined channel-forming flow that could be related to a bankfull condition (Heritage, 2001).

With occasional flash floods of varying magnitude in dryland areas, flow in channel is ephemeral. Hydrological variability is a feature of dryland rivers and is associated with highly variable effective rainfall (Hooke, 2016). This is usually explained using statistics from flood–frequency curves, time series of annual discharge and flow duration curves (McMahon et. al., 1992). This study will focus on the correlating floods of extreme, infrequent flows with island geomorphological changes in dryland environment.

The geomorphology of the Orange River in the Northern Cape Province is dominated by point bar-like features that are up to 5 km long and 1-2 km wide and the bedrock islands (Zawada and Smith, 1991). These islands and bars are vegetated and separated by river channels of up to 30m wide. In the year 1988 Orange River experienced flood of high magnitude, the water overtopped almost the entire area between the rock-cut, basement terraces (Zawada and Smith, 1991). From the aerial photograph of the year 1944-1988, it shows that the position of the large bars, island and main channels have not changed in the past 46 years (Zawada and Smith, 1991). The stabilities of the observed bar, island and channel can be due to an underlying basement control, since it was observed that in some places the fluvial pattern in the Orange river controlled by basement exposures (Zawada and Smith,1991).

2.7 Development of ridges and islands

Several interacting factors that trigger the development of streamlined island or ridges have been proposed. Vegetation seems to be important in several ways. Firstly, trees growing within the channel act as barriers to flow and promote lee-side deposition in the form of a tail of the sandy sediment. Secondly, tree growth and associated root mats make the ridges more stable. The vegetation on the ridges decreases mean flow velocities prompts deposition and vertical accretion which leads subsequently to reduced flooding of the ridges. In the anabranches this results in increased flow depth and greater velocities and bed shear stresses which turn out to be zones of higher sediment transport and more frequent bed mobility. As a consequence, the development of vegetation in the anabranches is hampered by these enhanced flow conditions and the channels are left as sandy-floored conduits largely free of obstructions. The hydraulics of flow appears to determine the number and size of anabranches (Nanson and Huang, 1998).

Sediment prompts the development of streamlined island or ridges. For the observed vertical accretion of the ridges, sufficient sandy sediment transported in suspension by turbulent mixing is required; ridges are usually too steep-sided to receive sand as bedload. This suspended sediment basically needs to be readily deposited in areas where flow velocities are reduced. Therefore, for the ridge development, an abundance of fine to medium sand that can be moved into suspension from the bed-material appears to be beneficial (Nanson and Wende, 1998).

Flow triggers the development of streamlined island or ridges. The conditions leading to within-channel tree growth (especially M. leucadendron) along the seasonally dry sections of the sandy channel bed is provided by highly seasonal flow regime of the rivers. The vertical accretion of ridges is promoted by frequent overbank flows during the wet season and irrigation of the riparian vegetation is guaranteed by a range of flows (Tooth, 2004).

Joints and fractures promote island formation, where joints and fractures are closely spaced, then extensive hydraulic plucking will probably enable enlargement of some channels at the expense of others, and the dividing island will erode eventually (Tooth, 2004). Vegetation is an important factor enabling bank and island stability in rivers where the channels divide around islands composed largely of alluvium; example, rivers such as the Narmada and Caroni, many islands are thickly forested, and even along the arid Orange River, banklines are typically well-vegetated (Tooth, 2004). The bankline stabilisation helps to control extensive channel widening or lateral migration, thus protecting the anabranching pattern and promote the formation island between the spaces left in anabranching patterns (Tooth, 2004).

The islands in the study reach are often formed on the mixed bedrock-alluvial anabranching channels, and are very stable features that are only occasionally inundated even during floods. The islands which channels re-join and divide around them are formed when sediment supply probably exceeds local transport capacity which results in sediment deposition (Tooth, 2004).

2.8 Development and formation of anabranching rivers

Anabranching rivers are multiple channel rivers that are clearly divided at bankfull by subaerial vegetated islands or ridges, and are extensively considered in addition to meandering, braided, and straight rivers (e.g., Rust, 1978; Schumm, 1981, 1985; Brice, 1984; Knighton and Nanson, 1993; Nanson and Knighton, 1996; Makaske, 2001). Many large rivers are characterised by anabranching patterns, for example the Amazon in brazil, Congo in Zaire, Parana in Argentina (Latrubesse, 2008), Orange River in the Northern Cape Province South Africa (Tooth, 2004) and the Sabie River in the Mpumalanga province South Africa (Heritage et al, 1999).

Anabranching channels are characterised by the large stable vegetated island that do not periodically adjust with annual flow variability (Latrubesse, 2008).

The development of anabranching channels includes both erosion and deposition and it can start with either deposition or erosion (Kleinshans et al, 2012). The mid channel deposition initiates some small-scale bifurcation channels, as in typical braid-bar growth (Leopold and Wolman, 1957). In some other cases anabranching channels are initiated by erosion, it can be through headward incision of a channel which captures a cumulative amount of flow in the original main channel (as in chute cut-offs in meandering and braided rivers) or through bank erosion leading to capture of an adjacent channel or other depression (as in meander neck cut-offs and braid avulsion), (Hicks et al, 2002; Burge, 2006). Anabranching systems can be formed by within channel accretion or by avulsion-based erosional (Nanson and Knighton, 1996). The periodic removal of sediment, through erosion and downstream transport, is observed as vital to the functioning of such systems (Dollar, 2002).

High variable flow is a significant factor promoting anabranching channels in most of alluvial anabranching rivers, especially where this occur in conjuction with mechanisms to constrict channels (Tooth, 2004), Flow variable in floodplains or island, periodically promote overbank flows and cutting of anabranches (Nanson and Knighton, 1996). Variable flow regimes appear to be of secondary importance compared to other factors promoting multiple channel formation, as compare to bedrock joints or fractures in many bedrock and mixed bedrock alluvial anabranching rivers (Tooth, 2004). In other instances, where bedrock anabranching has been described from surfaces adjacent to bedrock canyons, extreme flows were noted to be the key factor. In these cases, anabranching has been proven as developing during catastrophic floods when flows have spilled out of the canyons (Bretz et al, 1956; Baker and Pickup, 1987).

Joints and fractured lithologies also aid on promoting the anabranching of rivers, for example most commonly granitoid rocks, although localised examples of bedrock anabranching have been noted along rivers in jointed basalts (e.g., Kale and Shingade, 1987; Deodhar and Kale, 1999) or jointed sandstones and quartzites, such as in Northern Australia (Baker and Pickup, 1987; Wende, 1997) and on a very short reach of the Orange River near Boegoeberg Dam, in Northern Cape Province (Tooth, 2004). Where long-term transport capacity exceeds sediment supply bedrock anabranching formed and these resulting in a tendency for channels to incise into bedrock (Tooth, 2004). River will preferentially exploit lines of weakness such as joints, fractures, and foliation where resistance of the intact rock mass is high, but for channel incision to occur, erosional energy must exceed the resistance threshold of the bedrock (Tooth, 2004). Joints and fractures promote multiple channel incision by providing multiple lines of weakness, and as erosion proceeds it left the area between the channels as topographic highs. By providing multiple lines of weakness, joints and fractures promote multiple channel incision, and as erosion proceeds, the areas between the channels are left as topographic highs (Tooth, 2004).

The other most significant factor that also contributes to the development of anabranching channels is aggradation of the main channel (Kleinshans et.al, 2012). Aggradation promotes mid-channel deposition, increases the probability of flow over bar and bank tops, and decreases the elevation of the bank that needs to be removed for lateral capture to occur (Kleinshans et.al, 2012). Once anabranching channels exist the two flow channels may or may not both be in sediment-transporting equilibrium. A path will enlarge and capture more flow if and only if its transport capacity exceeds the sediment supply to it (Kleinshans et al, 2012).

Variable channel-bed gradient appears to be a key factor influencing the distribution of the alluvial and bedrock reaches in rivers where alluvial and bedrock anabranching occur (Tooth, 2004). In Sabie and the Narmada River the variable channel-bed gradient seems to be significant, where alluvial anabranching more common along lower gradient reaches and bedrock anabranching appears to be most common along relatively steep reaches (Tooth, 2004). The spatial distribution of relatively weak lithologies (Miller, 1991), or lower than average channel-bed gradients is determined by the location of alluvial anabranching reaches along a river course in other rivers (Wende and Nanson, 1998).

In Anabranching Rivers riparian vegetation can have a strong influence in controlling channel formation (Harwood and Brown, 1993). The availability of water largely controls the distribution of the riparian vegetation in semi-arid regions and dense woody vegetation is usually only found within or close to channels (Hupp and Osterkamp, 1996). Not like humid areas with thick vegetation cover, dryland anabranching rivers are categorized by sparse vegetation, which plays a significant role in channel morphodynamics of dryland anabranching rivers by changing bank strength and flow dynamics (Tooth and Nanson, 2000).

Nevertheless, anabranches can also be scoured into the floodplain by floodwaters focused on the lower parts of the floodplain (Brizga and Finlayson, 1990). And incisions of such new channels can arise from headward cutting (Schumann, 1989; Miller, 1991). Anabranch development by avulsion includes the diversion of channel flow resulting into new channel formation or palaeo channel at a lower level on the floodplain. Typically, such new channels are disconnected from the main by a remnant of a formerly adjoining floodplain. Within-channel accretion resulted to the development of semi-permanent islands (or ridges) to approximately floodplain height (latrubesse, 2008).

Four types of processes about anabranching development have been recognised in the Río Capilla, Bolivia study which are lateral migration leading to partially active channels, chute channels, reactivation of partially abandoned channels, and connection of headcuts and crevasse channels. In the Río Capilla, Bolivia in the period of satellite observation from 2004 to 2013, ten anabranches resulted from connection of headcuts and crevasse channels, and one anabranch was initiated by chute channel cutoff. Another anabranching event resulted due to the process of lateral migration. Hence, connection of headcuts and crevasse channels appears to be the main mechanism of anabranching development within the Río Capilla. (Jiaguang, 2015). In some studies, for instance in the Rio Capilla, anabranching channels resulted from lateral migration and overbank flooding in combination with headcuts on the floodplain (Jiaguang, 2015).

2.9 Impact of water resources development in rivers

The water resources provided by rivers in semiarid are subject to high levels of exploitation due to low and highly variable rainfall (Braune, 1985). About 50% of all the flows in the South African river are held within storage dams, with an unknown percentage diverted (Thoms and Sheldon, 2000). The aquatic ecology of the southern African rivers has been drastically impacted by such hydrological changes (Allanson et al., 1990).

In the Colorado River, in the American southwest less than 1% of the natural flow now reaches its mouth (Petts, 1984) and the seasonality has changed with summer flows vastly increased and high spring flows reduced (Carlson and Muth, 1989). The ecological character of the river has changed due to the huge amount of water resource development in the Colorado catchment, salinity levels are increasing rapidly and endemic fauna are threatened (Stanford and Ward, 1986). Another example of the consequence of diverting water from a dryland river system, is that of the Aral Sea in Uzebekistan and Kazakhstan where water has been diverted for irrigation from the incoming Amu and Syr-Darya Rivers. There has been a drastic change in sea volume from 1090 km^3 in 1960 to 310 km^3 in the 1990s (Aladin and Williams, 1993). As a result, 96% of the macro-invertebrate fauna and 83% of the fish fauna of the Aral Sea are destroyed, with only 3.6% of the vast reedbeds remaining (Micklen, 1988).

The seasonality of flow may also be impacted by water resource development (Petts, 1984). For instance, in the Barwon– Darling the highest impact has been on summer flows from the month of October to March, and in this month there is a greatest demand of water from upstream irrigation industries. Monthly flows in the Barwon– Darling have been reduced by up to 56% in summer months compared to a maximum of 36% during winter months (Thoms and Sheldon, 2000).

2.10 Approaches used to determine the Effects of flood dynamics on island geomorphology

Correct hydrological information is very importance, especially in dryland countries like South Africa due to variability in hydrology. Measurements of flow in many rivers such as South African rivers are regularly not only complicated by the high variability of water discharge, but also by heavy debris and sediments loads (Wessels and Rooseboom, 2008). Different methods have been adopted to measure the discharge: instantaneous measurements (where discharge is measured at a particular point in time) and continuous measurements (for a record of discharge variations through time) (Wessels and Rooseboom, 2008 and Charton, 2008).

In this study the continuous measurements were proposed. In this method discharge is much easier to record as it is related to stage, the water level or height. the gauging station situated on a cross-section is used to measure the water level and stage. *'A gauging station is a site on a river which has been selected, equipped and operated to provide the basic data from which systematic records of water level (stage) and discharge may be derived. Essentially it consists of a natural or artificial river cross-section where a continuous record of stage can be obtained and where a relation between stage and discharge can be determined'* (Lambie, 1978).

The level of water in the gauging station is monitored using a stage recorder. Rating curve is used to convert stage into discharge, the discharge corresponding to a given stage can either be read off from the graph or calculated using the rating equation. The equation $Q = ahb$, is used, where Q = discharge, h = stage and a and b are coefficients, which describe the single relationship between stage and discharge for the cross-section (Wessels and Rooseboom, 2008 and Charton, 2008).

Most rating curves tend to be less reliable at high flows which make it difficult to measurements and tend to be less reliable at high flows. Another problem is that if a large flood alters the shape of the cross-section, or gauging station the rating curve has to be re-calibrated (Charton, 2008).

When calculating flood return period should preferable be calculated with a record length of flow data of at least thirty years (Volpi, et al., 2015 and Charton, 2008). Where possible flow data with longer record should be utilized as this will include large number of flood events and also sample of all flood events will be represented. Firstly, the peak flow for each year need to be identified in the record to produce an annual maximum series (Charton, 2008). The mean annual flood is a results of mean of this annual maximum series for instance, mathematical analyses have revealed that the recurrence interval of the mean annual Flood is 2.33 years and this means that, this flow will be exceeded by the highest flow of the year once every 2.33 years on average years (Leopold et al., 1964).

The annual maximum series flood peaks are ranked in order of magnitude, with the highest flood peak ranked first and gradually smaller events given higher numbers. The following formula is being used to measure the return period in years: $T=(n+1)/m$ where T = return period in years, n = rank and m = number of years in record (Stedinger et al., 1993).

In order to estimate the size of floods with larger return periods than those on record it is possible to extrapolate or extend this line, However the complications associated with fitting a best-fit line through the existing data mean that a small difference in its gradient could make a big difference to the projected size of the flood. Practical there are also number of difficulties associated such estimates and errors of flood discharges and errors in flood discharge estimates are normally considered to be in the range of 10 per cent to 100 per cent (Benito et al., 2004). Since gauging stations can be damaged or even destroyed during high flows, Large floods are very difficult to record accurately due to critical gaps in the flood record (Benito et al., 2004).

However, hydrological records are frequently short and often have missing observations (Elshorbagy, 2000). The presence of data gaps might be due to a number of issues such as interruption of measurements because of equipment failure, effects of extreme natural phenomena such as flooding or mishandling of observed records by field personnel, or accidental loss of data files in the computer system. The commonly used techniques for estimation of missing data in water resources, are based on regression analysis, time series analysis, artificial neural networks and interpolation techniques (Supriyaa, et al., 2015). In regression analysis one variable is taken as dependent variable and the other as independent variable thus making it possible to study the cause and effect relationship (Supriyaa. et al., 2015).

Useful and important information for the spatial, ecological and many other changes in the environment can be obtained by analysing historical aerial photograph. When the analysis of aerial images from the past and contemporary aerial images compared the information about the nature and trends of the observed phenomena is obtained (Bakrac, et al., 2021). The use of aerial imagery gives a solid base for many researches e.g., in the landscape and living environment generally (Gong, 2012; Liu & Yang, 2018; Melnyk, 2008).

Relationship between images and object coordinate systems is established by Georeferencing. It is essential to make satellite and aerial as well as terrestrial imagery useful for mapping by georeferencing (method of aligning geographic data to a known coordinate system in a way that it can be viewed and analysed with other geographic data) (Zhu1, et.al ,2008). Researches in georeferencing methods has been developed long time ago, in recent years, photogrammetrists have been discovering the georeferencing approaches that can improve consistency, completeness, and reliability of referenced spatial information (Zhu1, et.al ,2008).

In the study of Strickland River drains a mountainous region of Papua New Guinea's Western and Highlands Provinces three satellite images (1972, 1990 and 1993) were used and some georeferencing or rectification were performed. prior to their distribution some rectification had been performed on all three images, and there were clear misalignments between images when observed at a scale fine enough to resolve individual river bends. This was indicated on the 1990/1993 mosaic and the error was on the order of 500 m between the 1990 and 1993 portions of the image. All of the 1972 image and 1990 portion of the 1990/1993 mosaic were re-rectified to the 2000 image using a set of approximately 15 control points each and the second order polynomial transformation available in ArcGIS 8.3. Small tributary channel junctions or identifiable features on oxbow lakes that would not have moved over the time period between imagery were used on the Control points for rectification. The error in rectification was not meaningful since it does not include the errors associated with defining the position of the channel on each image (Alto, 2008).

CHAPTER 3: METHODS

3.1 Introduction

The chapter describes the upper Vaal River catchment with a focus on its physical environment (hydrology, topography, climate, vegetation and geology), to provide a context for the research problem. Therefore, this section provides a full description of the study area and displays the locations of all study sites. This chapter also describes the methods used for data collection and data analysis.

3.2 Overview of the Study Area

The study site for this research is located in Vaal River near Parys, Free State Province. On the western slope of the Drakensberg Mountains, the Vaal River rises and flows about 900 km west-south-west across the interior plateau to join the Orange River near Douglas (Braune and Rogers, 1987). The study area is located in quaternary C23C at approximately coordinates of latitude 29˚4’15˚S and longitude of 23˚38’10˚E at the elevation of 1269 m. The Vaal River has a catchment area of 192 000 km^2 (Braune and Rogers, 1987).

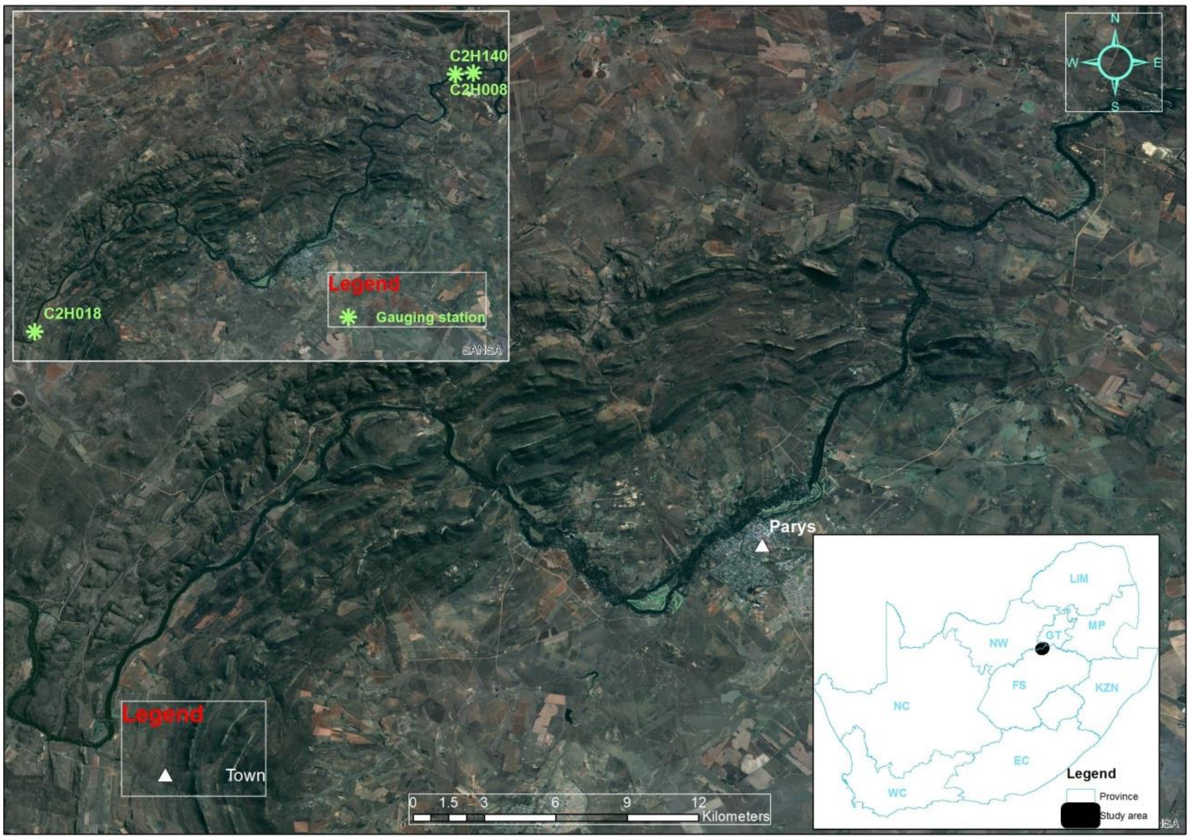

Figure 3. 1: Location of the study area

Vaal River is divided into three water management areas; the Upper Vaal, Middle Vaal and Lower Vaal. The study site for this research is located in the upper Vaal water management area. The Upper Vaal water management area covers part of four provinces. This includes the southern half of the water management area which extends over the Free State, the north-east mainly falls within Mpumulanga, and the northern and western parts in Gauteng and North West (DWAF, 2004).

The Upper Vaal Water Management Area covers a catchment area of 55 565 km2 (DWAF, 2004). This WMA includes the very significant dams which are Vaal Dam, Grootdraai Dam and Sterkfontein Dam (DWAF, 2004). Major rivers in the WMA are the Vaal and its tributary, the Wilge River, both perennial rivers that flow throughout the year. The Upper Vaal Water Management Area (Upper Vaal WMA) also includes the Vaal, Klip, Wilge, Liebenbergs vlei and Mooi Rivers (DWAF, 2004). The Vaal River near Parys in the Free State Province is characterised by a variable degree of mixed bedrock-alluvial anabranching channels which divide and rejoin around semi-permanent Islands.

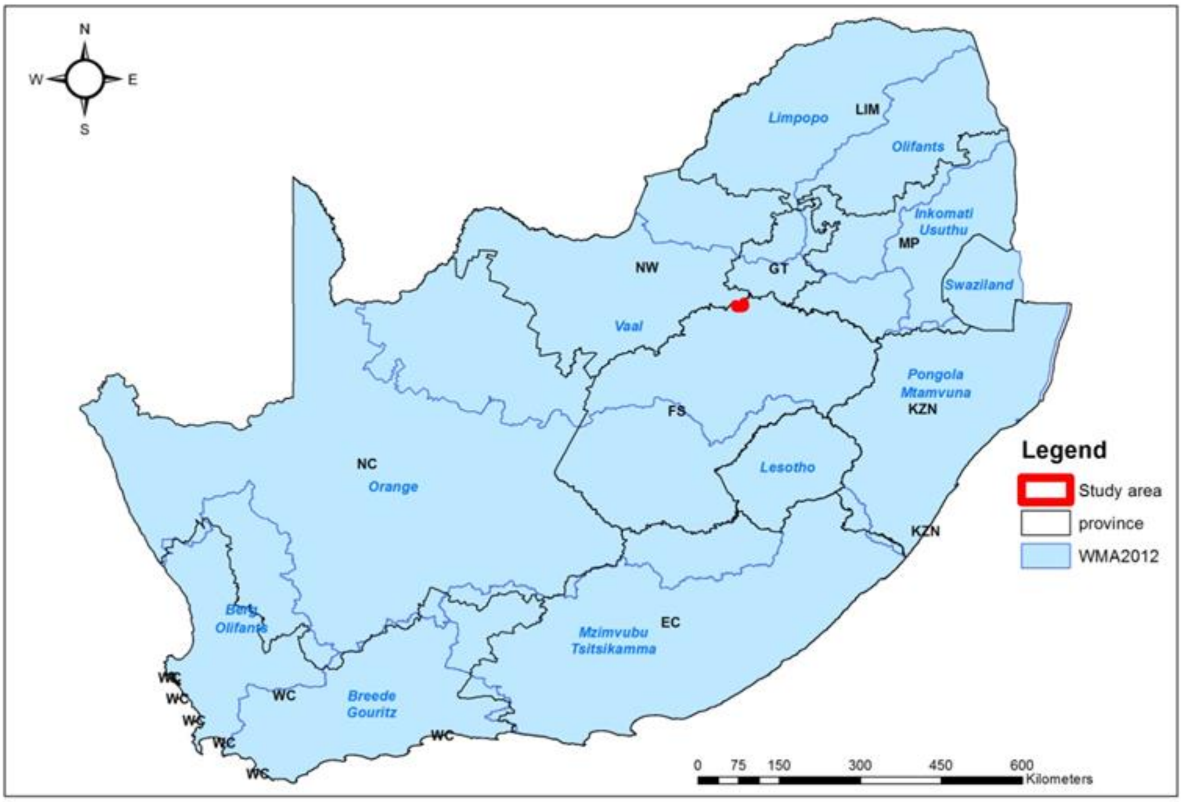

Figure 3. 2: Location of the study area

3.2.1. Topography

The water from the Upper Vaal WMA flows through the Middle Vaal, Lower Vaal and Lower Orange WMAs before it reaches the Atlantic Ocean near the town of Alexander Bay in the west of the country. The Vaal catchment slopes gently from the east to the west from 1 800 m to 1 450 m in the vicinity of Vaal Barrage. In the south-eastern side where the headwaters of Wilge tributary borders with the Orange River, there are some steep areas (DWAF, 2004).

3.2.2. Geology and Soils

The Karoo Supergroup covers approximately about 80 % of the Vaal catchment. As a result, fine-grained sedimentary rocks dominate in this catchment. The aquifers are secondary aquifers with water associated with fracturing. Groundwater is frequently associated with dolerite intrusions and the yields are very variable between 0.1 – 10 l/s subjected on the type and fracturing of the sediments. In the Beaufort group, the yields are normally higher when compared with the Ecca (Barnard, 2000). The north western part (west of longitude 28° E) of the Vaal Catchment includes igneous (e.g. granite rocks) and metamorphic rocks with extensive dolomitic exposure in the central areas of Mooi Sub-catchment (DWAF, 2004). The minerals which are predominant are gold, uranium, base metals, semi-precious stones and industrial minerals (DWAF, 2004). There are three main soil types that are distributed cross the undulating relief of this catchment which are clay loam, sandy loam and clay (DWAF, 2004). In the area considered in this study (Vaal river near Parys) the soils are sandy loamy to sandy clay loamy.

3.2.3. Climate

The average temperature for the catchment is about 15°C, with the Maximum temperatures experienced in summer month of January and minimum temperatures occur in winter month of July. The mean annual temperatures are high in the west (16°C) and lower in the east (12°C) of the catchment (DWAF, 2004). The rainfall in the catchment is strongly seasonal with high rainfall occurring from October to April in the summer season, and the rainfall peaks in the month of December and January and drops in the months of July. Rainfall usually occurs as convective thunderstorms and sometimes it is accompanied by hail (DWAF, 2004). The mean annual precipitation (MAP) for the catchment ranges from high in the east (1 000 mm) and lower in the west (500 mm) with an average of about 700 mm (DWAF, 2004). On the high lying areas of the catchment there is infrequent light snow experienced during winter months, and frost also occurs in the winter months (DWAF, 2004). The 1975 flood was the highest recorded flood in the Vaal river catchment and was estimated to have a recurrence interval of 34 years. From a statistical analysis of flood flows in the Vaal River, there was approximately 3% chance of probability of exceedance in any one year (Chang, 1989). The Average potential mean annual gross evaporation is higher in the western parts (2 200 mm) and lower in the eastern part (1 600 mm) of the catchment (DWAF, 2004). The highest evaporation is experienced in January and the lowest in June (DWAF, 2004).

3.2.4. Vegetation

The Vaal river catchment falls under the grassland biome of South Africa and is mainly characterised by grass species with intermittent areas where shrubs and trees occur (DWAF, 2004).

The Free State and Northern Cape Province; Broad alluvia of the Orange River, lower Caledon as well as lower stretches of the Vaal, Riet and Modder rivers as far as Groblershoop is covered by the Upper Gariep Alluvial Vegetation (Mucina and Rutherford, 2006). Mucina and Rutherford 2006, also noted that these river stretches are surrounded by vegetation units of broad transitional regions between the dry facies of the Savanna and Grassland and northern regions of the Nama-Karoo Biome. The Upper Gariep alluvial Vegetation altitude ranges from 1000 – 1500 m (Mucina and Rutherford, 2006).

Due to the higher rainfall, the north eastern part of the catchment and northern areas of the Wilge sub-catchment covers the area of temperate and transitional forest and shrubs. The Vaalbos Rocky Shrubland covers the Northern Cape and Free State Provinces and it extends along solitary hills and scattered ridges east of the confluence of the Orange and Vaal Rivers. This shrubland is situated on an altitude of 1000-1400 m (Mucina and Rutherford, 2006).

Mucina and Rutherford (2006), also noted that the North West, Free State and Northern Cape Provinces: Most of the Kimberley, Hartswater, Bloemhof and Hoopstad Districts as well as substantial parts of the Warrenton, Christiana, Taung, Boshof and to some extent the Barkley West District are covered by the Kimberley Thornveld vegetation. This thornveld vegetation is located on an altitude of 1050 m – 1400 m (Mucina and Rutherford, 2006). Trees and shrubs are inadequate due to the occurrence of frost and veld fires in the catchment (DWAF, 2004).

3.2.5. Demography

The Upper Vaal WMA is the most populated WMA in South Africa, and in the year 1995 the total population was estimated at 5.6 million. In the WMA more than 80% of the population reside in the area downstream of the Vaal Dam with approximately 97% living in an urban environment. The economic opportunities and potentials will influence the demography of the water management area. Population residing in the sub-area downstream of the Vaal Dam is estimated to grow since it is where most of the economic activities are centred. The population is projected to decline in the sub-area of Wilge due to the movement of people out of Phuthaditjaba and the former QwaQwa area (DWAF, 2004).

3.2.6. Land Use

Land use is dominated by agriculture, urbanisation and industry. The dominated crop cultivated in the Wilge sub-catchment and Vaal dam to Vaal Barrage sub areas are maize and wheat. In the Vaal dam sub catchment, stock farming and agricultural crop farming is more practised. Urbanisation and industry are highly concentrated around historic mining activities in the western and northern parts of the catchment. Sasol (Sasolburg) and Mittal steel are some of significant industries in the catchment which produce petrol chemical and iron and steel product. Other important manufacturing industries are Sappi and AECI located in the catchment. Most of the industries are located downstream of Vaal Dam sub-catchment. The dominated minerals which are mined in the catchment include; gold, coal, uranium base metals, semi-precious stones and industrial minerals (clay and sand). There is also coal mining west of Grootdraai dam in the upstream Vaal sub-catchment area (DWAF, 2004).

3.3 Data collection and analysis

3.3.1 Data collection

3.3.1.1 Acquisition of flow data

Three flow gauging stations within the study area were identified and selected; stations C2H008 (Lindequesdrift) and C2H140 (Goose Bay Canyon) located just upstream of the study reach, and station C2H018 (Schoemansdrift) located downstream of the study reach (Figure 3.3). These stations were selected based on the quality of data, record length and their location. Station C2H008 has a record length of 42 years from 1952-1996, while station C2H140 has a record length of 20 years 1996-2016, and station C2H018 has a record length of 78 years from 1938 to 2016. Daily flow data (in m^3/s) from the three flow gauging stations, for the period 1938-2016, 1952-1996, and 1996-2016 were sourced from HYDSTRA (Department of Water and Sanitation database).

3.3.1.2. Acquisition of aerial photography

Historical aerial photograph images for different years were sourced from National Geo-patial Information (NGI). The earliest aerial photograph images in the area of study were flown in the 1938 while the latest aerial photograph images were flown in 2015. Historical aerial photograph images for the year 1938, 1961, 1970, 1973, 1984, 1991, 2002, (in black and white) and rectified orthoimagery of 2006, 2012 and 2015 (in colour) were available and were used. It was noted that the aerial photograph images obtained from NGI has different Scale (see **Table 3.2 below**) and from the year 1938 to 2002 the images are scanned images. In order to see channel details at least a scale of 1:30 000 is required (Rountree, 2013).

Table 3- 1: Aerial photographs scale

Aerial Images	Scale	Year
129_071_55472	1:18 000	1938
129_071_55473	1:18 000	1938
129_071_55474	1:18 000	1938
129_071_55475	1:18 000	1938
129_072_55462	1:18 000	1938
129_069_55546	1:18 000	1938
438_026_04371	1:36 000	1961
438_026_04372	1:36 000	1961
438_026_04373	1:36 000	1961
438_027_03388	1:36 000	1961
438_027_03389	1:36 000	1961
670_011_00307	1:25 000	1970
670_011_00308	1:25 000	1970
670_011_00309	1:25 000	1970

Aerial Images	Scale	Year
670_011_00310	1:25 000	1970
670_011_00311	1:25 000	1970
670_011_00312	1:25 000	1970
670_011_00313	1:25 000	1970
698_006_03106	1:50 000	1973
698_006_03107	1:50 000	1973
881_002_00320	1:150 000	1984
952_013_02137	1:50 000	1991
952_013_02138	1:50 000	1991
952_013_02139	1:50 000	1991
1064_013_03368	1:50 000	2002
1064_013_03369	1:50 000	2002
2627CD_12_498_592_08_0191	1:50 000	2006
2627CD_13_498_592_08_0193	1:50 000	2006
2627CD_14_498_592_08_0195	1:50 000	2006
2627CD_15_498_592_08_0197	1:50 000	2006
2627CD_16_498_592_09_0212	1:50 000	2006
2627CD_17_498_592_09_0210	1:50 000	2006
2627CD_18_498_592_09_0208	1:50 000	2006
2627CD_19_498_592_09_0206	1:50 000	2006
2627CD_20_498_592_09_0204	1:50 000	2006
2627CD_12_2012_511	1:50 000	2012
2627CD_13_2012_511	1:50 000	2012
2627CD_14_2012_511	1:50 000	2012
2627CD_15_2012_511	1:50 000	2012
2627CD_17_2012_511	1:50 000	2012
2627CD_18_2012_511	1:50 000	2012
2627CD_19_2012_511	1:50 000	2012
2627CD_20_2012_511	1:50 000	2012
2627CD_12_2015_511	1:50 000	2015
2627CD_13_2015_511	1:50 000	2015
2627CD_14_2015_511	1:50 000	2015
2627CD_15_2015_511	1:50 000	2015
2627CD_17_2015_511	1:50 000	2015
2627CD_18_2015_511	1:50 000	2015
2627CD_19_2015_511	1:50 000	2015
2627CD_20_2015_511	1:50 000	2015

3.4 Data Analysis

3.4.1. Flow data

The three stations were evaluated to determine; the hydrological metrics and periods of missing data (Table 3.2). The metrics considered in this study include three key facets flood frequency, duration and magnitude. In most cases the periods of missing data for the stations differed. For example, in the year 1990 and 1991 there were missing data for the downstream station, but in the upstream station there were data. It was suggested that the data from the upstream gauging station could be used to patch or fill in the missing data for the downstream station by doing regression analysis. This method has been used in many researches for example in a process of filling missing data, in Great Ruaha River in Tanzania eleven gauging stations were involved. In the study of Great Ruaha River the selection of independent and depend variables for regression methods were based on the following factors; the correlation coefficient between gauging stations, Data availability for the donor stations (independent variables) and location of the gauging stations within the catchment (Mfwango et al., 2018). In order to predict the missing data of the either stations the gauge stations with strong correlation in consideration with other criteria were chosen. Adjustment was done by picking gauging stations with a complete dataset without gaps of five years, for two (Linear regression analysis) or three (Multiple regression analysis) stations with strong correlation between them. The equation developed was then used to fill/patch missing data of the dependent variable during the period of high flow (Mfwango et al., 2018).

Table 3- 2: Period (Date) of missing data

C2H018 (Schoemansdrift) Downstream	**C2H008 (Lindequesdrift) Upstream**	**C2H140 (Goose Bay Canyon) Upstream**
1943/02/28-1943/03/31		
1965/11/12-1966/01/17		
1973/12/24-1973/12/26		
1974/02/25-1974/02/27		
1975/12/16-1975/12/22		
1977/02/02-1977/02/07		
1981/11/17-1981/11/25		
1988/12/11-1988/12/14	1988/01/02-1988/01/12	
1989/01/03-1989/01/25		
1989/02/14-1989/04/11		
	1990/11/18-1991/01/10	
	1991/10/27-1991/11/11	
	1991/11/17-1992/10/12	
1994/10/18-1994/10/24		
1995/03/07-1995/03/14		
1995/06/06-1995/06/13		
	1995/11/16-1996/05/30	
	1996/07/22-1996/07/25	
		1996/11/21-1997/01/06
1997/06/11-1997/06/17		
1999/01/26-1999/02/02		
1999/03/10-1999/03/18		
2000/05/03-2000/05/03		
2000/05/27-2000/06/06		
2000/08/29-2000/09/05		
2000/10/14-2000/10/18		
2000/10/22-2000/10/24		
2000/11/03-2000/11/08		

C2H018 (Schoemansdrift) Downstream	**C2H008 (Lindequesdrift) Upstream**	**C2H140 (Goose Bay Canyon) Upstream**
2000/11/18-2000/11/21		
2000/11/26-2000/11/28		
2000/12/10-2000/12/20		
		2002/03/31-2004/07/31
2002/06/03-2002/08/07		
2002/08/13-2002/08/22		
2002/09/25-2002/10/02		
2002/11/03-2002/11/06		
2002/12/07-2002/12/10		
2003/01/12-2003/01/21		
2003/02/18-2003/04/01		
2003/04/10-2003/04/17		
2003/05/10-2003/05/20		
2003/06/14-2003/08/05		
2003/08/10-2003/08/12		
2003/11/11-2003/11/18		
2003/11/25-2003/12/02		
2004/01/13-2004/01/20		
2004/02/03-2004/02/10		
2008/04/14-2008/04/17		
		2009/05/19-2009/05/21
		2011/02/01-2011/02/02
		2011/05/03-2011/10/05
		2011/10/09-2011/11/11
		2012/11/11-2013/02/28
2013/01/27-2013/01/28		
2013/03/18-2013/04/11		
2014/04/30-2014/05/01		

Regression analysis was performed to determine: the relationship between the outflows downstream at C2H018 (Schoemansdrift) and the inflows upstream at C2H008 (Lindequesdrift) and C2H140 (Goose Bay Canyon), to extend the dataset and to patch missing data. The correlation analysis was performed for the period when there was overlapping data from the downstream and upstream stations. The equation obtained from the regression analysis was used to extend the data at C2H008 (Lindequesdrift) upstream and also to patch the missing data on the record. Since station C2H018 (Schoemansdrift) located downstream of the study area opened first in 1938, it was then used to extend the record length of the two other stations located upstream C2H008 (Lindequesdrift) and C2H140 (Goose Bay Canyon).

3.4.2. C2H008 (upstream)

The flood hydrological data for station C2H008 was analysed. The station has data from 1952 to 1996 and the station data were patched and extended from 1938 to 1951 using a linear regression equation. The monthly peak discharge data of gauging station C2H018 (Schoemansdrift) weir, which is located upstream of the C2H008 (Lindequesdrift) weir was used to extend the data record for the weir for the period 1938 to 1952. Regression analysis was performed to determine: the relationship between the inflows downstream C2H018 (Schoemansdrift) and the inflows upstream C2H008 (Lindequesdrift) see **Figure 4.1**. The regression analysis was performed for the period when there was overlapping data (1952 to 1996) from the downstream and upstream station. The equation obtained from the regression analysis was used to extend the data at C2H008 (Lindequesdrift) from 1938 to 1952 and also was used to patch the missing data on the record.

From the regression analysis between the station C2H018 and C2H008 and the following relationship was obtained:

$$Q_{\mathrm{C2H008}} = 0.944Q_{\mathrm{C2H018}} - 3.051$$

R^2=0.912

The equation was used to generate flows peaks at C2H008 for the period 1938 to 1952. For the period 1952to 1996 peaks estimated at C2H008 were used.

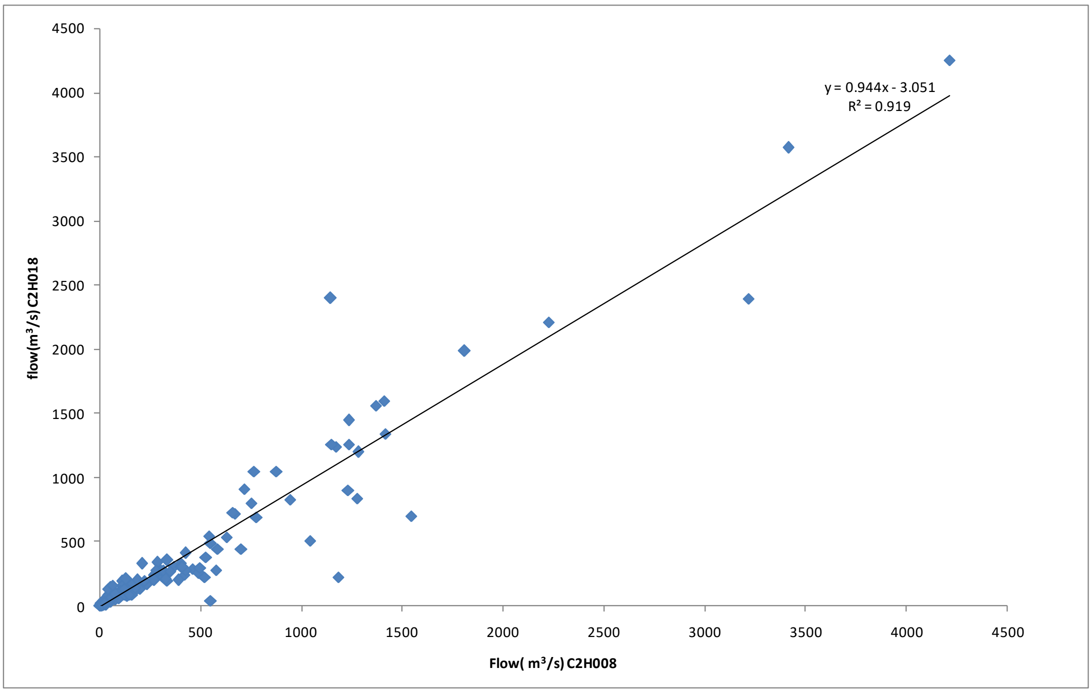

Figure 3. 3: Correlation between C2H018 and C2H008

3.4.3. C2H140 (upstream)

The flood hydrological data for station C2H140 (Goose Bay Canyon) was analysed. The station has data from 1996 to 2016 and the station has some period of missing data for instance 2002 April to 2004 June and also in 2011 June to 2011 September. The missing data was then patched using linear regression equation. The monthly maximum peak discharge data for gauging station C2H018 (Schoemansdrift) weir, which is located upstream of C2H140 (Goose Bay Canyon) weir was used to patch the missing data record for station C2H008 weir. Regression analysis was performed to determine: the relationship or correlation between the inflows downstream C2H018 (Schoemansdrift) and the inflows upstream C2H140 (Goose Bay Canyon) see **Figure 3.4**. The regression analysis was performed for the period when there was overlapping data (1996 to 2016) from the downstream and upstream station. The equation obtained from the regression analysis was used to patch the missing data

From the regression analysis between the station C2H018 and C2H140 the following relationship was obtained:

$$Q_{\mathrm{C2H140}} = 0.783Q_{\mathrm{C2H018}} + 9.216$$

$R^2 = 0.964$

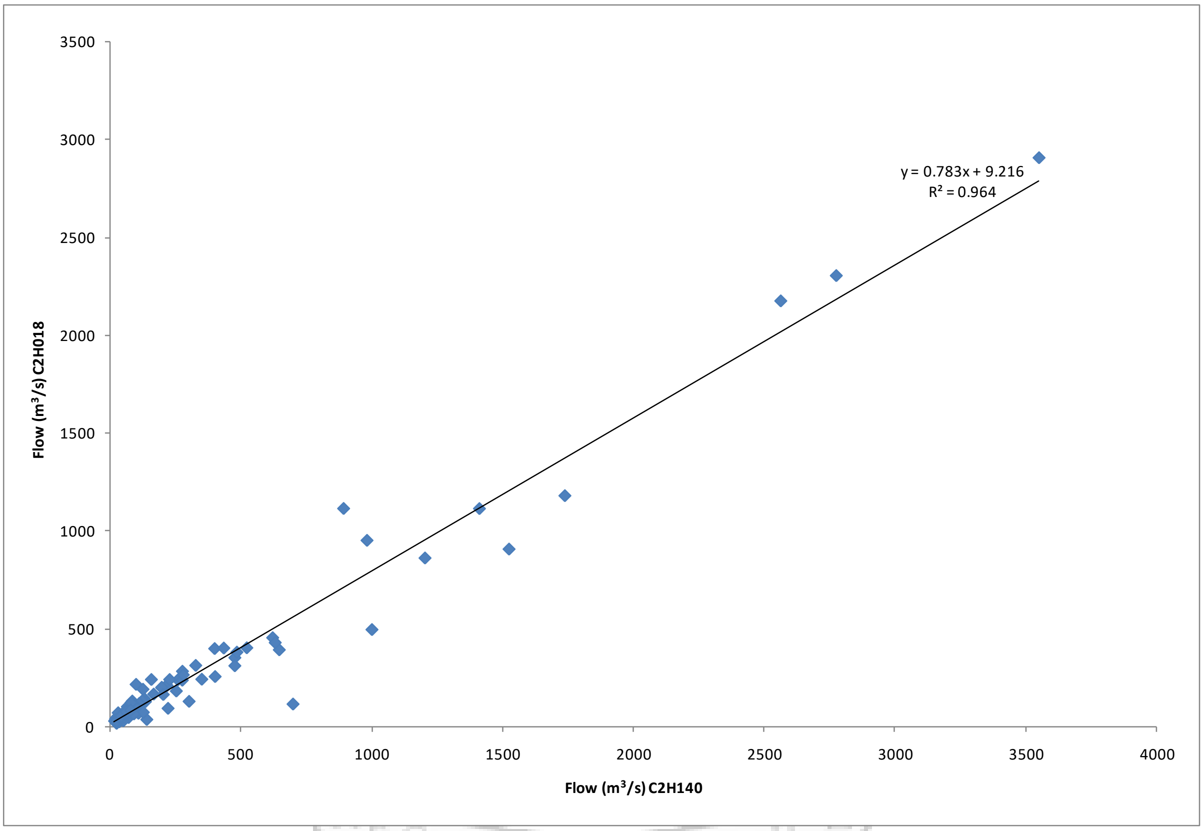

Figure 3. 4: Correlation between C2HO18 and C2H140

3.4.5. Aerial photograph images data

The historical aerial photograph images were used to investigate island geomorphological changes over the period of 78 years from 1938 to 2016. In order to map the channel and island features, historical aerial photograph images needed to be georeferenced (method of aligning geographic data to a known coordinate system in a way that it can be viewed and analysed with other geographic data) in order to show changes through time when compared from year to year and with current orthophotos. Aerial photograph images for the year 1938, 1961, 1970, 1973, 1991and 2002 were georeferenced by the 2015 rectified images using a set of approximately 6 to 7 control points each in GIS 10.2.2 software. Georeferencing of images were done by selecting the points of features that have not moved or changed shape from one year to the other. For instance, old buildings and roads that are in the aerial photographs and on the rectified othorimagery (2015). The 1984 aerial photograph image was omitted due to poor resolution. The current 2006, 2012 and 2015 are rectified othorimagery, there is no need for georeferencing.

A method of checking the accuracy of georeferenced images before starting to map channels and islands was developed. First approach, the georeferenced images set of each year, were overlaid on top of each other on the GIS software to evaluate the accuracy. This approach is useful in case were some years are way off (aerial photograph image of different years overlapping), and then the georeferencing can be tweaked to improve overlay accuracy. Second approach was to set the control points for rectification like in the road crossings, buildings and channel junction that are present in all georeferenced images and rectified orthoimage for each image year, and then measure the distance in between the control points in the rectified orthoimage. The error estimation for the georeferenced images were presented in table below. The channels and bars or islands were mapped when the error was reasonably small less than 65 m, since some of the scanned aerial photographs have small resolution hence is not simple to georeference them. Since the error in rectification does not include the errors associated with defining the position of the channel on each image, the error was not considered significant in this study.

Table 3- 3: estimation of georeferenced error

Aerial Images	Distance between reference point(rectified orthoimegery 2015) and georeferenced photo
129_071_55472	04 m
129_071_55473	09m
129_071_55474	13 m
129_071_55475	0 m
129_072_55460	0 m
129_072_55462	14 m
129_069_55546	0 m
438_026_04372	28 m
438_027_03389	33 m
670_011_00307	35 m
670_011_00308	29 m
670_011_00309	24 m
670_011_00310	38 m
670_011_00311	14 m
670_011_00312	29 m
698_006_03106	19 m
698_006_03107	23 m
952_013_02137	61 m
952_013_02138	65 m
952_013_02139	42 m
1064_013_03368	51 m

Since dryland rivers are characterised by infrequent extreme flows (literature review). This study will determine the influence of flood magnitude, duration and frequency on island geomorphological changes. Data on extreme flows from the three gauging stations were examined and quantified to determine the impact on the channel water width. The island and channels were mapped for the year (1938, 1961, 1970, 1973, 1991, 2002, 2006, 2012 and 2015 and overlaid from each year to show changes in channel lines and changes in island shape and position. These were evaluated by showing a map for part of the channel that does not change over a time for all the images on the record. The aerial photos for the year 1938 to 2001 are scanned black and white images and is not easy to see where there is a contact of water and vegetation. Very few islands were mapped. The aerial photos for the year 2006 to 2015 are visible rectified images, a lot of islands were mapped. For the year 1938 to 2001 only six islands were mapped and from the year 2006 to 2015 twenty-three islands were mapped.

The graphical representation of data method from statistical were utilised in this study. The changes of flow metrics (flood frequency, duration and magnitude) from year to year when the aerial images are available were presented, with the flow plotted on the Y ordinate and the year on the X ordinates and also the changes of island bar area from year to year when aerial images are available were presented as bar graphs.

Channel banks were digitized using GIS 10.2.2 software at the boundary of the channel every year and the island and bars were also digitized on the water line where the water and the vegetation come into contact. On bends with multiple channels, it was not easy to digitize the bars and the island. The area of the islands or bars was quantified from 1938 to 2016 using GIS, in order to identify the changes over the period. Because of the limited data in aerial images in the study, it was not possible to investigate the effects of individual floods from year to year. The mean monthly discharge for each image date was examined to consider how variation in stage height would influence digitised island dimensions.

Table 3- 4: Image date verses daily average flow

Image date	Flood peak	Image date	Flood peak	Image date	Flood peak
1938-12-31	55.43	1980-05-17	2.22	2006-08-12	34.82
1961-24-08	28.46	1984-06-04	2.01	2010-08-23	23.87
1970-05-10	17.98	1991-06-24	20.60	2012-04-10	14.78
1973-06-09	5.91	2002-06-16	missing data	2015-08-03	19.37

CHAPTER 4: RESULTS

4.1 Introduction

This chapter presents and describes the results obtained from flood hydrology analysis, the channel and island geomorphology changes observed through time when compared from image set to image set. The chapter present the results obtained on metrics of flood magnitude, duration and frequency that could play a role in fluvial island geomorphological change and the metrics of island geomorphological change that can be detected and measured using image analysis. The chapter will also present the relationships between metrics of flood magnitude, duration, frequency and metrics of island geomorphological change over the past ~78 years.

4.2 Presentation of Results

4.2.1 Largest flow data on the record

The largest floods on record occurred in the years 1944, 1957, 1975, 1977, 1978, 1996, 1997, 2000, 2010 and 2011, with 1975 being the largest, and exceeding the rating table.

Table 4-1: Flood peak record for the period of available data.

Flow date	**Flood peak (m^3/s)**	**Flow date**	**Flood peak (m^3/s)**	**Flow date**	**Flood peak (m^3/s)**
C2H008		**C2H140**		**C2H018**	
				1944-02-09	3717.8
1957-09-29	3568.2			1957-09-29	3411.5
1957-10-01	2395.8			1957-10-01	3214.4
1967-02-19	2208.9			1967-02-19	2226.1
1975-02-21	4251			1975-02-22	4211.6
1977-02-03	2399.1			1978-01-29	2553.6
				1996-02-18	3376.7
		1997-03-10	1110.3	1997-05-27	2335.8
				2000-02-13	2434.1
		2010-01-29	2301.5	2010-01-30	2775.3
		2011-01-08	2904.5	2011-01-08	3550.7

4.2.2: Hydrological data from gauging weirs

4.2.2.1: C32H008 (upstream of the study reach)

After the station C2H008 data had been extended, the flood hydrological data was then analysed for the period 1938 to 1996 **(Figure 4.1)**. The 1975-year flow peak (4251m^3/s) was the highest in the record followed by 1957 (3568 m^3/s), 1944 (3506 m^3/s), 1996 (3190 m^3/s), 1977 (2399 m^3/s), and 1967 (2208 m^3/s) flow peaks. The 1981 (April) to 1984 (October) flow peaks are the lowest (ranging from 69 to 2.3 m^3/s).

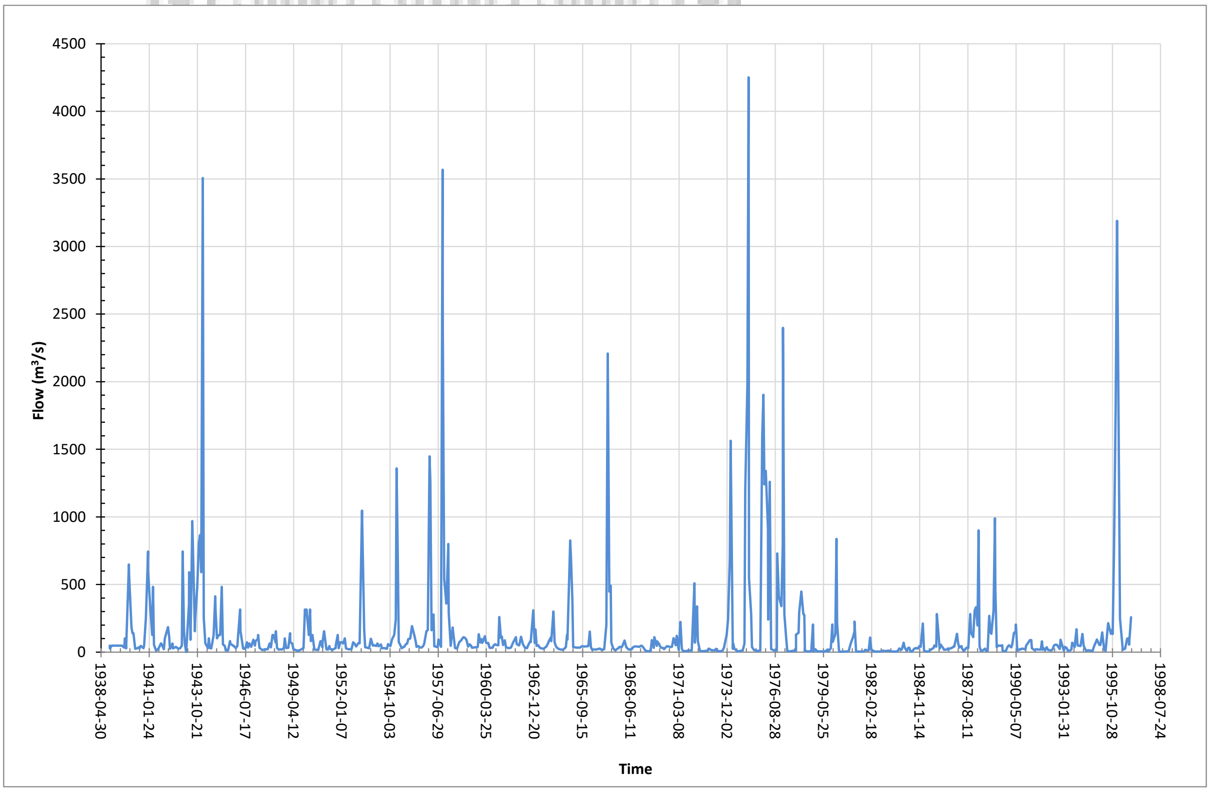

Figure 4. 1: Monthly flow data for gauging weir C2H008 (upstream of the study reach)

4.2.2.2: C2H140 (upstream of the study reach)

After the station C2H140 data had been patched, the flood hydrological data were then analysed for the period 1996 to 2016 **(Figure 4.2)**. The 2010 year flow peak (2904 m^3/s) was the highest in the record followed by 2009 (2301 m^3/s), 2014 (1109 m^3/s), and 2006 (902 m^3/s) flow peaks. Most of the flow peaks during this analysis period are lower than 200 m^3/s.

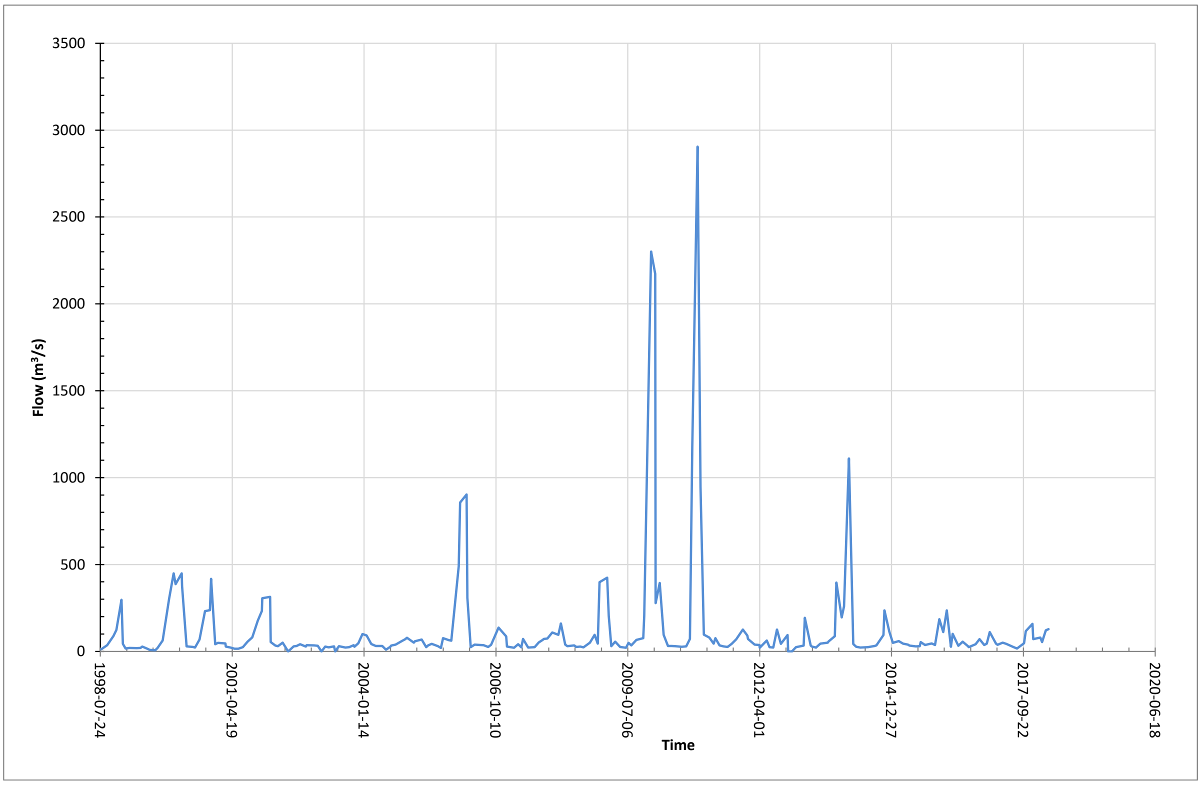

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Figure 4. 2: Monthly flow data for gauging weir C2H140 (upstream of the study reach)

4.2.2.3: C2H018 (downstream of the study reach)

The flood hydrological data for station C2H018 were analysed for the period 1938 to 2017 **(Figure 4.3)**. From the period 1938 to 2017 the 1975 year flow peak (4211.6 m^3/s) was the highest on record followed by 1944 (3717 m^3/s), 2011(3550 m^3/s), 1957(3411 m^3/s), 1996 (3376 m^3/s), 2010 (2775 m^3/s), and 1978 (2553 m^3/s) flow peaks.**)**. Flow peaks for the period 1981 April to 1984 December are the lowest (ranging from 82 to 2.938 m^3/s).

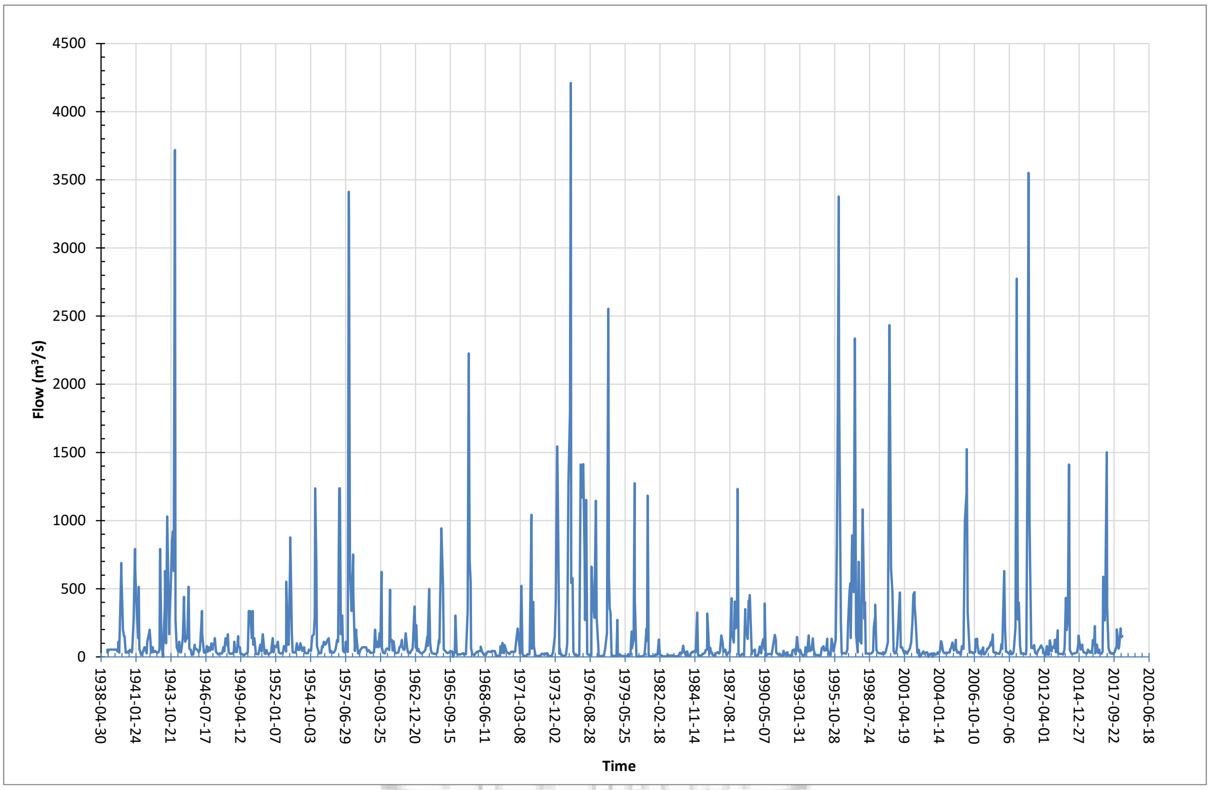


Figure 4. 3: Monthly flow data gauging weir C2H018 (downstream of the study reach)

4.2.3: Recurrence interval

Statistical analysis was performed for the period 1938-2016 to estimate the recurrence interval of flood peaks. Statistical analysis used the observed maximum annual flow peaks data for estimation. When performing the statistical analysis to determine the probability of occurrence the Cunane plotting position was used. The LN, LP3, GEVMM and GEVPWM distributions were used in the analysis. A combination of the LP3 and GEV distributions fitted the data points best.

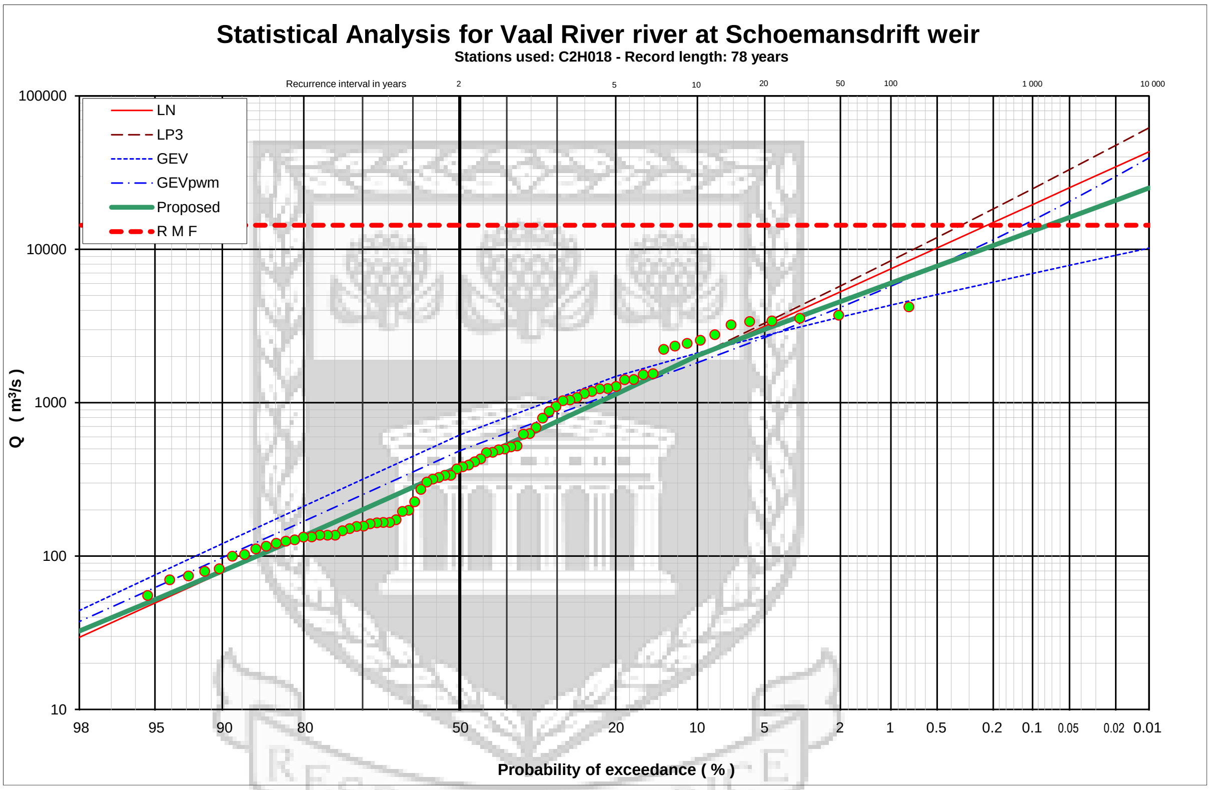


Figure 4. 4: Distributions used to calculate the estimated flood peak

Table 4-2: Recurrence interval and estimated flow peaks (1938-2016)

AEP	RI	LN		LPIII		GEV_{MM}			Proposed
		WT	Q (m^3/s)	WT	Q (m^3/s)	WT	Par.	Q (m^3/s)	Q (m^3/s)
0.50	2	0.00	395	-0.02	385	0.37		616	**385**
0.20	5	0.84	1144	0.83	1134	1.60	**k**	1485	**1134**
0.10	10	1.28	1995	1.29	2028	2.48	-0.083	2107	**2028**
0.05	20	1.64	3156	1.68	3304	3.37		2741	**3010**
0.02	50	2.05	5290	2.12	5776	4.61		3621	**4573**
0.01	100	2.33	7465	2.42	8425	5.61	**E(y)**	4327	**6038**
0.005	200	2.58	10230	2.70	11947	6.66	1.056	5072	**7784**
0.002	500	2.88	14987	3.04	18330	8.14		6124	**10595**
0.001	1000	3.09	19590	3.28	24828	9.34		6973	**13158**
0.0005	2000	3.29	25230	3.51	33146	10.61	**var(y)**	7874	**16155**
0.0002	5000	3.54	34579	3.79	47662	12.40	0.015	9146	**20879**
0.0001	10000	3.72	43347	4.00	61973	13.86		10175	**25111**

4.2.4: Island area data from aerial images

Changes in island areas were mapped according to the availability of aerial photography (refer to Chapter 3). Time-series image analysis was used to compare island area changes. The aerial images were compared from year to year to see the changes. The outer boundary of the mainstream channel-set and the primary visible islands where digitized, and the areas of each island were quantified in GIS. Since the aerial photos for the years 1938 to 2001 are scanned black and white images and was not easy to see where there is a contact of water and vegetation, only the larger clearly and visible islands (6 in total) were mapped for this period. For the higher-resolution and/or colour aerial photos from 2006 to 2015, further islands were mapped (23 in total). The aerial photos were divided into two set from year 1938-2001 and 2006-2015.

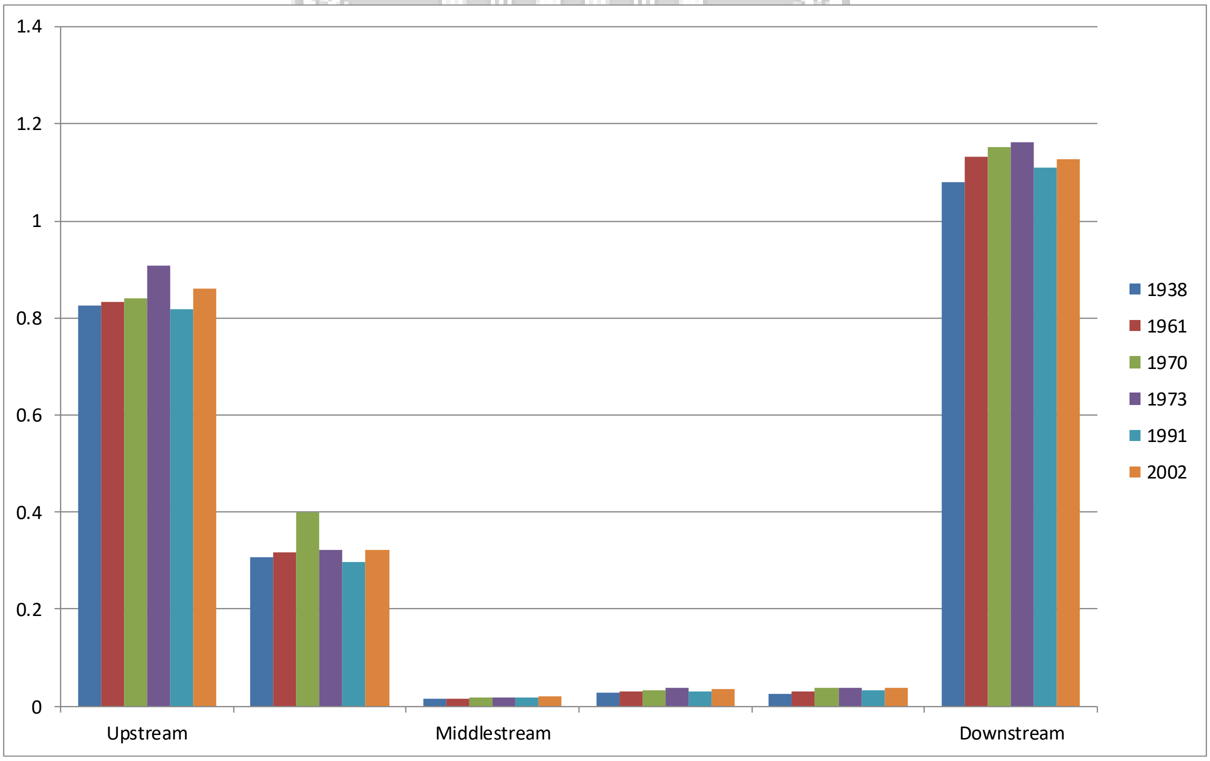


Figure 4. 5: Islands and bar area for the image set of 1938 to 2002

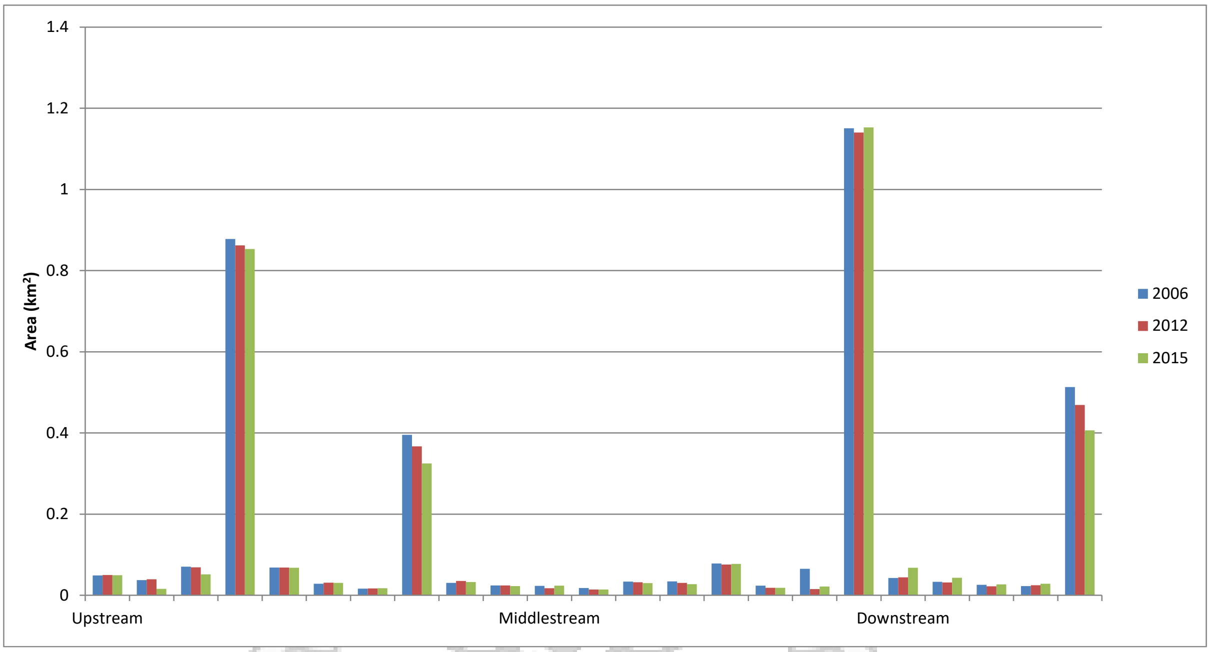


Figure 4. 6: Islands and bar area for the image set of 2006 to 2015

4.3: Metrics of flood magnitude, duration and frequency and metrics of island geomorphological change from 1938-2001

4.3.1. Metrics of flood magnitude, duration and frequency for the period 1938-1961

The flow data for the year 1938-1961 were extracted in order to determine the metrics of flood magnitude, duration and frequency that could play a role in islands and bars changes over the period 1938 to 1961. For the period 1938 to 1961, the 1944 flow peak (3718.8 m^3/s) is the highest on record, followed by the 1957 flow peaks (3411 and 3214.4 m^3/s), while the 1949 flow peak (11.8 m^3/s) is the lowest on record. The high flow peaks occurred during summer. The 1944 and the 1957 flow peaks prolonged for approximately eleven days (1944-02-04 to 1944-02-14) and twelve days (1957-09-27 to 1957-10-08) with a flow ranging from 1000-3718.1 m^3/s with a corresponding stage of 2.2 and 5.3 m.

From the period 1938-1961 the flow record comprised three major flow peaks which occurred in 1944-02-10, 1957-09-29 and 1957-09-30. The flow peaks that exceed 3214.4 m^3/s occurred three times in a record (1944-02-09 and 1957-09-29), with a return period of 20-50 years. Approximately 90% of the flow on the record length ranges between 0-500 m^3/s with a return period of 2-5 years, which also indicate long period of low flows see **Table 4.2**.

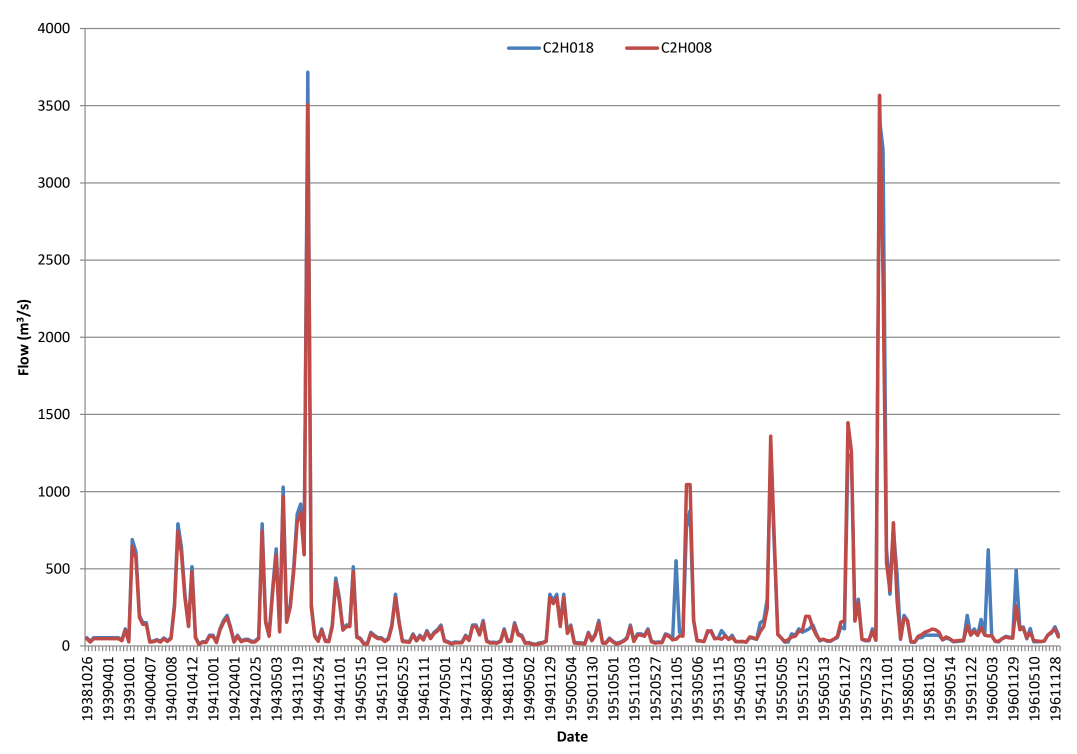


Figure 4. 7: Monthly flow data for the period 1938-1961 (gauging weir C2H018 and C2H008)

4.3.2. Metrics of island geomorphological change for the year 1938 and 1961

Time-series image analysis was used to compare island area changes between 1938 and 1961. The outer boundary of the mainstream channel-set and the primary visible islands where digitized, and the areas of each island were quantified in GIS.

From the image analysis results the islands in the upstream part of the study area for the year 1961 were partially larger than the 1938, and the difference in areas ranges between 0.011 and 0.007 km^2.

The changes in the middlestream part of the study reach were quite small (ranges between 0.009 and 0.0002 km^2). The change were be due to error in georeferencing or digitising since the islands were quite small and the 1938 and 1961 images were scanned black and white photos.

In the downstream part of the study area, island area increased by 0.052 km^2 from 1938 to 1961 refer to **Figure 4.8**.

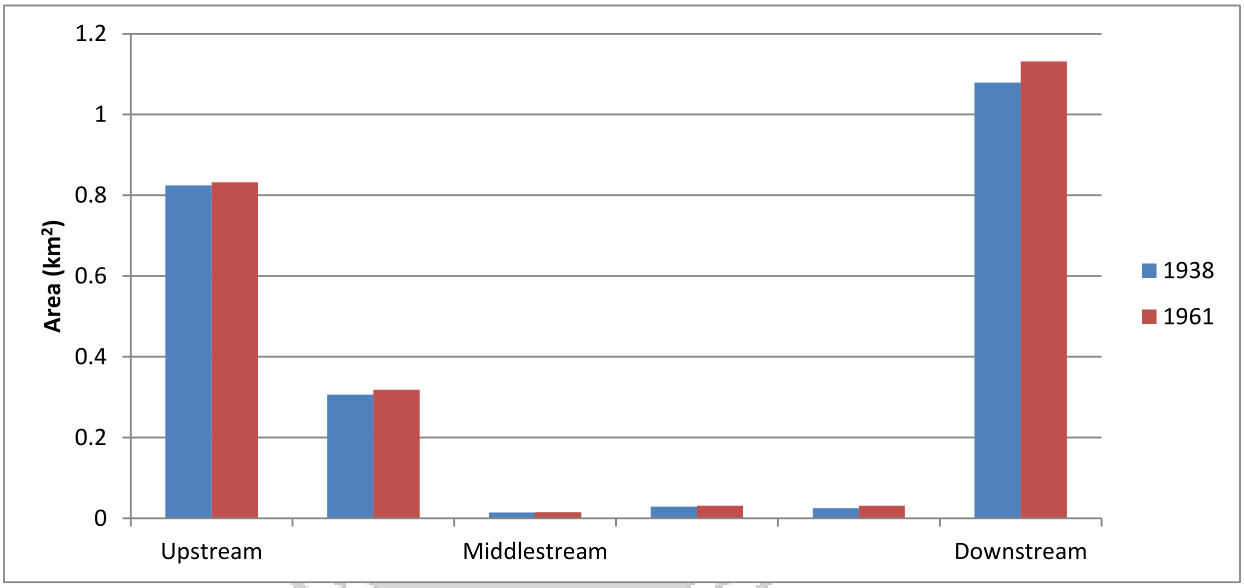
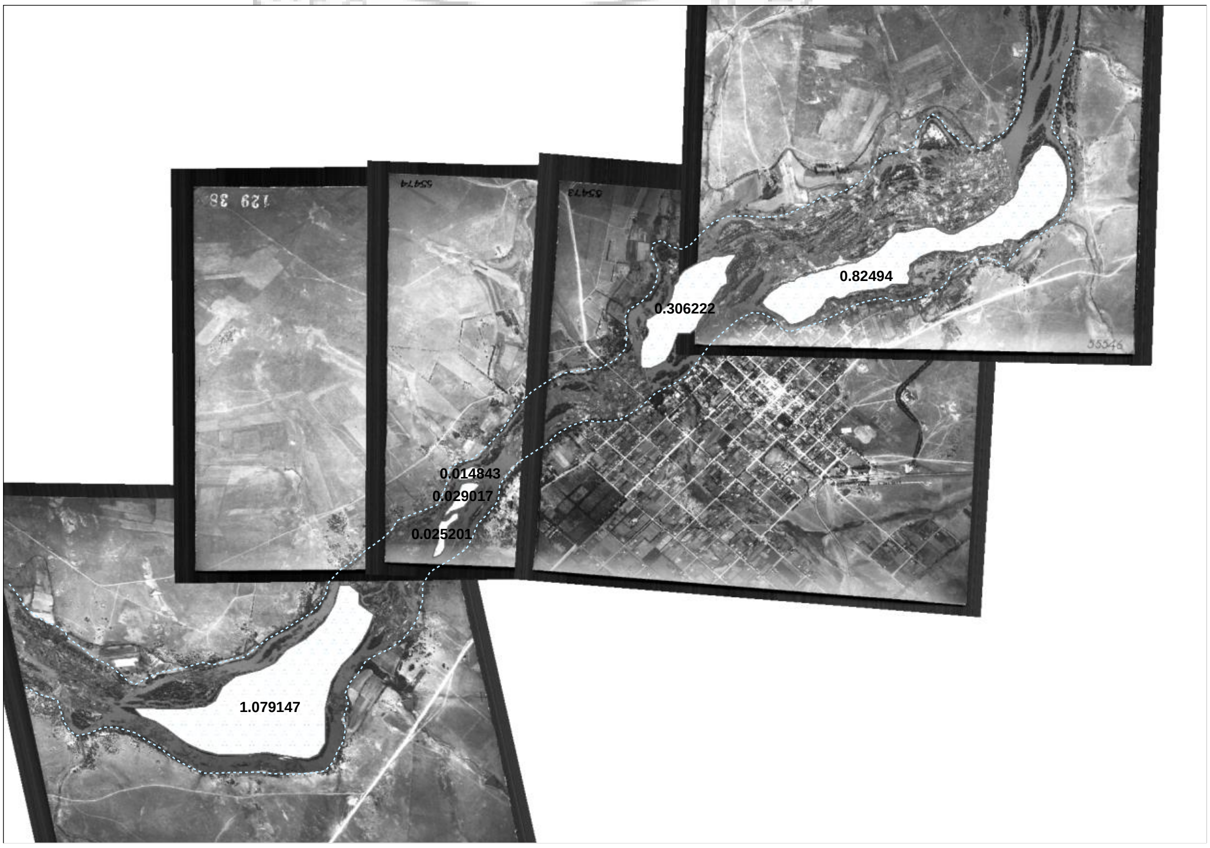


Figure 4. 8: Comparison of islands and bar area for the image set of 1938 and 1961



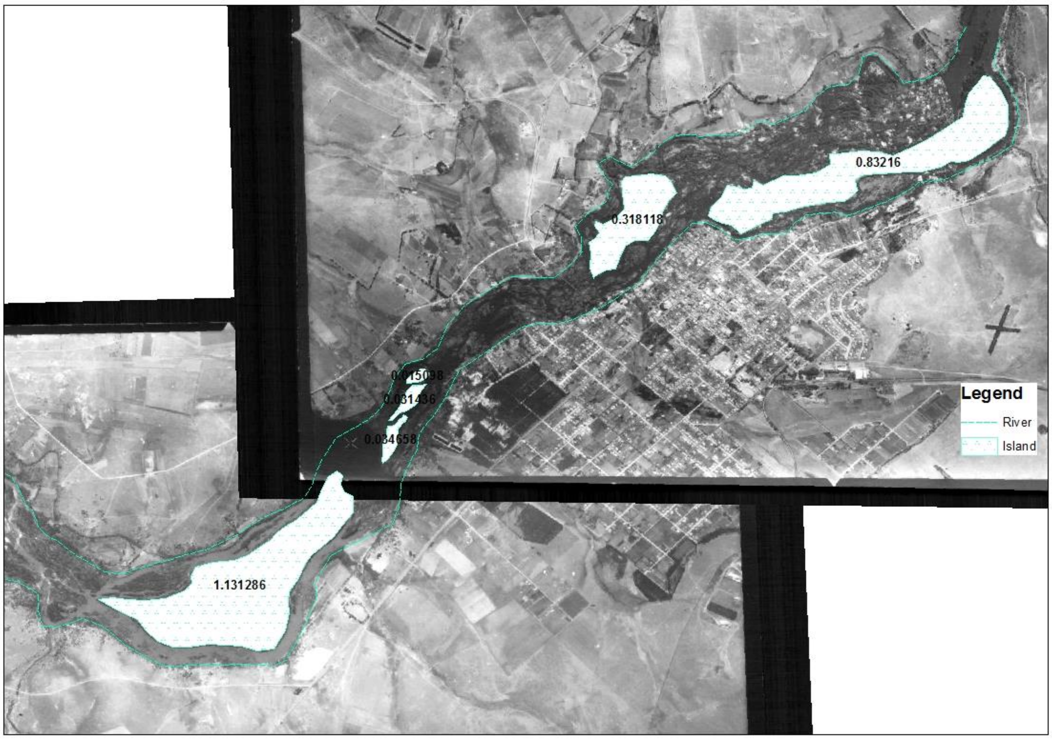


Figure 4. 9: digitized aerial photographs for the year 1938 and 1961, the numbers inside the island represent the area of the island in km^2

4.3.3. Metrics of flood magnitude, duration and frequency for the period 1961-1970

For the period 1961-1970 the flow data were extracted to determine the metrics of flood magnitude, duration and frequency that could play a role in islands and bars changes over the period 1961 to 1970. For the period 1961-1970 and 1938-1961 the 1944-year flow peak 3717.7 m^3/s (1938-1961) was the highest on record exceeding 2226.1 m^3/s of 1967 (1961-1970). The high flow peaks occurred during summer.

The daily flow record indicate that the 1967 flow peak prolonged for approximately five days (1967-02-18 to 1967-02-21) with a flow ranging from 1000-2181.1m^3/s with a corresponding stage of 2.9 and 3.7 m. When examining the flow data for the period 1938-1961 and 1961-1970 the 1944 flow peak 3717.3 m^3/s prolonged for twelve days and exceeded the maximum flow peak (2226 m^3/s) of 1967 which prolonged for five days.

During the period 1961-1970 the flow record comprised one major flow peaks which occurred in 1967-02-19. When observing and comparing the annual flow peaks for the period 1938-1961 and 1961-1970, the highest flow peak of 1967-02-19 (2226 m^3/s) for the period 1961-1970 was exceeded three times in a record by the flow peaks of 1944-02-09, 1957-09-29 and 1957-10-

01 (3718.8 m^3/s, 3411 and 3214.4 m^3/s) for the period 1938-1961. The 1967 (2226 m^3/s) flow peaks have a return period of 10-20 years refer to **Table 4.2**. Approximately 95% of the flow on the record length ranges between 0-500 m^3/s with a return period of 2-5 years, which also indicate long period of low flows see **Table 4.2**.

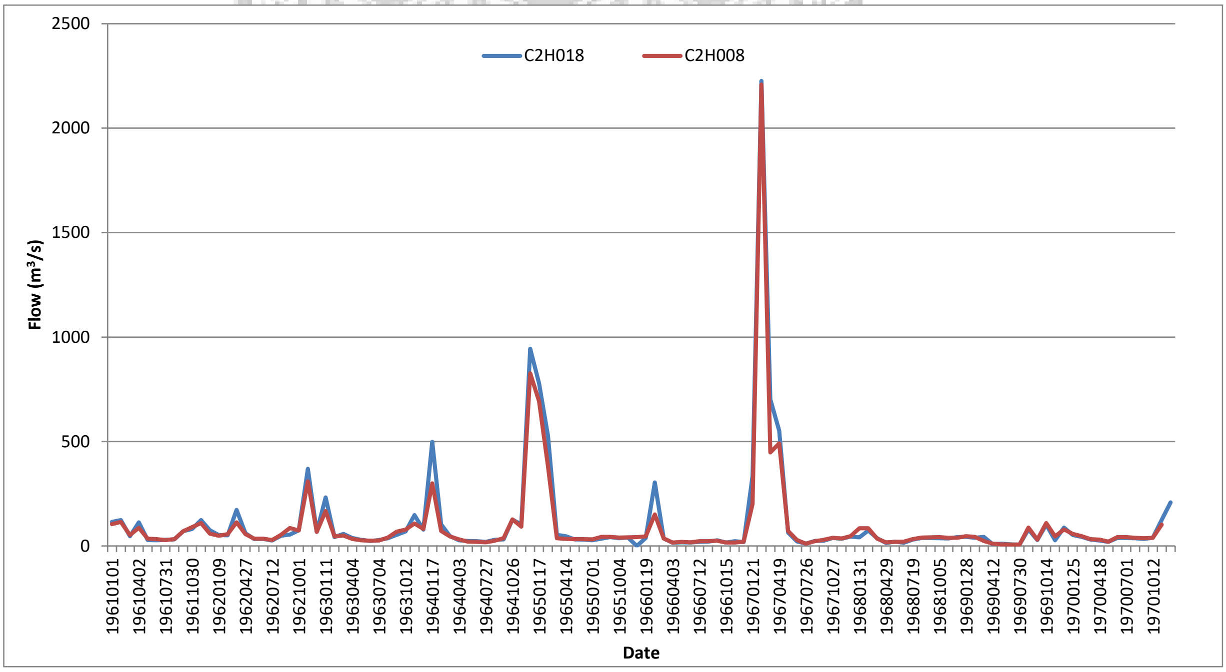


Figure 4. 10: Monthly flow data for the year 1961-1970 (gauge weirs C2H018 and C2H008)

4.3.4. Metrics of island geomorphological change for the year 1961 and 1970

Time-series image analysis was used to compare islands area changes between 1961 and 1970. The outer boundary of the mainstream channel-set and the primary visible islands where digitized, and the areas of each island were quantified in GIS.

The islands areas upstream of the study area slightly increased by 0.008 and 0.081km^2 from year 1961-1970.

The changes in the middlestream part of the study reach were quite small (ranges between 0.009 and 0.0002 km^2). The change can be due to error in georeferencing or digitising since the islands are quite small and the 1938 and 1961 images were scanned black and white photos.

In the downstream part of the study area, island area increased by 0.021 km^2 from 1961 to 1970 refer to figure 4.5.

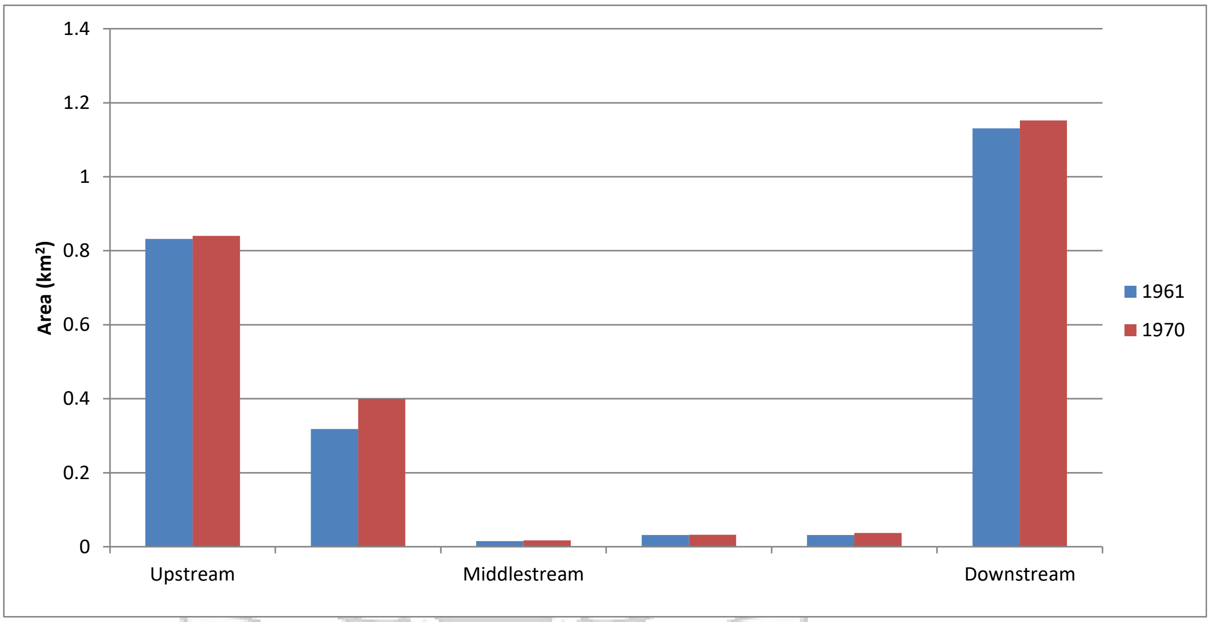


Figure 4. 11: Comparison of islands and bar area for the image set of 1961 and 1970

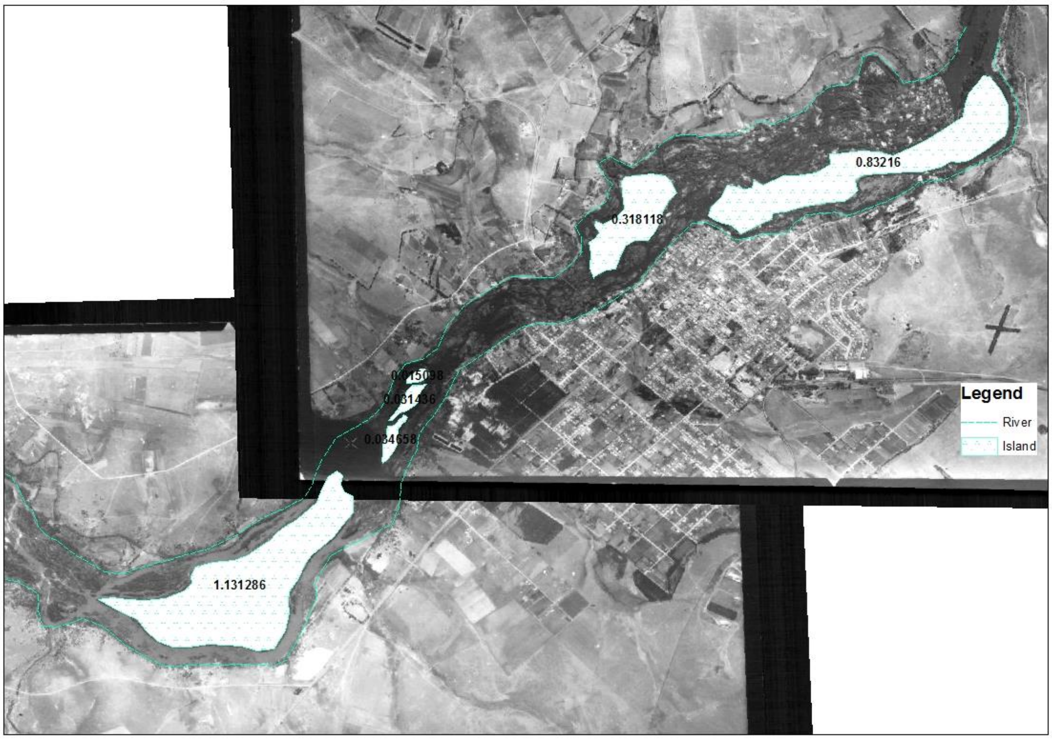


Figure 4. 12: digitized aerial photographs for the year 1961 and 1970, the numbers inside the island represent the area of the island in km^2

4.3.5. Metrics of flood magnitude, duration and frequency for the period 1970-1973

The flow data for the year 1970-1973 were extracted to determine the metrics of flood magnitude, duration and frequency that could play a role in islands and bars changes over the period 1970 to 1973. For the period 1970-1973 and 1961-1970 the 1967 year flow peak 2226.1 m^3/s were the highest on record (1961-1970) exceeding 1042.6 m^3/s of 1972 (1970-1973). The high flow peaks occurred during summer.

From the daily flow record data the flow peak of 1972 happened for one day with a corresponding stage of 2.3 m. When examining the flow data for the period 1961-1970 and 1970-1973 the 1967 flow peak 2226.1m^3/s prolonged for five days and exceeded the maximum flow peak (1042 m^3/s) of 1972 which only occurred for one day.

During the period 1970-1973 the flow record has one major flow peak that happened in 1972-01-23. The flow peaks for the period 1970-1973 and 1961-1970 were compared to determine the frequency of particular flow. When comparing the annual flow peaks for the period 1938-1961 and 1961-1970, the highest flow peak of 1967-02-19 (2226 m^3/s) for the period 1961-

1970 exceeded the flow peaks of 1972-01-23 (1042 m^3/s), period 1970-1973. The 1972 (1042 m^3/s) flow peaks have a return period of 2-5 years refer to Table 4.2. Approximately 95% of the flow on the record length ranges between 0-500 m^3/s with a return period of 2-5 years refer to **Table 4.2** and **Figure 4.13**.

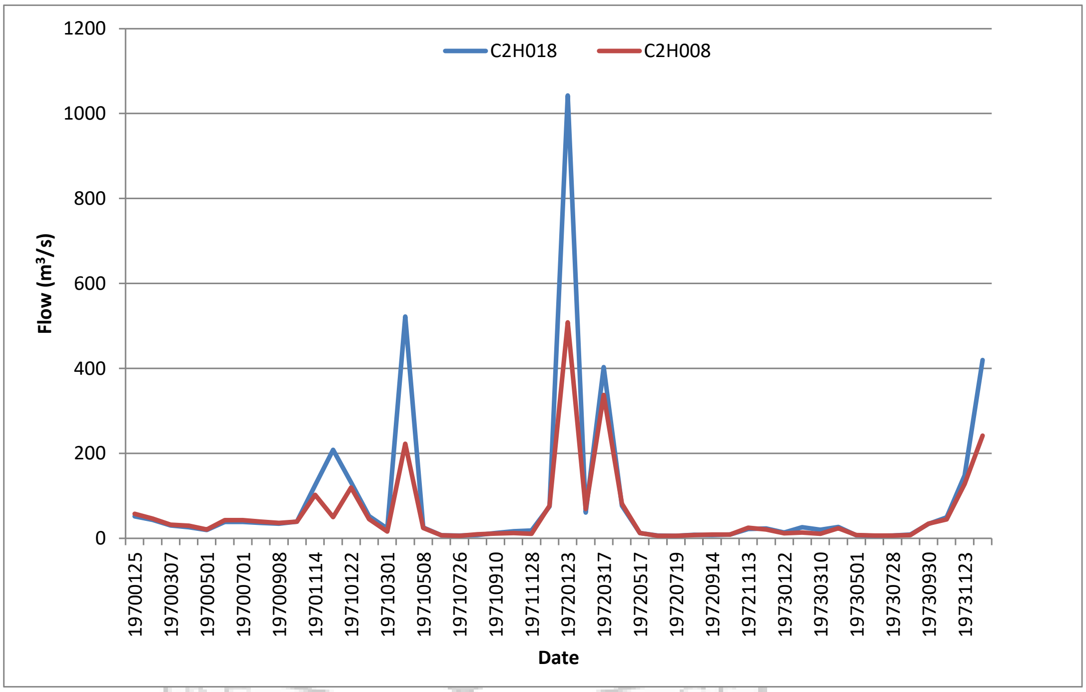


Figure 4. 13: Monthly flow data for the year 1970-1973 (gauge weir C2H018 and C2H008)

4.3.6. Metrics of island geomorphological change for the year 1970 and 1973

Time-series image analysis was used to compare islands area changes between 1970 and 1973. The outer boundary of the mainstream channel-set and the primary visible islands where digitized, and the areas of each island were quantified in GIS.

From the digitised aerial photographs images results one of the island area in the upstream part of the study area increased by 0.068 km^2 from 1970-1973, while the other island area decreased by 0.078 km^2.

The changes in 1973 and 1970 island bars area on the middlestream of the study reach were quite small and increased by 0.001 and 0.006 km^2 from 1970-1973.

The large downstream island bars area increased by 0.008 km^2 from 1970-1973.

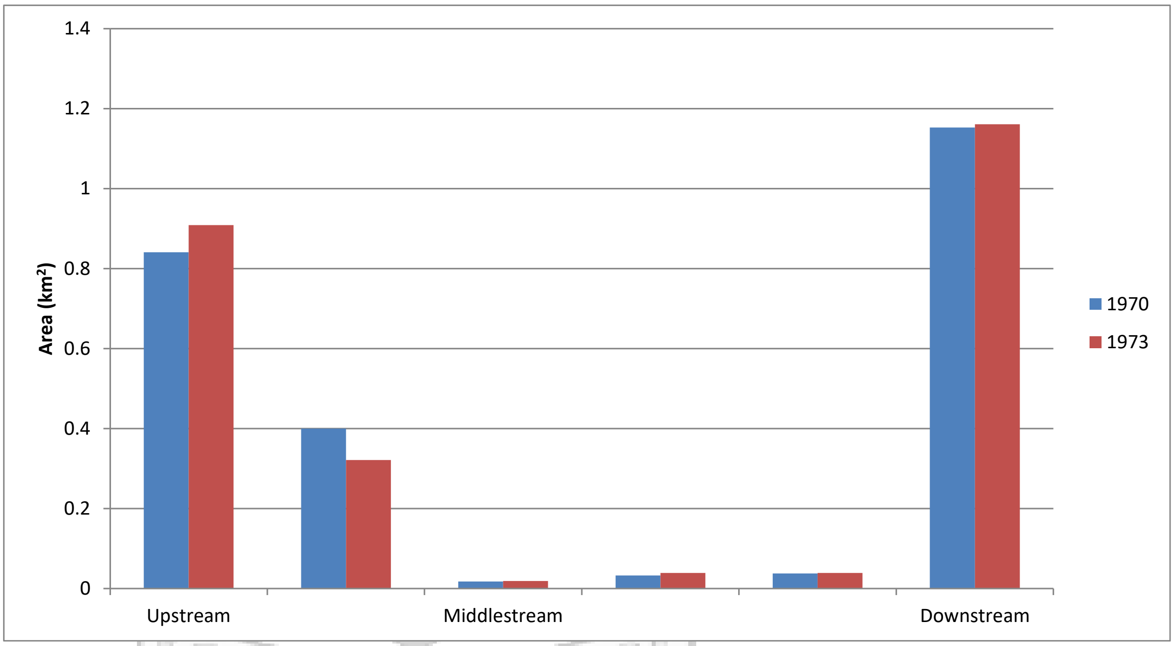


Figure 4. 14: Comparison of islands and bar area for the image set of 1970 and 1973

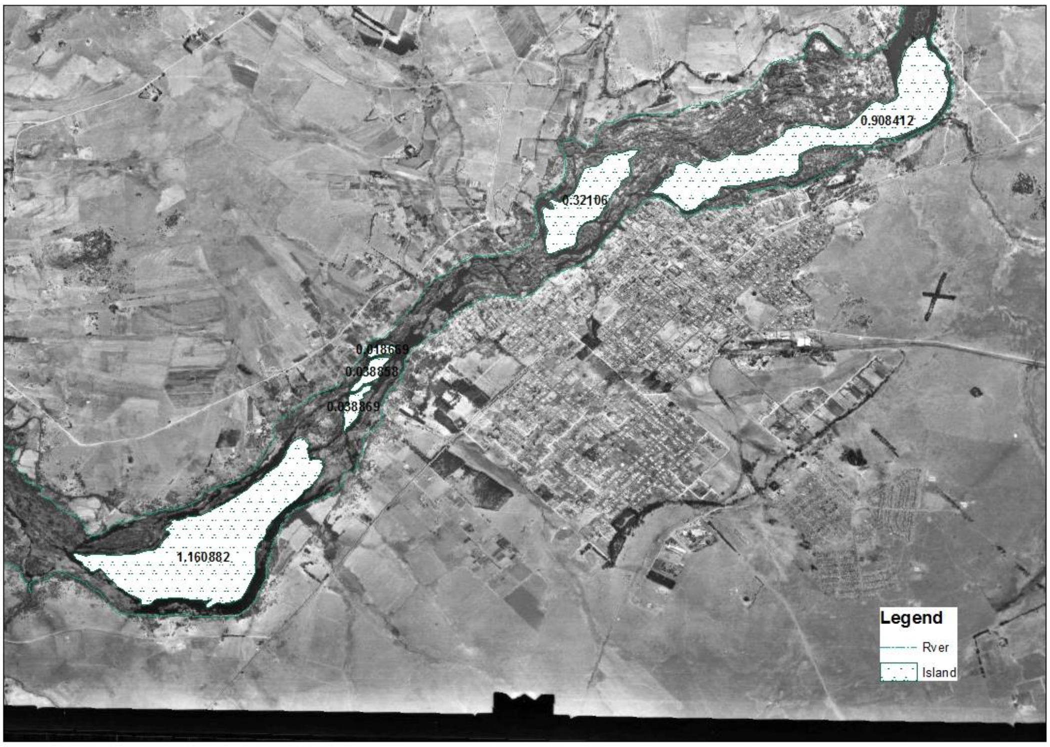


Figure 4. 15: Digitized aerial photographs for the year 1970 and 1973, the numbers inside the island represent the area of the island in km^2

4.3.7. Metrics of flood magnitude, duration and frequency for the period 1973-1991

The flow data for the year 1973-1991 were extracted to determine the metrics of flood magnitude, duration and frequency that could play a role in islands and bars changes over the period 1973 to 1991. For the period 1973-1991 and 1970-1973 the 1975-year flow peak 4251 m^3/s was the highest on record (1973-1991) exceeding 1042.6 m^3/s of 1972 (1970-1973). According to the data from the department of water and sanitation, the 1975 flow peak exceeded the rating table.

During the period 1973-1991 the flow record include one major flow peak that happened in 1975-02-22. The duration of the 1975 flow were determined by observing the daily flow record and the findings indicated that the 1975 flow prolonged for approximately eight days (1975-02-18 to 1975-02-25) with a flow ranging from 2700-4211.6 m^3/s with a corresponding stage of 4.2-5.8 m. When examining the flow data for the period 1970-1973 and 1973-1991 the 1975 flow peak 4211.6 m^3/s prolonged for eight days and exceeded the maximum flow peak (1042 m^3/s) of 1972 which happened once.

The flow peaks for the period 1970-1973 and 1973-1991 were compared to determine the frequency of a particular flow in a record. When comparing the annual flow peaks for the period 1970-1973 and 1973-1991, the highest flow peak of 1975-02-22 (4211.6 m^3/s) exceeded the flow peaks of 1972-01-23 (1042 m^3/s). The annual data indicated that the flow of 1972 (1042 m^3/s) was exceeded seven times in a record for the period 1973-1991. The 1975 (4211.6 m^3/s) flow peaks have a return period of 20-50 years refer to **Table 4.2**. Approximately 95% of the flow on the record length ranges between 0-1000 m^3/s with a return period of 2-5 years refer to **Table 4.2** and **Figure 4.16**.

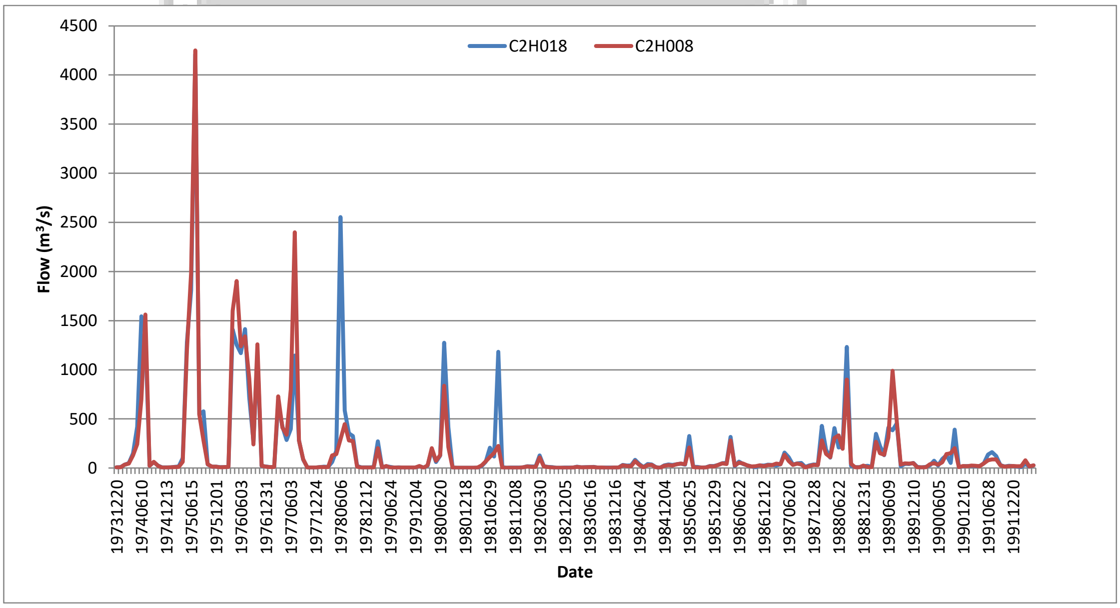


Figure 4. 16: Monthly flow data for the period 1973-1991(gauge weir C2H018 and C2H008)

4.3.8. Metrics of island geomorphological change for the year 1973 and 1991

Time-series image analysis was used to compare islands area changes between 1973 and 1991. The outer boundary of the mainstream channel-set and the primary visible islands where digitized, and the areas of each island were quantified in GIS.

In the upstream reach of the study area the island areas decreased by 0.091 and 0.023 km^2 from 1973-1991.

The small islands areas in the middlestream of the study reach partially decreased by 0.008 and 0.001 km^2.

The downstream island bar area decreased by 0.052 km^2 from the year 1973 to 1991.

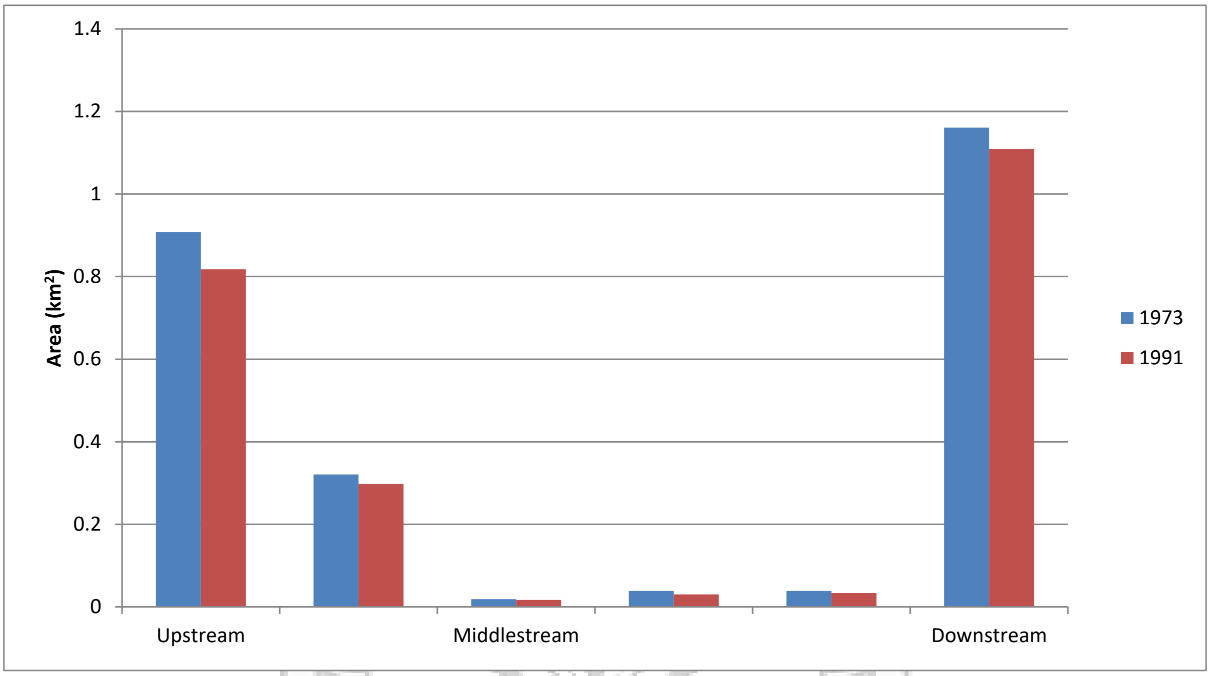
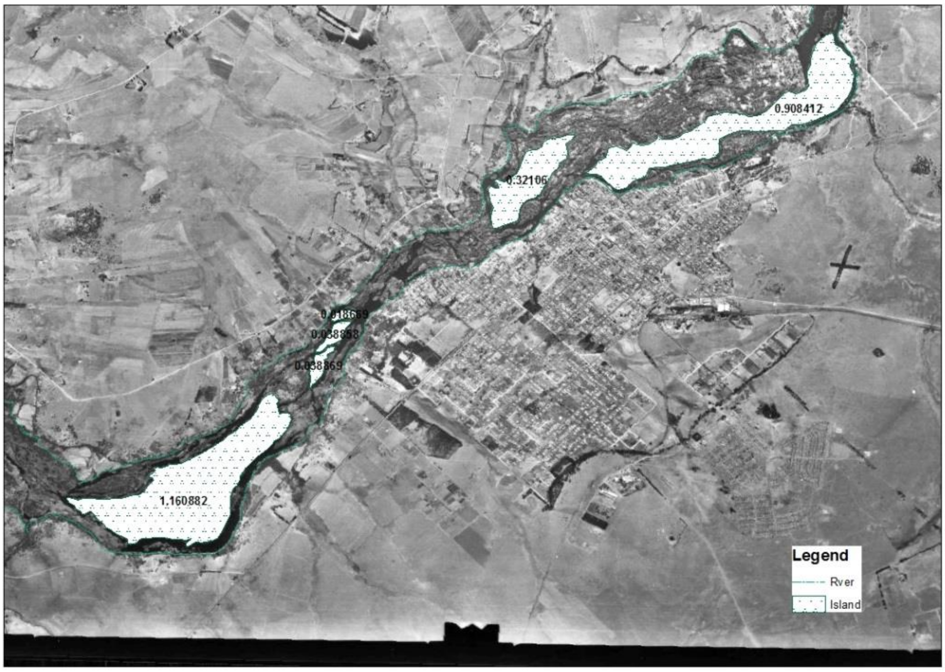


Figure 4. 17: Comparison of islands and bar area for the image set of 1973 and 1991



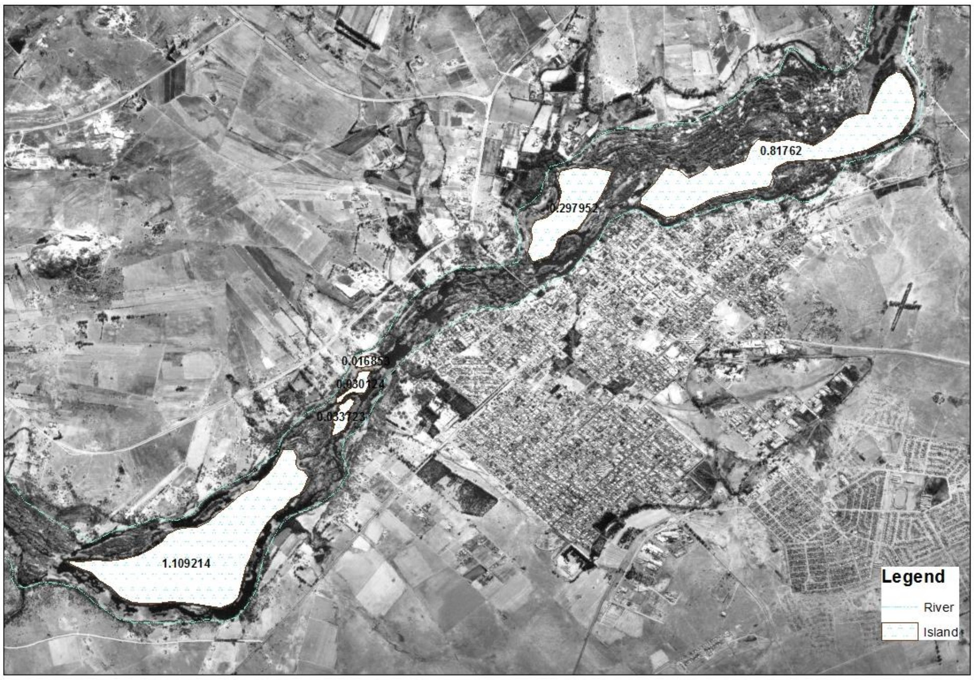


Figure 4. 18: Digitized aerial photographs for the year 1973 and 1991, the numbers inside the island represent the area of the island in km^2

4.3.9. Metrics of flood magnitude, duration and frequency for the period 1991-2001

The flow data for the year 1991-2001 were extracted to determine the metrics of flood magnitude, duration and frequency that could play a role in islands and bars changes over the period 1991 to 2001. For the period 1991-2001 and 1973-1991 the 1975-year flow peak 4211 m^3/s was the highest on record (1973-1991) exceeding 3376.6 m^3/s of 1996 (1991-2001). The flow peak occurs during the summer. For the period 1991 to 2001 only the station C2H018 was used, station C2H008 data end in 1996 and C2H140 data start mid-1996.

During the period 1991-2001 the flow record include three major flow peaks that happened in 1996-02-18, 1997-05-27 and 2000-02-13. The duration of the 1996 flow peaks was determined by observing the daily flow record and the 1996 flow prolonged for approximately seventeen days (1996-02-14 to 1996-03-01) with a flow ranging from 2000-3376.6 m^3/s with a corresponding stage of 3.8-4.9 m. When examining the flow data for the period 1973-1991 and 1991-2001 the 1975 flow peak 4211.6 m^3/s prolonged for eight days and exceeded the maximum flow peak (3376.6 m^3/s) of 1996 which prolonged for seventeen days.

The flow peaks for the period 1973-1991 and 1991-2001 were compared to determine the occurrence of a maximum flow peak in a record. When comparing the annual flow peaks for the period 1973-1991 and 1991-2001, the highest flow peak of 1975-02-22 (4211.6 m^3/s) exceeded the flow peaks of 1996-02-18 (3376.6 m^3/s). The annual data indicate that during this period 1973-1991 and 1991-2001 the flow of 1996 (3376.6 m^3/s) was exceeded once in a record by the flow of 1975-02-22 (4211.6 m^3/s). The 1996 flow peak has a return period of 20-50 years refer to **Table 4.2**. Approximately 95% of the flow on the record length ranges between 0-500 m^3/s with a return period of 2-5 years refer to **Table 4.2** and **Figure 4.19**.

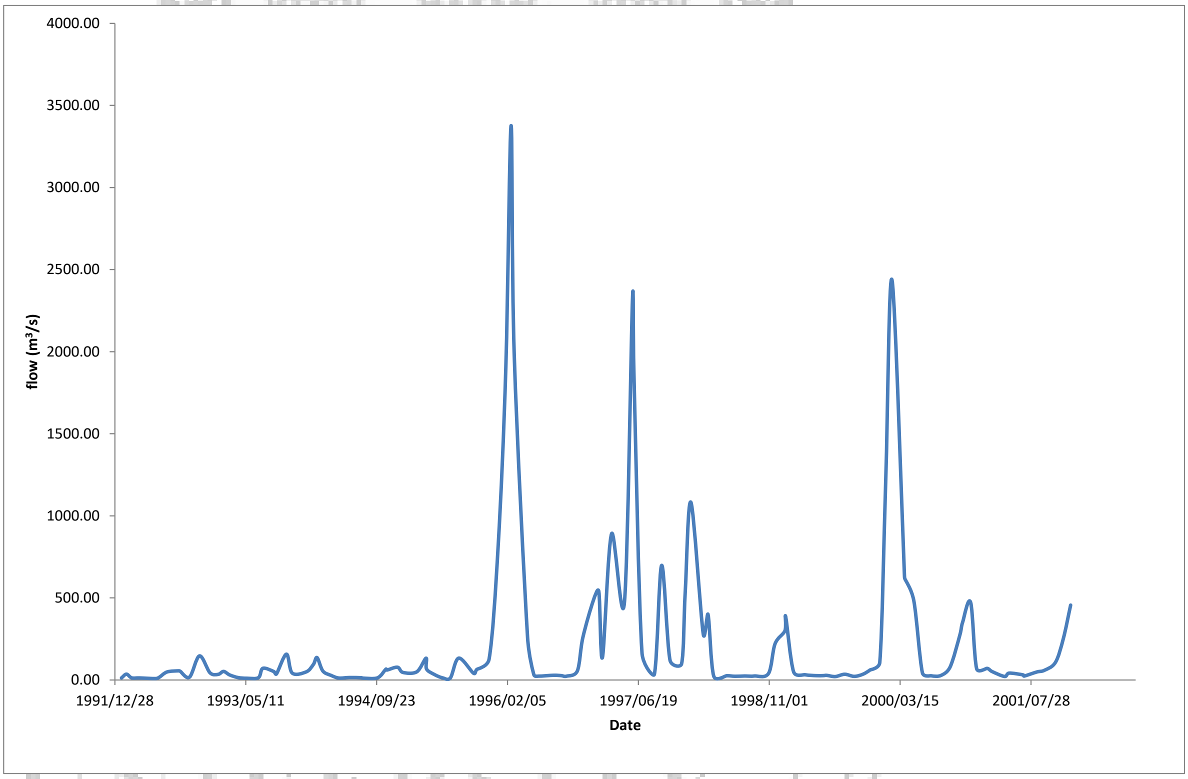


Figure 4. 19: Monthly flow data for the period 1991-2001 for gauge weir C2H018

4.3.10. Metrics of island geomorphological change for the year 1991 and 2001

Time-series image analysis was used to compare islands area changes between 1991 and 2001. The outer boundary of the mainstream channel-set and the primary visible islands where digitized, and the areas of each island were quantified in GIS.

From the digitised images results the upstream island areas increased by 0.024 and 0.043 km^2 from 1991 to 2001.

The small islands areas in the middlestream of the study reach increased by 0.005 and 0.003 km^2 from year 1991-2001. The islands were quite small and images were not visible enough to identify the contact of water and vegetation.

The large downstream island bar area increased by 0.018 km^2 from the year 1991 to 2001.

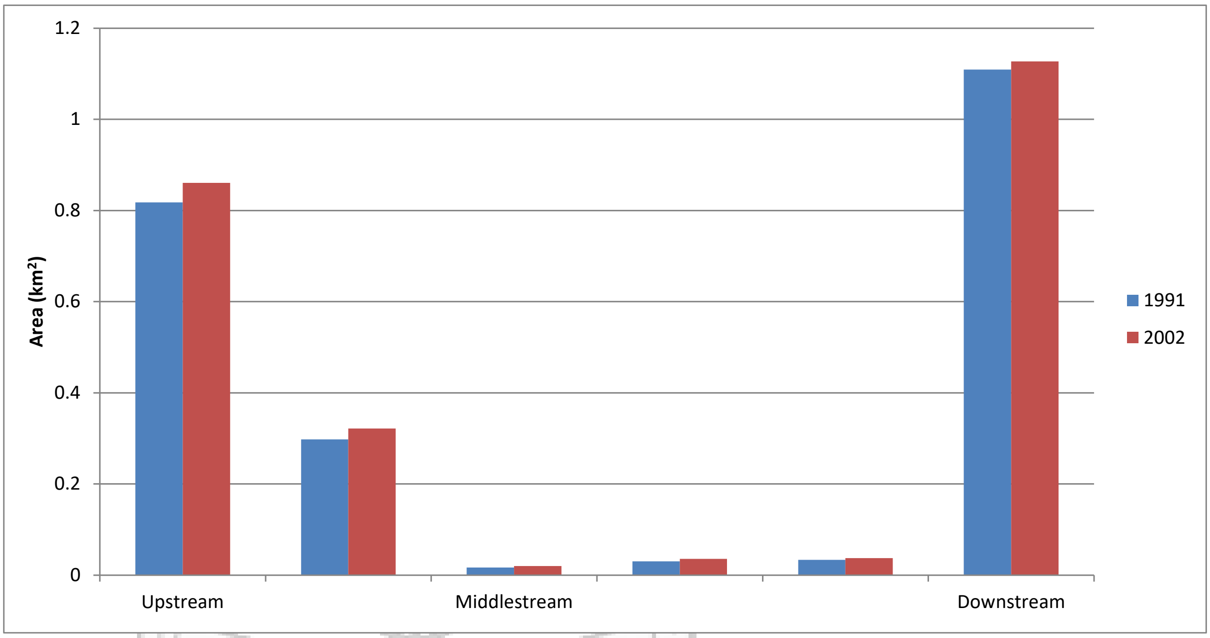
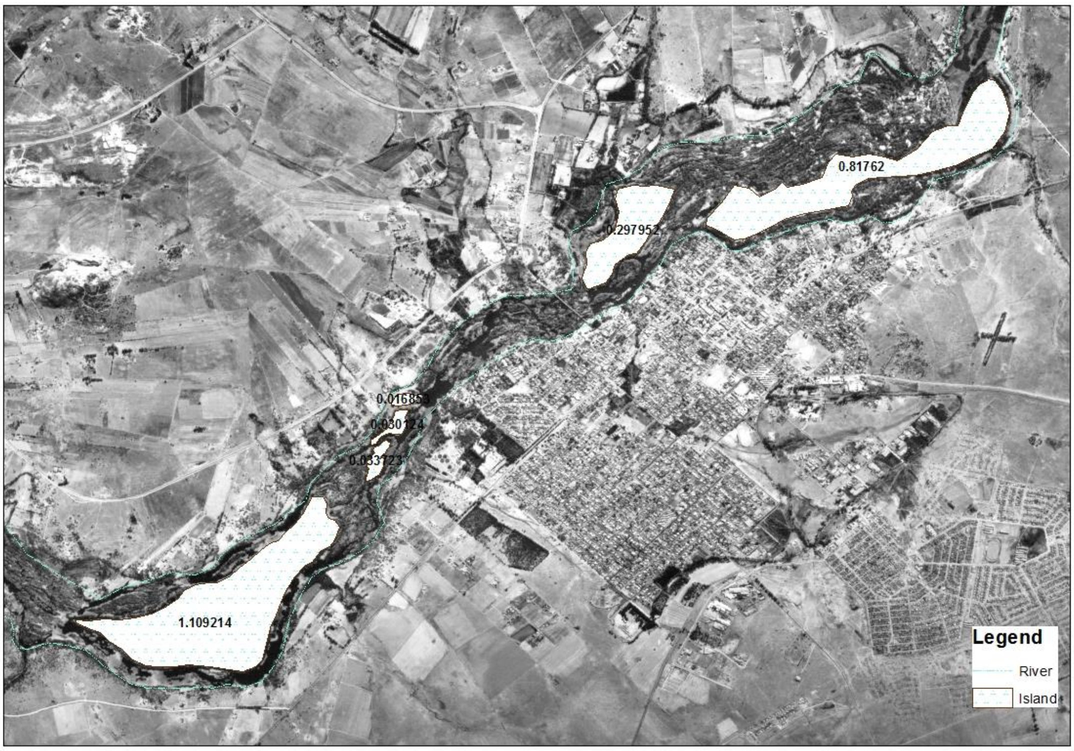


Figure 4. 20: Comparison of islands and bar area for the image set of 1991 and 2002



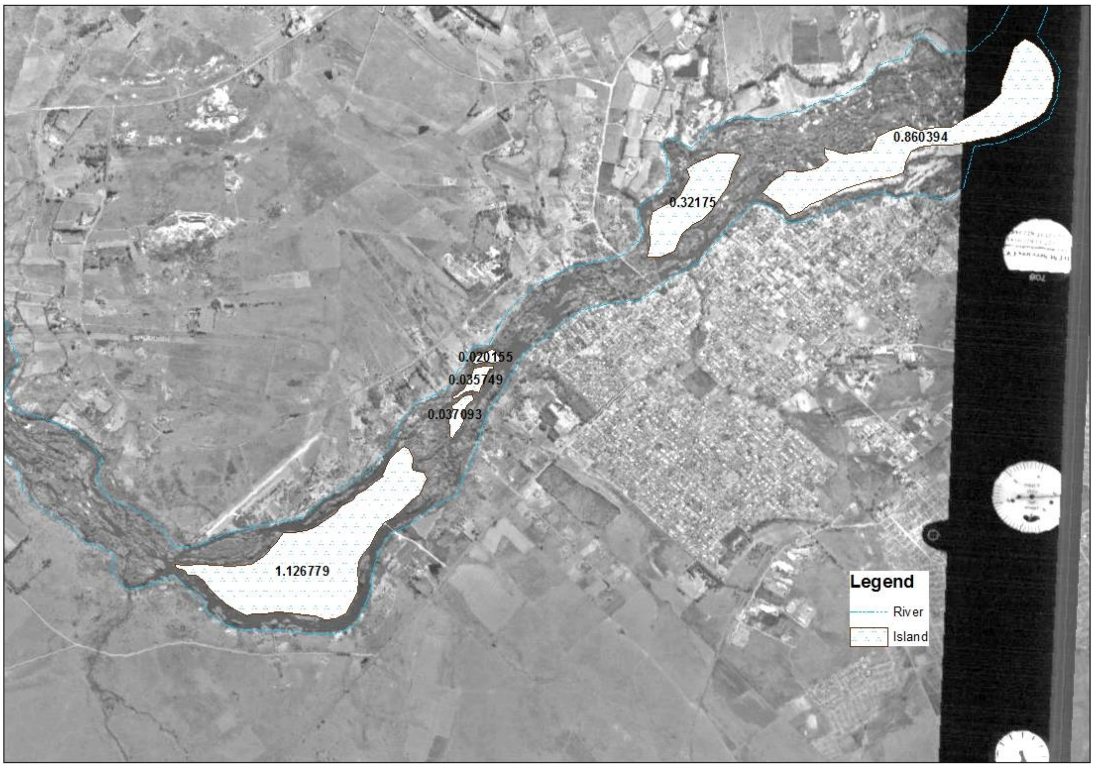


Figure 4. 21: digitized aerial photographs for the year 1991 and 2001, the numbers inside the island represent the area of the island in km^2.

4.4. Metrics of flood magnitude, duration and frequency and metrics of island geomorphological change from 2006-2015

4.4.1. Metrics of flood magnitude, duration and frequency for the period 2006-2012

The flow data for the year 2006-2012 were extracted to determine the metrics of flood magnitude, duration and frequency that could play a role in islands and bars changes over the period 2006 and 2012. For the period 2006-2012 and 2001-2006 the 2011 year flow peak 3550.6 m^3/s is the highest on record (2006-2012) exceeding 1523.7 m^3/s of 2006 (1991-2001). The high flow peaks occurred during summer.

The daily flow record indicates that the 2010 and the 2011 flows prolonged for approximately six days (2010-01-28 to 2010-02-03) and (2011-01-06 to 2011-01-11) with a flow ranging from 2000-3550.6 m^3/s with a corresponding stage of 3.7 and 5.1 m. When examining the flow data for the period 2006-2010 the flow peak of 3550.6 m^3/s exceed the flow peak of 2006 (1523.7 m^3/s).

During this period the annual flow record comprised two major flow peaks which occurred in 2010-01-30, and 2011-01-08. When observing the annual flow for the period 2006-2012 the flow of 2011 (3550.6 m^3/s) exceeded the flow of 2006. When comparing the annual flow peaks for the period 2001-2006 and 2006-2012, the highest flow peak of 2011-01-08 (3550.6 m^3/s) exceeded the flow peaks of 2006-03-03 (1523.7 m^3/s). The annual data indicate that during this period 2001-2006 and 2006-2012 the flow of 2006 (1523.7 m^3/s) was exceeded twice in a record by the flow of 2010-01-30 (2775.26 m^3/s) and 2011-01-08 (3550.6 m^3/s). The 2011 flow peak has a return period of 20-50 years refer to **Table 4.2**. Approximately 95% of the flow on the record length ranges between 0-500 m^3/s with a return period of 2-5 years refers to **Table 4.2.**

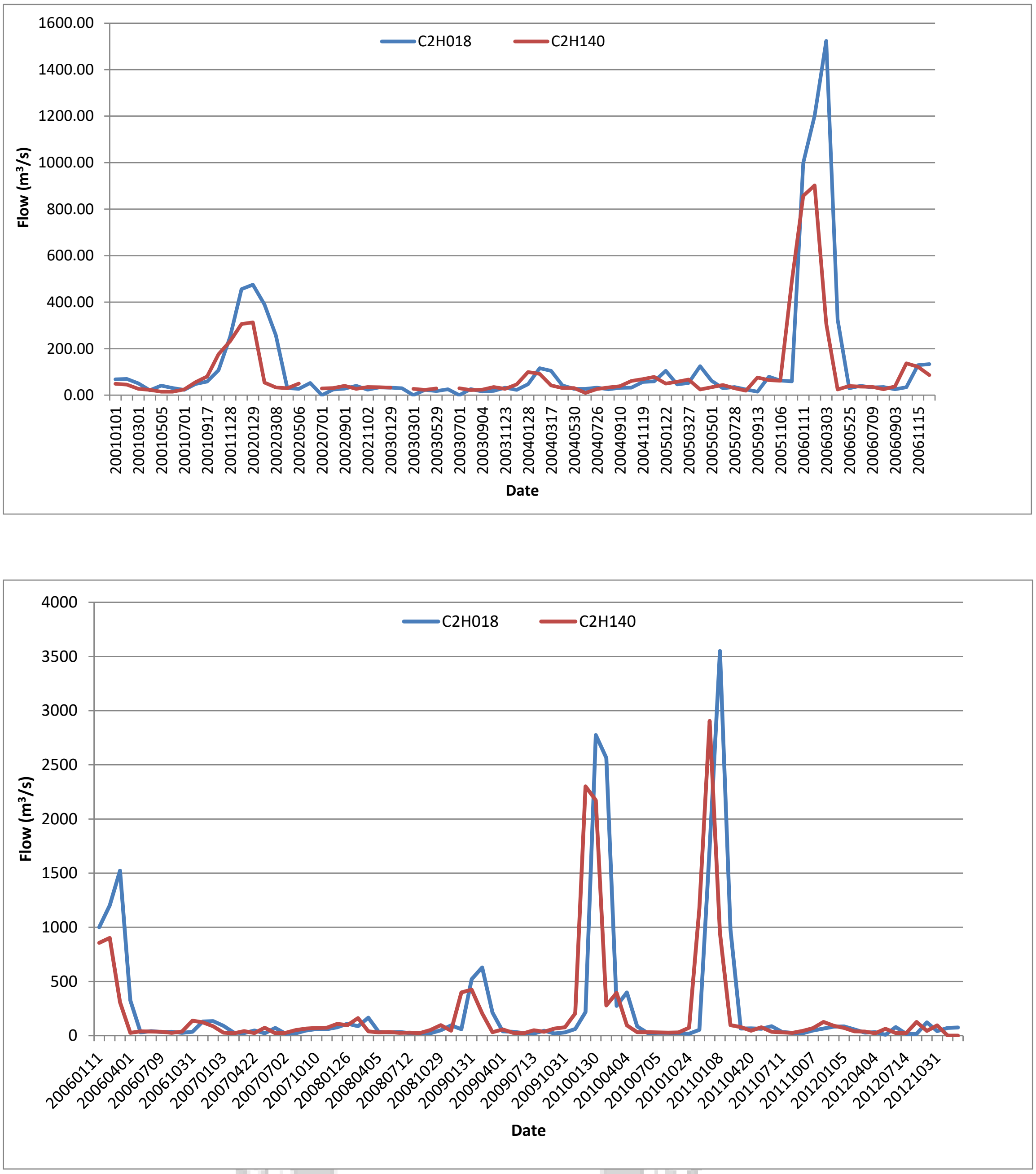


Figure 4. 22: Monthly flow data for the year 2001-2006 and 2006-2012 from gauge weir C2H018 and C2H140

4.4.2. Metrics of island geomorphological change for the year 2006 and 2012

Time-series image analysis was used to compare islands area changes between 2006 and 2012. From the year 2006 to 2015 the rectified othorimages were obtained, and more islands and bar were digitized and the areas were quantified (23 in total) to detect the changes between 2006 and 2012.

The digitised aerial images results indicate that the big islands areas in the upstream of the study area decreased by 0.016 and 0.0287 km^2 from 2006 to 2012. The small islands and bars in the upstream were not showing clear changes some partially decreased and some slightly increased from 2006 to 2012. These changes can be due to error in digitising since the islands were quite small and images were not visible enough to identify the contact of water and vegetation.

The small islands and bar areas in the middlestream of the study reach decreased by 0.008 to 0.001 and from the year 2006 and 2012.

The two large downstream islands areas decreased by 0.01 and 0.04 from the year 2006 to 2012 and the small islands and bars areas did not show a clear change, since two of the bars areas increased.

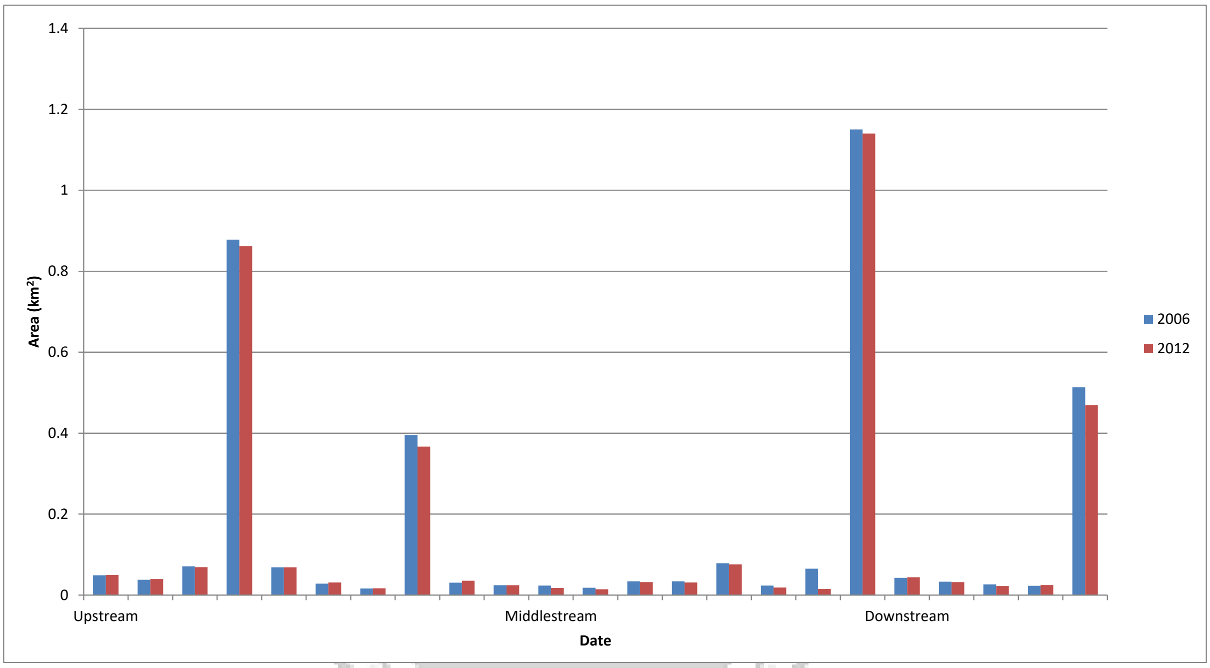


Figure 4. 23: Comparison of islands and bar area for the image set of 2006 and 2012,

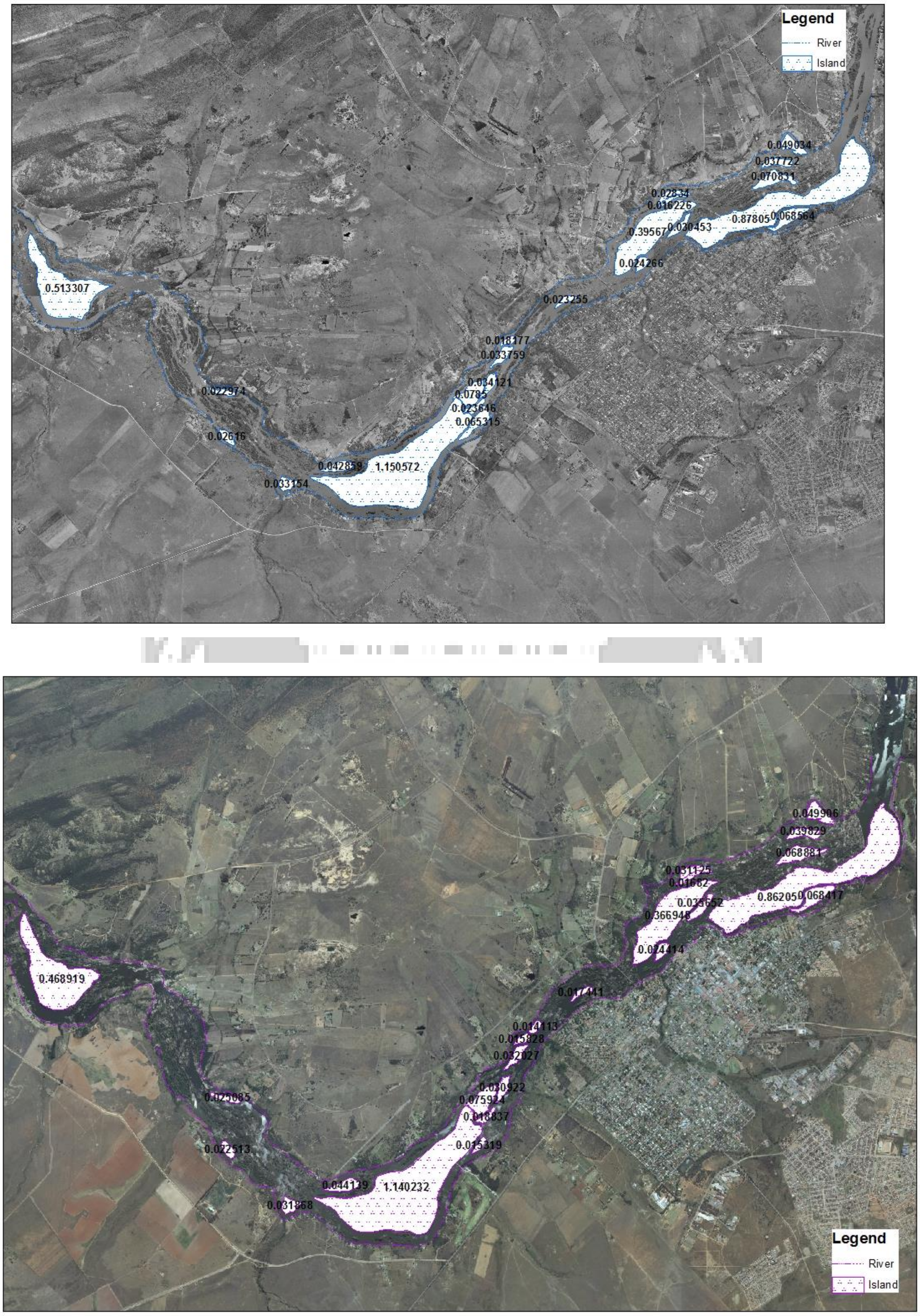


Figure 4. 24: digitized aerial photographs for the year 2006 and 2012, the numbers inside the island represent the area of the island in km^2.

4.4.3. Metrics of flood magnitude, duration and frequency for the period 2012-2015

The flow data for the year 2012-2015 were extracted to determine the metrics of flood magnitude, duration and frequency that could play a role in islands and bars changes over the period 2012 and 2015. For the period 2012-2015 and 2006-2012 the 2011 year flow peak 3550.6 m^3/s was the highest on record (2006-2012) exceeding 1410.4 m^3/s of 2014 (2012-2015). The high flow peak occurred during summer.

The 2014 flow prolonged for approximately five days (2014-03-11 to 2014-03-15) with a flow ranging from 1000- 1410.5 m^3/s with a corresponding stage of 2.2 and 2.7 m. When examining the flow data for the period 2006-2012 and 2012-2015 the 2011 flow peak of 3550.6 m^3/s exceeded the flow peak of 2014 (1410.5 m^3/s).

During the period 2012-2015 the annual flow record has one major flow peak which occurred in 2014-03-11. When observing the annual flow for the period 2012-2015 the flow of 2014 (1410.5 m^3/s) is less than the flow of 2011. When comparing the annual flow peaks for the period 2006-2012 and 2012-2015, the highest flow peak of 2011-01-08 (3550.6 m^3/s) exceeded the flow peaks of 2014-03-11 (1410.5 m^3/s). The annual data indicate that during that period 2006-2012 and 2012-2015 the flow of 2014 (1410.5 m^3/s) was exceeded twice in a record by the flow of 2010-01-30 (2775.26 m^3/s) and 2011-01-08 (3550.6 m^3/s). The 2014 flow peak has a return interval of 5-10 years refer to Table 4.2. Approximately 95% of the flow on the record length ranges between 0-300 m^3/s with a return period of 2 years refers to **Table 4.2** and **Figure 4.25.**

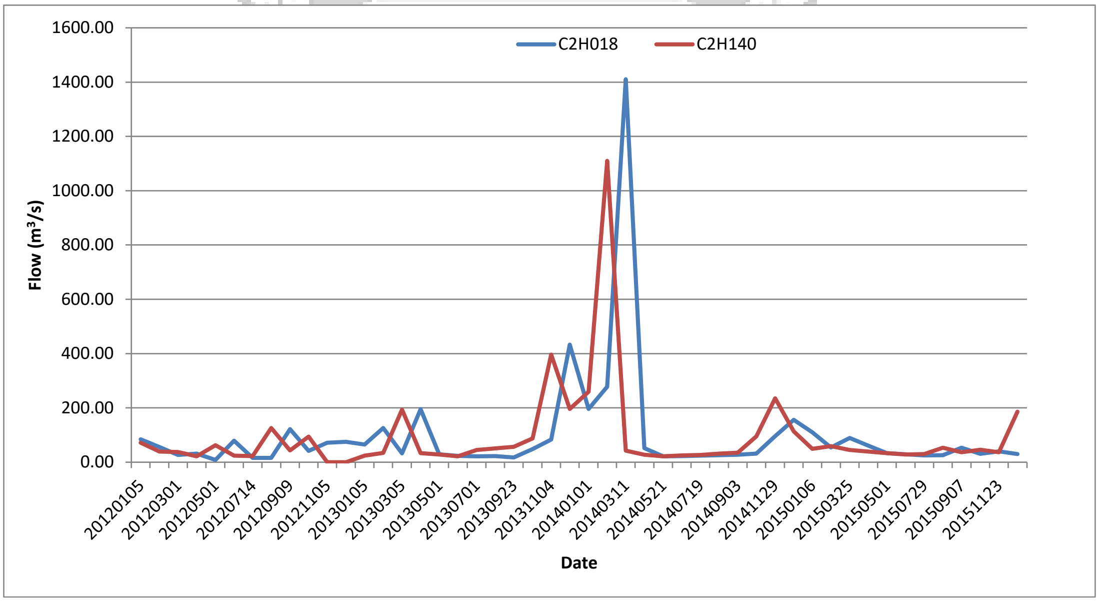


Figure 4. 25: Daily flow data for the year 2012-2015

4.4.4. Metrics of island geomorphological change for the year 2012 and 2015

Time-series image analysis was used to compare islands area changes between 2012 and 2015.

The large islands areas in the upstream of the study area decreased by 0.008 and 0.041 km^2 2012 to 2015. Most of the upstream small island bars decreasing from 2012 to 2015.

The changes in the middlestream was not clear since most of the small islands and bar areas decreased and some increased from 2012 to 2015.

From the digitised aerial images results one of the large downstream island bar area increased by 0.01, the other one decreased by 0.06 from 2012-2015 and the small islands bar areas increased by 0.004 to 0.02 km^2 from 2012 to 2015.

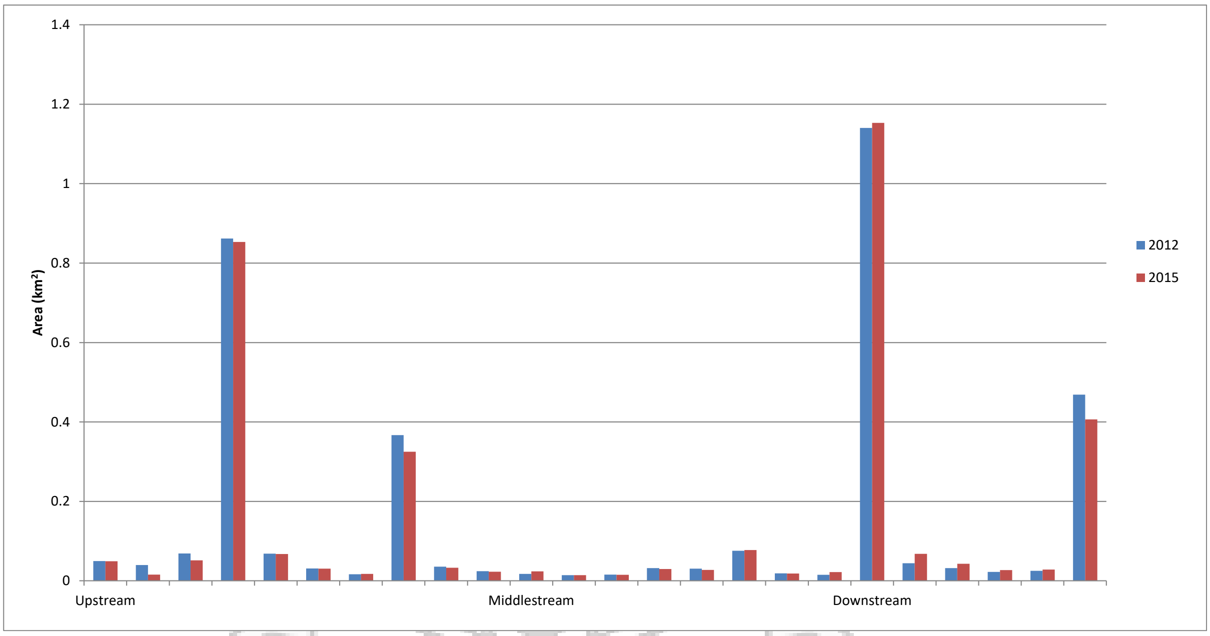


Figure 4. 26: Comparison of islands and bar area for the image set of 2012 and 2015

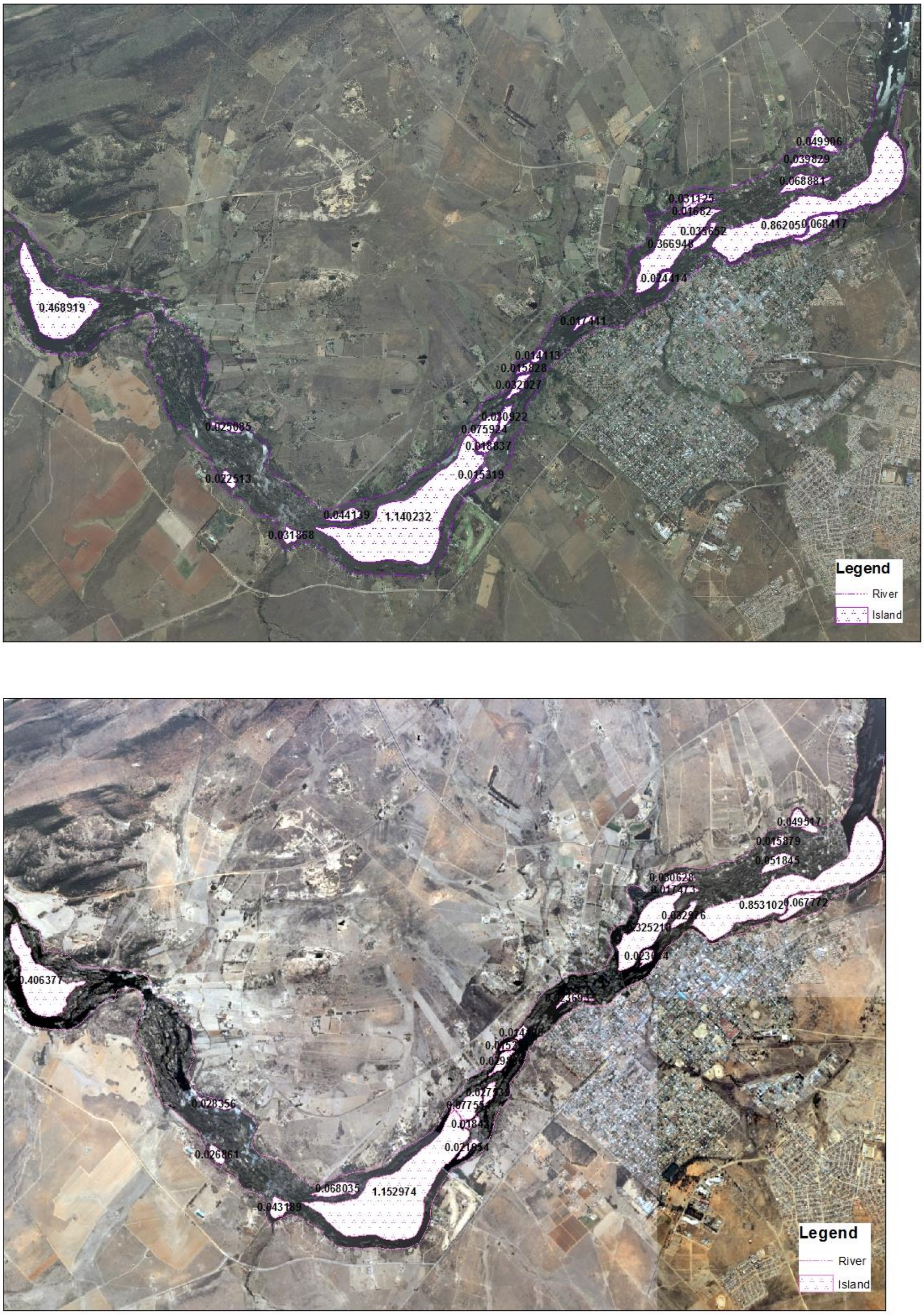


Figure 4. 27: digitized aerial photographs for the year 2012 and 2015, the numbers inside the island represent the area of the island in km^2.

CHAPTER 5: DISCUSSION

5.1. Introduction

The current chapter discusses results of the effect of flood dynamics on island geomorphology and relationships between metrics of flood magnitude, duration and frequency and metrics of island geomorphological change over the past ~78 years that will provide insight into how the river may change in relation to the observed flow variability. The argument in the present chapter is that the flood of rare magnitude of short duration and infrequent can play a role in island geomorphological changes and the metrics island geomorphological change can be detected and measured using image analysis. The results from the aerial image acquisition and analysis and historical flow peak events provide an opportunity to analyse and interpret flood-related change along mixed bedrock-alluvial anabranching river.

5.2. Metrics of flood magnitude, duration and frequency

Metrics of flood magnitude, duration and frequency that could play a role in fluvial island geomorphological change were investigated in this study. From the results obtained from the historical gauge weir record, flow peaks that exceed 3010 m^3/s occur infrequently in the area of study, and are thus considered to be rare magnitude and infrequent events. The 1975 flow peak (4211.6 m^3/s) was the highest on record and was sustained for 6-8 days, and exceeded the rating table for the gauge. The frequency or the probability of occurrence of such particular floods >3010 m^3/s is 20-50 years. Approximately 80% of the magnitude of the flow peaks range between 0-1000 m^3/s, and the frequency of such particular flow peaks ranges between 5-<2years. The historical flow record indicates that the area of study is dominated by moderate and low flows.

The duration of the flow peaks were also examined to determine duration of the flow that has an impact on island area changes. When observing the duration of all flow peaks that exceed 3010 m^3/s and has a return period of 20-50 years, from 1944, 1957, 1975, 1996 and 2011, the 1975 and 2011 flow peaks were sustained for a shorter duration (6-8 days) while the 1996 peak was sustained for 19 days. The flow peaks' magnitude, frequency and duration were compared from year to year in order to determine the metric of flow that has an impact on the fluvial island geomorphology and river channel changes for the past 78 years (1938-2015). It was observed that during the year 1975 the island area decreases in association with a flow peak of rare magnitude, infrequent and shorter duration.

5.3. Metrics of island geomorphological change

Metrics of island geomorphological change that can be detected and measured using image analysis were investigated and presented. The island bar areas were measured and the channels were digitised to detect any changes that might have occurred over the period of 78 years. From the results obtained the island bar area within the upstream part of the reach shows little change and the changes were consistent in all the images. The changes in most of the small island bars in the middle part of the study reach were not consistent. The inconsistency can be due to error in georeferencing and digitizing, since most of the images used are scanned black and white and it is not easy to identify the contact of water and vegetation for small islands. Even on the rectified images from the year 2006-2015 the changes in most of the small islands were not consistent and not showing clear trends. The large islands bars downstream of the study reach also shows some minor changes and the changes were consistent in all the images for the whole period. A possible implication of this is that the larger islands are more stable overall and respond in a predictable way to changes in flow, perhaps due to the presence of rock within the island core, or induration of sediment (Tooth and McCarthy, 2004). Smaller islands may be composed of alluvium that is more mobile over a wider range of flows.

5.4 Relationships between metrics of flood magnitude, duration, frequency and island geomorphological changes

Changes in island areas were mapped according to the availability of aerial photography (refer to Chapter 3). In order to be able to determine which metrics of flood magnitude, frequency and duration could play a role in island geomorphological changes, the metrics of flow was analysed from year to year when the aerial images where available. The visible islands and bars where digitised and the area of the islands were quantified in order to detect the changes over period of 78 years. The relationship between the metrics of flood and island geomorphological changes were determined from 1938-2016.

The 1938-1961 and 1961-1970 flow peak and digitised islands area where compared to determine the changes over the period. For the period 1938-1961 and 1961-1970 the 1944 flow peak (3717.7 m^3/s) is highest on the record followed by the 1957 flow peak 3411.5 m^3/s and 3214.4 m^3/s, when compared to the 1967 flow peak 2226.1 m^3/s, the duration for the flow peak of 1944 prolonged for eleven days and twelve days for 1957 while the 1967 prolonged for 5 days and the frequency of the 1944 flow peak with a return period of 20-50 years occurred three times in a record exceeding the 1967 flow peak with a return period of 10-20 years which only occurred once in 1961-1970 period. When looking at the island and bar areas for the period 1938-1961 and 1961-1970, the 1961 island and bar areas are partially increasing as compared to the 1938 and partially decreasing compared to 1970.

The 1961-1970 and 1970-1973 flow peak and digitised islands area where compared in order to determine the changes over the period. For the period 1961-1970 and 1970-1973 the 1967 flow peak (2226.1 m^3/s) is highest on the record when compared to the 1972 flow peak 1042.6 m^3/s, the duration for the flow peak of 1967 prolonged for five days while the 1972 flow peak prolonged for one day and the frequency of the 1967 flow peak with a return period of 10-20 years occurred once in a record (1961-1970) and the 1972 flow peak with a return period of 2-5 years which only occurred once during 1961-1970 period. The results for the island and bar areas for the period 1961-1970 and 1970-1973 indicate that the 1970 island and bar areas are partially increasing as compared to the 1961 and partially decreasing compared to 1973.

The 1970-1973 and 1973-1991 flow peak and digitised islands area where compared. For the period 1970-1973 and 1973-1991 the 1975 flow peak (4211.6 m^3/s) is the highest on the record when compared to the 1972 flow peak 1042.6 m^3/s, the duration for the flow peak of 1975 prolonged for eight days while the 1972 flow peak occurred for one day and the frequency of the 1975 flow peak with a return period of 20-50 years occurred once in a record (1973-1991) and the 1972 flow peak with a return period of 2-5 years only occurred once during 1961-1970 period. The results for the island and bar areas for the period 1970-1973 and 1973-1991 indicate that the 1973 island and bar areas are partially increasing as compared to the 1970 and 1991.

The 1973-1991 and 1991-2001 flow peak and digitised islands area where compared in order to determine the changes. For the period 1973-1991 and 1991-2001 the 1975 flow peak (4211.6 m^3/s) is highest on the record when compared to the 1996 flow peak 3376.6 m^3/s, the duration for the flow peak of 1975 prolonged for eight days while the 1996 flow peak prolonged for nineteen days and the frequency of the 1975 flow peak with a return period of 20-50 years occurred once in a record (1970-1975) and the 1996 flow peak with a return period of 20-50 years only occurred once during 1991-2001 period. The results for the island and bar areas for the period 1973-1991 and 1991-2001 indicate that the 1991 island and bar areas are partially decreasing as compared to the 1973 and 2001, the 2001 island and bar areas are partially increasing as compared to the 1991.

The 2006-2012 and 2012-2015 flow peak and digitised islands area where compared in order to determine the changes. For the period 2006-2012 and 2012- 2015 the 2011 flow peak (3550.6 m^3/s) is highest on the record when compared to the 2014 flow peak 1410.4 m^3/s, the duration for the flow peak of 2011 prolonged for six days while the 2014 flow peak prolonged for five days and the frequency of the 2011 flow peak with a return period of 20-50 years occurred once in a record (2006-2012) and exceed the 2014 flow peak with a return period of 5-10 years which also occurred once during 2012-2015 period. The results indicate that island areas for the period 2006-2012 and 2012- 2015 are partially decreasing except some of the 2015 islands and bars downstream of the study reach.

Relationships between metrics of flood magnitude, duration, frequency and island geomorphological changes were investigated for the study area. From the results obtained the impact of the largest historical floods in the area of study for the year 1944, 1957, 1975, 1996 and 2011 with a 20-50 years return period were observed and compared with the changes in islands bar areas. The island bar areas partially decrease from the aerial image of 1961 after the historical largest flow of 1944 and 1957 when compared to the year image of 1971. The island bar areas partially decreases from the aerial image of 1991 after the historical largest flow of the year 1975 when compared to the previous year image of 1973. The island bar areas partially increase from the aerial image of 2001 when compared to the previous year image of 1991 since the flow peak of 1996 was lower than that of 1975 and prolonged for longer duration, the island bar areas partially decrease from the aerial image of 2012 after the historical largest flow of 2011 when compared to the previous year image of 2006.

From the results obtained in this study there is a few general relationships emerge. Firstly, from high to low flow transitions the island bars areas partially increase, and from low to high flow transitions the islands bar areas partially decreases. This is a typical function of sedimentation during waning flood periods, and erosion during the flood rise (Heritage et al., 2004). From 1938 to 1973 the flow peaks were decreasing and the island bar areas were increasing, and from 1975 the flow peaks increase and island bar areas decrease. There are a few exceptions to this, such as the flow peaks decreasing during the year 1996 and the island bar areas decreasing, and from 2006-2015 the flow peaks of 2006 were lower than that 2012 yet the islands and bar areas increased as compared to 2012.

5.5. Comparison with previous studies in South Africa

Orange River Northern Cape

The Orange River is characterised by multiple channels which divide and re-join around semi-permanent ridges or islands (anabranching river). The flow regime in the Orange River is highly variable, with low flows followed by infrequent large summer flood events. The 1988 flood was a 1-in-20-year event, peaking at 8300 m^3/s with a height of 9.43 m (du Plessis et al., 1989; Zawada and Smith, 1991). The 1988 flood covered the entire valley surface and resulted in loss of life and damage to infrastructure. The geomorphic changes in the area of study were moderately uncertain, with bank erosion along the main channels considered insignificant but with erosion and deposition occurring on areas of floodplain (du Plessis et al., 1989; Zawada, 1991; Zawada and Smith, 1991).

The geomorphology of the Orange River in the Northern Cape Province is dominated by point bar-like features that are up to 5 km long and 1-2 km wide and bedrock islands (Zawada and Smith, 1991). The islands and bars are vegetated and separated by river channels of up to 30 m wide. Zawada and Smith (1991) noted that during the year 1988 Orange River experienced flood, and the water overtopped almost the entire area between the rock-cut, basement terraces (Zawada and Smith, 1991). From the aerial photograph of the year 1944-1988, it was revealed that the position of the large bars, island and main channels have not changed in the past 46 years (Zawada and Smith, 1991). The stabilities of the observed bar, island and channel can be due to an underlying basement control , since it was observed that in some places the fluvial pattern in the Orange river controlled by basement exposures (Zawada and Smith,1991). The Orange River islands are vegetated and this shows some degree of stability.

These results are broadly consistent with the current study of the Vaal, which has shown that large islands are more stable and change in a more predictable way than small islands. The islands and bars in the Vaal River indicate some degree of stability as those in the Orange River as they did not change position over the past 78 years and even during occasional flow of rare magnitude that prolong for shorter duration with a 20-50 years return period. For both the Orange and Vaal River the stabilities of the observed bar, island and channel can be due to an underlying basement control.

5.6. Implications

- duration e.g. flow of 1975 and 2011.

- The island and bar area decreases during large magnitude e.g. 1975 and 2011 in the area of study,
- Island and bar areas increases when the flow is from high to low and when the flow prolong for longer duration e.g. 1996 flow peak and 2001 islands and bars.

The flood modelling exercise performed at Sabie River indicates that sediment yield from the catchment is mainly associated with large flood events (Heritage et al, 2004). During rare large floods the river is able to transport a large sediment load which may results in reduction of island bar areas. The relationships between metrics of flood magnitude, duration, frequency and island geomorphological changes, which were observed during high to low flow the island bar increases, due to sediment being deposited during waning flow periods after high flow periods when sediment has been mobilised.

From the flow data results and quantified aerial images it appears that the islands in the area of study are susceptible to minor changes, since for the whole period the changes which were detected were very small. Due to minor changes in the island and bar areas these islands show some stability as they are not prone to major changes even during rare magnitude floods. This is characteristic of anabranching rivers in general (Kleinhans, 2010), but especially mixed bedrock-alluvial anabranching (Tooth and McCathy 2004). The time-series image analysis for the period 1938 to 2015 shows that the positions of the large and small islands and main channels have not changed substantially in the past 78 years. The stabilities of the observed islands and channels is likely due to an underlying bedrock control, as it was observed that in many places the fluvial pattern in the Vaal River is controlled by underlying bedrock.

CHAPTER 6: CONCLUSION

In order to review and determine the metrics of flood magnitude, duration and frequency that could play a role in fluvial island geomorphological change, the historical flow peak data from the three gauging station for the year 1938 to 2016 was utilised, and data was sourced from HYDSTRA (Department of Water and Sanitation Database). The graphical representation of data method from statistical were utilised in this study to determine the changes of flow metrics from year to year and the Cunene plotting position method was used to determine the frequency of such particular flood. The flow peaks were compared from year to year when the aerial photographs were available to detect the changes.

Historical aerial photograph images for different years were sourced from National Geo-spatial Information (NGI) in order to review and determine metrics of island geomorphological change that can be detected and measured using image analysis. A qualitative but verified analysis of aerial photographs was used to reveal some important island morphological changes. The island bar area where digitised and measured using GIS 10.2.2.

To investigate relationships between metrics of flood magnitude, duration and frequency and metrics of island geomorphological change over the past ~78 years that will provide insight into how the river may change in relation to the observed flow variability, the measured islands bar area and the plotted flow peaks were compared from year to year to detect island changes.

The results reveals these relationship: island and bar areas decreases during infrequent high flow magnitude that prolong for shorter duration with a return period of 20-50 years and island and bar areas increases during regular flows that prolonged for longer duration with a return period of 10-20 years and less and when the flow is from high to low.

Because of the limited data in aerial images in this study it was not possible to investigate the effects of individual floods from year to year. Historical aerial photograph images for the year 1938, 1961, 1970, 1973, 1984, 1991, 2002, are scanned black and white images and is not easy to see where the is a contact of water and vegetation when georeferencing and digitising in GIS, and six islands were mapped. Some of changes in small island areas were due to error in georeferencing and digitizing since the islands are quite small and images are not visible enough to identify the contact of water and vegetation.

From the discussion above the effects of flood dynamics on island geomorphology in a large mixed bedrock-alluvial anabranching river, in relation to channel and island geomorphological changes and metrics of flood magnitude, duration and frequency need further investigation in the area of study.

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